TIME AND SPACE IN PROCESS CONTROL

csapc '97

EDITORS
SEBASTIANO BAGNARA
ERIK HOLLNAGEL
MICHELE MARIANI
LEENA NORROS

SIXTH EUROPEAN CONFERENCE ON COGNITIVE SCIENCE APPROACHES TO PROCESS CONTROL

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Errata Corrige

Errors in the 'Contents' section:

Zardetto G., Majni M., Nicoletti R., Bagnara S.
is:
Zardetto G., Maini M., Nicoletti R., Bagnara S.

Cara F.
is:
Cara F. and Lagrange V.

Strönberg D.
is:
Strömberg D. and Alfredson J.

Page 9, third line, name mispelling:

Majni is Maini

Page 12, last line, uncomplete sentence:

This process took place in the continous comparison with the opportunities ...

.... offered by the new tool with those of the traditional one.

G.V.

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Erik Hollnagel
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FOREWORD

Cognitive Science Approaches to Process Control (CSAPC) is a conference series initiated in 1987 by a number of well-known experts in cognitive psychology, man-machine systems, and artificial intelligence research. The purpose of the CSAPC conference is to bring together researchers from different disciplines to present and discuss recent results regarding socio-technical problems in the control of complex environments.

In the world of large, multi-disciplinary, multi-track conferences, the conference on Cognitive Science Approaches to Process Control remains firmly rooted in the principle of a small, single track, limited focus conference. It has never been an aim of the CSAPC to have a big conference with a large number of participants. On the contrary, the organisers have always striven to keep the size of the conference to a reasonable level and to make it affordable to attend.

Since 1987, this principle has turned out to be very successful in the CSAPC conferences. The single focus on process control applications has never narrowed the discussions or the views presented at the conferences, but has rather been instrumental in maintaining a high technical level and in keeping a firm link to practice and reality. The CSAPC conferences have also been successful in attracting a broad audience, and in particular in bringing new people into the field.

The number of papers that are submitted has been growing, and the success has therefore to some extent become a problem for the organisers. Yet rather than depart from the principle of a single track of presentations or extend the conference with a fourth day, the solution has been to assign a number of papers to sessions with shorter presentations. In this way all participants still have an opportunity to hear all the presentations and to contribute to the discussions. Although this solution is a compromise, the organisers hope that it is acceptable both to the presenters and the participants, and will very much appreciate any feedback and comments, to ensure that the conferences continue to achieve their main goals and maintain the high technical standard.

The theme of the sixth CSAPC conference is "Time and space in process control". Process control can be said to encompass time and space in several ways.

Firstly, dynamic processes are themselves distributed in both time and space. They evolve and change over time and the processes take place in systems that are constituted of physically distributed subsystems and components. The distributions in time and space may easily cover five orders of magnitude.

Secondly, to proper control the processes, operators must have an adequate understanding of both time and space. This understanding must match the time and space characteristics of the physical process well enough for actions to be planned and carried out.

Furthermore, time itself is important for the control of the process, as thinking and planning use their time which thereby is lost. Finally, the design of the interfaces between people and processes must encompass

both time and space. The interface must provide an adequate representation of the dynamics and the topology of the process. In addition, the interface medium itself will have temporal and spatial features that designers must take into account.
This theme has shown to stimulate proposals and to serve as a useful background for the presentations. We hope it will also stimulate lively discussions at the conference.
The proceedings have been conceived as a tool for easing presentations' comprehension and facilitating interactions. The papers are ordered according to the conference's programme. The sessions roughly correspond to the main issues: organisation, theories and models, human error and system reliability, cooperation, aviation, tools and practices, decision making, individuals in process control, and design.
The organisers would like to express their gratitude to a number of people and organisations without whom this conference would not have been possible:
ANIPLA - Italian National Association for Automation
CNR - I.P. - Italian National Research Council - Institute of Psychology
EACE - European Association of Cognitive Ergonomics
SIE - Italian Ergonomics Society
University of Siena
AEI-GSA -Italian Association of Electronic - Specialistic Group of Automation
The collaboration of Enel- SRI/PEA in supporting the organisation has been extraordinary. Ms. Maria Grazia Nadaletti has been in charge of local secretariat. On behalf of all the people, we feel the obligation to thank her for the excellent work done.
Finally, we would like to welcome all the participants to this CSAPC conference and look forward to three days of interesting presentations and intensive discussions. We hope that the CSAPC may serve both as relaxation from the demands of daily work and as a stimulus for the work in the future.

Sebastiano Bagnara
erik Hollnagel
Michele Mariani
Leena Norros

CSAPC 1997

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1 ORGANIZATION AND PROCESS CONTROL

SAFE OPERATION AS A SOCIAL CONSTRUCT

Gene I. Rochlin
Energy and Resources Group, 310 Barrows Hall
University of California, Berkeley, CA 94720-3050
armsis@socrates.berkeley.edu

ABSTRACT

Our empirical work on organizations that manage complex, potentially hazardous technical operations indicates that operational safety is not just the management or avoidance of risk, but a positive representation of the state of the system. Because safety so defined is socially constructed, it is not easily measured in terms of cultures, errors, or other common indicators. And because its construction is an interactive, dynamic, communicative act, it is particularly vulnerable to disruption or distortion by well-meant but imperfectly informed interventions aimed at operators that do not take into account the importance of the processes by which they interact.

Keywords
Operational safety, social construction, safety culture, nuclear operations, reliable organizations

INTRODUCTION

When the Berkeley "high reliability organization" (HRO) group first set out to examine the role of "operators" in maintaining safety in a variety of complex, high-technology operations, we focused initially on a search for indicators of managing or controlling risk (La Porte,1996; Rochlin,1993; Rochlin, La Porte and Roberts, 1987). What we found instead was a positive construction of safety in operations over and above avoidance of error. This was not merely a "safety culture" as usually described, but a socially-constructed culture of operational safety, based largely on a dialectic between continued success and the deep belief that operations are inherently dangerous and the knowledge base imperfect. This was not too difficult to describe in general, but providing a formal description proved far more difficult.

SAFETY IS NOT JUST THE MANAGEMENT OF RISK

It was not difficult to obtain in our interviews reasonable agreement on definitions of risk, both technical and organizational. Safety, however, has many interpretations. In one sense, safety can be defined rather mechanically and negatively as the absence of accident, or perhaps the control of risk. But it was also quite clear that when operators defined a set of operating conditions as being "safe," they were expressing a collective social perception of a desired state of the operational subsystem. The social science literature provides many different ways to express this. It might be called a "frame," or a "representation," or a "social construction," depending upon the model for analyzing the relationship between the actors, their equipment, and the task at hand. We found none of these literatures entirely satisfying as a mode of explanation for our observations. Yet, each (and all) expressed to some extent the idea that safety is an active construct, and not a passive organizational state or a behavioral overlay. For some of our organizations, there were types or classes of error or accident that could not be tolerated at all. Others performed tasks for which the complete absence or suppression of errors and accidents was not possible; they were judged effective because the measurable and observable rates of errors or near-misses was so much lower than one would expect by comparing with other more typical organizational behavior. Safety thus proved a relativistic as well as a poorly delineated concept, even when measured against real world performance.

Safety was even more difficult to specify in the most important domain of all, performance and behavior in relation to self-constructed expectations and demands. Most operators reported that the chance of error or accident actually increased when those at the controls felt that they were in an "unsafe state." Safety is therefore also self-reinforcing. They did not volunteer that the converse was true, i.e., that operations were more likely to be safe when operators were comfortable that they were operating safely; that is the logical consequent of the more negative

statement, but, as discussed below, it would be inconsistent for operators in a "hero-avoiding" organizational setting to actively promote the positive connotation.

It was clear that safety was in some sense an intersubjective construct, a story the operators were telling to each other about each other, and about the status and interaction of the processes they operate or manage. How then do they differ from other organizations for whom such behavior might be characterized as over-confidence or poor judgement? In our view, the lack of self-promotion or aggressive self-confidence is in itself a useful gauge, and part of the social construction. Nevertheless, determining which organizations are safe and which only maintain the illusion of safety is well beyond the scope of our research at this time. For the moment, we have continued to focus our attention on organizations that are broadly and generally considered to be safe, in some cases remarkably and even surprisingly so, and to describe what we observed that we think is unique and important for this class of organizations rather than trying to generate a comparative study.

Duality

One of the more notable characteristics of our organizations was their ability to maintain dual representations; in some cases that of safety in the midst of risk, in others that of independence of action in a context of exceptionally close and detailed regulation (Bourrier, 1996; Rochlin and von Meier, 1994). They see the duality as reinforcement rather than dialectic, and do not even note the organizational contradictions we can elicit by varying the framing and wording of specific questions put to them. As others have found for commercial pilots, they have long recognized that treating their operational environment as not only inherently risky but potentially hostile is essential for safe operation. Confidence in the equipment and the training of the crew does not diminish the need to remain alert for signs that a circumstance exists or is developing in which that confidence is erroneous or misplaced (Gras et. al., 1994; Rochlin, 1996). This is also true of US nuclear plant operators, who describe regulation as intrusive, distracting, and unnecessarily detailed, but also argue that it is necessary and important (La Porte and Thomas, 1995). The assumption of responsibility in these organizations is deep and structural. It is an element from which their behavior is created and not a culture superimposed on it. And it is a group property and not an individual one.

The Locus of Responsibility

Paul Schulman has suggested a frame for understanding the importance of collective behavior in defining operational safety by noting a sharp contrast between organizations in which hero stories were prevalent and welcome and those in which such stories are rare and not encouraged (Schulman, 1996). Organizations such as militaries and fire departments emphasize extraordinary individual performance and rapid response; hero stories serve as an effective means for organizational learning and the maintenance of cumulative knowledge. In contrast, "hero" is a critique in air traffic control and nuclear power, describing an operator who will act with little regard for the collectivity. Safety is sought through collective (inter)action, through shared knowledge and responsibility. Organizational learning is formalized, and cumulative knowledge transmitted not through legends or narratives but through the creation and modification of formal procedures.

The two frames for the intersubjective and collective construction and definition of operational safety lead to contrasting sets of social and individual behavior. The first establishes a context in which responsibility for performance of those tasks that are not routine (particularly those that entail the most risk, whether to the public or to the organization) rests primarily with individuals, potential heros to be sought out and nurtured; what lends confidence in collective performance is the belief that any contingency will be met by one or the other. The second rejects such an approach as dangerous, especially for those tasks that present the greatest potential for harm. Threats are to be identified, scoped, and routinized; when unexpected events do occur, they must be responded to through collective action; heroic individual initiative is a threat, not an opportunity. In both cases, safe operation is a positive outcome, and the constructed narrative is one of organizational rather than individual performance.

This analysis builds on and reinforces two earlier conclusions of our HRO research. First, that reliable organizations tend to reward the reporting of error and the assumption of responsibility for error; second, that even when human error does occur, the organization accepts the responsibility as a whole rather than displacing it on to the erring individual (Weick, 1987; Weick and Roberts, 1993). The latter behavior is quite remarkable, in that

it spans analytic conclusions ranging from responsibility for poor training or bad working conditions to a lack of collective wisdom in putting an unqualified individual into a responsible position. Even the extreme action of explicitly blaming the individual for malfeasance does not, in this view, absolve the organization of responsibility for the outcome.

Safety as Myth and Ritual

In search of analogies to explain our observations, we compare it with the notion of "health." Defining an organization as safe because it has a low rate of error or accident has the same limitations as defining health in terms of not being sick. When a person characterizes their medical state as one of being "healthy," they usually mean far more than not ill. Other factors that may enter include a calculation that they are not at the moment at any risk of being ill, or have a cushion or margin of protection against illness, that is having a low potential for being unwell. But that is still very reductionist. In most cases, it is also an expression of a state of being with many dimensions that is not entirely about the clinical state of the physical body, but a story about the relationship of the individual's mind and body with the world.

If one takes perceived risk as a constructed measure of the potential for error, safety stands in the same relationship to error, and risk, as health does to illness, and the potential for being unwell. Reason, for example, has pointed out that [good] health can be though of as "an emergent property inferred from a selection of physiological signs and lifestyle indicators" (Reason, 1995). He then constructs an analogy with complex, hazardous systems, pointing out that assessing an organization's "safety health" resembles the medical case in that it requires sampling from a potentially large number of indicators. Although Reason's argument then proceeds in more positivistic direction towards the development of separable indicators than the social constructivist perspective followed here, the analogy is nevertheless apt.

Health is in some sense a story one tells about one's self and one's relation to the world. Safety is in some sense a story a group or organization tells about it's self and it's relation to its task environment. Meyer and Rowan have noted that there is a correlation between elaborate displays of confidence, satisfaction, and good faith and the institutionalization of myth and ritual (Meyer and Rowan, 1977). Moreover, these are in most cases "not simply vacuous affirmations of institutionalized myths," but the basis for a commitment to support that facade by collective action ('t Hart, 1993). Putting these together with our observations, we argue that a collective commitment to safety is in fact "socially constructed," at least in the sense that the organizations we observe also weave into their operations the kinds of rituals and stories that not only serve to orally transmit operational behavior, but group culture and collective responsibility. And since these arise from the organization's perpetual reaffirmation of its commitment to safety not only as an institutionalized collective property but a constant process of re-enactment of its own stories, it is in many ways a dynamic, interactive, and therefore inter-subjective process that can only be nurtured and maintained if the means and modes of social interaction are preserved and reinforced.

COMMUNICATION

In our work on aircraft carrier flight operations, we found a constant stream of traffic taking place simultaneously over multiple communication links during flight operations, even when the level of operational activity was low (Rochlin, La Porte and Roberts, 1987). By comparing it with other similar, if less dramatic, activities taking place elsewhere on the ship during critical operations, we found that the constant chatter was an important means for maintaining the integration of the collectivity and reassuring all participants of its status. Similar behavior was also seen in nuclear power plant control rooms (Rochlin and von Meier, 1994). Air traffic control is radically different, in that controllers interact more with pilots than with each other. Nevertheless, Sanne's analysis of extensive video and audio recording of conversations between controllers and pilots at a Scandinavian control center also displayed many interactions that were not part of the formal control process, but meant to nurture communication and cooperation between controllers and pilots (Sanne, 1996). Their structure and content were shaped to a great extent by the recognition of all parties concerned that safety was indeed a collective property that "emerged" from the interaction between them.

Similar findings have long been reported in the literature. The importance of control room inter-communication is a fundamental finding of the Westinghouse group and others (Roth et. al., 1992). The "social organizational

safety" described by Janssens and colleagues (1989) depends on the "spontaneous and continuous exchange of information relevant to *normal* functioning of the system in the team, in the social organization;" such inter-communication was therefore identified as a primary goal of safety training programs for operators. But it has an additional safety function as well. In our HRO studies, every operational team we interviewed pointed out the importance of maintaining a free flow of information at all times, not only to keep the team integrated and because experienced operators monitoring the flow of what often seems to be trivial or irrelevant information can often discern in it warning signs of impending trouble.

Automation as Interference

The central role of free information flows as a means for constructing a cognitive frame for safe operations has long been a source of concern in critical studies of control room procedures. The fundamental issue is that automation and other technical strategies tend to be reductionist and overly objective, focusing on specifics of individual or small group behavior, and therefore often pay insufficient attention to representations, social constructs, and other more subjective collective behavior. There are already examples in the literature of cases where positivist efforts to "improve" the operating environment of control rooms have been antithetical to norms and routines that support and integrate the team (Roth et. al., 1992; Gras, 1993). These are not always direct, but may also arise from automation put into place for other reasons, such as plant or process efficiency.

The case of cockpit automation has long been raised as a prime example of the potential for reducing rather than increasing safety by interfering with the cognitive processes of integration (Gras et. al., 1994). There are other examples that have shown that as the level of plant or process automation increases, the role of the operator is more and more that of a supervisory controller of the equipment rather than of the plant, which can interfere with operators' sensitivity to warning signs, or ability to respond to unexpected events (Zuboff, 1984, Rochlin, 1997). Modifying equipment, task environment or organization in the name of reducing "risk" without fully understanding social and cultural factors may well result in increasing operational error by interfering with the less explicitly observable processes by which safety is created and maintained (Dougherty, 1993).

Automation insensitively or clumsily done can decouple the socially constructed image of safe operation from the reality, transforming an organization that is "safe" to one that only believes itself to be. This is a familiar problem to those who have followed the ongoing controversies over the safety and reliability of complex technical operations. Operators, teams, and organizations may overestimate their knowledge, misread the state of their system(s), or simply try to do more than they are capable of because it is expected of them (Rochlin, 1997). "Hero-seeking" organizations are known to be particularly susceptible to such representational errors, but similar cases have been observed in hero-avoiding systems where operators became so confident in their equipment (or organization) that they ignored procedures or become inattentive even to manifestly displayed signals. There are cases where operating teams assumed that a clear indication of malfunction was read as a problem with the instrument and not the plant, and other cases where the possibility of error at all was simply never considered (Sagan, 1993; Vaughn, 1996).

THE SEARCH FOR SAFETY

Throughout our research, we observed again and again, in different contexts and in different manifestations, that "operational safety" is more than a set of observable rules or procedures, externally imposed training or management skills, or easily recognized behavioral scripts. While much of what the operators do can be formally described one step at a time, a great deal of how they operate, and, more importantly, how they operate safely, is "holistic," in the sense that it is a property of the interactions, rituals, and myths of the social structure and beliefs of the entire organization, or at least of a large segment of it. Moreover, at least in the case of nuclear plants, air traffic control, and aircraft carrier flight operations, it is not just socially constructed within the group but establishes part of the structure of the relationship between task group and organization. The more technically complex the system (and nuclear plants probably do occupy that end of the spectrum) the less possible it is to decompose the interlocking set of organizationally and technically framed social constructs and representations of the plant in search of the "locus" of operational safety (La Porte and Consolini, 1991).

Analyzing these more subjective and social dimensions is difficult, because so much of our theory, and our research experience, remains grounded in reductionist approaches that are fundamentally oriented towards the relationship between individual workers and their tasks. This extends not only to technical model building and organizational analysis, but also to human-technical interactions, psychological theories of framing and scenario-building, and even cognitive analysis. Ritualization, seemingly non-functional displays, and expressions of confidence that are not grounded in empirically-determinable observables are all too often disregarded, or, worse, trampled on or overwritten in an effort to impose theoretically-argued strategies that are argued to be "functional" solely in terms of abstractly constructed models and rationalized and formalized observables.

The challenge is to gain a better understanding of such cultures and the means by which they are created and maintained. Because they are socially constructed, they arise as much from interpersonal and intergroup interaction as from the more commonly studied interactions with external designers and regulators. Because the interaction is anchored in cultural dynamics, there are wide variances in its manifestation even for similar plants in roughly similar settings. An even greater challenge will be to identify rules that correlate constructions of operational safety with empirical observations of performance, so as to separate those organizations that construct a representational framework of safety that is accurate from those who only construct the representation, and not the safety.

CONCLUSION

Intersubjective, social constructivist approaches, are clearly needed to understand how institutional behavior that encompasses such non-quantifiable and collective properties as enacted drama and ritualization of myth contributes to safety -- as a positive construct and not just the control of risk. To those of us trained in positivist disciplines, such an approach may seem strange, even unprofessional. Yet, throughout our research, we observe again and again, in different contexts and in different manifestations, that "operational safety" is not capturable as a set of rules or procedures, of simple, empirically observable properties, of externally imposed training or management skills, or of decomposable cognitive or behavioral frames. While much of what the operators do can be empirically described and framed in positivistic terms, a great deal of how they operate, and, more importantly, how they operate safely, is a property of the interactions, rituals, and myths of the social structure and beliefs of the entire organization, or at least of a large segment of it. Moreover, at least in the case of nuclear plants, air traffic control, and aircraft carrier flight operations, it intersubjective and emergent not just at the individual but also at the inter-group level. The more technically complex the system (and nuclear plants probably do occupy that end of the spectrum) the less possible it is to decompose the interlocking set of organizationally and technically framed social constructs and representations of the plant in search of the "locus" of operational safety (La Porte and Consolini, 1991; Rochlin and von Meier, 1994).

This paper essentially argues for continued and expanding research and inquiry into the way that safety is not just a measurable, statistical property or a gauge of the avoidance of error or accident. It is a positive affect of operations and organizations, intersubjective, socially constructed, and collective, that is most important in understanding the reliable operation of complex, potentially hazardous socio-technical systems. To the extent that regulators, systems designers, and analysts continue to focus their attention on the avoidance of error and the control of risk, and to seek objective and positivistic indicators of performance, safety becomes marginalized as a residual property. This not only neglects the importance of safety as a constructed property of operations, but may actually interfere with the means and processes by which it is created and maintained.

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Change management and participative design in continuous processes control: An illustrative case study.

Gaetana Zardetto*, Michele Majni*, Roberto Nicoletti+, and Sebastiano Bagnara°

*CRA-Enel Via Volta 1 Cologno Monzese (MI) Italy
+Institute of Psychology University of Urbino Italy
°Institute of Psychology CNR Rome and University of Siena Italy

Summary

A case study illustrates the main characteristics of an integrated change management strategy where a user-centered approach to design innovation was combined with a participative methodology of innovation introduction and use in work settings. The former was based in the continuous involvement of users in all the phases of the innovation conception, design, evaluation and production. The latter was centered on the co-presence in the work setting of both old and innovated tools and on a learning context where users previously involved in the design process take a coaching role in practicing on how to use the tools and understanding its systemic significance.

Introduction

The design and use of information technologies in work systems have been dominated by the idea of automation: humans have to be substituted by machines. When not just dismissed, they often have to carry out residual, impoverished, machine guided and paced operations. High level skills and competencies become obsolete: experience is devaluated. People are conceived as disposable components of a work system.

In the last ten years, despite the great technological push, an opposite trend has emerged. It has become apparent that knowledge is the key factor in providing competitive advantage. The technology-centered approach to work design has been questioned for its effects on productivity (see, e. g., Goodman and Harris, 1995), reliability (Sarter, Woods, and Billings, 1997), and quality of working life (Butera, 1990). New alternative approaches have been proposed in the design of the human-machine interaction: e. g., the user centered design (Norman and Draper, 1986), the participatory design (Schuler and Namioka, 1993), participatory ergonomics (Wilson, 1995) approaches. New ideas have been put forward about organizations and people in them (see, for a review, Rousseau, 1997). At variance with the previous alternatives to the predominant tayloristic paradigm, these proposals have been widespreadly adopted and turned out to be very successful.

Though originating by very similar ideas, the participative design approach and the new organizational paradigms have been rarely explicitly combined, and change management has put more emphasis on the latter rather than in the former (see, e. g., Barnett and Carroll, 1995). However, the importance of the former can be hardly denied. So, an integration of the two approaches should bring about an outcome comparatively better that can be obtained from the adoption of either one or the other.

What follows reports a technological and organizational innovation developed within an integrated change management strategy that can be characterized as evolutionary and participative.

The case study (1)

An integrated change strategy has been adopted for innovating control rooms of thermal power plants. The decision originated from the idea that people is the crucial asset, and any change has to be mastered by people (Bohle, 1994). To master change and innovation people needs to develop appropriate knowledge and skills: this require time and appropriate conditions and opportunities. It was strongly believed that change and innovation have to take place within a learning organization: people in the organization and organization itself should have the capacities to understand innovation as a change of the whole work system. By

understanding innovation and practicing it as a system transformation, people in organization would improve knowledge and skill, and, if needed, modify them.
It was reasoned that such conditions are met when innovations are introduced incrementally: this means that no radical change should abruptly take place in a work system; rather a work system should be coached toward new objectives through continuous cycles of innovation and adaptation. Each innovation has to parallel previous operational tools until for a while, until when, by making experience with innovation, people learns to use it, understands its specific advantages as compared with the previous tools and catches the systemic advantages deriving from the improvement it brings about to the whole work system. People should become aware that the innovation changes the whole system and master the relations of the innovation with the system. When the users "feels" and handle the innovation as a work practice in a cognitively dominated context the substitution has already taken place, and the old tool is left abandoned.
This evolutionary change process may greatly enhanced and speeded up when participative, user centered design is adopted in conceiving, designing, prototyping, evaluating, and implementing the innovation (Carroll, 1997). By having the users actively intervening in the conception, design and test of the tools and the very same people engaged in the shared cognitive process of embedding the innovation in the evolving collective and individual mental representation of the organization a dual process of learning take place: one is related the tool itself, the other about its use in the work context and the changes and opportunities it brings at a systemic level. Together, they improve organizational learning intended both as the process by which people learn the organization they are in and the process characterizing an organization that adapts itself to internal and external modifications (Argyris and Schoen, 1996).
The evolutionary change strategy is also characterized by a planning of the innovations. In the case under analysis, the planning was related to the transformation of the control rooms of the thermal power plants. Remarkable changes have taken place in control rooms in the last years: The information and communication technologies have progressively substituted mechanical technologies for supervision, diagnosis, action and control; physical environment has been modified, and space reduced. All these changes took place within a planning where modifications to be done were primarily tools and conditions which operators directly manipulate in their current activity. Though all these changes have influenced organization, no information technology based tool intended to directly modify and support organization itself has been yet introduced. The case by which the evolutionary participative change strategy will be illustrated is related to this stage of the planned work system transformation, when a support for improving collective organizational memory (Hutchins, 1993) became feasible and was deemed useful.

Diaries: an organizational support

Work processes may be continuous and last months and even years, whereas humans can efficiently work for few hours. Soon, they show severe degradation in performance: quality impairs, and then quantity slows down. In order to match characteristics and needs of continuous processes with the human limitations, shift work has been introduced and widespreadly adopted mainly in process industry. Such organizational solution, however, did not eliminated the fundamental mismatch between the humans and continuous work processes. It is well-known that most of accidents take place both around (i.e., soon before, during, or soon after) a shift change, and by the end of the operators' work-time. What apparently causes such a degradation of the system in the changes of shift teams is the transferring of knowledge, experience, information and even intuitions about the dynamics of the work system from one team to the other. There are procedures and tools to support such a passage. As in many other situations, in case under description the main tool was a diary.
The idea (developed partially as a task within the BRITE-EURAM Project AMICA -Advanced Man-machine Interface for process Control Application-) was to build a

computer-based diary aimed at supporting shift teams in keeping track of the activities carried out, breakdown and faults that take place, and main system states during their own shift, in transferring information to the incoming shift team, and retrieving information from the previous shift teams.
The idea was developed with the integrated change management strategy. As above summarized, this strategy implies the combination of the participative design and change methodologies, whose applications in the diary case will be briefly described in what follows..

Participative design
The design process comprised four main phases and by iterations among them. In the first phase, a participative analysis was conducted by the designers together with the users: There were: a) Shift operators who are in charge of the supervision and control of one unit of the plant, including analysis of plant behavior, symptoms detection and diagnosis identification, decision and planning of remedial intervention. The shift operators are in charge of the diary, and then required to keep in chronological order track of the actions performed, of unusual events which prevent normal plant operation, and of malfunctions which do not prevent normal working conditions in a diary to be handed over to the next shift team. They makes use of the information reported in the diary by previous teams when engaged in diagnosis activities. b) Shift coordinators who are responsible of the overall plant operations. They are required to meet the operating conditions and performance objectives, coordinate and supervise the operators, and set the shift schedules. They keep their own diary where the actions performed, phenomena observed, and any other information relevant to the operation of the plant are recorded. They use the operator's diary occasionally. c) Maintenance technicians who are in charge of the maintenance of sensors and plant components. On the basis of the records of plant behavior and operational procedures, detected malfunctions and identified diagnoses, carry out maintenance. They use occasionally the diary.
The preliminary analysis by and with the users and domain experts showed that it was rather difficult and time-consuming both to report and to find an information in the handwritten diary. Users, domain experts, designers and managers convened on the utility of the tool and its main requirements: easy data input and retrieval.
Subsequently, a thorough analysis of a number of handwritten diaries from various plants allowed to classify the information in the diaries in five categories. Operations: Short descriptions of relevant operations just performed (or to be performed) on some components/parts of the plant. Component faults: reports on faults or malfunctions of components of the plant. Instrument faults: reports on faults or malfunctions of instrumentation components. Plant management directives: often, deadlines for plant states. Plant declaration: at the beginning of the shift the operator has to report on the diary a set of parameters that identify the current plant state.
The analysis provided the basis of the development of the prototype. The prototype allowed to look through messages, make selections among them and identify selected messages by date and operator. Search for information was permitted through key words, subjects and categories. The operator was supported in reporting by menus and forms to be filled when recurrent and frequent events took place. Anyway, free text reports were always possible. There was also a reminder of messages or operations still to be completed.
In a following phase, the prototype was evaluated by users from different power plants in a laboratory setting. The prototype was illustrated to the users, and then they were asked to interact with it in group of two or three. Comments, collected both during the interaction and a successive debriefing session, convened on the usefulness of the tool. They identified deficits in usability: language was far from the idioms and phrasing used by their community of practice; navigation was difficult; there was lack of consistency. They also underlined that the standardization of messages induced by the tool was very positive because it could reduce misunderstanding. It was also stressed the importance of forcing the

operator to be complete the messages and not to forget deadlines. They also asked for having weekly and monthly summaries and trends.
All these comments showed that the users evaluated the tool for its usability, but also for its impact on the quality of work and reliability: It was seen as instrumental in preventing error and accidents. Moreover, they caught also its organizational significance by noticing the support it provides to the activities of successive shift teams, and its weakness because it does not provide timely and updated information to the maintenance operators.
This pattern of comments showed that the previous experience with the change management strategy influenced the process of evaluation of the new tool, which was considered within its system of use, rather than in its isolated usability, even in the laboratory.
On the basis of the results and comments of the evaluation of the "computer-based diary", a "shift agenda" was developed. Along the process of development the final users have been often called in the lab and asked to provide information, critics, suggestions and comments.
The final version of the shift agenda organized along three "streams": management of shift change, management of monthly and weekly registers, and message input and visualization.
The management of the shift change included all the functions of the prototype. Other opportunities have been added, such as: search for the names of the shift operators on duty in a given shift, schedules of the activities to be performed by the shift team on duty, list of the activities not carried out by the previous shift, activities to be carried out. The operators were presented with the related information timely when needed. Weekly and monthly trends and updating of the breakdowns, anomalies and non-availability states of the plant were presented mostly graphically. The stream "message input and visualization" was based on the categorization of messages already reported, and now further specified.
Task and activity analyses have shown and user confirmed that the operators use the Agenda in three different situations: when all the attention of the operator has devoted to a hard manoeuvre, when diagnosing and looking for information, and the normal running of the power plant. Consequently, there were two main areas in the interface: a main area, where the users can input and retrieve easily simple information, and a window area, where the user can input and retrieve detailed information.

Participative change
Once the shift agenda tool was deemed completed, it was set within a control room in a power plant and operators were invited to use it, but not forced to. To study the innovation at work an ethnomethological perspective (see, e. g., Zucchermaglio et al.,1996) was adopted and practiced a few months after the introduction of the innovation. During the study it was apparent that about all the people in the control room make use of the shift agenda rather than of handwritten diary. The process of substitution was almost completed.
The observations made clear that those people who had taken part in the design process played a crucial role. Of course, only a few of the the final users directly contributed to all the phases of the design of the new tool, some others contributed only to the conceptual and analysis phases, others to the evaluation of the prototype, and others were involved in the iterative cycles of evaluation and design of the final version. All those became active in the social process of learning that took place once the new tools were set in the working setting. Their role in showing how to use the tool can be hardly underestimated. The use of the tool become very soon a community practice, where tutors and coaches were easily identified and reachable. However, it was still hard to find the time to fill the diary when the operators were asked to perform activities demanding high mental effort. When in these situations, the operators still took handwritten notes on paper.
As expected, there was also a systemic learning: that is the processes of mastering the relations of the innovation with the whole working system. This process took place in the continuous comparison with the opportunities The shift agenda showed

the greatest benefits in supporting operators activity in diagnosing by providing easy to retrieve and reliable data and instances which allow reasoning by analogy. The agenda was felt as an efficient story teller. It was also quite soon and often used for supporting cooperation in diagnosing: it was the common ground to which differential points of view can make reference. Again, by bringing in the collective discussion on diagnosis the history of the plant, it was understood as a tool for developing the organizational memory. By signalling both what action (and when) has to be done, and when and how it has to be completed, it provided also support to the individual operators in handling time-related activities. However, this support was made available to all the others in the control room: the visibility made possible mutual control and help.
Two main issues were still considered questionable. People complain the loss of "individualization" in the messages: put in the words of an operator "through the handwriting I can see what my colleague felt". The other issue was related to reliability: people in the control room feel that while what written in the paper can not be cancelled, messages in the shift agenda can. This gave rise to a trust question which remained the main reason for still keeping the old diary on the console.

Conclusions

The integrated change management strategy where a user-centered approach to design innovation was combined with a participative methodology of innovation introduction and use in work settings was illustrated through a case study. The case study turned out as successful as others previously conducted by following the same change strategy in the same company. The suggestion is that the same approach can be generalized to different work setting contexts.

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When process controls operators' action

Francesco Cara
CREA- Ecole Polytechnique, Paris (cara@poly.polytechnique.fr)
Valérie Lagrange, EDF
EDF - Direction des Etudes et Recherches, Clamart (Valerie.Lagrange@der.edfgdf.fr)

ABSTRACT

This paper reports on a study of a critical nuclear power process control operation : power production regulation. The study has been the groundwork for formulating low-cost improvements of the existing C/C system as an alternative to increased automation. Here, we only present the cognitive model of the activity that we have developed to explain how operators solve two crucial problems : *when* to initiate compensation of the anti-reactive effects of xenon created by power variations and *how* to compensate for it by injecting boron dilution or water in the primary circuit. According to the model, the solutions to these two problems are worked out in the course of the interaction between operators and process. The behavioural structure comes partly from a general plan to carry out power regulation and partly from properties specific to the process, through the control environment.
Keywords : Nuclear power, power regulation, activity analysis, planning, interaction.

INTRODUCTION

Every day, French PWR nuclear power plants (NPP) regulate their level of power production to adjust to the electricity network demand. During winter, it is common for network management to require NPP to reduce power production by 40% during the night to then go back to full power in the early hours of the morning. The task consists of bringing the power produced by the reactor to the power level required by the network, keeping the process within its safety limits.

Power production regulation is critical because variations in power production move the process close to safety boundaries. The neutronic flow evolves towards the top/bottom of the core, and a transition beyond the safety limits could permanently damage nuclear fuel. During regulation, the control rods are inserted in the core, and if they are inserted beyond a certain level (called « the very low limit »), any further fall could not contribute to bringing the nuclear reaction to a halt in case of an emergency. The automatic protections which are activated when the safety limits are exceeded have a serious negative impact on productivity. In the existing system, operators perform

manual actions to keep the process within these safety boundaries. The main actions consist of either reductions or increases of boron concentration in the primary circuit with the objective of controlling reactivity.

In the first section, we introduce the problems generated by power production regulation. In the second section, we take a systemic view to describe how the man-machine system solves these problems. In the third section, we change perspective and focus on the agents' activity. We conclude by claiming that the structure of the power production regulation activity emerges from the interaction of the operator's general plan, which gives a broad description of the sequence of events and actions, with the process dynamics (as represented in the interface), which sets the temporal and quantitative parameters of the actions described in the plan. This highlights the importance of designing an information relevant environment for interacting with the process and for sustaining learning (Vicente & Rasmussen, 1990).

What are the problems raised by power production regulation ?
Any power increase or decrease is achieved by varying core reactivity. The physics of the variation is however extremely complex and does not follow a linear course. Some physical effects push in the opposite direction, increasing reactivity when a decrease is sought (e.g. primary water and nuclear fuel temperature) ; others over amplify the desired effect (e.g. boron density).

There is one phenomenon in particular which makes power production regulation a very delicate operation : power variation ends the equilibrium between xenon (Xenon 135 is a product of nuclear fission) production and consumption. When production is stable, the axial neutronic flow and xenon axial distribution go hand in hand. When a change in axial flow occurs, as is the case during power decrease, the equilibrium is broken causing a surplus of xenon. Xenon, which depends on the level of power and on its evolution, absorbs neutrons and has, hence, an antireactive effect, affecting both power and the distribution of the neutronic flow.

To regulate power, the problem is hence that of decreasing/increasing reactivity controlling temperature variations and neutronic flow distribution. Furthermore, during the operation of power production regulation, the NPP remains connected to the network. Its power production is automatically adjusted to minor network variations (frequency and teleregulation), and the NPP must be capable of rapidly adjusting production in case of an emergency in the network. The control of temperature variation and neutronic flow distribution must also allow room for these adjustments.

HOW DOES THE MAN-MACHINE SYSTEM SOLVE THESE PROBLEMS ?

The man-machine system to regulate power relies on three main means (The technical presentation that follows is very simplified. It is based on Drevon (1983)). Two are automatic regulations which consist of control rods which absorb reactivity. The G control rods are inserted/extracted in the core to align the reactor power to the power required by the turbine. These control rods also compensate the effects of power drop and redistribution of power. The R control rods regulate the primary circuit temperature and compensate the residual variations of reactivity. Their effect is instantaneous, at the same time on power and on the neutronic flow distribution (for ex. : if R control rods are extracted, the neutronic flow is pushed towards the top of the core). The third means is manual. Operators can vary primary circuit boron concentration by either injecting water or boron dilution. The first action feeds, while the second reduces reactivity. Operators can regulate the outflow of the injections (volume, concentration, duration).

The man-machine system we studied defines the following organisation of labour and responsibility. Whereas the G control rods automatically execute the alignment of primary to secondary power together with the control of some of the physical phenomena and require minor monitoring by the operators ; the R control rods' automatic regulation of temperature is constrained by a reduced domain of action. As we have already mentioned, these rods cannot be inserted deeply in the core to preserve their neutronic weight in case of an emergency halt of the reactor. During power production regulations, operators have to ensure constant monitoring of the R control rods position and to intervene directly on the primary circuit temperature to limit their insertion (mainly with injections of water or boron dilution). In particular, the antireactive action of xenon would systematically take these regulations beyond their domain of functioning. Even more importantly, operators are in charge of the neutronic flow distribution which must be kept within a small area, under the core centre, to avoid local temperature peaks and allow for further variations.

The two parameters : neutronic distribution and R rods position are related, as R rods movements cause a reorientation of distribution. Controlling them is a matter of creating a good compromise between shape of the neutronic distribution and R rods position, through actions on the primary circuit temperature. A further constraint acts on operators' action, that is that the use of water and boron dilution injections produces polluted rejections whose storage and processing are very costly.

Furthermore, the behaviour of the process during power regulation varies significantly as a function of the core life-cycle (which affects several parameters : primary circuit reference temperature, power default, effect of xenon on reactivity, absorption efficacy of G and R control rods, boron efficacy) and of the process recent history.

HOW DO OPERATORS CONTROL NEUTRONIC DISTRIBUTION AND R CONTROL RODS INSERTION ?

We have carried out a series of three participatory observations of power production regulations in a PWR 900 MWe NPP during night shifts, when most operations of this kind occur. These series of observations was prepared by a visit to a simulator and by interviews with operators from the same plant. The in situ observations were video recorded using two cameras. One was fixed and covered the whole of the control room ; the second was mobile and captured operators' focus on the instruments and their manipulations. An hour after the end of the operation we showed the 40 minutes video to the operator that we had filmed and asked him to describe his actions, the process evolution and to explain his strategy and decisions (i.e. « autoconfrontation interview »). We then analysed the video recordings, transcribing the words, actions and movements of each operator in the control room along a temporal line. All three observations converge towards a similar structure of the activity.

The onstart of the power decrease is followed by a global monitoring phase, from a central position two steps away from the deck. As the primary circuit temperature starts to drop, operators get closer to the deck, facing the neutronic flow, temperature and control rods position, indicators. Eventually, small manual actions on control rods are carried out if the neutronic flow starts to drift or the R control rods are too low. The initial water dilution is executed in the seconds that follow a drop of the primary circuit temperature below the reference temperature. The initial outflow is modified two or three times until the water dilution compensates the xenon effect. In the process, the neutronic flow distribution and the R control rods are also positioned in a central zone with respect to their domain of functioning. This positioning leaves the NPP in a better situation to satisfy network demands (teleregulation, frequency regulation, sudden requests for varying power production)

Two phases were identified as being particularly critical :
- the first action to compensate the antireactive effect of xenon
- the fixing of the water outflow level.

In principle both actions could be deliberately planned (Amalberti, 1996 ; Hoc, 1996). The evolution of xenon in fact can be predicted from the initial power level, the rate of decrease and nuclear fuel consumption, and is described in a series of curves. However these theoretical curves presuppose core stability, a state which is obtained only after a few days with no significant power production variations (In some French NPP, a computerised xenon simulator exists to provide real-time predictions of xenon evolution). This stability is rarely encountered and therefore operators do not use the theoretical curves to predict xenon evolution. We did not witness any exact predictions from the operators on when the effect of xenon would have appeared nor attempts to precisely quantify xenon antireactive effect.

What we observed instead was an increase in the operators' focus on the primary temperature indicators. Operators know that at some point there will be xenon surplus and wait for it to manifest itself. The signal is the primary temperature becoming inferior to the reference temperature. When the difference reaches 0,8°C, the R control rod is automatically extracted of one step to compensate. Between the inversion of temperature and the movement of the R control rod, the operators initiate the water dilution action that will limit the R control rod extraction and the associated movement of the neutronic flow towards the top of the core. Note that a delay of around ten minutes exists between the action of water dilution and its effect on primary circuit temperature (delayed feed-back). During this period, the R control rods do the compensation. To allow for this, in the first phase of the operation, operators let the R group insert quite deeply in the core, and the neutronic flow orient towards the bottom part of the core.

The second critical phase of operators' control of the power regulation process is finding the right water dilution outflow to compensate the xenon effect. Again, we found no evidence whatsoever of deliberate planning. The operators know that they will at some point make a water dilution, but do not engage in calculating exactly the volume of water that will be needed. The dilution is done in various steps by a progressive adjustment of outflow amounts. The first outflow level is defined on the basis of the core life-cycle and of previous experience. This is an instance of a rule-based behaviour (Rasmussen, 1986) using what appears to be a socially-constructed rule. The second day of observation, the operator used the same outflow level that his colleague had used the night before, and which had demonstrated to be a good start to initiate the process of adjustment. However, before the water dilution can show its effect, the operators modify it. They increase it when the temperature drop is pronounced and R control rods are rapidly extracted ; they reduce it when the temperature and the R control rods are stable. The water outflow which stabilises temperature, and hence the control rods, is found by progressive adjustments, in close interaction with the process data.

DISCUSSION

Our analysis shows that operators have a general plan to carry out power regulation. This memorised plan, that operators can easily verbalise, indicates that, at some point in the process, there will be an effect of xenon to be compensated with some dilution actions. This plan however does not specify when the xenon effect will show nor how much water dilution will be necessary to compensate it. The plan specifies the type and sequence of events and actions, but does not represent temporal and quantitative parameters of the actions. These are constructed in the interaction with the process. The structure of activity is the product of implementing the general plan in a particular situation, which, in return, exerts part of the control (Agree, 1995 ; Conein & Jacopin, 1994). Some constraints on

actions selection come from the plan, some from the process dynamics, others from the C/C interface. The structure of control appears hence to be located in the local operator - process interactions, through the control/command interface.

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2 THEORIES AND MODELS IN PROCESS CONTROL

ANTICIPATION AND HIERARCHY : CONTROL/COMMAND IMAGERY EVOLUTION

Alain ROY, Jean-Pierre CRUCIANI
DCN/ING/SUD BP 30
83 800 TOULON NAVAL FRANCE

ABSTRACT

This paper describes the approach of interactive mimics used for the control command of various plants on board of french navy ships. The possibility of anticipating on events is given to operators, the trouble-shooting delays are shortened, breakdown can be avoided. This approach can be adapted as well for electric power plants, weapon systems, as for other domains after specific ergonomic study and adaptation.

KEY WORDS

Imagery, hierarchy, anticipation, driving, diagnosis, integral objects, platform management system PMS, driving "through" mimics, Displays.

INTRODUCTION

When designing computerized interfaces, operator's mental representation and functionalities coding must be taken into account at the very begining of the studies. Concerning driving devices for complex process this approach is really complementary to usual ergonomic approach.

Nota : In this text, **Driving** activity concept is the union of **monitoring** and **control-command** activities.

CONTEXT OF STUDY

The exemple described refers to platform management for military ships (all but combat and weapon systems). Operator's informational needs have soared during this last ten years, partly due to increased performances and a more closer management of related systems.

This management results from new consideration about use of modern ships.

This is not only a trend due to modernity, even if new techniques and technologies allow this necessary improvement, which first concerns the information taking aiming at solving problems with a "constant of time" (span "given" to solve the problem) is decreasing rapidely.

STATEMENT

A great number of more or less serious defects have been pointed out in former generation of monitoring mimics.

Defects were mainly about lack of homogeneity in representing objects, errors in the general orientation of mimics (bow and stern inverted...), differences of informational capabilities noticeable changes in abstraction/agregation level of used representations, between mimics belonging to the same hierarchical level ,

These defects were eliminated when building new programs imagery.

We simultaneously conducted experiments on visualisation devices for monitoring and on driving activity from screens. Concerning driving devices, we aimed several goals including the following:

- operator's task simplification,
- possibility to anticipate on events,
- enhancement of general safety of concerned systems.

Evolution from *monitoring* imagery to *driving* imagery lead to adaptation concerning several domains of imagery.

Information layout was studied accordingly with Rasmussen (1) abstraction/agregation degrees, mimics (design, colours...) interaction rules were acutely defined and were gathered in a standard now connected with french navy standards.

DRIVING OPERATOR'S TASK

This task covers two aspects

- He has to bring his system in the state requested by authorities in charge of the ship. State changing has to be made with all the safety expected, results are bound to the precise knowledge:
    - of the current state of propulsion,
    - of the possibilities of state changing (intrinsic system dynamic),
    - of the capability to respect the "deal" with the bridge.
- He has to maintain the requested speed whatever the conditions or functioning capabilities of the machinery may be. Sometimes, this challenge is impossible to overcome leading therefore to a reduced possibilities situation. Keeping speed implies the management of events particularly management of break down and malfunctioning.

Anticipation within driving activity

Possibility given to operators to reduce the span necessary to correct defects is mainly due to the possibility of anticipating events

Display devices and data hierarchy enable operators to perceive variations of displayed data and assess the dynamic of occuring phenomena. Thus they can valuate the time scale between the current state and the defect threshold, advantage is twofold: emergency stops can be avoided and transient phenomena and their possible consequences can be treated without rushed action.

IMAGERY

Operators rapidely showed us that two domains of activity are closely linked to mimics: monitoring and diagnosis settlement following defect indications. Operators reasoning appeared as beeing structured in abstraction/agregation levels, i. e. in accordance with Rasmussen scheme. So we had to map our working environment with this scheme.particularly by determining in which place of the Rasmussen matrix operator are more frequently working in.

Diagnosis activity is the other main domain. Operators working from statements, had difficulties to "rebuilt" the sequences of the break down. Their reasoning was based on deductions and probabilities: the reliability of the result beeing directly linked to their level of expertise and the frequency of defect occurrence.

These latter statements have lead us to establish and make use of a certain number of criteria in order to be as close as possible to operator's mental representations.

Representations are graded from general-abstract to particular-concrete. It should be stressed that abstraction level depends on operator's skill. So we had to take into account the operator's trouble-shooting strategies for the proposed break downs included in our experiments.

One of the difficulties was to describe the space problem shared by operators. Differences can be found, this is related to the operator's role: officer of the watch does not need every details but he has to survey every thing from a certain abstraction level so he prefers a more general level and rarely accesses to object level. Operators acces every level and they mainly work with the lower level in case of malfunctionning.

As result, we built an imagery broken down as follows:

- General level of information: abstract and qualitative data,
- Functionnal level: mimics concerning main functions, displaying quantitative data and allowing actions at the sub-functions level,
- Object level: display thorougly any behaviour (normal or not) of the components. If needed, this level can display information and procedures to get back to the normal state.

Graphical approach of imagery

In order to achieve mimics consistent with operator's needs, we have used plant representations built by operators. These representations make possible the description and recognition of objects by any operator. Standards are used to represent normal objects.

High abstraction level mimics are a result from our experiments and work from ROUSE (2), TURECK (3), WICKENS (4) etc. Mimics are mainly composed of integral objects allowing the direct perception of:

- the "distance" between the current state and the normality,
- the thresholds,
- the phenomenon dynamic.

The logic of our integral objects is the following:

As long as -every thing is going on properly-

Then -nothing moves-

Else -detect and diagnose and act-

At a general level of information, integral objects can help to reduce time pressure allowing the operator to work in "best" stress conditions. We have experimentaly shown that, in equal experimental conditions, results are much better when using integral objects than usual displays.

Operator's approach for problem solving

Constitution and evolution of space problem are some of the main diffculties we had to face when extracting expertise. The trend about space problem is to cut it in sub-problems easier to manage and generally resolved in sequence. If new elements can help the operator to refine his reasoning, they also provide the opportunity to refine the diagnosis. Thus our studies were focused on this dual aspect and on the way to ease the space problem in an acceptable way.

Operators comments after trial confirm the impression of both easiness and increasing certainty ,which are of a great help to settle a more reliable diagnosis.

Structure for the proposed imagery is based on a deep knowledge of the system and the operator's skill level and working conditions. This pragmatic approach allows operators to reach the necessary data as they progress in problem solving, by allowing them to access levels including more refined data.

This structure of imagery is based upon Rasmussen works, mimics are represented in an Agregation/Abstraction matrix in order to propose the most suitable mimics corresponding to the reasonning step reached by the operator.

The operator has the possibility to reach rapidly and at every moment the upper level of imagery to acquire complementary general data. about the whole plant .This is far more easy if the console is fitted with two screens, one beeing devoted to general (high level) mimics giving symbolic data, the other beeing used for displaying convenient mimics, thus permitting to refine the diagnosis and so to act with a high certainty degree

Graphical aspects are strictly taken into account during the design phase. Every object is defined by its size, shape and attributes which can be coded (colour...) or functional (state...). Object animation is submitted to state spreading, which enables the operator to follow circuit changes in a nearly real time.

A change in an object representation on display strictly results from the real change on the corresponding real object. Changes on display may either indicate the result of an order or information about object evolution.

Every requested change in an object state should be confirmed. In case of possible dangerous actions, the system asks for a second confirmation. Logic of use is always homogenious. Such precautions are essential to "drive through" mimics.

Mimics

Screen partition has also been considered in order to facilitate information taking and geographical orientation in the mimic space. Mimics tree is very simple and operators easily know where they are and how to come back to generic mimic (higher level).

CONCLUSION :

This approach has its own limits

It is currently rather specific to the domain of warships propulsion. So, its adaptation to other systems is nevertheless possible but would require more or less of evolution.

But whatever is the domain, ergonomists should be included very early in the project in order to have the capability to respond quickly to a project evolution (technical, operational...),

This driving-through-mimics approach is based on his own coherence which must include adaptation capabilities in order not to be blocked if the project would evolve.

It is thus the role of the ergonomist not to limitate the possibilities of the system as well in the possible domains of future extent as in the field of visualisation techniques

But,

We can ascertain on a both objective and mesurable way that this work has considerably simplified the operator's tasks, allowing them to easily solve break down and the most important of all, to anticipate on events in order to avoid defects and to lower their stress.

This system gives mimics built for them and with them.

This possibility for anticipation has permitted a decrease in the amount of break down when alarms are perceived too late, to premature solving or to reasoning based on inaccurate or incomplete set of data.

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A Human—Process Interaction Model for Automated Discrete Part Manufacturing

Anna Johansson and Johan Stahre,
Dept. of Production Engineering, Chalmers University of Technology
S-412 96 Göteborg, SWEDEN
email: aj@pe.chalmers.se, jost@pe.chalmers.se

ABSTRACT

A model of the human-machine system in discrete part manufacturing has been evaluated through studies in several industrial settings. The model is based on supervisory control theory and has been modified to fit discrete part manufacturing. Interest is focused mostly on the operator capability, even though a holistic view of the advanced manufacturing system (AMS) is kept. By using the model, different systems can be compared in terms of process functions, human performance, and human-machine interaction modes.

Keywords

Human-Machine Interaction, model, discrete part manufacturing

INTRODUCTION

Highly automated discrete part manufacturing systems are to a large extent dependent on humans. As the market demands larger varieties of complex products and the product life-cycle shortens, the manufacturing technology need to be highly sophisticated. This in turn makes the systems more vulnerable and dependent on humans for control and maintenance [Karwowski et al., 1994]. Interaction between human machine operators and advanced, computer-controlled manufacturing equipment, i.e. industrial robots, numerically controlled machining systems, etc. is in most situations very complex.

To achieve the expected productivity in this kind of human-machine systems, where human capability is a key issue, there has to exist a common area of interest between the goals of the company and the goals of the individual [Mårtensson, 1995]. On a certain level this can be seen as a balance between the system complexity and the capability of the humans tending it (here called operators). On one side of the balance there are technical processes and machines which are the realization of the company's visions and goals in terms of short production time, automation level, etc. On the other side there are the operators' visions and goals. These are in terms of requirements on physical and psycho-social work environment, but also in terms of having the competence level required to perform the tasks correctly and be provided with the information and communication possibilities necessary to be in control of the process.

MODEL

To analyze the human-machine balance, a model of the human-machine system was needed. Based on Sheridan's classical paradigm of human supervisory control (Ferrell and Sheridan, 1967), an Operator – Process Interaction Model (OPIM) has been suggested by Stahre and Johansson (1994) and Stahre (1995). In OPIM the man-machine interaction is regarded as three interconnected parts: the technical processes on one side, the human operators on the other, and between them the human-machine interface.

The OPIM provides a generalized description of operator tasks in AMS by dynamically describing five operator roles, i.e. planning, teaching/programming, performing (including supervision and manual tasks), intervening, and learning (by experience when encountering new situations). Manufacturing processes are described in three generalized modes, i.e. manual, semi-automatic, and fully automatic processes. Finally, interaction between the operator(s) and the manufacturing process(es) is described by a set of interaction modes ranging from direct physical interaction to the use of a higher-level computer in conjunction with a low-level, task-interactive, computer to control the manufacturing process(es).

Balance can basically be achieved by three types of actions. Actions increasing the human capability are e.g.: hiring operators with the required competence, on-the-job training, or formal education. Actions that lower technical complexity e.g. less complex processes, or different task allocation between humans and machines. A third type of action is to provide more sufficient support tools, e.g. presenting valuable information to make the system more transparent, or provide instructions for error identification and repair.

METHODS AND RESULTS

Model applicability has been tested using qualitative analyses of four advanced systems in Swedish manufacturing industry. Observational and participative methods (Johansson, 1996) have provided insight to the work performed by the operators in the manufacturing cells and given the researchers opportunity to qualitatively describe the context, i.e. working procedures, modes of interaction, etc. The criteria for selecting AMS for the studies have been to find systems with very different characteristics, in terms of products, production processes, batch size, number of units, number of operators, etc.

Production of parts/products could in all cases be described in terms of manual, semi-automatic, and automatic processes. In all four systems, manual operations were required to fulfill the objectives of the system, operating under normal conditions (i.e. no stops or breakdowns). Even so, the cells were all regarded as highly automated systems. Communication between the operators and the processes took very different forms in the four systems, but all interaction with the process could be described using the model's modes of interaction. All the operators' work tasks were possible to describe using the five operator roles.

DISCUSSION AND CONCLUSION

Case study results indicate model validity. During the studies, it was possible to identify several operator work tasks where there was a lack of balance between process complexity and operator capability. It was also possible to compare situations and solutions from the different studies in terms of the model. In the work of identifying and specifying actions to increase the balance, the model served as a common ground for people from different disciplines.

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Some features affecting diagnosis in air traffic control: Some comparative data

Paola Amaldi */, Marcel Leroux *, & Jean-Marie Cellier ****

* C.E.N.A. B.P. 4005
31055 Toulouse Cedex - France

** Laboratoire de Travail et Cognition
Université Toulouse-Le-Mirail - France

amaldi@cenatls.cena.dgac.fr

ABSTRACT

This paper discusses two main approaches to automation, dynamic task allocation and integrated automated aiding system. Within the second approach, a study is carried out to validate a particular function of an expert system for en route air traffic controllers. Results indicate that the objectives of diagnostic activities as represented by the expert system are a subset of those exhibited by air traffic controllers.

Keywords:
automated decision aiding, diagnosis, air traffic control

INTRODUCTION

This work is part of a wider project whose aim is to test and evaluate an integrated decision support system developed for en route air traffic control operations. The actual version of ERATO (En Route Air Traffic Organizer) is the result of a number of design-test-evaluation cycles. At present, we shall focus upon one of such cycles, whose aim was to validate one of the system's functions designed to assist controllers during diagnostic processes. Before discussing the study, we shall outline two main approaches to task automation.

Approaches to automation

Current approaches to automation of activities carried out by operators, consider with interest the notion of dynamic task allocation (Hancock & Scallen, 1996; Parasuraman, Mouloua, and Molloy,1996). The basic idea is that automation is not always necessary, in particular in cases where the task demands are low, automation might be unwarranted. Issues that need to be considered is which tasks should be allocated to the automated system, for how long and what the triggering conditions should be (Scerbo, 1996). Current limits of the dynamic task allocation approach include the lack of satisfactory criteria to define these three issues and a lack of appreciation of the interdependability nature of tasks (Amaldi & Cellier, 1997)

An alternative approach is to develop tools that are *permanently* integrated into the current activities without disrupting them. The aim of an *integrated* automated aiding system, is to assist operators by providing them with representations that would enhance their working through the problems (Amaldi and Leroux, 1995). The advantage of such an approach is that it does not disrupt the current activities by taking some of the tasks away from the attention of the operators. The challenge faced by these aiding tools is to show that they can effectively be integrated into the current practice by providing the needed assistance.

PURPOSES OF THE STUDY

ERATO includes a knowledge base and a set of algorithms allowing the identification of traffic problems that require further analysis by the controllers that need to adapt the representations provided by the system to their assessment of the situation. The objective of the external representation is to provide controllers with all of the information they might need to achieve a satisfactory *understanding* of the situation under control (Amalberti, 1996). One of the available functions, called *information* filtering, provides, for a given "reference" aircraft, those airplanes that interfere or interest the trajectory of the reference aircraft. Thus, through clicking on any call sign, on the radar image, the information filtering function highlights the *Set of Interfering Aircraft* (IAS).

The objective of this study was twofold: Verify that the system output, the IAS, was complete and that the external representations provided by the system was compatible with the activities of the human operators. We called the first a problem of *technical reliability* and the second an issue of *psychological plausibility*. A complete IAS means that all of the airplanes that interest the trajectory of a given aircraft are identified by the system. Through the concept of psychological plausibility we mean to describe the output of the system in

terms of controllers activities. That is, the IAS has to be explained as the result of applying certain knowledge and information filtering strategies that are well known to operators. In this context, the psychological plausibility intends to avoid the occurrence of "automation surprises" well documented, among others, in the interactions between pilots and automated systems introduced in the cockpit (Sarter & Woods, 1995). Differences between the diagnosis made by the controllers and those generated by ERATO help to identify the scope of validity of the system and thus define what controllers can realistically expect from the automated filtering function (Mosier, 1997).

Method

Forty-for expert operators from the five French Air Traffic Control Centers were individually interviewed while watching an already played simulated air traffic scenario. The scenario was stopped at pre-determined times and each time the interviewer had a list of aircraft designated as the "reference" aircraft. Each time the scenario was stopped (about 5 times), the controller was asked one by one, to focus on a reference aircraft and list the conflicting airplanes as well as those that needed to be monitored or could become interfering depending upon certain developments. Most often controllers described the characteristics of the problem and why they diagnosed the presence (or absence) of conflicts. By "conflict" we mean a loss of standard separation among two or more aircraft. Verbal protocols containing explanations about identified traffic problems, were recorded and analysed.

Results and discussion

Here we will be concerned with explaining the differences between ERATO and the controllers. In particular we will deal with those cases where the IAS identified by the controllers (IAS-controllers) exceeded those generated by ERATO (IAS-ERATO). Even though these differences have to be accounted in terms of a model of diagnostic activities in ATC (see Boudes, Amaldi & Cellier, 1997), here we will refer only to some aspects of such activities.

Broadly specking, mismatch between the two IAS were due to two reasons. Either controllers expressed the need to monitor the uncertain development of traffic, or their performance indicated that diagnostic activities were not carried out only for detecting conflicts in the sector under control. In the first case, they mentioned the need to monitor that certain aircraft would follow the standard flight trajectory. That function is accomplished by ERATO which would put on an alert sign if any aircraft exit the tolerated envelope of the critical parameters.

The second class of reasons for mismatch showed that identifying relevant aircraft fulfills a number of objectives which go beyond the detection of conflict. Firstly, we observed that some of the aircraft that were not detected by ERATO were included in the IAS by controllers because they shared the same destination, be it a radio beacon or the same airport, with other airplanes independently of any existence of conflict among them. Therefore it seems that *one of the objectives of seeking for relevant information is to maintain a global situation awareness, not just to identify conflicts*. Knowledge of the entire traffic situation allows controllers to maintain high degree of control over the situation. Secondly, we found that the detection of conflict goes beyond the boundaries of the sector under control. We found a consistent amount of conflict detection carried out with the aim of cooperating with neighboring sectors. In this case, anticipation of future conflicts is a form of cooperation which aims at the following objectives:

- avoid to let the conflict develop over time;
- avoid to transfer traffic problems that will aggravate the workload of the neighboring sector;
- monitor that future possible interferences will be treated by the adjacent sector.

Within this frame, anticipation seems to aim at regulating workload and at providing a backing the process of controlling air traffic.

To summarize, we found that detecting and diagnosing conflicts is a naturalistic kind of decision making which reflects the interaction of environmental, social, and cognitive constraints (Zsambok & Klein, 1997). Given the temporal structure of the task and the decisional power of controllers, conflict detection is far from being an homogeneous activity. For example, people can decide whether to deal with a conflict right away or to let the adjacent sector take care of it.

CONCLUSIONS

The results of this study led us to verify that the information filtering function provides controllers with a selected set of information which requires to be further processed in order to be adjusted to the particular needs of the operators. Such a set represents, however, the outcome of an analysis carried out to eliminate that traffic that will not be of interest to the controllers, no matter what their specific objectives are. The mismatch between the IAS-controllers and the IAS-ERATO, has thrown light on the complexity of diagnostic processes. A number of

objectives not specifically related to conflict detection, have been highlighted. These objectives fall beyond the scope of validity of ERATO and support the view that automated decision aids should supplement rather than attempt to replace human expertise (Mosier, 1997).
Those activities that are not taken into account by the automated aiding system delimit the *domain of validity* of ERATO and contribute to specify the logic underlying the functioning of the system. Other works in the aviation domain, show the interest of making explicit to the operators the underlying working principles of the automated system (Pritchett, 1997). Generally speaking, operators must have sufficient knowledge of what an automated system can do, as well as knowledge of its limitations in order to be able to efficiently interact with it (Mosier, 1997).

Implications for the dynamic task allocation approach
The high degree of interrelation of diagnostic activity might imply that tasks are not independent units that can be subtracted from the context without disrupting the overall control activity. Diagnostic activities do not simply aim at detecting and resolving conflicts. As described above, they are undertaken with the aims, among others, of cooperating and of maintaining situation awareness. Operators showed the need of being aware of all of the traffic to be able to feel in control of the situation. By arbitrarily cutting off portions of the task, the system might increase the probability that operators would "loose the picture". Another cost of arbitrarily partitioning the traffic situation is that controllers have to devote additional efforts to integrate those sub-tasks that are out of the controllers' reach. For example, results reported by Hoc and his team (Hoc and Lemoine, 1997) seems to suggest that that might be the case. Controllers reported that during planning solutions for those problems under control, they needed to take into account the solutions implemented by the automated systems for those conflicts that were affected to it.

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GRAPHICAL PERCEPTION AND SIGNAL DETECTION THEORY FOR ANALYZING HUMAN RELIABILITY IN A SPACE SUBMITTED TO VISUO-VESTIBULAR AND TEMPORAL DISTURBANCES

Laurent DESOMBRE, Yannick LOUAS, Noèl MALVACHE

L.A.M.I.H. - U.R.A. C.N.R.S. N° 1775 - University of Valenciennes
B.P. 311, F- 59304 VALENCIENNES CEDEX
{surname@univ-valenciennes.fr}

ABSTRACT

The proposed research takes place in human reliability study in a space submitted to disturbances and deals with the perception of graphic information when the available observation time is bounded. The aim of this study is to understand better the influence of specific vibrations, graphic disturbances and temporal pressure on the human operator performances during a task of variation detection of bargraph displays. The measures were performed using a Signal Detection Theory rating procedure. It was found that the performances of the human operator decreased during the detection task when the working conditions were submitted to disturbances, and especially in the presence of graphic disturbances.

Keywords : Perceptive Difficulty, Graphic Perception, Temporal, Visual and Postural Disturbances.

1. INTRODUCTION

This paper tries to set the problem of perception for graphic representation of information, for a human operator submitted (or not) to vibrations, and graphical and temporal disturbances. It follows works carried on by the L.A.M.I.H. (Beka *et al.* 1992, Desombre *et al.* 1993). The question is to know if the changes of the perceptive performances are sensorial or determined by a fluctuation of the behaviour during the task and the answering strategy for the various types of work environments provided. It is in the field of the vehicle piloting - by air, sea and land-, that those sights are noted (when the piloting deck is submitted to disturbances).

2. PROBLEMATICS

The point is to collect physical and behavioural indicators related to the postural, visual and temporal strains of the visuo-cognitivo-motor task of the operators placed in a constraining environment in order to obtain fiabilistic or ergonomical recommendations concerning the man-machine communication in a disturbing environment. More precisely, the question is to know if the presence of a temporal strain,the presence of a visual strain which is characterized by the decreasing amplitude of the variation to detect, and the low intensity gravito-inertial strains generated by the postural displacement of the human operator in roll, pitch and yaw are likely to affect the visuo-cognitivo-motor activity of variation detection that the pilot has to carry on.

3. DESCRIPTION OF THE EXPERIMENT

3.1. Experimental platform

The experimental site is made up of a triaxial platform configurated to generate roll, pitch and yaw) rotations .The movements that we decided to apply to the platform for the postural disturbance of the subjects, and which correspond to movements of a sailing ship, are a combination of low-frequency roll, pitch and yaw rotations This rotatory platform comprises a seat, in which the subject takes place. The visual information are displayed through a monitor which is made dependant on the movements of the seat. We use a sensitive keyboard as answering tool.

3.2. Subjects

A group of six subjects has been submitted to this set of experiments. They are all male subjects and they are from 21 to 27 years old ($x=23.8$; $\sigma=2.6$). They do not show any apparent visual deficit and their anxiety is considered normal.

The subjects were selected by a perceptual test called the Embedded Figures Test (EFT), (Witkin 1971). Only the subjects known as "field-independent" were chosen for the experiment, in order to avoid misinterpretation of the results that could be due to differences in perception abilities.

3.3. Task of variation detection of graphic displays

The task is based on the visual detection of an unpredicted variation of the graphic displays. This task rests on the observation and the evaluation by the human operator of two graphic displays of the same type which appear successively on the screen .The task of the subject consists in evaluating, by means of two sensitive keys, whether the amplitudes of the bars of the two graphic displays are identical or different.

3.4. Graphic displays

The bargraph display is used in this research. The characteristics of the graphic shapes, which have been chosen according to our former studies (Desombre *et al.* 1995/96) and to our theoretical basements from the psychophysics are defined as follows (Wickens 1992) : *(i)* the bargraph displays are composed of four bars in order to enable the analysis of the comparisons between the results ; *(ii)* the variations in the height to detect by the human operator during the experimentation are 2 and 4 pixels*.

3.5. Application of the Signal Detection Theory (SDT)

We can categorize the possible answers of the subject in four classes.If the variation is presented and the subject answers correctly by indicating its presence, this is a *hit*. If the variation is presented and the subject does not detect it, it is a *miss*. If the variation is not presented but the subject expresses he has detected it, it is a *false alarm*. Finally, if the variation is absent and the subject answers correctly, it is a *correct rejection.*

The Signal Detection Theory (Swets *et al.* 1982) enables an analysis of the distribution of the various answers of the subject. It is possible to determine the sensorial sensitivity of the subject, that is his perceptive difficulty to detect the presence of the signal : this measure is called *d'*. The higher *d'* is, the easier is the discrimination. We also get a measure of the decision criterion of the subject during the detection task : it is the measure of *beta*.. The higher the criterion *beta* is, the lower is the risk of wrong detection.

3.6. Workload evaluation

The technique used during this experimentation is a version of the NASA TLX method (Hart 1988), adapted to the retained task of variation detection of a graphic display. The main principle is the same as for NASA TLX, with an evaluating scale composed of six descriptors. The subjective evaluations, related to the estimation of the workload (achieved through a questionnaire) concern thus six semantical differentiators assimilated to components of the workload, where for each of them a mark locates the answer of the operator. The six chosen indicators are the mental, physical and temporal demands, the estimated performance, the mental effort and the stress felt.

3.7. Experimental procedure

We distinguish three phases in the experimental procedure. During the three phases, questions regarding the subjective evaluation of the workload by the TLX method are asked through a questionnaire every ten decision makings to not interfere with the execution of the task.

j-) The first phase is the learning phase (phase A), during which the subject becomes familiar with the material and the experimental task.

jj-) During the second phase, called reference phase (phase B), the subject performs the task of variation detection in the absence of temporal or visual strain and in a stable postural situation.

jjj-) The third phase (phase C) presents or not changes related to the modalities of the main factors characterising the temporal strain, the visual strain and the postural situation affecting the working situation during the detection task.

3.8. Main factors

The experimental plan contains three main factors, which are respectively an individual variable characterizing the temporal strain applied to each subject (a) and two variables characterizing the visual strain (b) and the postural situation (c) concerning the task of variation detection of graphic displays.

a. Temporal strain : Two modalities define this factor, according as the available time to make a decision during the phase C is equal to the available time during the former phases, set to two seconds, modality "TS/absent" or reduced (set according to the results of former experiments as a function of the subject), modality "TS/present".

b. Visual strain : Two modalities characterize this factor, depending on whether the amplitude of the variation to detect during the phase C, is identical with the amplitude of the variation to detect during the former phases (four pixels), modality "VS/absent" or reduced by half (two pixels), modality "VS/present".

c. Postural situation : Two modalities are retained, according as the subject is during the phase C in the same postural or vestibular position as in the former phases, modality "PS/stable" or submitted to vestibular disturbances of vibratory origin, generated by the movements of the mechanical seat, modality "SP/unstable".

3.9. Recording data

The variables necessary to carry out the statistical analysis of the performances are, for each observation, the nature of the observation (variation or no variation of the bargraph display) and the answer of the subject (detection of a variation or not). The values taken from the workload evaluation questionnaires are also registered in order to evaluate the subjective workload of the subjects with the TLX method.

4. RESULTS

4.1. Observed variables

The observed variables concern the activity and the performance of the subjects. In this paper, we focus on the following variables : probability of hit p(hit), probability of false alarm p(false alarm), indicator of perceptive difficulty *d'*, decision criterion *beta* and an evaluation of the workload WL (TLX method) characterizing an experimental module.

4.2. Effects of the main factors of the experiment on the observed variables

We use the fiducial inference (Lecoutre 1996) to evaluate the effects of the various factors on the observed variables. The method of significance tests used in the classical analysis of variance aims to determine whether a factor has or not an effect on a given variable, but does only allow conclusions about the existence of the studied effect. The fiducial inference allows us to complete this analysis by proposing conclusions related to the importance of the effects with a measure δ for a notable or a negligible effect (Hoc 1983).

4.2.1. Probability of hit

With the change of modality of the factor "visual strain" during the phase C, we can observe a significant difference at the threshold of 0.10, considered notable, on the variable "probability of hit" (δ >15.2, γ =.90, t(142)=8.96, p<0.0001). The probability of hit for the given answers is thus lower in the presence of a decreasing amplitude of the variation to detect. None of the differences observed according to the factors "temporal strain" and "postural situation" is statistically significant at the threshold of 0.10. These factors have therefore no influence on the variable "probability of hit".

4.2.2. Probability of false alarm

When the available time for the detection task decreases, with the change of modality of the factor "temporal strain" (δ >0.9, γ =.90, t(142)=1.82, p<0.04), when the amplitude of the variation to detect decreases, with the change of modality of the factor "visual strain" (δ >11.4, γ =.90, t(142)=9.48, p<0.0001), or when the subject is under conditions of postural displacement in roll, pitch and yaw, with the change of modality of the factor "postural situation" (δ >3.0, γ =.90, t(142)=3.02, p<0.002), we verify that the probability of false alarm rises for the phase C (when the working conditions are disturbed). The changes of modalities of these three factors allow thus to observe significant differences at the threshold of 0.10, considered notable only for the two latter factors ("visual strain" and "postural situation") on the variable "probability of false alarm".

4.2.3. Indicator of perceptive difficulty *d'*

We observe an effect, considered notable, of the factor "visual strain" (δ >1.2, γ =.90, t(46)=10.74, p<0.0001) and a significant effect of the factor "postural situation" (δ >0.1, γ =.90, t(46)=1.56, p<0.06). When the visual strain is present (modality VS/present), and when the subject is under conditions of postural displacement in roll, pitch and yaw (modality PS/unstable), we observe a lessening in the perceptive capability . The factor "temporal strain" does not act on the perceptive capability ($|\delta|$ <0.5, γ =.90, t(46)=0.74, p<0.23, n.s.).

4.2.4 Decision criterion *beta*

When the available time for the detection task is reduced, with the change of modality of the factor "temporal strain" (δ >0.1, γ =.90, t(46)=1.51, p<0.07), when the amplitude of the variation to detect decreases, with the change of modality of the factor "visual strain" (δ >0.5, γ =.90, t(46)=2.88, p<0.003), or when the subject is under conditions of postural displacement in roll, pitch and yaw, with the change of modality of the factor "postural situation" (δ >0.4, γ =.90, t(46)=2.50, p<0.008), we can stress a significant decrease in the decision criterion value beta, at the threshold of 0.10, considered notable only for the factor "visual strain".

4.2.5. Subjective workload (TLX method)

The analysis of the results does not show any noteworthy effect of the factors "temporal strain", "visual strain" and "postural situation" on the subjective workload during the phase C, but some components of the workload are notably affected by the deterioration of the working environment. In particular, the temporal demand increases in the presence of temporal strain (δ >28.62, γ =.90, t(142)=14.53, p<0.0001) and the estimation of the performance decreases in the presence of visual strain (δ >8.11, γ =.90, t(142)=8.11, p<0.0001).

CONCLUSION

By way of conclusion, the effects of the various disturbances on the performance of the subjects can be summarized as follows :

i-) The presence of a visual strain causes a notable decrease in the probability of hit. This result confirms the conclusions found through the former sets of experiments.

ii-) The presence of a visual strain and an unstable postural situation provoke an increase in the probability of false alarm and a decrease in the sensitivity indicator *d'*. These findings point out the existence of a visuo-postural interaction effect on these variables. These variables are therefore more sensitive to sensorial stimulations (visual and postural disturbances) as to temporal disturbances. As the perceptive capability is reduced, the discrimination is more difficult, and the consequences are the rise in the probability of false alarm and the lessening in the probability of hit.

iii-) The presence of a visual strain brings about a lessening in the decision criterion value *beta*. This means that the behaviour of the subjects is more risky, so they commit more errors. This leads to more false alarms.

iv-) The subjective workload (TLX method) is not notably affected by the disturbances of the working environment. However, some of its components are affected by the disturbances but, as the global workload is a combination of the six descriptors which contribute to calculate it, the global effect of the disturbances on the workload is not notable.

Finally, this study represents an intermediary indicator necessary to the understanding of the operator's responses to the type of work environment provided. The results are far from being perfectly codified and standardized but they can already be used in short term applications and in actual situations.

ACKNOWLEDGEMENTS

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NOTES : * A pixel is equal to the visual angle in 0,03° vertical direction.

VISUALISED CO-ORDINATION SUPPORT IN DISTRIBUTED DECISION MAKING*

Peter Svenmarck
Division of Industrial Ergonomics
Linköping Institute of Technology
Email: petsv@ikp.liu.se

ABSTRACT

This paper is concerned with support of the communication of intentions, as this information is important for individuals co-ordinating locally. A visual communication of intentions was attempted by visualising the behaviour of actors on a dynamic blackboard shown to all, and compared with electronic written messages. Contrary to expectations performance decreased with the blackboard. There is, however, a significant decrease in the frequency of communicated intentions, since this information was present on the blackboard.

INTRODUCTION

A previous experiment by Brehmer and Svenmarck (1995) showed that groups which only co-ordinated locally reached a reasonable performance level, even though there was no central collection of information as in a hierarchical architecture. Instead, these groups used a form of co-ordination based on intentions. The rationale for intentions is that co-ordination of behaviour takes time and it is therefore necessary to predict the behaviour of the other decision makers using some other information than their current activities. If the co-ordination is based on information about their current activities there is always a risk of being late since the activities might have changed when the co-ordination is completed. The time delay until the others intentions becomes their current activities can only be handled with information about their intentions.

In the experiment by Brehmer and Svenmarck (1995), intentions were communicated verbally with electronic written messages, and the purpose of this experiment was to investigate if some other means of communicating intentions would improve the performance of groups co-ordinating locally. Studies of social perception have shown some promise in this direction with direct perception of higher order properties as intentions from actors motions. In the experiment by Runeson and Frykholm (1983) only a minimum amount of information about a persons movement was sufficient for *direct perception* of the persons intention, and studies using animated film techniques have shown how anthropomorphic terms are attributed to actors based only on motion (Kassin, 1981). Similarly, if the actors motion in a distributed system was visualised on a dynamic blackboard shown to all, the intentions could be perceived directly.

In this experiment a dynamic blackboard was implemented in D^3FIRE, a general experimental paradigm for studying distributed decision making, and compared with groups using only electronic written messages. D^3FIRE require four subjects to assume the roles of fire chiefs that co-operate in extinguishing simulated forest fires. Each subject work at their own terminal connected through a computer network. However, they only receive direct information about the fire from a limited window of the fire as a whole. Figure 1 shows the layout of the subjects computer screen. The only command the subjects could issue to their unit was an order where to go, and they did this by clicking on the destination on the screen. The speed of the unit was one cell step per time unit, in this case 30 seconds. When the unit arrived to the destination it started to fight any fire automatically. The quartet's goal was to fight the fire with a minimum loss of squares, and a trial ended when the fire had been put out or when the maximum time was reached. When a fire initially started the subjects were informed about the fire location from a alarm central. This was necessary since it would have taken too long a time to find the fire by unplanned search. In the blackboard condition information about movements was visualised by small trains of arrows moving along a smooth curve. The moving arrows produced a compelling visual pattern, but there was no rationale or test of this design other than the subjective impression. This visual-

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ised information of the movement of all units was displayed simultaneous to all subjects on their terminal. To co-operate and co-ordinate their efforts, the subjects communicated by electronic written messages using the two boxes to the right. In both conditions in this experiment subjects communicated freely with one another in a fully connected architecture.

Contrary to expectations, the information on the blackboard did not improve performance. There is a reduction in frequency of information about intentions and locations in groups with a blackboard, since this information was directly available to these groups. But the reduced demand on communication resources was not used for a better awareness on where the fire was heading, or a better local prediction of the spread of the fire. Some possible explanations are discussed. First, the design of the blackboard where the location of the units is always visible might explain the reduction in communication of important information about the progress of the fire fighting and this could result in a overconfidence of the control of the fire. Second, only behaviour could be insufficient for visualising the processing involved in fire fighting. More factors such as the wind direction and the location of the fire fighting units in relation to the fire could be required for a unambiguous perception of what the subjects are doing. Finally, perception of higher order invariants in general non-linear systems could require inferences concerning intentions based on more information about the causes of the behaviour.

Although the results were disappointing, the possibility that higher order properties, as intentions, could be perceived directly with appropriate visualisation of changes in system variables is a interesting approach to support control of dynamic systems that should be investigated further.

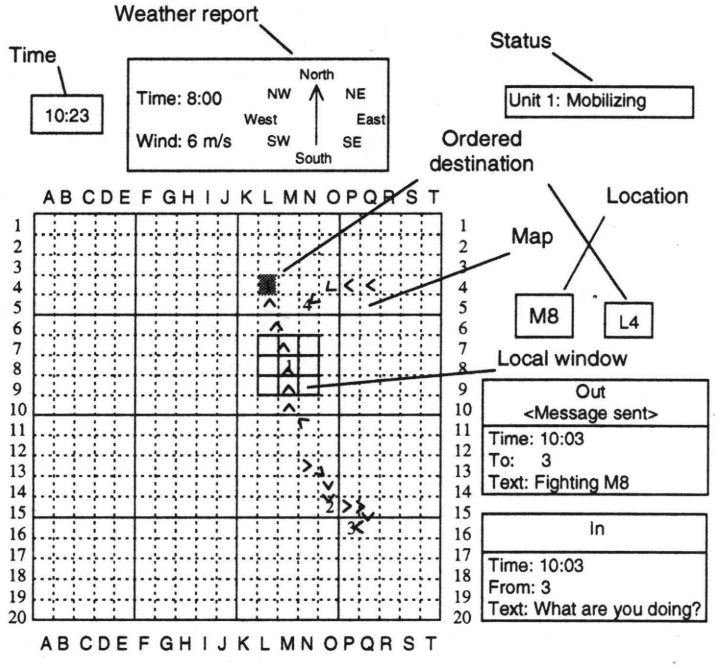

Figure 1. The task in D^{3}FIRE as it appeared on the subjects computer screen. The map was displayed on a grid of 20 x 20 cells. Subject could observe the fire only trough a local window of 3 x 3 cells. The visualisation of movement was displayed only in the blackboard condition. Subjects without a blackboard could only see the location of the others when they were within the nine cells covered by the local window.

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Design of an Overview Display for a Waste Incineration Plant

Jette L. Paulsen[1] and Steen Weber[2]
Risø National Laboratory
P.O. Box 49, DK 4000 Roskilde, Denmark

[1] jette.l.paulsen@risoe.dk
[2] steen.weber@risoe.dk

ABSTRACT

The development of a user interface for a waste incineration plant is described. The interface is connected to an advisory system based on neural network techniques. We argue that the design of display systems to process plants needs to be based on an explicit definition of the purpose of the display. In the case of the display for the waste incineration plant, the purpose is to optimise the incineration process and keep the flue gas as clean as possible.

Keywords
Interface Design, Process Plant, Waste Incineration,

INTRODUCTION

The present report describes an advanced display system for a waste incineration plant. The development of the display system is a part of the CLEAN (EC sponsored) project, the main goal of which is to decrease the emission from waste incineration plants. To achieve this the project seeks to optimise the control system. For the optimisation of the control system a neural net controller has been developed based on experience from the plant.
The operator must be considered as a part of the control system, but without a *specific* transfer function. The information to the operator about plant status must be very precise enabling him to take the right decisions about actions to be done manually. This, therefore, constrains the selection of information to the operator and the way it is presented .
For the initial implementation of the neural network controller the operator is regarded as a part of the controller. The operator has to perform manually the actions which the controller will execute in the final implementation. The initial implementation is therefore a test of the neural network controller. The display must present, besides the information about plant condition, advice to the operator for manual adjustments of set points. On Fig.1 is shown the set-up for the use of the display.

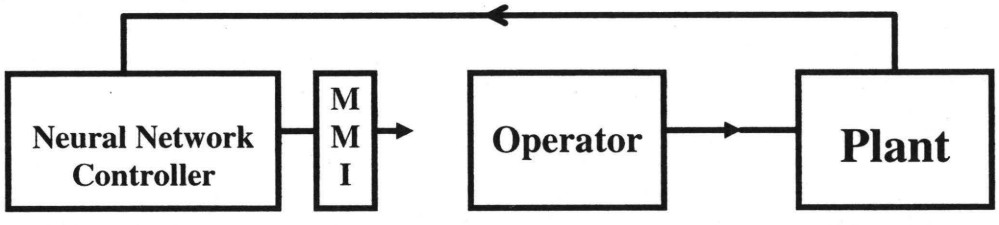

Fig.1 The display (MMI) has been tested in the above configuration at the Waste Incineration Plant in Darmstadt

THE INFORMATION REQUIRED.

The values present on the display are chosen from a strategy described in (Paulsen 1996)

- What are the problems?
- How do they occur
- How are they observed?
- How to present them for the users?
- How to avoid them?

The problem in the project is the emission of unwanted elements in the crude gas, for example too high CO level and a dioxin content. These problems can be avoided by maintaining a sufficiently high temperature in the incineration chamber and a sufficient air flow to the incineration process. Due to unknown variation of humidity and heating value of the waste it is difficult to estimate the airflow The optimal way of running the process is to keep the energy output constant corresponding to a constant airflow. The problem is the amount of input waste to the process. The same strategy as described above can be used to analyse the problem of deviation from normal energy output: why, what to observe and what to do.
As seen on the display developed (figure 2) the variables are presented in a graphical form from which it is easier for the operator to see if the operation of the plant is normal or any deviation is occurring.

TESTING OF THE DISPLAY

The neural network controller has been tested against the target incineration plant in Darmstadt using the display in (figure 2). The display turned out to give the information required. During the development the display has been tested against logged data from the incineration plant and against a simulation model of the plant.

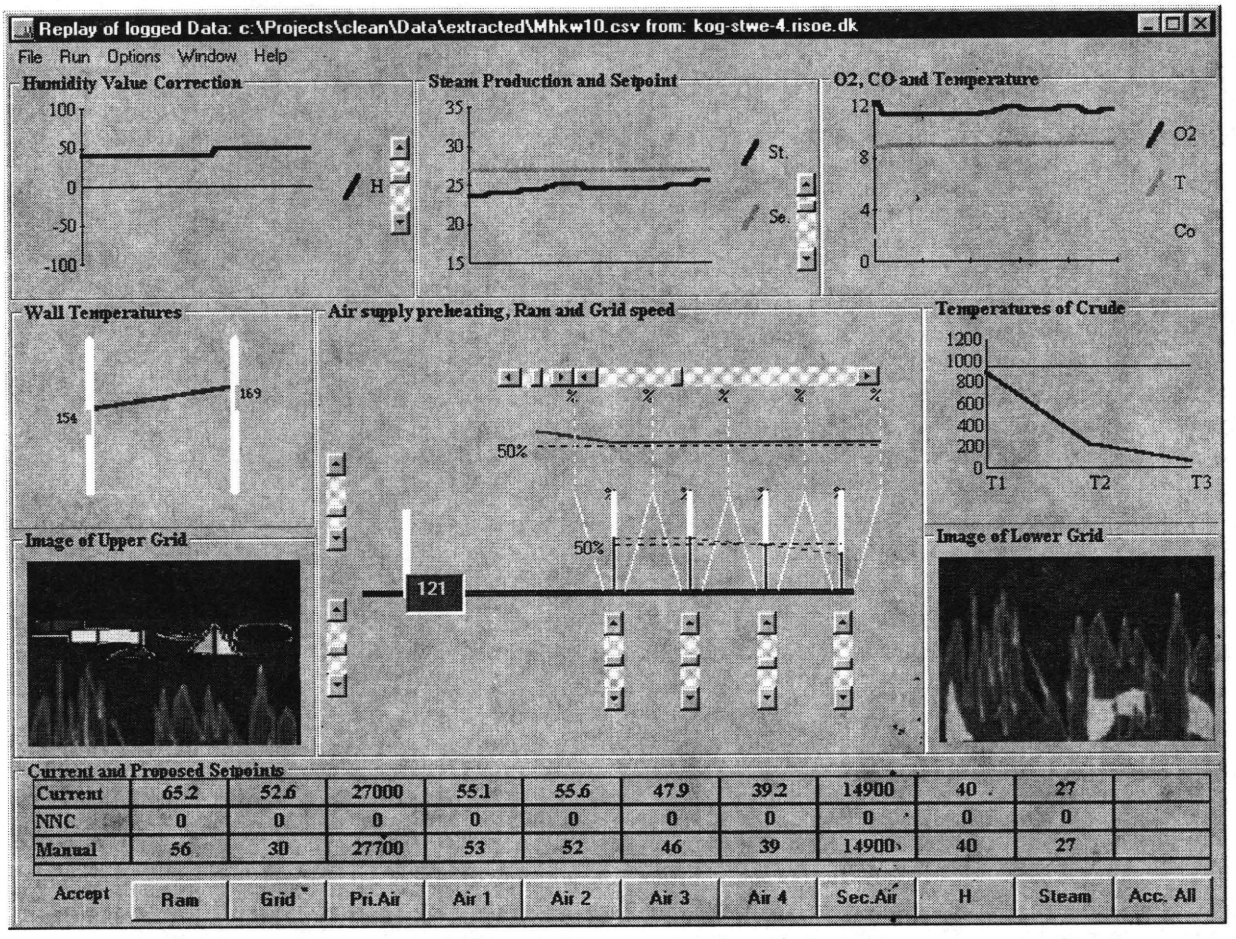

Figure 2. User Interface for a Waste Incineration Plant

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Scenario Use in Conceptual Control Room System Design

Sotiris A. Papantonopoulos

School of Engineering and Applied Science
The George Washington University
Washington, DC, USA
sotiris@seas.gwu.edu

ABSTRACT

An empirical study of the use of scenarios in conceptual design, requirements analysis, and the design of control room automation was conducted. Scenarios are descriptions of activities that the user engages in when performing a task and may be used by the system designer to keep the future use of the envisioned system in view as it is being designed and proactively guide the design process. The study investigated the differences in the use of narrow and rich scenarios and analyzed their impact on the design strategies and design conjectures of mission operators and spacecraft control room system designers.

Keywords
System design, scenarios, conceptual design, design strategies, design conjectures

INTRODUCTION

An empirical study of the use of scenarios in conceptual design and requirements analysis in control room system design was conducted.

Scenarios are descriptions of activities that the user engages in when performing a specific task and may be used by the system designer to keep the future use of the envisioned system in view as it is being designed and proactively guide the design process.

In the case of spacecraft control room system design, scenarios may be used to describe the on-line functions of operators or other mission operations staff working multiple shifts to monitor the spacecraft and detect, analyze, and control anomalous spacecraft behavior. On-line command and control functions are expected to become more difficult as the complexity and automation of the mission operations increases. To avoid the escalation in mission operations costs and to reduce the risk of spacecraft and/or payload data loss, significant innovations in control room system design are being introduced.

OBJECTIVES AND METHODOLOGY OF THE STUDY

The objective of the study was to investigate the differences in the use of narrow and rich scenarios (Kuutti, 1995) in conceptual design, requirements analysis, and the design of automation between mission operations (users) and system designers (designers) in control room system design. Narrow scenarios are narrowly focused descriptions of end-to-end transactions involving the system and its environment. Rich scenarios depict activities in a full context, describing the social settings, resources, and goals. Narrow and rich scenarios employ different concepts in their description of mission operations. Narrow scenarios describe the functions of mission operations and the physical processes of the equipment supporting these functions in terms belonging to the vocabulary of system designers. Rich scenarios depict the work practices and activities supported by the above functions and equipment.

The study analyzed the impact of narrow and rich scenarios on the design strategies and design conjectures of users and designers. Design strategies are defined by the major design decisions mapped into a two-dimensional abstraction and aggregation design space (Rasmussen et al, 1994). Design conjectures are defined

as the limited set of objectives or solution concepts that system designers rely on very early in the design process to reduce the variety of potential solutions to the as yet imperfectly understood design problem to a small set of solutions which are cognitively manageable (Darke, 1979).

Two command and control tasks were solicited by missions operators and each was transcribed into one rich and one narrow scenario, resulting into two rich and two narrow mission operational scenarios. Sixteen subjects were solicited among missions operators and control room system designers at NASA Goddard Space Flight Center in Greenbelt, Maryland, USA. The subjects were administered two scenarios and were asked to describe an appropriate operator response and to elaborate on the design of suitable automation. The verbal protocols were recorded, transcribed, and analyzed and the design strategies and design conjectures of each subject were identified.

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3 HUMAN ERROR AND SYSTEM RELIABILITY

Error Mode Prediction

Erik Hollnagel & Magnhild Kaarstad
OECD Halden Reactor Project, P. O. Box 173, N-1751 Halden, Norway
Email: <firstname.lastname>@hrp.no

Hyun-Chul Lee
KAERI, HF Research Team, P. O. Box 105, Yusung, Taejon, Korea 305-606
Email: leehc@nanum.kaeri.re.kr

ABSTRACT

The study of accidents ("human errors") has been dominated by effort to developed "error" taxonomies and "error" models. In the field of Human Reliability Analysis (HRA) there is, however, a significant practical need for methods that can predict the occurrence of erroneous actions - qualitatively and quantitatively. The present experiment tested an approach for qualitative performance prediction based on the Cognitive Reliability and Error Analysis Method (CREAM). Predictions of possible erroneous actions were made for operators using different types of alarm systems. The data were collected as part of a large scale experiment using professional nuclear power plant operators in a full scope simulator. The analysis showed that the predictions were correct in more than 70% of the cases, and also that the coverage of the predictions depended critically on the comprehensiveness of the preceding task analysis. The method will be refined and tested in further experiments.

Keywords: Human erroneous actions, performance prediction, HRA, nuclear power plant, man-machine interaction, error modes

INTRODUCTION

The study of human erroneous actions has traditionally followed two different lines of approach. One has been concerned with finding and explaining the causes of erroneous actions, such as studies in "error psychology". This approach has used a variety of models stretching from classical human factors (Altman, 1964; Swain, 1963) over information processing models (Norman, 1981; Reason, 1990; Rouse & Rouse, 1983) to cognitive engineering (Woods, et al., 1994) and socio-technical models (Reason, 1997). The other has been concerned with the qualitative and quantitative prediction of possible erroneous actions, exemplified by the field of human reliability analysis or HRA (e.g. Dougherty & Fragola, 1988; Park, 1987; Kirwan, 1994). The former approach has been dominated by an academic point of view, hence emphasising theories, models, and experiments, while the latter has been of a more pragmatic nature, hence putting greater emphasis on data and methods. For people faced with practical problems in system design, operation, or maintenance, the great need is for applicable methods rather than elegant theories.

HUMAN ERROR ANALYSIS PROJECT (HEAP)

The OECD Halden Reactor Project has since 1994 been engaged in a long term effort to study human erroneous actions (HEAP). The purposes of this study are: (1) to provide a better understanding and explicit modelling of how and why erroneous actions occur (specifically when they involve cognitive activities such as diagnosis), and (2) to provide improved design guidance for the development of man-machine systems that can avoid or compensate for erroneous actions.

Four initial pilot studies put the emphasis on methodological aspects, in particular the development of methods to investigate cognitive aspects of behaviour using real operators in difficult scenarios (Kaarstad et al., 1994 & 1995; Kirwan, 1994a).

The objective of the first pilot study was to evaluate concurrent and interrupted verbal protocol techniques with regard to their applicability to identify operators' problem solving strategies, diagnostic strategy types, and possible "cognitive inefficiencies" while locating a fault. The main finding was that the two methods provided different types of information about problem solving strategies and human erroneous actions. The methodological recommendation for the main HEAP study was therefore to use a combination of the two methods.

The objective of the second pilot study was to test whether eye movement tracking analysis was a feasible supplement to verbal protocols in studying operators' cognition during fault-finding. The main finding was that the analysis of eye movements helped to make the interpretation of verbal protocols more robust and gave a better insight into the operators' problem-solving behaviour. Wearing the eye-tracker equipment had no apparent effect on the quality or quantity of verbal protocols or upon diagnostic performance.

The third pilot study investigated the effects of scenario complexity on operators' diagnostic behaviour. Complexity was assumed to be a multidimensional concept that was varied by manipulating the number of underlying faults in three different scenarios. The main findings were that number of underlying faults did not by itself prove to be a dominant complexity factor when the performance measures were the degree of operator success in diagnosing the faults and the use of different diagnostic strategies. This study also used operators from two different operating environments, but the results showed no systematic variation with respect to either subject pool or performance measures.

The fourth pilot study looked at the quality of information provided by different data sources. The preceding studies had shown the need of multiple data sources, typically concurrent plus interrupted verbal protocols and eye movement data. Since considerable resources are needed to analyse a combination of different data sources, it is important to know in advance what the relative contribution is from each source of data. The findings were that all three types of protocols (concurrent, auto-confrontation, and expert) produced similar results for a set of pre-defined target activities, although concurrent verbal protocols were the richer source of data. Furthermore, it was found that concurrent verbal protocols can effectively be used for teams as well as for single operators

Performance Prediction In HEAP

The pilot experiments had demonstrated how diagnostic errors could be found from performance records (Follesø et al., 1996), but another essential issue is to be able to predict the likely error modes. In order to achieve this an experiment was designed with the purpose of developing and refining a method, or set of methods, for predicting performance failures, specifically the error modes that can be expected for a specific task. The method should specifically enable the analysts to:

- identify the types of incorrect performance (error modes, cognitive failure modes) that are possible for the given task or scenario;
- qualitatively rank or rate the possibility of the possible error modes, to identify those that are the more likely to happen.

The basis for any kind of performance prediction must be a detailed description of the situation where the performance takes place and a specification of the critical aspects of the performance. since the error modes basically are deviations from the expected performance, the starting point for making a prediction of this type must refer to a description of the expected performance. This can either be developed from scratch or make use of already existing descriptions from e.g. a task analysis, existing operating procedures, ideal paths or performance time-lines and event trees such as they are used in PSA/HRA.

In this experiment case the predictions were based on the task descriptions provided by the Operator Performance Assessment System (OPAS). For each scenario OPAS provided a description of the operators' actions, using a simple hierarchy of main goals, subgoals, and operator tasks where the latter were classified as either detection or operation.

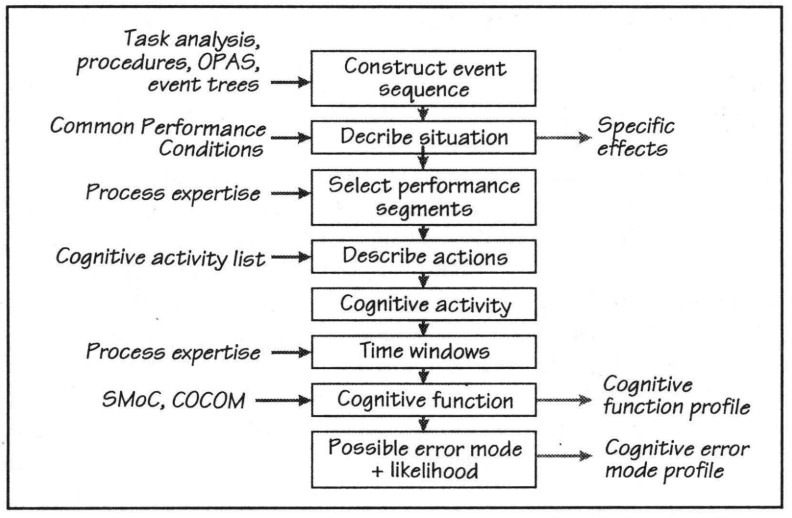

Figure 1: Basic steps of performance prediction.

PERFORMANCE PREDICTION METHOD (CREAM)

The basic steps of the prediction method used in the experiment are shown in Figure 1. The method was derived from the basic method of CREAM (Cognitive Reliability and Error Analysis Method), cf. Hollnagel, 1997. The most important steps are described in the following.

Describe Situation. Although HRA uses a large number of Performance Shaping Factors (Swain, 1967) it is possible in practice to define a relatively small set of Common Performance Conditions (CPC) to describe the general determinants of performance, hence the common modes for actions in a context. Table 1 shows the basic CPCs and the qualitative descriptors that are used to characterise the actual value for each CPC in a given situation or scenario.

Table 1: Common Performance Conditions.

CPC name	Level / descriptors
Adequacy of organisation	*Very efficient / Efficient / Inefficient / Deficient*
Working conditions	*Advantageous / Compatible / Incompatible*
Adequacy of MMI and operational support	*Supportive / Adequate / Tolerable / Inappropriate*
Availability of procedures / plans	*Appropriate / Acceptable / Inappropriate*
Number of simultaneous goals	*Fewer than capacity / Matching current capacity / More than capacity*
Available time	*Adequate / Temporarily inadequate / Continuously inadequate*
Time of day (circadian rhythm)	*Day-time (adjusted) / Night-time (unadjusted)*
Adequacy of training and experience	*Adequate, high experience / Adequate, limited experience / Inadequate*

Select Performance Segments. The CPCs were applied to the OPAS description of the scenarios. The analysts selected the appropriate descriptor for each CPC and produced an overall characterisation of the major segments or sub-parts of the scenario, since it was expected that there would be significant differences between segments. The assessment of available time was later refined by more precise estimates of time windows.

Describe Actions And Assign Cognitive Activity. In order to attain a uniform level of description, each of the actions in a task segment was described using a set of standard categories referred to as the **cognitive activity list** which contained the following categories: *co-ordinate, communicate, compare, diagnose, evaluate, execute, identify, maintain, monitor, observe, plan, record, regulate, scan,* and *verify.* The list has an empirical rather than

an analytical basis, i.e., it is derived from accumulated experience from operator performance studies rather than from a model of operator performance.

Cognitive Functions. Based on the assignment of the cognitive activity types the likely error modes can be identified. The assignment can nominally be made on the level of phenotypes (Hollnagel, 1993), but in order to be really useful for the performance prediction, the assignment needs to be made on the level of representative cognitive functions. This means that reference must be made to an underlying model of the operator, which fortunately does not have to be very complicated or detailed. We used the generic Simple Model of Cognition (SMoC; Hollnagel & Cacciabue, 1991) which makes a distinction among four groups of cognitive functions, called **observation**, **identification**, **planning**, and **execution**. Based on the fundamentals of the model, a generic mapping can be produced of the dominant cognitive function(s) for each of the cognitive activities. A bi-product of this step is the cognitive function profile that is a graphical representation of the expected distribution of cognitive functions for each task segment. The profile is useful to get a quick appreciation of the possible differences between task segments with regard to the cognitive functions that are involved. In particular, the profile will show whether there is a possible dependence on a single or a few cognitive functions.

The **Possible Error Modes** are found by using a table of the possible cognitive function failures for each of the basic cognitive functions. This table refers both to observable and inferred failures, which are more in the nature of causes. Examples of the former are provided by execution errors, while examples of the latter are provided by other categories. The list shown in Table 2 is limited to the main (cognitive) error modes. This list can easily be extended if the analysis requires that.

Table 2: Generic (cognitive) error modes.

Cognitive function	Potential (cognitive) error mode	
Observation errors	O1	Observation of wrong object. A response is given to the wrong stimulus or event.
	O2	Wrong identification made, due to e.g. a mistaken cue or partial identification.
	O3	Observation not made (i.e., omission), overlooking a signal or a measurement.
Interpretation errors	I1	Faulty diagnosis, either a wrong diagnosis or an incomplete diagnosis.
	I2	Decision error, either not making a decision or making a wrong or incomplete decision.
	I3	Delayed interpretation, i.e., not made in time.
Planning Errors	P1	Priority error, as in selecting the wrong goal (intention)
	P2	Inadequate plan formulated, when the plan is either incomplete or directly wrong.
Execution Errors	E1	Execution of wrong type performed, with regard to force, distance, speed or direction.
	E2	Action performed at wrong time, either too early or too late
	E3	Action on wrong object (neighbour, similar or unrelated)
	E4	Action performed out of sequence, such as repetitions, jumps, and reversals.
	E5	Action missed, not performed (i.e., omission), including the omission of the last actions in a series ("undershoot").

For each cognitive function the analyst must select among several possible error modes the one that best matches the description of the scenario and the performance conditions. This combination requires a thorough consideration of the nature of the scenario, together with appropriate knowledge of the method. For this step it is also possible to construct a cognitive error mode profile that shows the (relative) distribution of error modes for each task segment. This can be useful to get a general appreciation of the types of problems that may be expected for different task segments.

EXPERIMENT AND DATA COLLECTION

The actual experiment was carried out together with the NRC Alarm Project that aimed to investigate the effect of various types of alarm display and alarm processing methods. The experimental design is summarised in Table 3. The main independent variables in the alarm experiment are three kinds of alarm display types and three alarm processing levels. However, the experiment was carried out in only eight experimental conditions because

of limited experimental resources such as subject schedule, time requirement, and so on. The selected eight experimental conditions are shown in the table underneath.

Table 3. Experimental Conditions in the Alarm Experiment

	ALARM PROCESSING LEVEL				
	No processing	No nuisance alarms		No redundant alarms	
Display type		No availability	Availability	No availability	Availability
Tile	1	7			
Mixed	2	3	4	5	6
Integrated		8			

The HEAP experiment used the conditions where performance differences were most likely, i.e., conditions 2 (no processing, mixed display) and 8 (nuisance alarms removed, integrated display). In addition, condition 7 (nuisance alarms removed, tile display) was selected as a base line condition for comparison purposes. This selection resulted in a total of 36 scenarios to be analysed.

The experiment was conducted in the HAlden Man-Machine LABoratory (HAMMLAB) at the Halden Reactor Project using a full-scope simulation of a PWR NPP. The subjects were 12 licensed commercial power plant operators (six crews of operators participated with two operators per crew) from the Loviisa NPP in Finland.

The data includes a record of the alarms presented to the operator during the scenario, all the operators' interaction with the simulator, and the manipulations done by the experimental leader. The variable log includes the process parameters known to change during the scenario. Other data sources were eye movements, video recordings together with soundtracks of the operators' communication and an expert commentator. Furthermore, the OPAS checklist was used to score whether the operators followed the predefined operating sequence. After the experiment this could be compared with the simulation log and video recording to validate the scoring and calculate performance rating.

OPAS was used as a main source for both the predictions of error modes and for analyses of the observed errors during the experiment. The predictions were analysed using the time windows, the process expert rated OPAS formats, simulator data and expert commentators. Video and the eye movement data were used for clarifications when needed.

RESULTS

To evaluate the precision of the predictions the scenarios were scored independently by two analysts. The agreement was high, with a mean of about 72%, ranging from 53% to 88% agreement. The quality of the interpretation can be determined by using a test of interscorer reliability, such as Cohen´s Kappa (Breakwell et al., 1995). Cohen´s Kappa compares the nominal scales from the scoring and takes into account the probability of the same scoring due to chance. The value of Cohen´s Kappa was calculated to 0.66 which is significant ($p < .05$) even if the probability for agreeing on the same error mode by chance was set as high as 40%.

All predictions were analysed and a match percentage for each scenario was calculated. The match percentage ranged from 42% to 100%, with an average at 67.8%. The histogram (Figure 2) shows the hit percentage distribution of the different scenarios.

A more detailed analysis showed that the overall match between predicted and observed observation error modes was 100%, while there were no observed planning errors. Interpretation errors had a 68% match and execution errors had a 56% match.

The predictions also included an evaluation of what the most likely error mode to happen would be for each scenario. This was based on the scorers` judgements together with the characterisation made by the common performance conditions of the scenario. The error mode judged to be the most likely for each scenario actually occurred in 72% of the cases.

Some of the error modes were not predicted (O1, O2, P1, P2 and E3). This is probably due to the fact that OPAS was made for a different purpose and that the task analysis therefore served a different objective. If more work is put into defining the operator tasks, a higher match between predicted and actual error modes is expected. This will be investigated in a further study later in 1997.

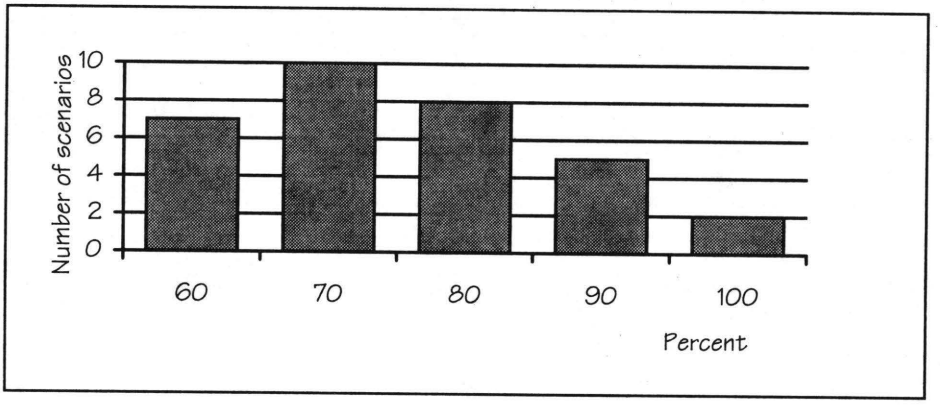

Figure 2: Percentage match of scenario predictions.

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TWO METHODS FOR ACCIDENT ANALYSIS: COMPARING A HUMAN INFORMATION PROCESSING WITH AN ACCIDENT EVOLUTION APPROACH

Ola Svenson (1,2) and Petra Sjöström (1)

(1) Department of Psychology Stockholm University, S-106 91 Stockholm, Sweden.
E-mail: osn@psychology.su.se
(2) School of Business University of Leeds, Leeds LS2 9JT United Kingdom

ABSTRACT

The primary goal of an accident investigation should be to find out how to prevent the same or other similar accidents to occur in the future. To attain this goal it is necessary to perform an accident analysis which identifies as many contributing factors as possible and to suggest actions for removing or blocking each contributing factor. The effects of different analyst backgrounds on the results on the analyses of a hospital accident were illustrated in an earlier study (Svenson, Lekberg & Johansson, 1997). A tendency for analysts to find more contibuting factors outside their own field of expertise (engineers found more human errors) was illustrated. In addition, it was shown that psychologists had a tendency of attributing less responsibility for an accident to the person who made the fatal errors and relatively more responsibility to the hospital management responsible for the workplace and organization than engineers did. The earlier analyses used the same method for analysing an accident. In the present study, the effects of not only using different analysts but also using different methods will be illustrated and possible differences depending on this will be pointed out. Both methods model an accident as evolving over time with human and technical systems in interaction. The first of the methods (HINFO) applied was based on a human information processing approach (Englund et al., 1978) and the other method (AEB) was based on an accident evolution model with interacting technical and human factors system (Svenson, 1991). The results illustrated how results from different methods and analysts may differ. To exemplify, the latter method listed about 50 per cent more contributing causes to the accidents analyzed than the former method. Still, the fundamental causes identified were almost identical and the difference could be explained by the much more fine grained analysis of human errors in AEB. Concerning suggestions for actions to prevent future accidents, the analyses according to the HINFO method resulted in more technical solutions and the AEB method analyses offered more behavioral actions to prevent further accidents.

INTRODUCTION

The most important aim of an accident investigation should be to find out how to prevent the same or other similar accidents to occur in the future. To fulfill this aim it is necessary to perform an accident analysis which identifies as many contributing factors as possible and to suggest actions for removing or blocking each such contributing factor.

There are many different approaches for analysing incidents and accidents. Common to all of them are the fact that they all rely on models of what an accident is (Englund, 1978; Englund et al., 1978; NRC, 1986; LePlat, 1987; INPO, 1988; Svenson, 1991; CCPS, 1992). There are simple intuitive one-factor models (e.g., it all depends on a too weak construction), more complex causal tree models (e.g., LePlat, 1987) and very complex scenario like models of accidents (e.g., INPO, 1988) which relate all the different decisions, actions and events which lead up to an accident. Recently the effects of different perspectives and analyst backgounds on accident analyses were illustrated by Svenson, Lekberg and Johansson (1997). They found differences in distribution of responsibility to people involved in an accident. A legal perspective gave all the responsibility to one person while engineering and psychoological perspectives distributed the responsibility among several persons. The psychology and engineering experts used the same method and the same accident and yet the engineers found

more human errors than the psychology analysts. Concerning the person given all the legal responsibility, psychologists tended to attribute less responsibility for the accident to her than did the engineers.

Automatically and theoretically coupled with an analysis of an accident are the recommendations given for actions which should be undertaken to avoid an accident in the future. If, for example, only one person is found responsible for an accident, as in the legal analysis covered by Svenson, \Lekberg and Johansson (1997), it is also reasonable, strictly speaking, to punish and/or remove that person from the activity affected by the accident. Here, relatively minor effort is likely to be spent on, for example, improving organizational and technical conditions. If engineers find more human errors made by individuals, they may be more likely to recommend change of personnal or increased training than analysts who find more technical errors. However, it is also possible that engineers suggest relatively more technical changes to make it possible to improve human performance, although this was not shown in the study by Svenson et al. (1997). In this study, the same method was applied to the same accident by psychologist and engineering analysts. However, not only the analysts background but also the method they use may affect the results and recommendations following an accident investigation.

Therefore the present study will search for differences when methods based on different models are applied to the same accident by different analysts. The methods are derived from two different fundamental models. Both fundamental models use time as an important variabel along which an accident develops in a series of interactions between human and technical systems. One of the methods is based on an human information processing approach in which an accident is the result of insufficient or missing information to a person at a crucial point in time. The other approach is based on an accident evolution model in which an accident is seen as a series of interacting errors in human and technical systems developing over time.

Two Accident Modelling Approaches

Each one of the two accident analyses methods applied in the present study emphasizes a particular perspective on an accident. Only the first one, the Human Information Processing, HINFO, method is used in its fully developed form and its prior analyses are based on data which will be used also as data for the other method. The other method is the Accident Evolution and Barrier Function, AEB, method which is applied on the accident narratives provided in the HINFO method. In this way it is possible to conceive the present study as a repeated analyses with another method stressing the variable of time in the gradual development of a sequence towards an accident.

The first of the approaches chosen for analysis of accidents, the HINFO method, rests on the assumption that an accident in which an operator plays an active part can be related to erroneous, distorted or missing information. Englund et al (1978) presented an elaborated model for accident analysis also including a very thorough data collection method involving engineering expertise and on the spot investigations of road traffic accidents. As mentioned above, the data collected in this investigation will be used as data for also in the AEB analyses because the data are of such a high quality that they can be used for this purpose.

Fundamental to the HINFO method is the system character of the humna-technology-environment character of the road traffic system. In this system the driver is a component in the system, but also an operator. In order to fulfill the requirements as an operator the driver needs information to make important decisions. An accident is seen as the result of a brake down of the information decision action system of the operator. In an analysis of an accident there are three important questions that should be answered, namely (1) what information was necessary for the operator to manage in the driver-vehicle-environment system interactions? (2) to what extent did the drivers input and use this information? and (3) what factors could explain the difference between these two sets of information? Because of the system perspective, different experts have to be involved in accident investigations. Englund et al. (1978) used one engineerer specializing in vehicle egnineering and another in road engineering in addition to a psychologist in the team of three experts gathering the data in on the spot investigations.

The second approach, the AEB method is based on the concept of an accident as a sequence of interacting human and technical failures, malfunctions and errors which are necessary for the evolution of an accident (Svenson, 1991). The method uses a response sheet requiring the analyst(s) to work through both the technical

errors and failures and the human malfunctions and errors at the same time following an approximate chronological order. Between each error box in the response sheet describing the accident evolution, there is room for error barrier functions which can interrupt the sequence towards the accident. For example, a brake which had functioned well, could have served as a barrier function, and interrupted the accident sequence in two of the traffic accidents analysed here. Barrier function systems are systems that execute the barrier functions. To illustrate, a traffic signal system may produce a signal that arrests a threatening accident evolution. The particular version of the AEB method used here models each of two drivers in separate but parallel analyses until the two vehicles reach physical contact. This separation makes it possible to get an overview of the two interacting drivers involved in an accident. The original one-sequence model was used for single vehicle accidents.

METHOD

The Accidents

In all 13 road traffic accident were investigated in on the spot investigations by the team performing the HINFO analyses. The data was collected by teams of three members as mentioned above two engineerers and one psychologist. The analyses were made on the spot sometimes before ambulance and police had arrived. This was because the invetigation team used the same radio as the police and ambulance personnal and also were on a stand by in a special car. The data used for the present analyses were published by Englund et al. (1978). The accidents used here represent a subset of the 23 analysed in that publication. The 13 accidents used here represent all different kinds of accidents covered in the original report.

Procedure

The earlier analyses made by Englund et al were used as they were and the narratives of the accidents used as data in the AEB analyses. The AEB analyses were first performed by the second author and based on these analyses the first author went through the analyses to obtain complete agreement concerning the analyses. Following this, the different contributing causes and recommended actions were classified in four categories presented in the results section.

RESULTS

It is important to stress, before presenting the results, that the analyses performed here represent just an illustration of how the different methods have been applied to the set of road traffic accidents. There is no reason why not each of the approaches can be adjusted so that at least a somewhat different coverage of the contibuting factors can be achieved. In addition, there is usually no final answer to the question of which approach is the best one from simple listings of contributing factors and suggested actions. For example, one method as applied by an individual analyst may list a great number of less realistic actions to avoid future accidents, and another method may generate a smaller number of more relevant actions. This could result in the smaller being the better. However, it is possible to eliminate irrelevant causes and actions, but more difficult to invent factors which one did not think of, so in this respect more is better.

Coupled with each method of analysis and with each analyst is the risk of a delimiting the perspective both when it comes to contributing factors and suggested actions for avoiding further accidents. This will be illustrated in the following results. The AEB analyses were based on the HINFO data and the AEB analyses were made with knowledge about the accounts of the accidents given in the former analyses. Therefore, not surprisingly, most of the causes and recommended actions of the HINFO analyses also appear in the AEB analyses. However, the AEB analyses still differ from the original analyses which will be illustrated in the following.

Table 1 lists the contributing factors and the suggested actions to be taken to prevent further accidents resulting from the HINFO and the AEB analyses. Note that due to the fact that several causes and actions were suggested in an analysis of a single accident, the numbers in Table 1 cannot be analyzed in a simple statistical manner. Still, the table shows that more different contributing factors are listed in the analyses (92) than in the HINFO analyses (59). In particular, the number of driver errors are many more in the AEB approach. This indicates that the AEB method has resulted in greater resolution in terms of driver behavior than HINFO. The difference

is there despite the fact that performance shaping factors are listed as contributing factors only in the HINFO analyses and not in the AEB analyses. In the AEB analyses the performance shaping factors (time stress, tiredness, driver distraction etc) are listed separately and were not included in the table. That is, if they had been included, the difference would have been even greater.

Table 1 Listed causes and suggested actions for the HINFO and AEB methods. Environment includes road and concurrent traffic factors . The majority of vehicles are cars, but in one case a truck and in another a bycycle was involved in the accidents. This category also includes vehicle regulation such as checks of breaking efficiency and passive safety (e.g., seat belts). Regulation stands for regulation of vehicle movements such as signals, one way street, speed limit and warning signs. Driver includes all driver characteristics, perception, cognition and behavior, training programs etc. A total of 13 accidents were analyzed.

	Technical		Behavior		
	Environment	Vehicle	Regulation	Driver	Total
Suggested causes					
HINFO	14	6	2	37	59
(%)	(24)	(10)	(03)	(63)	
AEB	14	10	1	67	92
(%)	(15)	(11)	(01)	(73)	
Suggested actions					
HINFO	17	2	6	2	27
(%)	(63)	(07)	(22)	(07)	
AEB	14	8	14	12	48
(%)	(29)	(17)	(29)	(25)	

Concerning suggested actions, there is a tendency of relatively more environment action suggested in the HINFO analyses and relatively more driver directed action (in terms of traffic regulation, driver instruction and training) suggested in the AEB analyses . This can be interpreted considering the data in Table1, that the HINFO method typically suggested changes in the environment in response to human failure and the AEB method typically suggested behavioral changes for avoiding future accidents.

There is no logical necessity depending on which method was used behind this difference. The explicit necessity in the AEB method to split up human behavior in a sequence of errors interacting with technology leads to a detailed account of human errors. However there is nothing in the HINFO method which prevents this detailed analysis, but there is no formalism which encourages it either. Part of the difference may reflect underlying assumptions in the methods about what factors cause and what factors can stop or avoid an accident. In part this may also reflect differences attributable to the analysts involved in the HINFO and AEB analyses. Such differences were described earlier (Svenson, Lekberg & Johansson, 1997) between engineers and psychologists. In the present study all analysts were psychologists. The HINFO method does not explicitly include performance shaping factors which is the case in the AEB method. Another difference is that AEB modelled more errors later in the sequence than the HINFO method.

Table 1 shows a difference in the number of actions suggested in relation to the vehicle which partly seem attributable to the repeated suggestion of ABS brakes (to avoid skidding) as a recommendation in the AEB analyses. Such brakes were not commonly available when the HINFO analyses were performed and their efficiency may be doubted because the accidents all occurred before the winter season in Sweden.

The results in terms of fundamental contributing factors causing the accidents were rather similar across the two methods. This indicates that the methods were compatible in efficiency given the same data. However, the more detailed accounts provided by the AEB method produced more minor contributing factors, many of which were consequential errors following an earlier error and errors later in the accident evolution.

CONCLUDING REMARKS

The present and the earlier investigation has illustrated how different analysts and methods may affect the analysis of accidents. In Svenson, Lekberg and Johansson (1997) it was shown that causes for accident were often allocated outside an expert's area of expertise. To counteract that possible bias, different experts can be used to perform deeper analyses in their own fields (e.g., psychology) after identification of a (e.g., human factors) error identified by an expert from another field (e.g., traffic engineering, or organizational science). It is also important to realize that although expertise also includes expertise about how to prevent or ameliorate errors, this knowledge is restricted and does not include actions in other systems (e.g., technical solutions to prevent human errors).

When an accident analysis is performed, it is important to understand the basic model behind the method used if it is not explicit. Then, different fundamental models should be considered and aspects not so well covered by the method identified. When the analysis is performed, special attention can then be paid to aspects less well covered by the method used. To exemplify, an AEB formalism perspective applied to the HINFO analyses would have highlighted the many different errors made by the drivers and perhaps resulted in a few more actions proposed in the HINFO analyses. Also, the focus on the post crash phase could have become more pronounced as a result of exposure to the AEB model. Because the AEB method was applied after the HINFO analyses were made, it is even more speculative to infer infer effects from HINFO to AEB. Still, the systematic analysis of the information available and used by the driver in HINFO gives an important reminder to an AEB analyst to model the human as a coherent system through the whole analysis in order to find barrier functions which could arrest the different errors made by that human.

There are many reasons for working in teams including members of different kinds of expertise. However, there is also a risk of too close cooperation in the sense that a common language and understanding is developed so that the different kinds of expertise partly disappear and merge into one common group perspective. For example, there is a risk of psychologists adopting too much of an engineering perspective in teams of behavioral scientists and engineers. However, this is not an argument against the simultaneous use of different experts in accident analyses. Perhaps, changing the members of such a group at regular intervals could be used to counteract this risk. To conclude, different methods and expertise seems much needed in order to ensure a full and unbiased picture of the factors contributing to an accident so that a multitude of different counteractive measures can be suggested, the efficiency and cost of which can be estimated for optimal resource management in future accident preventive work.

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An Experimental Study on Estimating Human Error Probability (HEP) Parameters for PSA/HRA by Using Human Model Simulation

Hidekazu Yoshikawa and Wei Wu

Graduate School of Energy Science, Kyoto University
Gokasho, Uji, Kyoto, 611 JAPAN
Phone: +81-774-38-4400 Fax:+81-774-33-3407
Email: yosikawa@uji.energy.kyoto-u.ac.jp

Abstract

A framework of Human Error Probability (HEP) parameters is first proposed, which is needed for Human Reliability Analysis (HRA) within a practice of Probabilistic Safety Assessment (PSA) of Nuclear Power Plant (NPP). Then, a laboratory experiment has been conducted for constructing a computer simulation model (human model) which describes human cognitive behavior on detecting and diagnosing plant anomaly cause. Inter-comparison between experimental data and human model simulation has been made to estimate Human Cognitive Reliability (HCR) curves , in order to confirm the applicability of human model for estimating such HEP parameters for PSA/HRA practice.

Keywords

human model, plant anomaly diagnosis, time reliability curve, human cognitive reliability, human error probability, human reliability analysis, probabilistic safety assessment

INTRODUCTION

Recently, researches and developments on human modeling of operator's cognitive behavior have been flourishing worldwide, in order to understand complex Human-System-Interaction (HSI) in process control more profoundly and to model the HSI by means of artificial intelligence. As for probable application areas of such human modeling, it has been pointed out (Kirwin, 1996) that human modeling would become a useful tool for the practice of Human Reliability Analysis (HRA) in the Probabilistic Safety Assessment (PSA), provided that the modeling capability be expanded so that it can well represent versatile human activities on monitoring and controlling the process plant, with various environmental effects surrounding human tasks being taken into consideration .

In this paper, the authors will first introduce the result of their literature study with respect to what sorts of Human Error Probability (HEP) parameters are required for PSA/HRA practice which deals with HSI in complex process plant, and then, they will proceed to the result of their pilot study to estimate Human Cognitive Reliability (HCR) curves as such HEP parameters (Hannaman, et al.,1984), first from subjects' data obtained from a laboratory experiment and then by a human modeling simulation.

HEP PARAMETERS FOR PSA/HRA

In view of the human modeling application for PSA/HRA, the authors first made the literature surveys on the existing methodologies of PSA/HRA for Nuclear Power Plants (NPPs) (Hannaman et al.,1984), (Swain et al., 1983), (Swain, 1987), (Gore, et al., 1995), (Spurgin, et al., 1990), in order to clarify the necessary HEP parameters for PSA/HRA practice. According to the present PSA/HRA practice for NPPs, there are two kinds of HEP;(1)Pre-initiator HEP(Type A), and (2)Post-initiator HEP for various HSI factors (Type C) (Spurgin, et al., 1990). The word "initiator" stands for the occurrence of an abnormal event which gives rise to incident/accident in NPP, and therefore the Type C HEP is more important but more difficult to estimate than the Type A HEP. As the result of literary surveys, the framework of the Type C HEP parameters the authors reduced are illustrated as shown in **Fig.1**. As seen in Fig.1, there are two failure rate parameters p_1 and p_2 for anomaly diagnosis phase, p_3 for response phase, and two recovery rates r_1 and r_2 for the both phases.

EXPERIMENTAL STUDY ON HCR ESTIMATION

Among those HEP parameters, the parameter p_2 gives the non-response probability until the crucial time that operator has to finish diagnosis for plant safety. Since this is very much time dependent, therefore p_2 is normally represented by a time versus reliability curve. The typical example of p_2 is given by HCR curve (Hannaman, et al.,1984) which has been widely used in PSA/HRA to estimate HEP value for operators' diagnostic action, considering three different cognitive modes (S,R and K) in manual process control. But according to the validation work on HCR model conducted by EPRI (Spurgin, et al., 1990), it is said that the HCR curves given

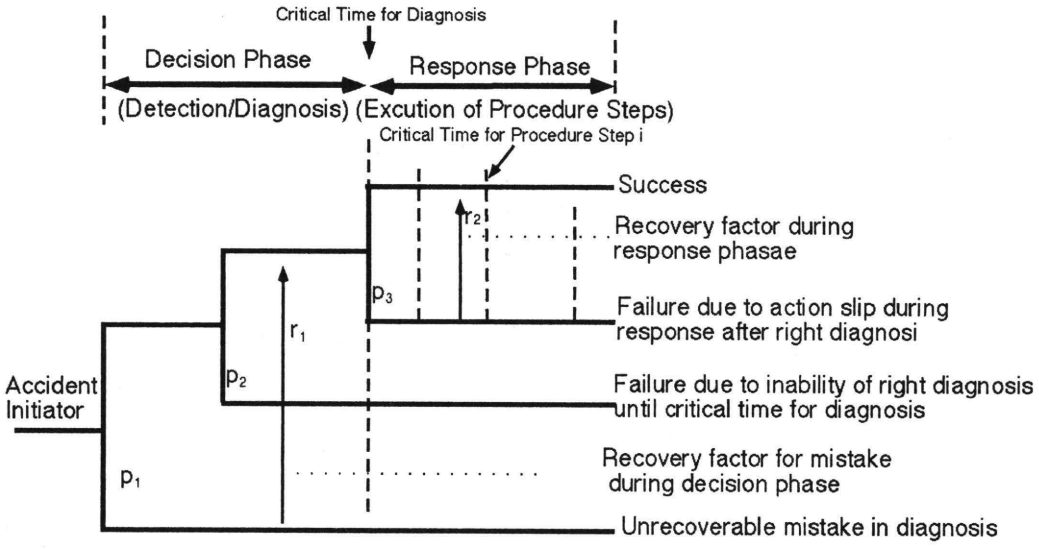


Fig.1 Framework of HEP parameters needed for PSA/HRA

by simple Weibull function did not match well with the operator data obtained by training simulator experiment. The authors would like to reduce HCR curves by themselves by examining subjects' data obtained in their past laboratory experiment and then to interpret the experimental HCR curves by applying their developed human model for operators' diagnostic behavior of PWR plant. The authors' previous works on their laboratory experiment and the related human model development were already presented at the last CSEPC96 conference (Takahashi, et al., 1996), and so in this paper, the authors will only concentrate on the new results after then and highlight their recent advance in the work.

Reduction of HCR Curves from Experimental Data

The laboratory experiment itself was conducted two years ago, for the purpose of obtaining behavioral data of experts who would detect plant anomaly and then identify the cause of anomaly through the man-machine interface of nuclear power plant. As the subjects in the laboratory, three engineers who had been either engaged in the designing of the control system and training simulator of PWR plant, or had the experience of instructor in a PWR operator training center, were participated in the authors' simulator experiment. In the experiment, twelve kinds of abnormal transient in the PWR were generated by a PWR plant simulator, and the subject was asked to monitor the CRT interface which was connected to the plant simulator to show the change of plant parameters on the display screen of hierarchical menu configuration with usage of trend graphs. (Note: Neither alarm sounds nor alarm tiles were used in the CRT interface in this experiment.)

During a session of consecutive trials of accident simulation experiment, the subject watches the CRT interface and when he thinks he detect anomaly, he pushes "anomaly detected" button on the screen, and afterwards, when he finish identifying root cause of the abnormal transient, he pushes "cause identified" button. All the experimental data obtained from the three subjects were tested on their validity for the later analysis, and the subjects' data on (1) consumed time to detect anomaly occurrence, and (2) time span from anomaly detection

until he reaches right diagnosis were sorted with ascending order of time. Then, the two non-response probability curves, that is, one for anomaly detection while the other for diagnosis, were obtained by the following equation;

$$P_i(\text{non-response}) = P_i(\text{response time} \supset t_i) = 1 - \frac{i}{n+1} \quad (i = 1,2,...,n)$$

where i : the i-th data point,

t_i : time of the i-th data point, and

n : total number of samples.

Then, if the time point of the median data is defined as $T_{1/2}$ and all the data points P_i are divided by $T_{1/2}$, then this will give the experimentally obtained HCR curve.

By looking into the difference of the slope seen in thus obtained HCR curves for the twelve cases of transient, the authors also investigated why probabilistic nature would appear in human behavior of either anomaly detection or diagnosis of the root cause.

Human Model Simulation to Reduce HCR Curves

Based on the observation on the characteristics seen in the experimentally derived HCR curves, the authors made several improvements on their previously developed human model in which there were also inappropriate assumptions such as infinite storage of STM, etc., which seem unrealistic from the psychological viewpoint. The major model improvements were on the following three factors:

(1)Detailed modeling of cognitive behavior to monitor CRT display of hierarchical configuration,

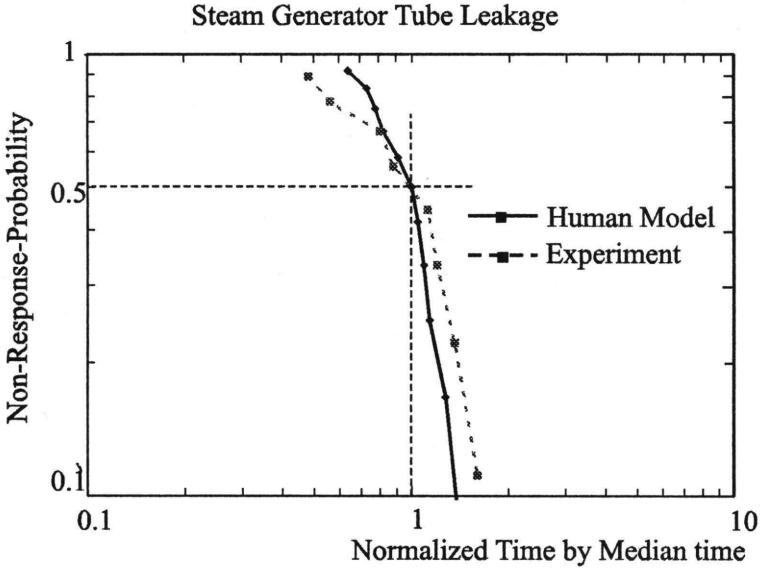
(2)Introduction of various probabilistic factors in human cognitive activity, and

(3)modeling of peripheral sight effect as a combination effect of PWM and FWM of human memory.

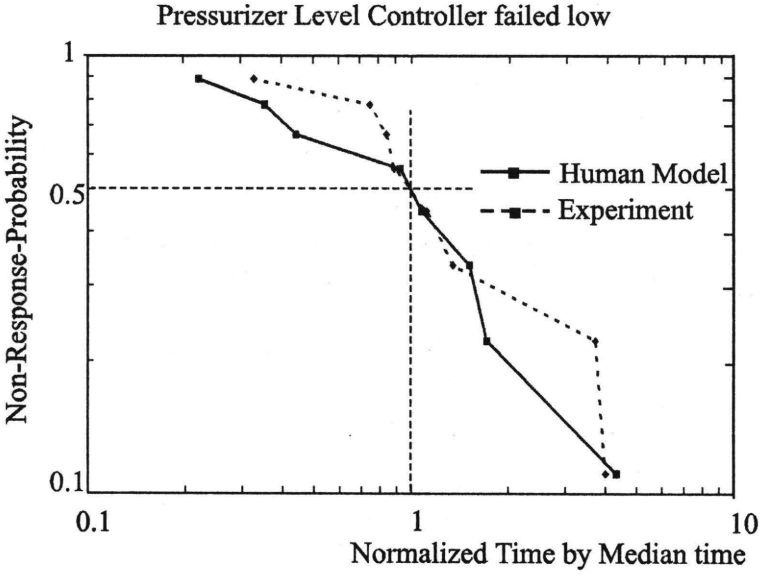
Table 1 Usage Method of Human Model to Reduce HCR Curves for Detection Phase

Items of Human Model	Introduction Method of Probabilistic and Chronological Factors
1. Way of Monitoring Plant Parameters	Monitoring patterns are realized by random number generation,based on the stochastic data of subject's monitoring fraction to the categorized groups of plant parameters.
2. Way of Judging Parameter Values	Logics of how to judge parameter values are modeled by fuzzy logic, and the personal differences are expressed by the membership function which was reduced by quenstionnaire to the subjects.
3. Peripheral Sight Effect	The introduction of peripheral sight effect in the human model works as probabilistic factor in the simulation because the subject's attended point in the display will change from time to time.
4. Needed Time for Parameter Reading	The required time for reading one parameter is randomly set in the span between 1 to 2 seconds.

By using the upgraded model of operator diagnostic behavior, the authors conducted on simulation experiment to reduce HCR curve for anomaly detection phase. **Table 1** summarizes how the human model was used in the numerical experiment. The inter-comparison of the HCR curves between the human model simulation and the experimental data, resulted in as shown in **Fig.2**, for the both cases of the sharp slope HCR curve (a) for steam generator tube leakage, and the slow one (b) for pressurizer level control failed low. It is seen from **Fig.2**, that the HCR curves estimated by the human model simulation are almost the same realize trends of experimental ones.



(a)Case of Sharp Sloped HCR Curve



(a)Case of Slow Sloped HCR Curve

Fig.2 Inter-comparison of HCR Curves between Experimental Data and Human Model Simulation

CONCLUSION

As a conclusion, the authors introduced a framework of HEP parameters needed for PSA/HRA practice, and then presented that the HCR curves as such HEP parameter could be derived by human model simulation. Therefore, the authors believe that human model will be useful for the purpose of PSA/HRA application.

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HUMAN ERROR AND SYSTEM SAFETY:

Can lessons from process control be applied to other domains?

Tjerk W. van der Schaaf

Eindhoven University of Technology
Safety Management Group
P.O. Box 513, Pav. U-8
NL 5600 MB EINDHOVEN
The Netherlands

email: tsc@tm.tue.nl

Abstract

Lessons from the chemical process industry in managing human error and system safety have recently been applied also in other domains, like steel manufacturing, railways, software R&D and healthcare. Two examples are discussed: analytical lessons from a system failure causal taxonomy, and organizational lessons from a framework for implementing a voluntary near miss reporting scheme. The successes and limitations of these transfers are presented. Finally, a number of issues are raised in which process control in turn may learn from these adapted applications.

Keywords: Human Error, Safety Management,
Incident Analysis, Near Miss Reporting,
Chemical Process Industry

INTRODUCTION

For a number of decades already process control industries like chemical and nuclear plants have been at the front end of developments (both theoretically and practically) in understanding the relationship between "human error" and system safety. A variety of systems and techniques is now available to identify, model, predict and control the contribution of the human component in complex process control task environments.

Recently, other domains have started looking at these state-of-the-art safety management approaches as a model, or at least as a source of inspiration, to cope with their own growing needs to drastically improve the design, operation and maintenance of their production or service processes.

Therefore it would seem fruitful to address the following questions in this discussion paper:

- Which lessons in the management of human error have we actually learned in process control?
- How domain-specific are these lessons: do they transfer easily to completely different task situations or are fundamental adaptations required in order to be useful?
- Visa-versa, what can process control learn from the successes and failures of "copied" safety management systems in other industries and organizations?

Within the scope of a single paper it would be impossible to cover the entire range of such methods and techniques. Therefore we will limit it to discussing one example of a more analytical, cognitive-science based "tool" (e.g. a human-error taxonomy), and one example of a more sociotechnical, management-oriented system (e.g. a voluntary near-miss reporting framework). More specifically, the experiences of the last decade with the "Eindhoven Classification Model of System Failure" (ECM) and the "Near Miss Management System" (NMMS) Incident Reporting framework as applied in the chemical process industry (Van der Schaaf, 1992, 1996; Van der Schaaf, Lucas and Hale, 1991) will be contrasted with more recent applications based on the same ECM and/or NMMS in domains like:

- Steel industry: continuous casting, high-grade coke production;
- Railways: signals passed at danger;
- Software applications: national social security helpdesk, field-testing embedded software;
- Healthcare: hospitals (surgery, intensive-care, anesthesia, accident & emergency, radio-therapy), bloodbanks, institutes for the mentally handicapped.

For both the ECM and the NMMS, first their development in the chemical process industry will be briefly described. Subsequently, for the other domains mentioned above the transferable aspects and the necessary adaptations are summarized and related to the overlap and differences between that particular domain and the chemical process industry.
Finally, the prospects and limitations of this "case-study driven" approach to theory building will be discussed.

ANALYTICAL LESSONS: THE ECM TAXONOMY

Our more analytical, cognitive science based lessons from "managing" human error in process industry are discussed using the experiences with the Eindhoven Classification Model (ECM) (Van der Schaaf, 1992, 1996).
Since its first application in a chemical plant over a decade ago it has been tested in practical settings world-wide, so the following main ECM characteristics may be considered as "lessons learned" in modeling and classifying factors in system failure.

A widely accepted subdivision of main contributing factors to system failure is that of Technical, Organizational, and Human. These have sofar been found always to interact, creating dangerous situations which challenge the preplanned, built-in defenses of the system.
Like the above failure factors, also the defenses may be of a technical (e.g. safety valves), organizational (e.g. checking procedures) or human nature (e.g. a correct mental model of the process).
If, as sometimes occurs, the potential incident is not stopped by these defenses, it may develop further and challenge the second type of system failure barriers: unplanned, spontaneous recovery, mostly by insightful human operators, who (sometimes just in time) detect, diagnose and correct the ongoing incident development and, by reducing it to a "near miss", prevent a possible accident.

Investigating "human error" without placing it in its technical (hardware, software, workplace, etc.) and organizational context (procedures, management pressure, culture, etc.) has proved nonsense. On the contrary, first the technical and organizational contexts have to be checked for any human-error triggering conditions, before we consider the possibility of purely human root causes of system failure. Rasmussen's SRK model (Rasmussen, 1976), combined with a task-analysis of the process-control operator, has proved to be highly usable to classify such operator errors, both for researchers and practitioners. This biased order in classifying root causes counteracts the wide spread tendency in process industry to first or only look for "the guilty one(s)".

This bias to blame 90 percent of accidents to human error is also "justified" by a strong tendency to investigate incidents rather superficially, whereby any organizational "latent failures" (Reason, 1990) are not even considered as possible root causes.

ORGANISATIONAL LESSONS: THE NMMS INCIDENT REPORTING FRAMEWORK

The analytical efforts of incident investigations are only useful in as far as their input (:incident reports) are a representative sample of all actual process deviations, and if their results are interpreted in effective, structural countermeasures; in other words, if all these phases are part of an entire incident based safety-management system.

Again, the lessons learned in designing and implementing such incident reporting and analysis systems, of which the Near Miss Management System (NMMS: Van der Schaaf, Lucas and Hale, 1991) is the most complete one, may be captured by summarizing their main aspects.

First of all, any organization considering having a NMMS, should choose its goal(s) for doing so: do they primarily aim at modeling how new or unexpected incidents could develop within their organization (:qualitative insight); do they wish to monitor the effectiveness of their current safety management system in dealing with well-known problems (: quantitative insight); or is their goal mainly to keep a certain level of alertness on the part of their employees and not gradually start "cutting corners" after years without an actual accident.

Depending on the goal(s) chosen, design decisions should be made regarding each of the following 7 modules or phases which, combined, form a complete NMMS framework for a voluntary incident reporting and analysis system: Detection (recognizing and reporting process deviations); Selection (filter out the most interesting reports for further analysis); Description (show all causal elements in their logical and chronological order); Classification (of root causes, according to the ECM); Computation (statistical analysis of large database of incidents to uncover patterns of frequently occurring causal factors); Interpretation (based on the same models as the ECM, suggesting the most effective countermeasure per causal factor to be reduced); and finally, after implementing the suggested countermeasure, Evaluation of its success in reducing the target causal factor frequency in later reported incidents.

After the design stage described above, the following organizational requirements have to be met for the implementation phase: management commitment, to ensure that organizational learning is not hindered by punishing employees who voluntarily report an incident; training and demonstration of what to report, how to analyze, interpret, etc.; and fast, frequent and complete feedback regarding all phases in handling a report, to the ones) who generated the report, to motivate them to do so again in the future.

Another vital aspect is to break away from any existing tendency to react immediately with "improvements" after every single incident: this will encourage a move from "fighting symptoms" towards "diminishing fundamental problems".

Finally, systems specifically looking at human error are mostly aimed at Safety, thereby neglecting its effects on other types of consequences like Reliability, Quality and Environmental Pollution. An integration of databases of such diverse process deviation consequences should benefit from the fact that they probably stem from identical sets of root causes.

TRANSFER TO OTHER DOMAINS

During the last 7 years applications of the NMMS and/or the ECM have been implemented in the steel industry, railways and software R&D (all in the Netherlands), and in different sectors of healthcare: hospitals (also in the UK) and bloodbanks (also in the U.S.A). By and large, both the ECM and the NMMS could be transferred perfectly (for the steel industry and railways) or at least reasonably well (for software R&D and healthcare).

In the former case, the system failure taxonomy and the reporting framework remained fully intact, requiring only minor changes in jargon and helpful examples to fit the new domain. In software R&D an interesting change in the order of looking at the different types of main contributing factors proved helpful: because of their tendency to think only in terms of technical problems requiring technical solutions, in this ECM version first the Organizational and Human failure factors are checked, with Technical failures as the last possibility (Van der Schaaf, 1997). For the ECM - Medical Version the changes go even further (Van Vuuren, Shea, and Van der Schaaf, 1997): for healthcare, the patient is both part of the "process" to be protected, and a possible causal factor in itself, so a fourth main failure type was added as Patient Related Factors. Also, the general lack of cooperation (or even competition for resources) between different departments of the same hospital severely limits the possibility for any department to implement countermeasures focused on problems originating in external departments: an additional distinction between Internal failure factors (which can be influenced directly) and External ones (to be fed back to those other departments, hoping they will then act) solved this change of management scope (from the company or plant level in process industry to a single hospital department as system-owner).

LESSONS FROM OTHER DOMAINS

Rather than comparing process control industry with each of the other domains at a time, several general issues will be raised below, either as possible lessons or as points of interest for process control.

On the dimension of Skill or Professionalism at the work floor, process control (PC) operators seem to lie in between steelworkers on one hand and medical staff (: nurses and doctors) on the other. This is also reflected in the use and importance of operating procedures : very strict in the steel industry to very loose or absent in hospitals ("we are highly trained professionals"), and the level of distrust between the workfloor and line management: high in steel (and railways) to nonexistent in medical teams (whose managers are either professional teammembers themselves, or merely administrators). By comparing itself with these other domains, PC industry should be able to benefit in the continuous discussions of the optimal shift member's level of the "mental model", shift composition, and level of automation of PC tasks.

Apparently unrelated to the above dimension is the type of view on "human error" and how to deal with it: it is still wide-spread to "find out who's to blame" and prevent reoccurrence by punishing or eliminating such scapegoats. In terms of safety culture and how to model, validate, measure and influence this vital construct, PC industry could improve its already high level by comparing with similar efforts in these other domains as well, rather than restricting itself to learning from its own much smaller variety of safety culture levels.

By looking at hospital organizations, new ways how to deal with the important issue of contractor safety could be found, since contractor activities are usually highly influential "external factors" in PC plants, especially during specialized maintenance and "turn-around" periods.

Finally, if software R&D should succeed in getting out of their technology-fix by fully acknowledging the human and organizational factors, PC industry should consider this approach as well. Also, engineering departments in PC industry could learn from the systems being set up to provide optimal feedback channels from end-users to testers to designers of complex software, aimed at increased detection of technical "latent failures" before releasing the imperfect "end-product" to the customer.

CONCLUSIONS

Somewhat surprisingly, techniques and systems developed in the chemical process industry could be generalized relatively easily to other domains. Whenever adaptive changes were necessary, usually interesting lessons for the PC industry could be drawn. A full-fledged metastudy to approach these issues more rigorously would seem very worthwhile.

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Using Incident Scenarios for the Design of an Anaesthesia Decision Support System

P.M.A. de Graaf[1], F. Koornneef[1], V. Chopra[2]

[1]Delft University of Technology , Department of technology and Society, Safety Science Group, Kanaalweg 2B, 2628 EB, Delft, The Netherlands, E-mail: philip@it.et.tudelft.nl
[2]University Hospital Leiden, Department of Anaesthesiology, P.O. Box 9600, Leiden, The Netherlands

ABSTRACT

Technology has become an integral part of today's anaesthesia process. Due to this fact, and the complexity of the process, the similarities between complex industrial process are prominent. We therefore tried to develop a decision aid for the anaesthetist using knowledge acquired in industrial settings. This approach resulted in a cognitive task analysis method, based on analysis of incident scenarios to find an information management strategy. Incident scenarios were acquired from a hands-on anaesthesia simulator and an anaesthesia crisis management handbook. Methods for knowledge extraction and representation are presented. Results from analysis of both resources where evaluated, and showed a high degree of consistency.

Keywords
Cognitive task analysis, incident scenario analysis, decision support, anaesthesia monitoring

INTRODUCTION

Technology has become an integral part of the anaesthesia process, making it the medical discipline with the highest resemblance to complex industrial processes such as nuclear power plants and chemical plants. Like operators in these industrial environments, the anaesthetist spends most of his time monitoring the process. Monitoring in this context is a continuous process of assessing the current values of state variables and their evolution over time.

Anaesthesia monitoring has shown a lot of development over the past 40 years. In the forties and fifties monitoring equipment was limited to the stethoscope and the senses of the anaesthetist. Starting in the fifties, however, more and more sophisticated monitoring equipment was introduced in the operating room. Until the eighties this development continued, resulting in a situation with numerous independent monitoring modalities, each with its own design. This Christmas-tree-like configuration, was difficult to oversee for the anaesthetist. A lot of different devices were stacked on top of each other, each device with different display colours, alarm sounds and control panels. Integration of this equipment in one device was very much needed.

Facilitated by the smaller dimensions and prices of electronic components and microprocessors, a new generation of integrated patient monitors was introduced in the nineties. These devices offer all monitoring modalities in one device, with all data presented on one display. State of the art commercial anaesthesia equipment now offers a fully integrated anaesthesia workstation including ventilator, anaesthesia delivery equipment and monitoring equipment. But despite integration of display and control of monitoring devices, monitoring systems are still single signal oriented. This means that all physiological signals are treated as if they are independent quantities with no relation to each other. Every parameter has its own threshold alarm and only momentary parameter values are displayed. Raw measurement waveforms of all physiological signals occupy 60-80% of the display area. Parameter trend displays and other essential information are often only accessible through extensive menu interaction (Cook & Woods, 1996), or are squeezed in somewhere on the already crowded display. It is quite clear that only physical integration is not the solution to all problems.

Despite integration, gathering all information relevant in the current situation can take a lot of time, and current systems do not offer comprehensive support for this task. Because of the laborious procedures needed to gather all relevant information, the anaesthetist will tend to rely on his memory instead of retrieving the information from the monitoring system. This is especially true in case of crisis situations when workload is high and time to react is limited. Considering the amount of data to process and the lack of support described above, it

is not surprising that between 70 % and 80 % of all incidents involve human error (Chopra et al., 1992, Short et al., 1992).

A decision support system which provides the anaesthetist with easy access to all the information needed, will be able to eliminate the information management problem.

ANALYSIS

We will first look at what the anaesthetist does with the available information. To this end we developed a model of the decision making process of the anaesthetist, the Cognitive Activity Flow (CAF) model (de Graaf , 1996). In this model we distinguish four distinct cognitive activities in the decision making process: *Monitoring* and *evaluation* of the state of the system to detect potential problems, *diagnosis* of the perceived problem, *choice of action* to correct the problem, and the *adjustment of goals and expectations* regarding the behaviour of the process. In every stage of decision making different sets of information are relevant.

The information available is used by the anaesthetist to maintain an accurate image of the process. This image consists of the current state of the system indicated by momentary parameter values, parameter trends, and interventions during the preceding part of the operation. This space-time image of the process must be continuously monitored in order to detect undesired changes and devise a proper diagnosis of the situation. Diagnosis can be considered as a process of hypothesis generation and testing. This model of diagnosis is supported by field studies and experimental cognitive psychology. It was, for example, successfully implemented in the cognitive simulation model COSIMO (Cacciabue et al., 1992; Cacciabue and Kjaer-Hansen, 1993). Every diagnosis hypothesis carries with it an expected space-time image. Hypothesis testing means that the observed space-time image is held against the expected space-time image. The hypothesis is accepted if these two images show sufficient similarity.

Although the other activities are also important, we will for now concentrate on the *diagnosis* stage of the decision making process. The *monitor/evaluate* activity should be supported by intelligent alarm systems, whereas the *choice of action* and *adjustment of goals and expectations* activities are closely related to *diagnosis* and require more or less the same information.

Given the hypothesis driven nature of diagnosis, we think that a promising strategy for information management is to group information relevant for individual hypothesis. If such a information set is presented as a complete image to the anaesthetist, s/he can easily assess whether the space-time image of the process matches the space-time image of a diagnosis hypothesis. For example, the information set associated with hypertension contains heart rate and blood pressure evolution over the last half hour. The information sets can also be used to find alternative hypothesis with a similar information set. A user interface allowing for easy access to information sets is a promising method to support the anaesthetist's decision making process.

We have now found a solution to the information management problem on a conceptual level, but how do we design such a system? In order to be able to implement this information management strategy, we will have to find out which set of information should be presented to the anaesthetist for which event. This knowledge concerning the cognitive task of the anaesthetist can be gathered by Cognitive Task Analysis (CTA) methods.

METHOD

Most CTA methods are based on observational techniques or interviews. All these methods however have limitations. Observational techniques are in general limited to visible activity and require large amounts of time to perform, especially if you are interested in cognitive activity during crisis situations. This is caused by the fact that in essence they are indirect knowledge elicitation methods. That is, you do not ask what you want to know directly but you wait until all possibly relevant situations have occurred and draw conclusion from these observations. This means that because some situations occur only once in 10.000 anaesthesia procedures it is impossible to observe these situations, unless you have endless amounts of time. We used observations for the purpose of model building and validation, which showed that they can be very useful to obtain a general impression of the process. Furthermore, observational techniques can be used to validate assumed properties of generic task elements (i.e. the CAF-model (de Graaf, 1996)). For the purpose of CTA, however, we found them less practical.

A more direct approach to CTA is to directly ask operators what they think is relevant information in a given situation, in an interview or questionnaire. Although interviews can be completed in a much shorter period of time, and asking about rare situations is very well possible, their usefulness is limited by the time an anaesthetist is prepared to spend on such an interview. Furthermore, the complexity of the anaesthesia process is such that it is questionable whether it is at all feasible to accurately capture it in a few hours of interviewing. Subjective

judgement of individual anaesthetists is likely to compromise the generality of the results. In order to verify this assumption, we interviewed three anaesthetists of varying age and experience. Results from those interviews varied considerably (only 30 % overlap), despite the fact that the interviews were structured using the Attribute Association matrix (see below), and where conducted by the same interviewer. In conclusion we could state that both observational techniques and interviews suffer from practical problems resulting in insufficiencies and subjective judgement in the acquired knowledge.

Table 1 CTA method properties

CTA method	objective	complete	valid	accessible
observations	-	-	+/-	+
interviews	-	-	+/-	-
simulator script analysis	+	+/-	+	+
handbook analysis	+	+	+	+/-

+ = Good - = Bad +/- = Reasonable

Since completeness and objectiveness are crucial properties for knowledge used in a decision support system, we looked for a different method;. analysis of incident scenarios. Incident scenarios as are used in anaesthesia simulators or described in anaesthesia crisis management handbooks, were used to extract the knowledge we needed. These scenarios are collected over large periods of time by expert anaesthetists and are validated through their use by other anaesthetists. These sources of knowledge, therefore fulfil the completeness and objectiveness requirement. Perhaps one could argue that this knowledge is only theoretical and therefore is not valid for practical situations. However, both simulators and crisis management handbooks provide practical skills and knowledge for use anaesthesia practice. Table 1 summarises the properties of the CTA methods we considered and evaluated for our purpose.

Now that we have found a source for our required knowledge, we also need a way to represent it, along with a method to convert the available scenario knowledge to this data-representation. Our data representation is a matrix, which contains a row for every event (dependable attribute) and a column for every information item or any other attribute (undependable attribute). In our definition an attribute is a anything related to the anaesthesia process which plays a role in the decision making process of the anaesthetist. More or less the same representation is used by Moray for the representation of interactions between persons (Moray 1992). Cacciabue uses the Attribute Entity (AE-) matrix for linking diagnosis hypothesis (attributes) with symptoms (entities) (Cacciabue et al., 1992). Since we where looking for a representation allowing for links (associations) between attributes at all levels of abstraction, we have called it the Attribute Association (AA-) matrix. Although this representation is very similar to the AE-matrix, we chose not to separate attributes and entities as strictly as in the AE-matrix. Attributes may occur both across rows and columns allowing for relations between attributes. We identify five different types of attributes, which are described in Table 2.

Table 2 Types of attributes of the anaesthesia process

attribute type	description
categories	any group of events or processes (e.g. generic or cardiovascular)
events	any event related to the anaesthesia process (e.g. ventilator disconnection or cardiac arrest)
observable features	any kind of observable feature of the anaesthesia process which is not measurable (e.g. patient skin colour)
measurable features	any kind of (automatically) measurable parameter of the anaesthesia process (e.g. heart rate)

For example, an event in the surgical event category is acute haemorrhage, which can be detected by visible blood in the surgical field (observable features), arterial blood pressure parameters, central venous pressure, and heart rate (measurable features). This can be represented in an AA-matrix as is done in Table 3. The numbers in the AA-matrix indicate the number of direct relations the column attribute has with the corresponding row attribute. If for example, during an event, the blood pressure can rise or fall two relations will exist between that event and blood pressure.

Table 3 Example AA-Matrix

	acute haemorrhage	blood in surgical field	heart rate	blood pressure	central venous pressure
surgical events	1				
acute haemorrhage		1	1	1	1

The AA-matrix will be the basis for a user interface design, which allows the anaesthetist to simultaneously access all the information relevant to test a certain hypothesis by simply selecting the hypothesis from a (hierarchical) list of hypotheses. For the example of Table 3 this would mean that if the anaesthetist would suspect acute haemorrhage, s/he would first select the group surgical events, from which s/he could choose the event acute haemorrhage. The monitor display would then show the heart rate trend, the blood pressure trend and the central venous pressure trend on a suitable time scale. An additional message could be shown to also check for visible bleeding in the surgical field, and to consider some alternative hypotheses associated with similar changes in parameters. The second application of the matrix is to supply diagnosis hypotheses based on automatic detection of patterns in the data, which can be done with pattern recognition algorithms (de Graaf et al., 1997). We can illustrate what this means with the example in Table 3. If a pattern is detected which involves changes in heart rate blood pressure and central venous pressure this would result in a diagnosis suggestion: 'acute haemorrhage', and some alternative diagnoses suggestions, involving similar feature changes. Subsequent testing a hypothesis would be the same as mentioned above.

In order to transform simulator or handbook knowledge to the AA-matrix, terms used in the knowledge sources were mapped to standard terms (attributes). Although observable features can have high clinical value, we, we limited our mapping to measurable features. The reason for this is that the simulator scenarios only describe measurable features, and the decision support system can only present measurable features. The relations found in simulator scripts and the crisis management handbook were then used to build an AA-matrix. The actual storage format for the AA-matrix is a table in a relational database, which allows for specifying the nature of a relation as well (e.g. does a parameter value increase or decrease).

RESULTS

The feasibility of translating incident scenarios into an AA-matrix was tested using knowledge from both the Leiden Anaesthesia Simulator (LAS) covering 35 incident scenarios (Chopra et al., 1994) and a handbook on Crisis Management in Anaesthesiology (CMA) covering 84 incident scenarios (Gaba et al, 1994). Nineteen incidents where covered by both sources, which provide the opportunity to compare the two knowledge sources. We will only report on these nineteen incident scenarios because they can show discrepancies in knowledge contained in handbooks and simulators, and the results for these incidents are comparable to the other 16 and 65 incidents.

Table 4 Causes of differences between CMA and LAS

cause	**CMA relations**	**LAS relations**	**total**	**relative total**
match	53	53	106	54 %
negligible change	-	10	10	5 %
late symptom	8	1	9	5 %
secondary symptom	4	20	24	12 %
not simulated	36		36	18 %
no match/other reason	7	6	13	7 %
total	108	90	198	100 %

Table 5 shows the results of the transformation process pair-wise for the CMA handbook and the LAS. The number of relationships between two attributes is indicated by the number in the corresponding cell. The type of relation is not indicated although this is taken into account in the underlying relational representation for the matrix and can thus be incorporated in the user-interface design. For example, time scale and direction of changes (up or down) are also part of a relation between two attributes.

Table 5 Results of knowledge extraction from scenarios

Source	Scenario \ Feature	Total number of relations	ABP Mean	ABP Waveform	Blood in Container	Blood K Concentration	Blood O2 Concetration	CO2 End Tidal	CO2 Waveform	CVP Mean	ECG Waveform	Heart Rate	PAP Mean	PAWP Mean	Respiratory Frequency	Respiratory Pressure PIP	Respiratory Volume Minute	Respiratory Volume Tidal	SpO2 Mean	SpO2 Waveform	ST parameter	Temperature Body	Urine Output
CMA	Acute haemorrhage	7	1		1		1			1		1	1										1
LAS	**Acute haemorrhage**	**4**	**1**					**1**		**1**		**1**											
CMA	Air embolism	4	1					1				1	1										
LAS	**Air embolism**	**7**	**1**					**1**		**1**	**1**	**1**							**1**		**1**		
CMA	Anaphylaxis2	10	1					1	1	1	2		2			1			1				
LAS	**Anaphylaxis2**	**9**	**1**					**1**		**1**	**1**	**1**				**1**			**1**		**1**	**1**	
CMA	Bradycardia sinus	3	1								1	1											
LAS	**Bradycardia sinus**	**3**	**1**					**1**				**1**											
CMA	Bronchospasm	6						2								1	1	1	1				
LAS	**Bronchospasm**	**4**	**1**							**1**						**1**			**1**				
CMA	Cardiac temponade	7	1	1						1			1	1							2		
LAS	**Cardiac temponade**	**4**	**1**					**1**		**1**		**1**											
CMA	Endobronchial intubation	6						2								1	1	1	1				
LAS	**Endobronchial intubation**	**7**	**1**							**1**	**1**	**1**				**1**			**1**		**1**		
CMA	Hypertension	2	1									1											
LAS	**Hypertension**	**3**	**1**					**1**				**1**											
CMA	Hypotension	6	1					1											2	1			1
LAS	**Hypotension**	**2**	**1**					**1**															
CMA	Hypoxaemia	6	1								2	2							1				
LAS	**Hypoxaemia**	**1**																	**1**				
CMA	Malignt hyperthermia	9	1			1		1			2	1			1				1			1	
LAS	**Malignt hyperthermia**	**8**	**1**					**1**			**1**	**1**				**1**			**1**		**1**	**1**	
CMA	Myocard. infarction	7	1								2	2									2		
LAS	**Myocard. infarction**	**6**	**1**					**1**		**1**	**1**	**1**									**1**		
CMA	Pneumothorax	8	1					2		1		1			1	1			1				
LAS	**Pneumothorax**	**6**	**1**					**1**		**1**		**1**				**1**			**1**				
CMA	Pulmonary embolism	10	1					1			1	2	1		1				1		2		
LAS	**Pulmonary embolism**	**8**	**1**					**1**		**1**	**1**	**1**				**1**			**1**		**1**		
CMA	Pulmonary oedema	8						2		1			1			1	1	1	1				
LAS	**Pulmonary oedema**	**7**	**1**							**1**	**1**	**1**				**1**			**1**		**1**		
CMA	Sinus rhythm	2									2												
LAS	**Sinus rhythm**	**1**									**1**												
CMA	ST depression	2																			2		
LAS	**ST depression**	**1**																			**1**		
CMA	Total spinal anaesth	3	1									1			1								
LAS	**Total spinal anaesth**	**6**	**1**					**1**		**1**	**1**	**1**										**1**	
CMA	Vent arrh (non-lethal)	2									2												
LAS	**Vent arrh (non-lethal)**	**3**	**1**								**1**										**1**		

Table 5 clearly shows that there are quite a lot of differences between knowledge acquired from both the CMA handbook and the LAS. Without paying attention to the exact nature of the relationship, the mismatch is considerable. The double relationships (a 2 in Table 5) are primarily caused by parameters that can become unstable due to an event and can change in both directions. Generally these double relationships occur in the CMA since the LAS can only simulate one of the two possibilities at a time. Table 4 summarises the results of match between the LAS scenarios and the CMA handbook scenarios.

The differences between LAS and CMA were discussed with the leading designing anaesthetist of the LAS. About 5% of the relations were different due to minimal changes in the simulator scripts which were not mentioned in the CMA handbook. Another 5 % differed because one source included late symptoms, where the other source did not. About 12% of all relations differed because secondary consequences of a certain event were included in one but not in the other. The largest source of differences could be attributed to attribute changes that

could not be simulated in the LAS (18 %). Only about 7 % of the differing relationships could not be attributed to any of the above reasons. Part of these differences were caused by the fact that some features can change in both directions, whereas only one direction of change at a time can be simulated in a simulator script.
Overall the results show that the two sources of knowledge are consistent, despite the seemingly high number of differences at first sight.

CONCLUSIONS

The goal of this research was to find a method to group information in a comprehensive way for the anaesthetist. A promising method to achieve this was found, and procedures to acquire the knowledge to construct information sets were designed and tested. We tested a number of alternative existing cognitive task analysis methods for the purpose of finding information requirements. However, they proved to be limited in their application and the validity of their results were questionable. We therefore sought for a different approach to cognitive task analysis of the anaesthesia process. A procedure for translation of knowledge from a full-scale anaesthesia simulator and an anaesthesia crisis management handbook was developed and tested. Although a considerable number of relations found in both knowledge sources differed, we found the overall consistency of the two knowledge sources to be good. Most of the differences found could be attributed to limitations of the simulator or the inclusion or exclusion of late and secondary symptoms in the incident scenario. Overall, we can conclude that the use of simulator or handbook knowledge for the purpose of cognitive task analysis is feasible. Implementation of the user interface and its clinical evaluation in a real or simulated environment will have to show whether this kind of decision support will indeed improve the performance of the anaesthetist.

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4 COOPERATION AND PROCESS CONTROL

Consideration of the Information Flow and of Organisational Factors in the Safety Analysis. Some Case Studies in the Railway Transport System

C. Iani[1], F. Vanderhaegen[2], N. Moray[3]
[1] Department of Biomedical Sciences, Section of Physiology, University of Modena
Via Campi 287, 41100 Modena - Italy
E-mail: pinelli@unimo.it
[2] LAMIH, University of Valenciennes
Le Mont Houy BP 311, 59304 Valenciennes Cedex - France
E-mail: vanderhaegen@univ-valenciennes.fr
[3] Equipe PERCOTEC, University of Valenciennes
Le Mont Houy BP 311, 59304 Valenciennes Cedex - France
E-mail: moray@univ-valenciennes.fr

ABSTRACT

This paper presents an approach aimed at integrating information flow and aspects such as the interaction between different agents, both human operators and machines, in the safety analysis of complex systems in general and of railway systems in particular. A model for the analysis of accidents is presented which considers both human operator and machine as unreliable system components and, when integrated with a functional analysis of the system, aims at the identification of critical areas of unreliability.

Keywords
Human-machine system, information flow, safety analysis, accident analysis.

INTRODUCTION

In complex systems human behaviour and human errors seem to play an important role in many accidents. Therefore, to improve safety and reliability all factors related to human agents that may influence error occurrence should be an integral part of risk assessment and system design and realisation. The consideration of human factors such as perception and attention limits which influence information gathering and processing, decision making, stress and workload may help to develop measures to prevent incidents from occurring and also limit error consequences. It is also necessary to integrate in the safety analysis critical elements such as the information flow that characterises the interaction between different system components.

A human-machine system in general can be considered as an organisation in which several human agents and machines interact through communication tools and work to achieve a common goal (Sperandio, 1988). Different levels of interaction can be identified not only between the single human operator and the machine, but also between different human agents and between different interfaces. All these possible links become important when we consider a system from a reliability point of view. Accidents are often due to a combination of different conditions and actions which interact and influence each other. Actions can be connected and two parallel series of actions, possibly carried out by different agents, can come into conflict. Human errors are normally identified with reference to the behaviour of the individual agent, without considering that usually several people cooperate either in a direct way or in an indirect one through interfaces. Their performance can be influenced by these patterns of cooperation, and information flow can play an important role in the quality of these interactions.

In this paper we present our attempt to integrate the above mentioned factors in the safety analysis of railway systems. We propose a causal model of unreliability that tries to model different levels of interaction between the human operator and the machine and between different human operators, to localise where problematic situations can occur and to model the propagation of effects throughout the system. In the last part we present

an example of the application of the model to explain the development of events which led to the occurrence of a railway accident.

A CAUSAL MODEL OF UNRELIABILITY

According to Johannsen (Johannsen, 1982) a human-machine system is a functional synthesis between humans and machines where the interaction between these two entities takes place through the human-computer interface. From this starting point we have developed a causal model that considers the different levels of interaction that characterise modern systems and tries to identify where in the interaction between different agents, both human agents and machines, unreliable states for the process may be generated and what factors may produce them (Telle et al., 1996). This model tries to represent the different stages of control system processing and how errors that appear in one of these stages can propagate throughout the system. The starting assumption is that accidents may be the result of many inter-related factors having their effects in combination.

We start by considering both human agent and machine as unreliable agents which may produce unreliable states of the process. From a process point of view, an error is a deviation of an actual action from that required by the process (Leplat, 1990). When speaking of an human agent the approach is different, because the notions of intention and error are inseparable (Reason, 1990). This means that only human agents can make errors. However, if one considers the case of intelligent systems, the notion of error may be introduced because an intelligent system has a set of possible actions for a given input and may select a solution and examine its effects by entering a "what if" mode (Edwards, 1991).

The main components of the model are the following:
Acquisition related failure. In the model, failure is considered at the same level for both human and machine. For example, attention failures are comparable to a physical sensor failure because the consequence is in both cases the lack of information.
"Errorgenous" information processing. We have "errorgenous" information processing when the available information does not correspond to the real state of the process because of the erroneous processing of information and/or because of the processing of erroneous information. The term "errorgenous" has been employed to indicate that this condition can generate an unreliable situation for the process. For example, because of a display failure, the human operator does not perform the required action according to the real state of the system, so generating an unsafe situation. At the same time, an insufficient level of knowledge can result in erroneous processing of well perceived information.
Action. One must distinguish the action, its consequences for the process, and the output information which is generated. With regard to the agent who performs an action, this action is correct when it corresponds to a required action according to the input information whatever the quality of this information, otherwise the action is erroneous. On the other hand, a correct action for an agent can be an erroneous action with regard to its consequences for the process and on the environment.

If we consider a system with an high degree of cooperation between human operators and between human operators and machines, and if we consider decision and action support tools as fallible agents, links between the three entities can be defined. For instance, an acquisition related failure can generate "errorgenous" information processing and an unrequired action can be caused by this "errorgenous" information processing and generate an acquisition related failure. Moreover, consequences of an acquisition related failure involve their own "errorgenous" information processing, but can also have consequences on the information processing by another agent. For example, a display failure does not affect the computer, but influences the human operator information processing. Such "errorgenous" information processing can have an influence on the behaviour of another agent, e.g. a human operator as a consequence of a display failure inputs a bad value, so that the non-human agent performs an unrequired action. The consequent action can lead to an unsafe state for the process.

Our study has focused on the railway system in general and on the French and Canadian railway systems in particular. Through a functional analysis of the two systems we have identified functions that have to be carried out to ensure the achievement of their goals, who performs these functions (i.e. the allocation of roles between human operators and machines), what types of interaction they involve and what are the available tools. This functional analysis has been carried out by mean of the Structured Analysis Design Technique (IGL, 1989). Through the analysis of some accidents and incidents and through the application of the causal model of

unreliability we have tried to identify what functions can be interested by error occurrence and what links there are between error propagation and different patterns of cooperation.

AN EXAMPLE OF THE APPLICATION OF THE CAUSAL MODEL OF UNRELIABILITY

As an example we will apply the causal model of unreliability to describe the development of events that caused the railway collision which occurred on June 1994 in the Lac-Saint Jean Subdivision of Garneau Yard in Canada and is described in a report of the Canadian Transportation Safety Board (TSB, 1994).

The Functional Analysis of the Railway System

The Canadian railway system is characterised by a low degree of automation. Many functions are performed by human operators in interaction but without the support of computerised tools. Our analysis will focus on the function of control of the traffic in a marshalling and maintenance yard, which in the railway company considered is normally carried out by a single human operator, the yard master. To perform this function, he has to integrate the information by using his experience and knowledge of how aspects of the situation work together and influence each other, and to project this information into the future to make and modify plans as tasks are completed and a new situation arises. There is no status board or job aid to help the operator to remember or confirm the situations or plans and there seems to be no formal procedure used in communication exchanges between different operators.

Accident Description

On the day of the occurrence, the day yard master began transferring responsibility to the afternoon operator using a computer generated status report which was printed 35 minutes before the actual change of shift. During the transfer both yard masters reviewed the status report and discussed plans for train movement and control. There was no documentation of plans or changes occurring after the printing of the status report nor there was a procedure to ensure that the incoming yard master understood the situation and the plans at the time of the transfer. At the time of the transfer, the day yard master verbally communicated the positions of trains. All trains had been instructed to take different tracks. After the second yard master started his duty, the situation changed: he authorised a requested change in the instructions given by the first operator to the conductor of one of the trains which resulted in both train 418 and train 421 using the main track in opposite directions.

Application of the Model of Unreliability

In this paper the application of the model is limited to the function of control of the movements of trains and the interaction between the yard master and the crew members of one of the trains involved in the accident, in order to identify the unreliable components which caused the collision (Figure 1).

On the day of the occurrence the outgoing yard master transferred the information to the incoming one, but this transfer occurred in a distracting environment and all information was transferred only verbally. As a consequence of the lack of support tools, the second yard master did not develop an adequate situation awareness (1) and allowed two trains to employ the same track in opposite directions (2), without realising that in this way a conflicting situation would arise. His action generated an "errorgenous" information processing in the member of train 418 (3): because of the permission given by the yard master, train crew members were sure that there was no other train on the main track and they operated (7) at a speed that prevented them from avoiding the collision. This errorgenous information processing was also reinforced by an erroneous action of the crew members of train 418: the radio in the locomotive cabin has to be always set at a volume sufficient to ensure continuous monitoring, but it was set at a low volume (4). This action generated an acquisition related failure: train crew members did not hear the warning given by the crew of train 411 to train 421 about train 418 approaching on the same track (5). Trains 418 and 421 were operating within the cautionary limits, that is portions of the main track or main tracks within which speed has to permit stopping within one-half the range of vision from any equipment on a track unit. They relied on the yard master for permission to use the main track within those limits when they should have been complying with the rules governing the operations of trains within them. This is then a violation of the rules (6). All these different elements had as a consequence the collision of train 418 and 421. These critical points can be identified in the model of interaction and communication in our diagram of causal unreliability (Figure 1).

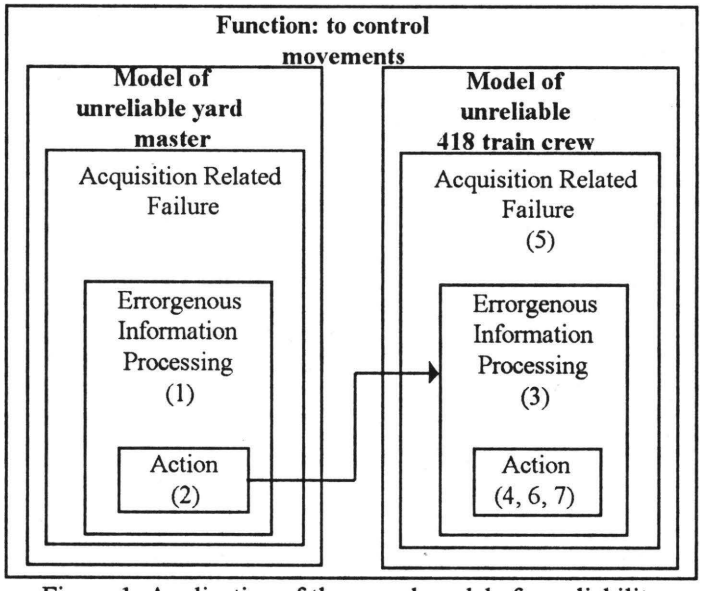

Figure 1: Application of the causal model of unreliability

CONCLUSION

The purpose of the model presented is to provide a structural description of the system which takes into account dynamic aspects such as information flow between different system components, and the allocation of roles between them, to model the different levels of interaction which can characterise a complex system and localise where problems may occur and how they may propagate throughout the system. This model can be considered as an integration of the functional analysis of the system. The functional analysis of the system identifies functions which have to be carried out to ensure the achievement of the system goals, who performs these functions and what are the available tools. The resulting functional model can be completed by the structural model proposed in this paper which, through accident analysis, identifies unreliable components of a given function. By representing communication and information processing both within and between agents, whether human or other, the model permits a new approach to identifying sources of unreliability which may result in errors and/or accidents, and hence provides an aid for the analysis and redesign of sociotechnical systems.

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Co-operation and Situation Awareness within and between Hierarchical Units in Dynamic Decision Making

Henrik Artman
Dept. of Communication Studies
Linköping University
Sweden
E-mail: Artman@tema.liu.se

ABSTRACT

This paper reports an experiment that tests three organizations (serial, parallel and optional) of co-operation and situation awareness within commander teams, as well as the communication between the commander team and the operative level. It was found that most groups in the optional condition performed worse than the groups in the other conditions. It was also found that members in the parallel condition differed from members in the serial condition in their situation awareness. The more successful commander team produced more planning in relation to hypotheses, as well as sent less messages in total between the units, than the less successful one.

Keywords: Dynamic Decision Making, Command and Control, Situation Awareness, Co-operation

INTRODUCTION

We'll here study the management of dynamic complex situations, with particular consideration of information distribution. In dynamic situations, information has to be communicated over distance. It is therefore important for organizations to understand how this information is most efficiently being distributed and the effects of different communication architectures within and between units. Some studies have indicated that in a dynamic situation, a hierarchical organization of information distribution results in a better performance than an organization where all participants can talk to everybody else (Brehmer & Svenmarck, 1995). One reason for this is that a central unit can collect and organize information on a more general level than the local units. The central unit can then concentrate upon understanding the overall situation and planning for appropriate actions, while the local units concentrate on meeting the demands of the local and immediate incident. In order for the whole controlling organization to be able control the dynamic environment different hierarchical units have to co-operate although they have different information on the problem.

In an exploratory field study of a military command and control training we found that the trainees used the communication technology (an electronic mail system), which enabled them to organize their work in different ways (see Artman, 1997 for details). One team used a serial organization and the other used a parallel organization. Here we will not discuss the specific interaction structures that emerged in the two teams, but restrict ourselves to attend to the fact that in the serial team the information flew from one person to the next, while in the parallel team both officers received the same information at the same time. From our analysis of the co-operation within these two teams we found that the serial team had more co-operating activities than the parallel team. In the parallel team they co-operated more or less only when absolutely necessary. This lack of co-operation made co-ordination very hard because no one knew what the other was doing (i.e. they lost the overlapping shared model of their collective responsibility). A co-operative situation we call 'teamthink'.

The flow of information serves the team's "situation awareness". This term has been defined as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995:36). When we now consider team situation awareness for co-ordination centres who have no direct perception of the incident we must also include other aspects in the unit of analysis such as the creation of external representations that help to shape an image of the situation (maps, shared verbal space etc.).

METHOD

In order to investigate the effects of different information flows, we developed a microworld simulation of a forest fire fighting situation (built on a model developed by Brehmer & Svenmarck, 1995). In our version, four people in a quartet were to control the simulated fire. Two of them formed a command team, two (on the operative level) served as chiefs of two fire fighting units. The command team consisted of two persons with different task assignments. One person was responsible for collecting and organizing information which was collected from the operative level. The other person was responsible for making decisions and for strategic planning. These task assignments correspond roughly to those of the above mentioned field study. The fire fighting chiefs could only see an area of 3X3 squares per unit, of the 400 square area. The command team did only get textual information from the fire fighting chiefs, thus they had to form an image of secondary information. All subjects had an approximate map of the area and pencils so they could update this papermap.
In order to make the situation even more challenging and realistic we added reconnaissance troops who sent information outside of the visual field of the operative troops. We also added houses which were to be saved as well as forest which burnt down in different pace. Furthermore we included false alarms of new fire which had to be checked. These complications forced the teams to consider multiple goals.

Design: The communication architecture was varied in three conditions: a parallel one, a serial one and an optional one. In the serial condition one person received all information, filtered this and forwarded only such information to the decision maker which was considered to be relevant. In the parallel condition both participants in the command team received all incoming information. In the optional condition the participants could chose, **at any time**, which communication architecture to use. The communication between the command team and the fire chiefs was managed through electronic mail, within the commander team they could also talk.

Subjects: Sixty computer literate undergraduate students were paid 300 SEK each to serve as subjects. There were a total of 15 quartets, five within each condition. The subjects were randomly assigned to each condition.

Procedure: All quartets were informed about the general nature of the task, their respective individual roles, how the communication network was configured (the conditions), the manual map and its relation to the area, about the fire, wind, the different types of forests, and were instructed that they should try to save the houses as well as to extinguish the fire. They were given thorough training in how to use the interface and were then allowed to familiarize themselves with the display and the electronic mail. They also answered a small questionnaire which included questions about the information they valued the most, where they thought the fire (fires, in case they felt several fires) started, and how these developed. The experiment took 4 hours.

RESULTS

First we can notice that the commander teams in the optional condition used the parallel structure 70% of the time. Secondly, we can notice that only commander team members used the maps. There might be two reasons for this. First the work load at the operative level may have been too high in order to permit the fire chiefs to also update the map. Secondly, when there is no one with whom to share the information, there is less incitement to make an external representation. Furthermore, we can notice that the commander teams used the maps in very different and creative ways. Some used one map each in the same way, some updated different information on each "personal" map trying to capture the dynamics of the fire and the fire units, others used a collective map and noted all information there. Teams that planned a strategy often used arrows to notate the general direction of the strategy.

Performance in the task was calculated in two different ways, firstly in terms of absolute numbers of lost squares, and secondly in a relative score where the number of houses saved and the checking of the (false) alarm were also incorporated.

As to absolute performance, it was found that the serial condition gave better result than the optional condition (Sign test, Chi-2 = 3.6, P=0.06).

The relative success score is calculated by giving 1 point for checking out each false alarm, 2 points for saving a house and 1 point for putting out the fire in a house on fire. By a Kruskal-Wallis test we found that the difference between the three conditions in terms of this score was significant on a 10 % level (H= 4.94, 10%, 2df). Once, again, it was the optional condition that had less success in terms of this weighted score.

This result suggests that the people in optional condition found it difficult to gain control over the dynamic system, both in respect of simple criteria or multi-goal criteria. But we cannot, in any way, attribute the difference in success to the particular conditions.

Communication and Co-operation between Hierarchical Units
All communication between the commander team and the fire chiefs was categorised according to the schema used by Brehmer & Svenmarck (1995). As we also have houses and different forests in the area we had to extend the categories with aspects regarding these problems.

We found that the optional conditions commander teams sent 4 times as many messages categorised as strategies as the other two conditions (ANOVA, F=4.04, P=.05). It seems like the optional commander team sent all strategic ideas they had instead of selecting a few.

Furthermore, we found that the commander teams in the parallel conditions asked their unit chiefs about their unit positions twice as often as the other two commander teams (ANOVA F=4.24, P=.04). This indicates that the parallel commander teams had difficulty assessing and creating an image of the progress of the units. More about that later.

Since the experimental variation gave few significant results we sorted the teams into two groups according to their success in terms of forest saved and we found that the better commander teams did not send as many messages as the poorer ones (ANOVA F=4.03, P= .07).

Situation Awareness and Co-operation within the Commander Team
It was hypothesised that agreement in situation awareness might differ between groups with different technological architectures, as a result of the information distribution and the possibility to assess the situation. Here we have asked the subjects to note on a blank map where they regarded the fire started (and if they experienced that there were many fires, to note where they started and number them). We then compared the maximum difference between the team members' assessments of where they thought the first fire started by counting the number of squares distance. The difference between conditions was significant on a 10% level, (Kruskal-Wallis, H= 4.64, 10%, df2). We then also made a Chi-2 test between the parallel and serial condition and found that they also differed on a 10% level. The average difference between the fires recorded by the teams in the parallel condition was greater than that recorded by the teams in serial condition. Further evidence for the problem of assessing the dynamic system in the parallel condition was found in the number of questions asked about the position of the units. The parallel commander team asked more questions (ANOVA F=4.24, P=.04; Kuskal-Wallis H=7.02, 5%). Still their performance does not differ from that of the teams in the other conditions.

We also looked in detail at three teams which in order represent a successful, an average and a less successful team in terms of forests saved. As the teams in the serial condition seem to have the most shared situational awareness and those in the parallel condition the most disparate, we chose the most successful team from the serial condition and the least successful one from the parallel condition. We did this in order to find out what information each team had processed during the session, since it might indicate what kind of information processing is best. These three sessions have been fully transcribed. We have also categorised each speaker's turn, that is coherent uninterrupted speech, with respect to the messages the team members shared. One turn might for instance contain several messages. Interreliability 73%. The categories were initially informed by Bolan's (1979) four suggestions for good situation awareness, i.e. monitoring position-specific information, confirming and cross-checking information, communicating relevant situation to others and co-ordinating activities, but these had to be extended. We came up with 16 categories. Monitoring position specific information (MC), Question about position specific information (MQ), Confirmation of Information (CI), Cross-checking (CC), Hypothesis (H), Evaluation of progress (EP), Planning (P), Intention (I), Suggestion for action (SA), Taskdistribution (TD), Taskconfirmation (TC), Taskconfirmation [late] (TCL), Taskquestion (TQ), Metaorganization (M), Question (Q) and finally Other(O).

The successful team (serial) made 638 turns, followed by the average (optional) with 450 turns and the least successful (parallel) team with 427 turns. It seems like talking a lot is good. For example the successful team cross-checked information three times as much as the least successful team. Most interesting is the fact that the successful team made fewer hypotheses (4.4%) than the other teams (8.2% respectively. 12.9%), but planned long-term collaborative action three times as much as the other teams (3.3%, 1.1%, 1.2%). Thus the successful team made something out of their hypotheses. The same goes for sharing intentions for single units.

Furthermore we can second what Samurçay & Rogalsky (1993) found, that it is important to distribute work explicitly within the team. The successful team confirmed tasks 8.8% of the turns while the other teams made 3.3% and 1.6% confirmations.

DISCUSSION

The results indicate, first, that it is better to have a fixed information flow than having to decide it on one's own. This is easy to understand as the team members in the optional condition never knew who had got the message. It is interesting to note that the commanders in charge of the information flow selected the parallel one. That may indicate that the person wants to have as much information as possible because it feels like being in control when having much information, which might result in quicker decisions. Objectively, however, the information flow per se does not seem to affect the performance. One reason may be that there is a trade off between speed and accuracy.

Secondly, we found that the most successful quartets had commander teams who interacted and planned a lot. This suggests that team members should be trained to talk about their reasoning and show it to others who then can monitor it (see also Heath & Luff, 1992).

Concerning situation awareness, it may be suggested that the team members had different ideas about where the fire started, according to whether the information flow configuration was parallel or serial. Furthermore, the commander teams in the parallel conditions had more difficulty in assessing where the units were. This might be explained by the use of the maps. The parallel teams more often used two maps, one signifying the positions of the fire units the other the position of the fire, whereas the serial commander teams often let one person update the map and the other rely on that map. What is more surprising is that these different models of the fire in the team did not seem to make any difference in the success of managing the fire. One reason for the lack of effect of different models of the system may be that the participants compensate for differences in models. If this is the case, shared situation awareness is not as important factor in joint performance as often suggested. It is also noticeable that the optional condition did not differ significantly from the other conditions as regards differences in situation awareness within the team. This might be due to the participants' need for discussion and thus their dependence on each other in all situations, because they lacked a fixed information flow organization.

When the military introduced electronic mail in the communication between different geographically separate units, they also, probably without intention, cut down on verbal communication within the commander team. This is because the person receiving the electronic mail could just pass on the paper on which s/he printed the message, instead of, when using loudspeaker phones, all team members had direct access to the information at the same time as the message came in and thus could update the team situation awareness immediately. The common listening and oral communication may also help the team members to directly articulate who is taking care of which task. The point is that when designing systems it is not only the information transfer that counts, but also how the information is received. Who gets the information? When? Who else but the intended receiver got the message? How can/is it handed on to others? What constraint and structure does the medium possess (both on individual and collective level)? It might be suggested that command and control units should be encouraged to interact and communicate as much as possible in order for the teams to be in concert with each other and then be able to handle breakdowns quicker.

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Modeling Complex Processes in GTA

G.C. van der Veer, M. van Welie, D. Thorborg†
Vrije Universiteit, Department of Computer Science
De Boelelaan 1081a, 1081 HV Amsterdam, The Netherlands
†Linköping University, Department of Computer and Information Science
581 83 Linköping, Sweden,
Email: {gerrit,martijn,thorborg}@cs.vu.nl

ABSTRACT
GTA is a method for groupware task analysis. Representations of task models in GTA originally focused on object oriented templates of the various elements, and on hierarchical relations between elements as seen from separate viewpoints (work, agents, and situation). In order to model time aspects and complex processes, we introduce new concepts as well as new types of representation inspired by workflow representation techniques.

Keywords
GTA, process models, task knowledge, task modeling, workflow

ANALYTIC MODELING IN DESIGN

Systematic design of complex systems starts with a phase where the current work situation is analyzed. Knowledge of a current work situation, collected by knowledge elicitation, ethnography and other methods, is of a broad variety. An important step in this phase of design is to model all relevant task knowledge, including both static knowledge and process knowledge, in a model that includes indications of conflicts, diversity in procedures and situational conditions of tasks. The resulting representation of this phase of task analysis we will label "Task model 1" (van der Veer et al. 1995) (TM1). TM1 is valid if it represents all relevant aspects of a current work situation as far as the knowledge is needed for future (re)design.

Ideally, the next step in design is to envision the new world, i.e., the work situation for the case that the intended design is finalized and the specified technology is implemented. New technology will change the work situation, and will often strongly impact the work organization and procedures. All of this is part of the envisioning, so all of this should be represented in this phase of design. We speak of "Task model 2" (TM2) to indicate a representation of the envisioned new task situation. TM2 should represent the same aspects of work, work organization, and work situation, in order to allow analysis of the changes and to make decisions for detailed design.

The development of TM2 will be based on TM1 (including the conflicts, needs, and diversities recorded), on negotiation with the client of the design (including standards, corporate image, usability criteria, budget for design and implementation), and on status and envisioning of enabling technology (situational constraints, predicted possible developments). In later phases of design (specification, evaluation) detail specifications will often require a re-consideration of TM2, and, hence, new negotiations with the client of design.

GTA - GROUPWARE TASK ANALYSIS

GTA (van der Veer et al, 1996a) is a method for task analysis that provides a conceptual framework and related techniques and tools that allow the analysis and design of complex systems, where different users with different roles and competences, as well as stakeholders

(significant others who do not physically use the technology concerned but who's work is affected by it) apply complex technology in complex work situations and work organization. The label Groupware indicates the basic assumption of GTA that complex interactive systems and work processes can not fruitfully be analyzed from the point of view of single work places or single user-computer interactions. Each element of work is part of a large process that involves organizational aspects as well as the situation - both in its spatial relations and in its history of past events. GTA allows three views on knowledge about the task domain: *work*, *agents* and *situations*. Together these views provide the conceptual framework for analyzing and modeling TM1 and TM2.

Work

Modeling work means representing work activities in their relation to each other. The classical approach in this view is best represented in "Hierarchical Task Analysis" (HTA, see Kirwan and Ainsworth, 1992), where work is described as a hierarchical structure of tasks and subtasks. Approaches like GOMS (Card, Moran, and Newell, 1983) connect a goal to each task (hence there is a structure of subgoals), and define the smallest elements of a task / goal hierarchy as "unit tasks" (which are the end-nodes of the task tree, and, as such, from the point of view of the user, the smallest elements that are meaningful complete tasks with a goal). Tauber (1990), in addition, defines the concept of the system's "basic task", indicating units of task delegation as provided by technology. The elements of GTA's conceptual framework for the work view consist of a small number of concepts:

- Work may be structured in one or more *task structures*, where the structure of subtasks has to be described by constructors, that are specific to the task domain. Constructors may indicate a temporal sequence, triggering of sub-tasks by each other, loops, conditional choices, etc.
- At the high end of a task structure are *business goals* and tasks related to them. This type of task is often not delegated to a single person or role, and, especially for high level goals there may be several tasks that could provide a way to achieve the goal requiring a flexible structure.
- At the low end of a task structure we find actions, elements that derive their meaning from the unit task they are part of. E.g. hitting a return key is meaningful, but the meaning varies between situations where one is typing text in a word processing, navigating between cells in a spreadsheet, or issuing a command to an operating system.
- A set of tasks that belongs to a single role, i.e., is intended to be performed by a single person, often has a well-defined structure. If the structure is generally considered to be "good" or common work practice, we label this *"protocol"*. If the procedure is characteristic for experts in a certain task domain (e.g., developed on the base of learning or experience) we call this *"strategy"*.

Agents

Many task analysis approaches seem to take for granted that task knowledge of experts contains a considerable part of generic task knowledge. However, in practice we immediately find that complex processes are performed by people playing different roles. Approaches like TKS (Johnson, 1992) introduce this concept and relate it to a specific set of tasks and a task structure. Most of the classical task analysis techniques only work if we focus on a single role. Ethnography, on the other hand, is strong in investigating whether roles exist and how they relate to structures of work and to situations. In our viewpoint an agent is an active entity, usually a human or a group of humans, but intelligent systems are also considered agents. In analyzing the viewpoint of agents, GTA needs several concepts:

- Groups of *agents* need to be described in terms of their relevant characteristics. This refers to the importance of relating actors to the requirements of tasks. General characteristics that my be relevant depending on the technology applied may be typing skill, experience in using devices like mouse, language abilities. More "remote" variables like spatial ability and fear of failure may impact the interaction between actors and technology in certain situations. Task related aspects of actors refer to knowledge and experience with the domain of work.
- People can take one or more *roles*. Groups of people may in some task domains do the same (the "secretariat" is an instance that may consist of one or more agents, from the outside it performs a single role). Agents may perform several roles simultaneously. The relation between agents and roles may be established and disconnected over time, based on conditions of the situation (election for a post, being the next in the row to succession, self-selection).
- Agents and roles are related to each other in an *organization*. The analysis and representation of an organization should include information on *responsibilities* for tasks, task *delegation*, and the *assignment* of roles. Another part of the analysis of the organization concerns competences and ownership of elements in the situation, like "things" (See below).

Situation

Describing the situation as far as relevant for task analysis is often neglected in classical task analysis. An exception is Walsh (1989) who actually starts his technique by identifying objects and environments, before concentrating on activities and tasks. Ethnographic schools, on the other hand, always start by literally going into the situation, experiencing and subsequently analyzing it from within. In GTA there are various concepts needed to deal with the situation:

- Designated objects as analyzed by Walsh will be labeled *"things"* in our framework. These may be physical objects, or non-physical things like passwords, PINs, standard jokes, or stories. Things feature in tasks, sometimes being manipulated or created by tasks, sometimes as elements in conditions for starting or stopping a task. Things may act as symbols for roles (uniforms, portable phones, boy-scouts' handshake). Things may have attributes (opportunities for change) like a date of last inspection, a pointer to an owner.
- Things feature in a *structure*. In some cases it makes sense to represent things in a type hierarchy (e.g., in offices, there may be a type structure of paper fill-in forms). Often things provide places for other things (a letter may contain a header, a content, several appendices, and a signature)
- *Events* model things that happen in the task world over which the actor does not always have direct control, e.g. lightning strikes, a power failure, a colleague has become sick, a burglary, arrival of new mail etc. When analyzing highly complex situations such as a cockpit or a construction yard the event may prove very useful in modeling the rapidly changing situations.
- All tasks in a work domain are performed in an *environment*. The environment can be conceived as a thing, which has static and dynamic aspects. Environments are characterized by the things, the agents and roles that live in it but also more dynamically by the events that have taken place and those that may occur in future.

The three viewpoints described in this section are described in shared concepts that are interrelated. In the first versions of GTA, we focused on representing the separate viewpoints. Work can be represented in task structures that mainly illustrate the hierarchic

nature of the relation between higher order tasks and subtasks. In the same way the organization of agents or situations can be represented in role type/containment hierarchies. From the start GTA provided object oriented templates for representing the single concepts in their relation to the other relevant concepts, much like MAD for tasks (Scapin and Pierret-Golbreich, 1989) and ETAG for things (Tauber, 1990). In these templates, a concept like an thing is related to other things (sub type relation, contains relation), to actors and roles (ownership), to tasks, etc.

NEED FOR REPRESENTATION OF PROCESS

Task analysis techniques often focus on a single viewpoint (HTA, MAD, GOMS) or at least restrict themselves to separate representations for different viewpoints: ETAG uses separate structure descriptions for things (the UVM) and for tasks (the dictionary of basic tasks), and so did GTA in its ancient format. Experience with GTA in a variety of actual design situations (office work, construction hall, mobile communication, business processes industrial process control) showed that GTA in its original versions lacks possibilities that are essential to completely model relevant task knowledge (van der Veer et.al 1996b). Like other modeling techniques, GTA did not allow adequate handling and representation of time aspects and synchronization, parallelism and dataflow;

A representation technique that seems promising in this respect may be found in workflow management tools. Here, tasks are in fact represented by streams of entities that travel between situations or roles. Workflow representations allow the distinction between three types of organizational processes (Grudin, 1994): *material* (to be interpreted as products of the process), *information* (where information is represented in its function of driving the material process), and *human* (the coordination of people and organizations in respect to the steering of information and material processes).

GTA EXTENDED

We try to overcome the problems by a two-fold extension to the original GTA method: addition of some concepts to the conceptual framework, and inclusion of new representation formats that allow modeling complex processes. Our solution exists of including certain concepts from workflow modeling in the conceptual framework of GTA:

- *Time*, related to tasks in the form of deadlines, interval and frequency, and process time. An absolute time value can enforce the start of a certain task execution, a relative time can trigger execution of a task (start within 1 hour from a certain event of from the execution of another task). A task can be stopped at a certain absolute time, or after a certain interval. In this way time may feature in both starting and stopping conditions for tasks.
- *Input and output containers*, relating data and object transfer between tasks. Tasks often concern the handling of things. Things may be created or removed, things may be changed by changing the value of attributes, by changing the set of (other) things they contain, or by changing their location (inside other things). In all these activities, other things and "data" play a role, both as input for the task, and as results that will be transferred to subsequent tasks, whether these will be initiated by the same agent or by others. To this end, the representation of tasks needs to be extended to contain the relevant things and data.
- *Workflow events*, representing triggering or enabling relations between tasks and between data or objects and tasks. Tasks not only are related by way of decomposition into (sets of) subtasks. Often tasks result in other tasks being enforced or enabled to start or to end, even if other actors are concerned (sending an email to another person).

The extended framework allows new characteristics for the technique of modeling complex processes:

1. each process can contain several different processes (in parallel, synchronous, alternative, etc.);
2. each process can be represented as a relation between time and either roles (or actors) or objects (including data, situations, or locations);
3. consequently, each process can be represented as a directed graph of tasks, each of which related to roles or objects;
4. a task or subprocess can be part of several processes.

TOOL SUPPORT FOR PROCESS MODELING

An experimental version of the GTA tool with the new workflow viewer is now available at http://www.cs.vu.nl/~martijn/gta/. The tool shows processes in separate windows that also offer graph-editing facilities. A process can be chosen from a list of process or by indicating the starting task of the process. When a task is the starting task of more than one process the user is presented with a list of process in which he can select the relevant process. Currently we are working on a complete redesign of our tool in order to be able to experiment with different kinds of views. We believe that there are many other useful views, other than the classic tree, that can be of use to analysts. Apart from the workflow view we have also developed an inspector view which gives a kind of magnifying glass on the network of concepts and relations.

CONCLUSIONS

In this paper we described how we extended our conceptual framework GTA with support for modeling complex processes. By using workflow representations we add new and useful information to the classic hierarchical representations used in task analysis. Apart from a workflow view we motivated the use of other views that may prove useful in representing tasks models. In future we hope to support these views in our tools.

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Conceptual Design of Industrial Process Displays

Chr. Rud Pedersen
Seven Technologies
Købmagergade 26, Post Box 81
DK-1003 Copenhagen K, Denmark
e-mail: crp@sevent.dk

Morten Lind
Technical University of Denmark
Department of Automation, Building 326
DK-2800 Lyngby, Denmark
e-mail: ml@iau.dtu.dk

ABSTRACT
This paper discusses aspects of process display design taking into acccount the designer's and the operator's points of view. Three aspects are emphasized: the operator tasks, the display content and the display form. The distinction between these three aspects is the basis for proposing an outline of a display design method, that matches the industrial practice of modular plant design and that satifies the needs of reusability of display design solutions. Further the method ensures a seamless transition from specification to implementation. The method is illustrated by an simple example.

Keywords: MMI, process industry, user-oriented design method, HCI, GUI

INTRODUCTION
The most common type of process display used in the industry today is the mimic diagram. The mimic diagram is based on the piping and instrumentation (P&I) diagrams and uses dynamic symbols to indicate the status of each component. There are several problems with this approach:

1. The presentation is based on the physical topology of the plant which originates from the P&I diagram, hence the plant functions and operational goals are not mediated, i.e. the content of the display is not explicitly considered.

2. The one-sensor-one-indicator principle is generally used, so the operators have to derive the overall status by integrating information of the plant from several individual indicators.

3. Displays are often designed without explicit consideration of the operator's tasks and information needs.

A systematic approach is required to guide the designers of process displays in both the conceptual design and the implementation phase. The method must facilitate transfer of process design knowledge to the display designer and must aid by determining *what* information to present and the controls needed by the operators. Further it must provide guidance in *how* to visualise the information and the controls. Finally the methods should generate specifications that map naturally into implementation concepts for graphical user interfaces (GUI) and support modular re-use of design solutions. The layout of the displays is not considered in this outline of the display design method.

No methods exist that treat all these requirements. Present methods do not convincingly facilitate the transfer of process design knowledge into display design. Modern industrial plants are highly modular, being composed of subsystems and associated controls and instrumentation for each processing operation. This approach to process design is widely used in the industry as a means of reducing development costs. It is therefore essential that methodologies for display design can utilise this information. The use of abstraction hierarchies (AH) (Rasmussen, et. al. 1981) has been proposed for this purpose. However, the AH in its present form seems only to be directly applicable to energy systems. According to the experience of one of the authors (Lind), it requires considerable amount of adaptation or does not work when used for other types of systems, such as e.g. batch processes or mobile robots. One major problem with the AH is the lack of conceptual distinctions between different types of means (e.g. according to product, process equipment and control aspects), and the lack of concepts to express the relations between the means and their aggregation. Since the modular composition of plants comprise an aggregation of product, process equipment and control aspects, it is obviously very difficult for the AH to represent the design rationale for many industrial plants. These distinctions are currently under development as part of the Multilevel Flow Modelling (MFM) methodology (Lind, 1994).

Ecological Interface Design (EID) (Vicente, et. al. 1990) gives a method for transforming the display content into a form which support the cognitive skills of the operator. EID uses the AH to determine the display content and structure focusing on treatment of unanticipated events. Mitchell, et. al. (1986) developed the operator function model to determine the appropriate display content based on a behavioural representation of the operator. None of these methods consider the implementation of the GUI and therefore fail to meet the industrial needs of re-usability.

ASPECTS OF DISPLAY DESIGN
The following three aspects comprise the backbone of a systematic display design method: 1) the operator's

tasks, 2) the display content and 3) the form of the display. The tasks of operators and the content of the display are obviously dependent on the actual construction of the plant and on the allocation of tasks between the operator and the control system (the degree of automation). Representations of the plant are needed to define the operator tasks and the display content. Examples of plant representations can be P&I diagrams, block diagrams, and goal-function hierarchies. The plant can be divided into *process modules* which are aggregations of components that constitute one or more functions which are applied to fulfil plant goals. The three aspects are clarified below.

Operator tasks are defined when the plant and the control system are designed. Here it is important to consider both how the operator should act on the plant system and how the system should respond back to the operator. Operator tasks comprise: 1) short-term goal setting to achieve plant goals by performing process operations, i.e. the tasks needed to accomplish the long-term production, economical or safety goals of the plant stated by management (an example of a process operation in a brewery could be to move beer from storage to the bottling machinery to fulfil the production goal of bottling a given amount of beer per day). 2) Perform activities i.e. the actual sequences of actions the operator must make to execute the process operations using the available equipment and plant functions (e.g. to push the start button for the transport program and monitor the flow).

Display content (i.e. the information conveyed) is derived from the plant model where the important attributes of the plant with regard to the operator's tasks are selected. The content of the display is also dependent on the available plant instrumentation.

Display form is the graphical or textual presentation of the content. The graphical items representing plant components or the state of process modules (the content) can be decomposed into entities such as lines, boxes, menus, buttons, trend curves, pictograms, etc. The entities can be aggregated to match a certain level of the operators' tasks.

The interrelations between the aspects are shown in Figure 1.

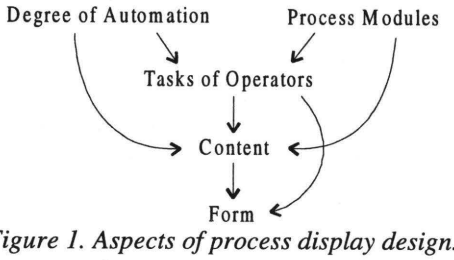

Figure 1. Aspects of process display design.

POINTS OF VIEW

Process displays can be considered from two points of view: from the designer's and from the operator's. A method for display design must obviously encompass both viewpoints.

The Designer's Point of View

When a new plant is designed the degree of automation and the decomposition of the plant into modules should be considered. These decisions influence the operator tasks and therefore the content of the display, as illustrated Figure 1. Hence the people designing process equipment, automation system and displays have to co-operate.

In practice, the automation and display developers are within the same company and receive the specification to the control programs and the displays from the plant designers. The task analysis is seldom explicitly considered and the process equipment and its instrumentation is specified by another company. This division of tasks between companies makes the transfer of plant design knowledge into display design difficult.

The Operator's Point of View

Norman (1988) states that the fundamental principles of designing for people are to 1) provide a good conceptual model and 2) make things visible. Figure 2 shows the conceptual models.

Figure 2. Conceptual models in designing for people.

If the system image does not make the design model clear and consistent, then the user will end up with the wrong mental model.

This is exactly the problem in current design of process displays in the industry. The only way the operators can communicate with the plant is through the developed process displays, which therefore should reflect the design solution. The content and the form of the display are essential to ensure that the operator develops a good conceptual model of the plant. Naturally, controls and the status of the control system must be visible, which again concerns the content and form. The operator's situation is illustrated in Figure 3.

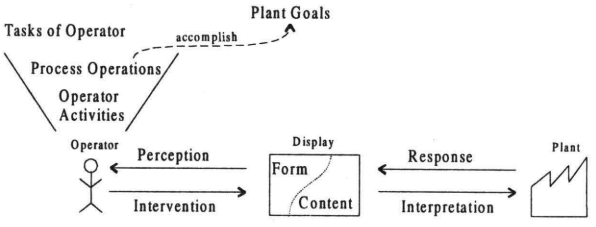

Figure 3. The operator's world.

The operator activities are in most cases performed on the display. Moreover the operators have to evaluate and schedule which process operations they have to apply, both in familiar and unfamiliar situations, to fulfil the plant goals.

A CONCEPTUAL DESIGN METHOD

The display design method is restricted to look at the three aspects: tasks of operators, content and form of the display because the degree of automation and the process modules are decided during plant construction and can usually not be changed by the automation and display designer. This is the industrial practice today and improved methods to display design must take that into account, i.e. be evolutionary rather than revolutionary.

The objective of the method is to yield the right specification of the displays which is also easy to implement. This can be obtained by adopting the Model-View-Controller (MVC) paradigm from the Smalltalk language, which has provided the conceptual basis for modern GUI implementations. In the MVC paradigm an item in the interface is modelled by three software objects, a model, a view and a controller. The MVC is based on object-oriented programming, but an object-oriented approach does not ensure that the specification solves the problem. Therefore, we use the MVC both for development of the specification, i.e. for analysis of the application and as a conceptual basis for implementation of displays, in this way creating a seamless transition from the early conceptual design phase to the implementation.

The model, view and controller of the paradigm corresponds to the content, form and operator's tasks as shown in Figure 4. The benefit of applying the MVC paradigm is that the tasks of operators, content and form of the display are separated. Hence the display content comprise different attributes of the plant modules depent on the operator tasks and different forms can be applied to the same content.

For each aspect different levels of aggregation can be applied as shown in Figure 4. For example, the content of the entire display (the outer circle) will be decomposed into a network of information elements that are mapped into an implementation by a network of corresponding model objects in the software.

Outline of a Design Method

The ideal sequence in the design of process displays is to do a process and task analysis which is the foundation for determining the content of the display. Having defined the content, the form can be chosen which again will be influenced by the activities of the operators (c.f. Figure 1). The dotted line in Figure 4 illustrates the progress of typical design.

The division of the plant into modules provides a decomposition of the display content. If the process modules correspond to a unit of process operations, it may be possible to reuse a display design within or between process domains. Notice that different operator tasks are affiliated to each module. For example, a heat exchanger process is used in different process domains and is associated with tasks such as: start up, monitoring and shut down.

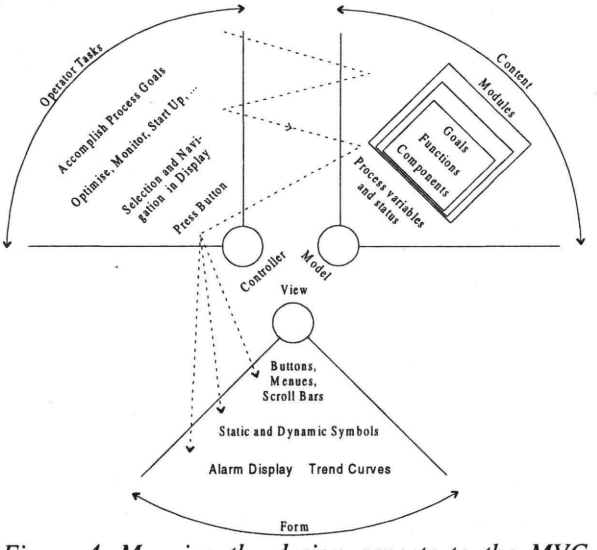

Figure 4. Mapping the design aspects to the MVC programming paradigm. Different levels of aggregation are shown together with a typical design sequence (dotted line).

A classification of process operations would therefore be usefull as a template for the display designer (and partly for the plant and automation designers), aiding with the first steps in determining the content of the display. A more detailed task analysis for the process at hand must be made before the content of the displays can be specified at a level from which the detailed form can be considered.

A more detailed procedure for the design method is illustrated by the following example. The suggested steps in the design are written in *italic.*

EXAMPLE

This example is a storage tank shown by the simplified piping and instrumentation diagram in Figure 6.

The production goal is to store material for some time before reusing it in the process. The first step is to define modules which allow reuse of the plant, automation and display design. Three *modules are defined* as shown with the dotted lines in Figure 6. To fulfil the production goal, three *process operations are identified*: filling, stirring and emptying the tank. The operations cannot be performed simultaneously and are here assumed to be automated, i.e. a program for each operation exists in the process computer.

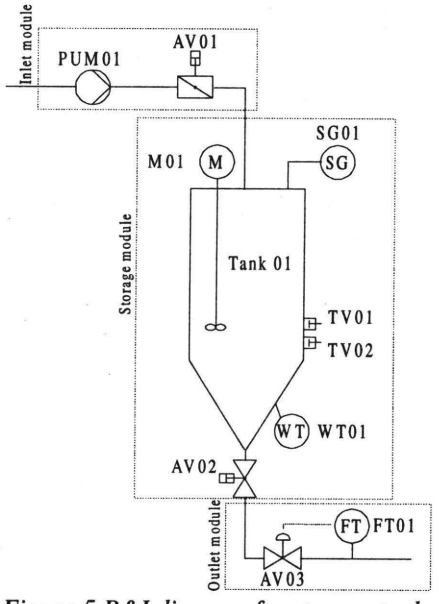

Figure 5 P&I diagram for storage tank.

Stirring is performed periodically and the flow is controlled when emptying the tank. Next the *modules are associated with the process operations* as shown in column 1 and 2 in Table 1. *The content of the display is then decided for each process operation* by selecting module attributes. Some process variables are more important than others which is indicated in Table 1. The modularisation will make this step easier in large plants. The *operator activities are then determined* and will as mentioned depend on the degree of automation. See Table 1 for the activities related to each process operation. Finally, *the form of the display must be chosen.* The form will depend on the number of process operations the operator must supervise simultaneously and the complexity of the activities. There are several possibilities for the layout of the display, but as mentioned the problems involved in the layout are not treated here. As shown in Table 1, several graphical items can be chosen for each category of operator activity.

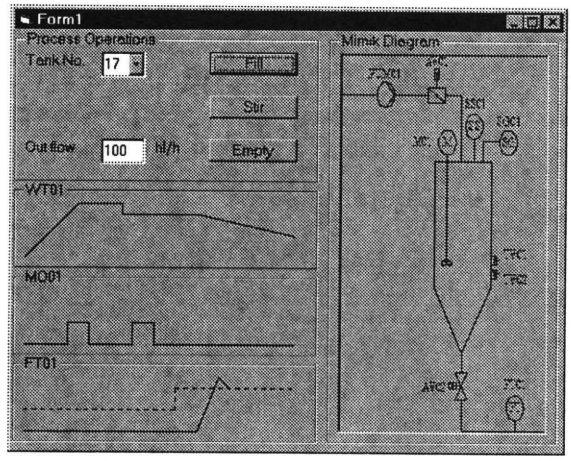

Figure 6. Suggested display for the example.

Figure 6 contains the graphical items and a suggested layout to initiate and monitor the operations from the example.

When several process operations run simultaneously, the operator must initiate new process operations while monitoring several other operations. In this case, advanced graphical items which at one glance tell the operator the state of the process operations are necessary. If the filling and emptying operation can be performed at the same time, the operator needs the relation between the out and in flow (which can be calculated from WT01 and FT01). A useful graphical item might be the one shown in Figure 7.

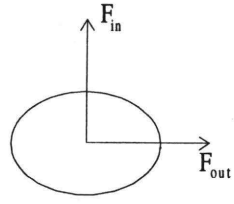

Figure 7. A graphical item for fast overview of the relation between F_{in} and F_{out}.

So far the display have been constructed from predefined graphical items, meaning that the top-down use of the MVC paradigm ends when

Process operation	Module	Display Content Primary	Secondary	Operator activity	Graphical items
Filling	Inlet, tank	WT01	PUM01, AV01, AV02	1. Choose tank number 2. Start filling program 3. Monitor filling process	Combo box or input box Command button Bar graph or trend curve
Stirring	Tank	M01		1. Choose tank number 2. Start stirring program 3. Monitor motor speed	Combo box or input box Command button Trend Curve
Emptying	Outlet, tank	FT01	AV02, AV03, WT01	1. Choose tank number 2. Enter desired outlet flow 3. Start emptying program 4. Monitor emptying process.	Combo box or input box Input box Command button Bar graph or trend curve

Table 1. Associations between process operations, modules, display content, operator activities and graphical items.

predefined items are available. Hence only the right specification has been achieved. Moving down to implementation, consider the graphical items in Figure 7. The view consists of 2 arrow lines with labels and an ellipse. The model consist of two process variables; in this example F_{in} and F_{out}. The purpose of the controller is to relate the radii of the ellipse (the view) to the process variables (the model). This can be implemented in a object-oriented graphical development environment. Even though the model, view and controller objects might not be as clearly distinguished as in Smalltalk, the conceptual separation is helpful and will often match a part of the structure of the chosen programming language. For example in Visual Basic 5.0 the controller and the model are integrated in procedures. This illustrates how the MVC paradigm can be used bottom-up to create new graphical items.

FUTURE WORK

The outlined design method is developed as part of a industrial Ph.D. project. The method will be developed and applied to a water treatment plant. Even though the layout problems are important they will not be considered in this project.

CONCLUSION

An outline of a design approach to process displays is described that separates three aspects:

- operator task,
- display content
- display form

The display design methodology builds on the modular approach to plant design used by the process industries.

A seamless transition from a conceptual design to implementation is proposed via the MVC paradigm from the object-oriented programming language Smalltalk.

The approach is illustated by a simple example but the viability is still to be proven.

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Parallel or event-driven goal setting mechanism in Petri net based models of expert decision behaviour

M. Rauterberg, M. Fjeld, and S. Schluep

Researchgroup Human Machine Interaction (MMI)
Institute for Hygiene and Applied Physiology (IHA)
Swiss Federal Institute of Technology (ETH)
Clausiusstrasse 25, CH-8092 ZURICH, Switzerland
+41-1-632 70 82, rauterberg@iha.bepr.ethz.ch

ABSTRACT

Decisions and actions produced by computer users (*observed process*) contain much information about their mental models, individual problem solving strategy and underlying decision structure for a given task. Our tool AMME analyses observed processes and automatically extracts a Petri net description of the task dependent decision structure (*logical structure*). This net is extended by goal setting structures (modelling) and executed (*simulated process*). The aim is functional equivalence between observed and simulated processes. Two modelling strategies, *event-driven* and *parallel* goal setting, are presented.

Keywords: Behaviour driven modelling, cognitive modelling, Petri net, goal setting strategy.

INTRODUCTION

What mental models are and how they work, is quite unclear. Most of the known modelling approaches are based on the assumption that the "mental model maps completely to the relevant part of the conceptual model, e.g. the user virtual machine (Carroll, et al., 1991). Unexpected effects and errors point to inconsistency between the mental model and the conceptual model" (Van der Veer, et al., 1990). This one-to-one mapping between the mental model and the conceptual model of the interactive system implies a *positive* correlation between the complexity of the observable behaviour and the complexity of the assumed mental model. But this assumption seems to be wrong.

Based on empirical results (Rauterberg, 1993), the complexity of observable *novice* behaviour is larger than that of *experts*. Hence, the behavioural complexity is *negatively* correlated with the complexity of the mental model. If the cognitive structure is too simple, the concrete task solving process must be filled up with heuristic or trial and error behaviour. Learning how to solve a specific task with a given system means that the behavioural complexity decreases and the cognitive complexity increases. Now, one of the central question is: What kind of knowledge is stored in the cognitive structure?

THE MEASUREMENT OF COMPLEXITY

The symbolic representation of the machine system consists of the following elements: 1. objects (things to operate on), 2. operations (symbols and their syntax), and 3. states (the 'system states'). The mental model of the user can be structured in representing: objects, operations, states, system structure, decision and task structure. A Petri net can be described as a mathematical structure consisting of two disjoint, non-empty sets of nodes, S-elements (signified by a circle or an oval '( )') and T-elements (signified by a square '[ ]'), and a binary flow relation F (signified by an arrow '->') (Petri, 1980). Bauman, et al. (1986) showed, that Petri nets are equivalent to formalism based on production rules (like CCT of Kieras, et al. (1985)). In this sense, our approach can also be subsumed under 'logic modelling'. The main operations (relations) between two Petri nets are *abstraction*, *embedding* and *folding* (Genrich, et al., 1980).

The *folding operation* in the Petri-net theory is the basic idea of the approach presented in this paper. Folding a process means to map S-elements onto S-elements and T-elements onto T-elements while keeping the F-structure.

Each state corresponds to a system context, and each transition corresponds to a system action. This sequence is called a 'process'. An example of the task solving process of an expert user is presented here (see also Fig. 1). The user's task is to find out how many data records there are in a given data base (DB) consisting of file A, file B and file C of a given database (DB). First, the system goes from (Main menu) to (Start menu) with system

transition ['G_2'], where it opens the DB. Then the system goes back to the (Main menu) with ['M_3']. Now, the user selects function key ['F_3'] and goes to the file selection menu, where he selects file A by pressing key ['1'], bringing him back to the (Main menu). Pressing ['I'] brings him to the (Info) module. Pressing ['d'], all DB information is displayed sequentially on three different screens (3* ['M_22']) and the system automatically goes to (Info) with ['M_11']. But part of the *task relevant* information is visible only on the first screen, which is overwritten by the two following ones. Trying once more to see all information, the user tries ['d'] again, but the same reoccurs. After a third time pressing ['d'], the user correctly follows up with a blank ['BL'] to interrupt the scrolling. Hence, the first part of the task relevant information stays on the screen. Pressing ['F_10'], the rest of the information is displayed (2* ['M_22']) and the system automatically goes to (Info) by ['M_11']. Pressing ['h'] twice brings the user to (Main menu) and then to (Start menu). Pressing ['F_10'] brings the user to (MsDOS).

The aim of the folding operation is to reduce the elements of an observed empirical decision process to the minimum number of states and transitions, with the reduced number of elements being the 'logical decision structure'. Folding a decision process extracts the embedded net structure and neglects the amount of repetitions, sequential order, and temporal structure. The result of a folding operation applied to the behavioural sequence (Fig. 1) is the Petri net given in Fig. 2.

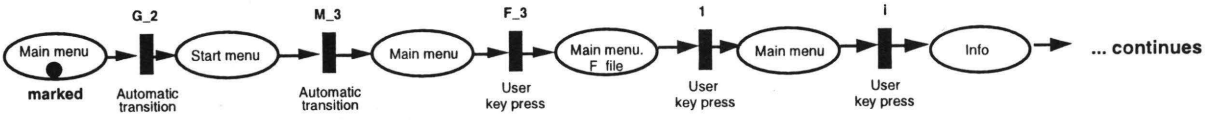

Fig. 1. Part of the original behavioural sequence of an expert with a relational database system (Rauterberg, 1992a).

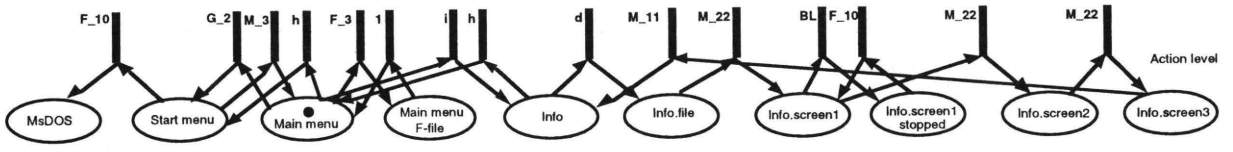

Fig. 2. *Model-1*: the pure 'logical structure' (the device model) of the logfile example sequence in Fig. 1.

C_{cycle} is the McCabe (1976) complexity measure (Formula 1), where F is the number of connections and [T+S] the number of nodes. (Different quantitative measures are discussed by Rauterberg (1992b).) P is a constant to correct the result of Formula 1 in the case of [F – (T + S) = -1]. In our context the value of P is 1.

$$C_{cycle} = F - (T + S) + P \qquad (1)$$

The C_{cycle} value of the model-1 in Fig. 2 is [30-25+1=6]; the complexity of the net shown in Fig. 2 is six. McCabe (1976) interprets C_{cycle} as the *number of linear independent paths* through the net. Other interpretations of C_{cycle} are *number of holes* in a net or *number of alternative decisions* carried out by the users.

Observing the behaviour of people solving a specific problem or task, is our basis for estimating 'model complexity' (C_{cycle}). The cognitive structures of users are not directly observable. Therefore, we need a theory with a method to estimate C_{cycle}, based upon observed behaviour. We call the complexity of the observable behaviour the 'behavioural complexity'. This behavioural complexity can be estimated by analysing the recorded concrete task solving process.

RECONSTRUCTION OF THE MENTAL MODEL

We carried out an empirical investigation to compare different types of interfaces (Rauterberg, 1992a). For the reconstruction of user's mental models we used the behavioural sequences of five different expert users, all solving the previously described DB task. The sequences were automatically recorded in 'log files' by an interactive software program.

The logged sequence contains three different types of knowledge: (1) the pure logical structure (or device model) (Fig. 2) of the task, (2) the sequential structure of all goals, and (3) the temporal structure of all actions.

Action regulation theory (Hacker, 1994) offers a coherent body of principles for human-centred task and work design. For Hacker (1986) the work task is "the central category of psychological consideration of activity..., as decisive specifications for the regulation and organisation of the activities occur with the 'objective logic' of its contents". Therefore, in the context of action regulation theory, the *task* has great importance for the behavioural

analysis. The concept of *complete task* calls for particular attention. Each complete task and action cycle starts with a goal setting part. In the analysis and design of human activities, the following characteristics of complete tasks must be taken into consideration:

(A) Task dependent setting of subgoals which are embedded in the superimposed task goal;

(B) Independent action preparation in the sense of taking on planning functions; and, selection of the means including the necessary actions for goal attainment;

(C) Mental or physical performance functions with feedback on performance pertaining to possible corrections of actions;

(D) Control with feedback on results and the possibility of checking the results of one's own actions against the set (sub-)goals.

Following the theoretical implications of action regulation theory, we can differentiate between (1) the action level (corresponding to C), (2) the goal instanciation level (corresponding to B), and (3) the cognitive level with the mental goal setting processes (corresponding to A). In the context of this paper we did not take into consideration the control and feedback level (D), but we plan to do this in our future work.

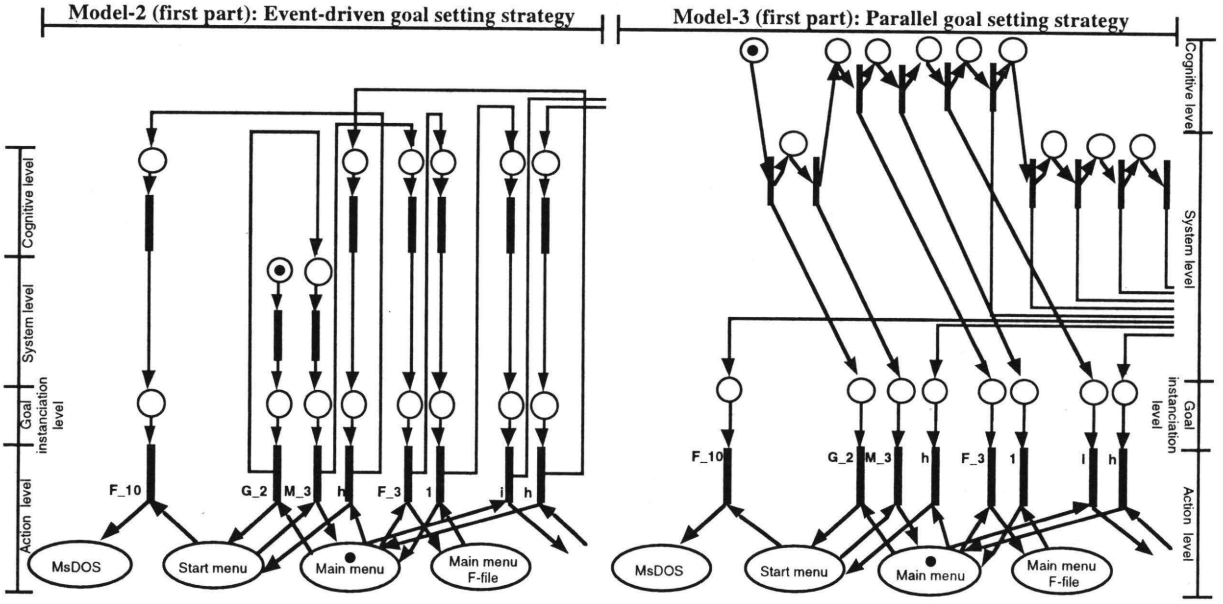

Fig. 3. a) *Model-2*: this Petri-net is equivalent to model-1 with added structure to model event-driven goal setting.
b) *Model-3*: this Petri-net is equivalent to model-1 with added structure for parallel driven goal setting.

Model-1: The pure logical structure is automatically extracted with our tool AMME (Rauterberg, 1993, 1996) from the 'log files'. This net is called model-1 (see Fig. 2). Model-1 does not contain any knowledge about goals and time. It is a subset of the complete system description (S-, T-, and F-rules: the rule base to describe the whole interactive system behaviour as part of AMME (Rauterberg, 1996)). However, we know that a mental process takes place at a cognitive level. So we have to find a way to model these mental processes by adding structure to model-1. Petri nets enable us to do this in a unified way: any further levels can be described and modelled with the same elements as at the action level.

All observed actions (e.g. ['G_2'] and ['M_3']) that are automatically carried out by the system itself, are primarily not part of the cognitive level. Therefore, the system level must be a part of our model. Although the user cannot control the system level actions, he can take them into consideration. So, at the goal instanciation level a selected action is either set from the cognitive or from the system level.

In a first modelling approach, *event-driven goal setting* , we added a minimal structure to model-1, to increase the *functional equivalence* between the simulated, new model and the original behavioural sequence. This new model, based on model-1, we called model-2. In a second approach, *parallel goal setting* , we elaborated model-3.

Model-2: Our *event-driven goal setting* example is given in Fig. 3a. Each action (or event) at the action level *directly* activates a mental process at cognitive level or a system action at system level. For the next action to

take place, a mental process or system action instanciates a corresponding goal at the goal instanciation level. Hence, there is an upward, direct synchronisation from action to cognitive and system level and a downward synchronisation via the goal instanciation to the action level.

Model-3: The *parallel goal setting* process (see Fig. 3b) was introduced by von Cranach's discussion of plans, 'anticipating representations', and intention (von Cranach, et al., 1982). For each goal at the goal instanciation level to be set, an anticipated counterpart must be set beforehand at the cognitive or system level. Parallel goal setting means that the mental goal setting process is running parallel to the action level, where the dialogue actions are executed. Hence, there is no upward synchronisation from action to cognitive or system level,, only downward via goal instanciation to action level.

VALIDATION OF COGNITIVE GOAL SETTING STRATEGIES

To validate the different goal setting strategies, a simulation study of model-1,-2 and -3 was carried out. We modelled the task solving processes of five expert users, all solving the same task, as pure logical structure (model-1), with event-driven goal setting structures (model-2) and with parallel goal setting structures (model-3). With the Petri-net simulator PACE all the models (5(#subjects)*3(model-1,2,3)=15) were implemented and simulated. We generated six different task solving sequences with each model, giving a total of 90 simulated sequences. Each simulation stopped either because the net was dead or $N_{sim}=N_{org}$.

To estimate the similarity between the original sequence (e.g. Fig. 1) and each simulated sequence, we used the following procedure that guarantees a *functional equivalence* strictly based only on (re-)produced actions:

1. Number all transitions ['G_2' = '1', 'M_3' = '2', 'F_3' = '3', ..., 'F_10' = '25'] in Fig. 1 consecutively. The number R is the rank-position of each transition [t] in the original behavioural sequence.
2. Assign these numbers to all generated transitions [t] of each simulated sequence. For example, one of the shortest simulated sequences we found, was generated with model-1: ['F_3', '1', 'G_2', 'F_10']. The rank positions R of these four transitions are: ['3', '4', '1', '19']. In general, if a transition appears m times in a original sequence and n times in the simulated sequence, the rules are as following: For the case n<=m, the simulated transitions get the ranks of the corresponding original transitions. For the case n>m, the first elements are handled as in the first case, whereas the rank of the elements m+1..n is m.
3. Calculate a 'similarity ratio' (SR; see Formula 2). SR is a sufficient measure for the similarity between the simulated sequence and the original sequence. N is the number of all fired transitions in a sequence. The maximum of R_{org} is equal to N_{org} (N_{org} in Fig. 1 is 25). SR is only valid for simulated sequences that fulfil the following condition: $N_{sim} \leq N_{org}$. SR of the above example ['F_3', '1', 'G_2', 'F_10'] is 13%.

$$SR = \left[1 - \left\{\sum_{t=1}^{N_{sim}} \left|R_{org,t} - R_{sim,t}\right| + \sum_{N_{sim+1}}^{N_{org}} \max\left(R_{org}\right)\right\} \Big/ N_{org}^2\right] * 100\% \qquad (2)$$

4. Average the similarity ratios of all simulated sequences per model (see Table 1). The results in Table 1 show that with increasing complexity of the mental model (C_{cycle}), the similarity ratio (SR) tends to 100%. We can also see that the standard deviation of SR decreases continually with increasing C_{cycle}.

Table 1. The model complexity (C_{cycle}) and similarity ratio (SR) of model-1, -2, and -3.

Model-no.	1	2	3
C_{cycle}: mean ± standard deviation	13 ± 5	43 ± 17	57 ± 25
C_{cycle}: min...max.	6...18	22...68	30...97
SR: mean % ± standard deviation	41 ± 28	66 ± 21	88 ± 11
SR: min...max. %	3...79	36...98	67...100
# simulated sequences	30	30	30

Three analysis of variances were done with StatView 4.02 (1993). Independent variables were model (1..3) and subject (1..5), dependent variable was similarity ratio (SR). Model was the only significant main effect (ANOVA, F=38.743, p<0.001), whereas subject (ANOVA, F=0.564, p≤0.690) and subject model interaction (ANOVA, F=1.068, p≤0.395) both were non-significant. So the similarity ratio increases from model-1 to model-3 and seems to be subject independent. We have not tested whether our results are task dependent. We got a clear, positive correlation between model complexity (C_{cycle}) and similarity ratio (SR) (R=0.660, 95% interval [0.524...0.763], p<0.001). The same analysis split by subject also gave a weaker, but still significant correlation (R=0.532, 95% interval [0.365...0.665], p<0.001).

From this outcome we can conclude that (1) model-2 is better than model-1, and model-3 is better than model-2, but (2) even the most elaborated model-3 can not guarantee a SR of 100%.

DISCUSSION

In the original sequence there was a cyclic behaviour (Rauterberg, et al., 1997). The user tried twice to see the task relevant information, but without success. The third time he succeeded. This is a typical learning effect based on trial and error. Analysing learning effects with Petri nets was achieved with other strategies (Rauterberg, et al., 1995). It seems to be difficult to simulate learning effects with event-driven goal setting, because repeated behaviour cannot be integrated in that modelling concept. For the parallel goal setting approach though, repeated behaviour is reflected in the model, with improved results from one to the next repetition. However, since there is no bi-directional synchronisation between the cognitive and the action level for the parallel goal setting approach, the similarity is still less than 100%. An integration of the advantages of both strategies will be a possible target for our further research.

CONCLUSION

We can conclude from the validation results that the SR value is considerably higher for the models with added goal setting (model-2 and model-3) than for the pure logical structure (model-1). So it seems to be possible to develop a completely automatic modelling tool based on a bottom up approach. Moreover, we see that with increasing model complexity (C_{cycle}), the mean value of SR increased and the standard deviation got smaller. Parallel goal setting performed better than event-driven goal setting. With the parallel goal setting strategy, we were able to include learning effects from the real task solving process.

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Intelligent Simulation Systems: the EXTRAS approach

Massimo Caimi, Cristina Lanza

CISE S.p.A.
Via Reggio Emilia, 39
20090, Segrate - MI (I)
0546caim@s1.cise.it, cristina@sia.cise.it

ABSTRACT

The ability to cope with uncommon or abnormal situations is an increasingly essential requirement on the operation of complex industrial processes. Process simulators are effectively used for this purpose both for offline training and online help systems. The paper presents the intermediate results of the EXTRAS project, aimed at developing a generic technology for producing Intelligent Simulation Systems by coupling existing simulators with an intelligent assistant system.

Keywords
Training, Knowledge-Based Systems, Process Simulators

INTRODUCTION

The typical problems that are faced by an operator of complex industrial processes is to deal with uncommon or abnormal situations where operating procedures give very little aid and operator experience can be insufficient. An effective way to help plant personnel to tackle this kind of situations is to utilise process simulators with a twofold objective: first to train operators to recognise such situations and to investigate the efficacy of possible control decisions, second to give to control room personnel an effective on-line decision support. However present simulators are not able to support their users in reminding the expected operations, identifying incorrect actions and understanding plant status. The industrial need is for Intelligent Simulator Systems (ISS). Such systems should be able to carry out in an integrated way a number of complex functionalities: accurately simulate the plant behaviour, answer user questions such as "why", "how", "what if"..., monitor the user actions and detect deviations from the expected optimal control strategy, explain errors consequences and propose the correct actions sequence.

The EXTRAS project[1] is aimed at developing a generic technology for producing ISS: such technology utilises Artificial Intelligence based techniques coupled with simulation techniques and will be customisable to particular applications. There are four application systems to be built, in the frame of the project, as examples of the common generic technology: they are in the field of fossil fuel power generation, paper and pulp production, combined cycle gas turbines for power generation and energy distribution centres.

The Fossil Fuel Power Plant Application (hereinafter FFPPA), jointly developed by CISE and ENEL, is aimed at building an ISS to be used for the off-line training of control room operators of thermal power plants by means of real-time full-scope simulators. The main goal of the application is to demonstrate the possibility of carrying out training sessions without the direct supervision of a human instructor and to assess the quality and the efficacy of the resulting training process, with a special emphasis to the capabilities of dynamically generating explanations aimed at improving trainees' knowledge and operational skill.

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[1] **EXTRAS** (**Ex**planation in Online Help and Offline **Tra**ining Based on Continuous **S**imulation), BRITE/EURAM Programme project BE95-1245 partly supported by the CEC, is a three-years lasting project started on January 1996. The partners of the consortium are: GEC Marconi Radar and Defence Systems (Prime Contractor - UK), CISE (I), ENEL (I), Heriot-Watt University (UK), Iberdrola (E), KCL (FIN), Labein (E), Tecnatom (E), UPM-Kymmene (FIN). The authors wish to acknowledge the contribution of all members of the project team to the ideas presented in this paper, whilst taking full responsibility for the way they are expressed.

The paper presents the intermediate results of the EXTRAS project, with a specific reference to the FFPPA application. The core of the paper presents two of the major topics tackled in this first part of the project: monitoring of operator's actions and classification of discrepancies with respect to the expected actions. Both are very challenging tasks due to the complex and unstable environment where such activities have to be performed.

APPLICATION REQUIREMENTS AND RESULTING ISS ARCHITECTURE

Special attention and effort have been devoted to the user requirements analysis and definition, given the innovative character of the applications. The reference training practice is the one actually deployed at the Training School of the Specialist Training Service of the Generation Direction of ENEL located in Piacenza, where a long term experience in operator's training through real time simulators is available. The identification of the user requirements for FFPPA has been carried out by a working team composed by CISE software specialists and instructors of the ENEL.

The focus of FFPPA is on the assessment and improvement of the personnel capabilities related to the plant operation, mainly in unusual and faulty conditions. Load Rejection was selected as representative procedure; the target simulator is an existing full scale compact simulator of a 320 MW oil fired thermal power plant with an UP furnace. Within a training session, the trainee will interact with the plant simulator by means of the SCADA (Supervisory Control And Data Acquisition system) dedicated consoles and will be given explanations on a dedicated console in form of final debriefing.

An overall view of the ISS architecture proposed for FFPPA is presented in Figure 1. The Simulator and the FFPPA are connected via Ethernet and users will be provided with separate consoles to operate the Simulator and to receive explanations from the FFPPA. The main subsystems and their dependencies are highlighted.

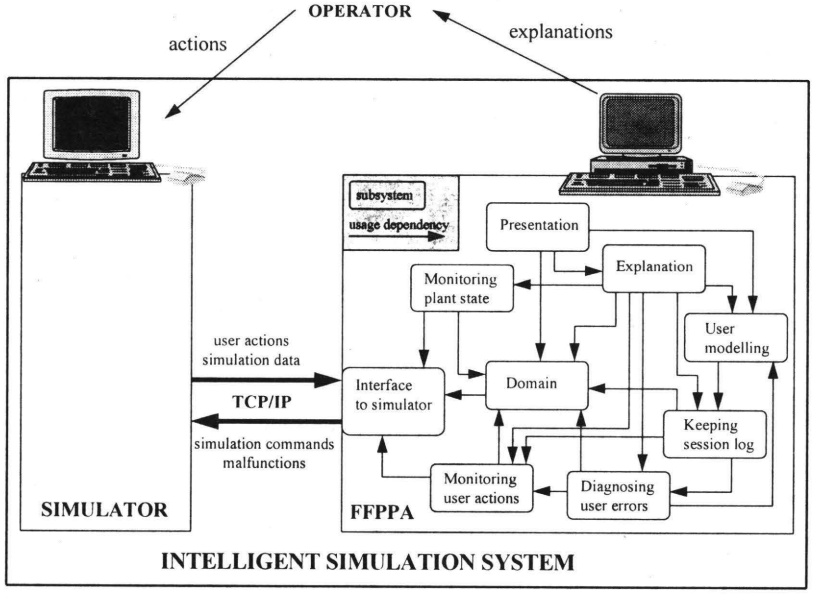

Fig. 1. - The Intelligent Simulation System overall architecture

MONITORING OF THE USER ACTIONS AND DISCREPANCIES DETECTION

A considerable amount of research has been conducted both in the interpretation of user's behaviour and in the analysis of error (Rasmussen, 1993; Hollnagel, 1991), particularly in the process industry. Interpretation of operator's behaviour and detection of errors is basically grounded on the analysis of the observable events during task execution. When a normative model of the procedure to be carried out exists and is fixed, a classification of the manifestation of errors can be done considering discrepancies detected with respect to the prescribed order of actions.

In more complex situations however, when either more than one procedure is possible either more than one action can be performed within a given procedure for a specific situation, some form of plan attribution, if not actually plan recognition techniques, can properly match the problem. The so-called "situated plan attribution" approach (Hill and Johnson, 1994), where the state of the plant as well as the operator actions are monitored, is promising for dynamic and highly interactive application environments. According to this view, environment (i.e. both plant and operator) monitoring can take the place of plan recognition, thus overcoming the limit of plan recognition techniques which often make rigid assumptions about the user's plans; in addition the hard task of constructing and maintaining an executable user model able to reproduce the exhibited behaviour and to justify it in terms of cognitive states can be escaped.

Moved by the above mentioned related work on the area, our work on monitoring of the user actions and discrepancies detection is based on explicit representation of procedures by means of flexible representation formalisms, and on accurate representation and maintenance of the plant state by means of the real-time connection to the plant simulator.

In the following we present the analysis of the selected representative procedure for FFPPA; then we simply sketch the formalism adopted for the representation of procedures. The monitoring process inclusive of the assessment of the operator behaviour in terms of discrepancies classification is then outlined.

The Selected Procedure for FFPPA and the Adopted Representation Formalism

Load Rejection (hereinafter LR) is an exceptional operation procedure, unfamiliar to most operators, for powering the auxiliary systems by means of the generator after the separation of the unit from the network. Although there exist written operational regulations to cope with it, their real-world application is not so immediate. There are various reasons for this:

1. It is unlikely that the plant state perfectly matches the situation which operational regulations cover: unexpected malfunctions of automatic operations are very common and they require a recovery procedure to be taken by the operator who has then to cope with both the malfunction and the exceptional transient of LR.

2. Expected actions depend on the plant state. The operator has considerable freedom of action and the operations he takes affect the plant state.

3. Time is very important for solving LR. For the set of "optimal actions" to be carried out an "optimal execution time" and also a "maximum execution time" for each action can be indicated. This can be done considering the final goal of solving LR within the optimal time of 20 minutes.

4. Actually, some timing constraints are variable and determined by the time taken by specific plant variables to vary during the exceptional transient condition of LR.

A thorough task analysis has been done for LR and its outcome was the definition of a generic frame applicable to all the tasks supposed to be covered by the application. The decomposition frame is based on the basic concepts of Tasks, Phases, and Actions.

Each Task is decomposable into sequential Phases. Within each Phase, Actions should be executed. Actions do not have a defined time sequence, nor a strict prescribed ordering to be followed, rather their execution depends on the plant state. However, enlarging the scope to other possible application domains, a specific structure is also set to represent Sequences of Actions, i.e. actions for which a specific ordering is required. Preconditions can be identified for Actions: they are conditions of the plant state which should stand in order for the actions being applicable. Goals can be identified for Phases and Actions: they are conditions on the plant state which are fulfilled when the relevant Phases or Actions are carried out properly.

The Monitoring Process

Several actors play key roles into the monitoring process. The core is the *plant state*, i.e. the set of simulation data coming in real-time to the Domain through the Interface to Simulator, which is the base of the two major functionalities of user actions interpretation and expected actions generation. The *interpreter of the user actions* recognises the actions made by the operator and verifies their success/failure by means of the information coming from the simulation.

The *procedure plan* is the set of actions the user is expected to apply: it maintains an explicit reference to the structure (Task-Phases-Actions) modelling the procedure within the Domain. The *plan tracker*, considering the identified operator actions, tracks the execution of a procedure, i.e. keeps the *procedure plan* up-to-date by means of a set of attributes. Attributes are provided both at the plan level (state active/inactive, execution completed/not-completed, overall goal satisfied/not-satisfied), and at the actions level (state executed/not-executed, goal satisfied/not-satisfied). In addition, the *plan tracker* generates the actions expected with respect to the plant state, i.e. those actions that have satisfied preconditions.

The *detector of the discrepancies* between the identified user actions and the expected actions with respect to the plant state compares expected and actual behaviour and classifies the discrepancies, if any, according to the following categories:

1. Plan deviation: an action has been performed not pertaining to the current procedure

2. Goal introduction: an action not expected within the current procedure was necessary: its effects were supposed to obtain some plant state conditions needed to successfully carry on the current procedure. This happens, for instance when defined preconditions for an expected action are not verified: some actions can then be done whose goal is to produce the effects needed to make the required plant state hold.

3. Preconditions violation: an action relevant to the current procedure has been performed, but the defined applicability constraints have not been respected, i.e. the action was not admissible in the current plant state.

4. Ordering deviation: an action relevant to the current procedure has been performed, but the expected order of actions is not respected. Different types of deviations can be identified: omission, inversion, jump-forward, etc. This category only applies for sequences of actions with prescribed order.

5. Goal failure: expected goals characterising the expected procedure have not been satisfied. This can be ascribed to other discrepancies detected, e.g. precondition violation, ordering deviation.

Discrepancies are collected and indexed by category and by plant state reference, and will be important inputs to the generation of final debriefing explanations.

CONCLUSIONS

With special attention to a particular application for training of operators of a thermal power plant the current intermediate outcomes of the EXTRAS project have been presented. The major issues of monitoring operator's actions and detecting discrepancies with respect to the expected behaviour have been considered. The adoption of a hierarchical task decomposition leads to a systematic and formalised description of the procedures to be performed in terms of phases and actions. The real-time data exchange with the simulator permits to maintain an up-to-date representation of the plant state which is together with the adopted procedure representation the basis for the identification of user actions, the generation of expected actions, and the classification of detected discrepancies. Particular effort will be devoted in the future work to the analysis and diagnosis of errors and to the generation of explanations. All these features make the proposed ISS a very promising step forward in the field of training operators of complex industrial processes.

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5 PROCESS CONTROL IN AVIATION

THE INFLUENCE OF AIRCRAFT PROXIMITY DATA ON THE SUBJECTIVE MENTAL WORKLOAD OF CONTROLLERS IN THE AIR TRAFFIC CONTROL TASK

Tab Lamoureux
Air Traffic Management Development Centre
National Air Traffic Services
Bournemouth Airport
Christchurch, Dorset
United Kingdom
BH23 6DF
tlamoureux@atmdc.nats.co.uk

ABSTRACT

This paper outlines an investigation of the impact of aircraft proximity and relationship data on the subjective mental workload of air traffic controllers. Aircraft relationships were categorised into one of 81 different categories, and these relationships were then used to predict subjective mental workload values (as reported by the participants). The results indicated that this methodology could predict subjective mental workload to an accuracy of 73%, with post-hoc analysis improving this prediction rate to 93%. These results are discussed with respect to their contribution to understanding of the drivers of mental workload in Air Traffic Control.

Keywords

Air Traffic Control, Mental Workload, Automation

INTRODUCTION

Air Traffic Control (ATC) is a highly complex, dynamic system that makes great demands on the mental resources of the controller (Hopkin, 1995). In order to address the increasing number of aircraft in the sky, automation and decision support systems are being developed to facilitate the controller's task. Additionally, "sectors" of airspace are being redesigned to make the task easier and separation minima are being lowered to increase the theoretical capacity of the sector.

The reduction of separation minima holds interesting questions for ATC. Admittedly, the information presented to the controller is now more accurate; but is the controller now confronted with a situation that challenges his/her ability to cope? To address questions such as this, an investigation was carried out into the effect aircraft proximities have on the controller's subjective experience of mental workload. For the purposes of this investigation, the definition of mental workload is based on the concept of spare capacity, where workload is considered to increase as the controller's ability to take on new tasks, or cope with existing tasks, falls (Kantowitz and Campbell, 1996). This is further defined in the table in Figure 1. A key question therefore relates to determining the main contributors to mental workload.

The current investigation followed detailed observations of, and interviews with, controllers in an attempt to identify the primary contributors to controller workload. Observations of the task identified communications and the interface as contributing significantly to a controller's workload. However, workload attributed to the interface can be discounted from this investigation as it is supplemental to the task and can be addressed through the provision of better interfaces or by using current operationally implemented interfaces.

Communications was found to be an indicator of workload, and is directly related to other factors in the task, in particular the number of aircraft under control, but also coordination with other sectors, unusual requests by

pilots, and emergencies. However, interviews with controllers revealed that the number of aircraft controlled may not lead to high workload; it is what the aircraft are doing, especially in relation to other aircraft. This idea has also been explored by Falzon (1982). Falzon postulated that aircraft whose flight paths will not interact at any time in the near future are not considered by controllers to be contributing to their workload, but that *aircraft whose flight paths will interact* do contribute to subjective mental workload. Additionally, the manner in which the aircraft's flight paths will interact influences subjective mental workload (see Table 1). This leads to the conclusion that the underlying reason for a controller's subjective mental workload has to do with the decision-making, mental calculations and projections involved in the successful control of air traffic.

The complexity of these cognitive operations, and consequently the subjective mental workload of the controller, is further influenced by the *time the controller has* to undertake them. By reducing separation minima, the controller will have less time to conduct these cognitive activities, thereby making more demand on the controller's mental resources, and increasing the subjective mental workload. With the volume of air traffic increasing every year, it is conceivable that reduction of separation minima to accommodate this increase will present controllers with situations that are more difficult to resolve in the timescale.

This study therefore investigated the influence of **aircraft proximities** on subjective mental workload in the case of Area Control, both in terms of the distances between aircraft and the "angle of incidence". Area Control is involved with aircraft that do not intend to land soon, and are generally flying at a high altitude or are a far from an airport. The hypothesis being tested was that aircraft proximity data would provide an objective indicator of controller subjective mental workload

METHODOLOGY

Procedure

Data for this investigation was taken during a simulation of ATC. Three participants were used over the course of a week.

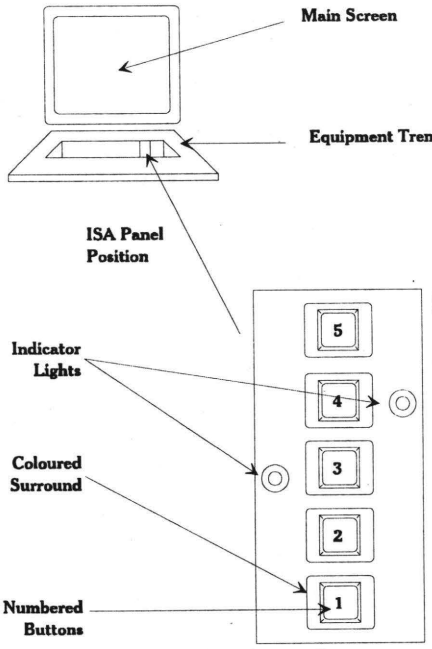
Automatic measurements were taken pertaining to the flight profile of the aircraft, allowing a great number of analyses to be performed in support of safety, expedition, and orderliness in ATC. Thus the data relating to aircraft proximities were recorded in a manner that was unobtrusive to the controllers involved.

An additional measurement, the Instantaneous Self Assessment (ISA) (see Tattersal and Foord, 1996) subjective mental workload measurement technique, was taken every two minutes during each exercise, allowing a real-time picture of the subjective mental workload of the controller to be constructed. Both ISA and the analysis of aircraft proximities are described in more detail in the *Data Collection* section (below).

The statistical analysis reported in this paper is the Discriminant Function Analysis (Norusis, 1994) which uses multiple linear regression combined with probability estimates to predict group membership. This technique was chosen because of suitability in predicting discrete ISA scores.

Data Collection

As stated above, many different analyses can be made with the data recorded from the simulator. Data are recorded every 12 seconds, a rate which corresponds to the time taken for a radar to complete one full revolution. These data are analysed for each two minute period in order that the data can be directly compared to ISA.). Physical implementation of ISA is via a panel with five buttons arranged vertically and two LED's to either side which alternately flash to prompt the controller's response . The physical arrangement as well as the colours and text descriptors used with ISA are shown in Figure 1.



Colour	Workload Heading	Spare Capacity	Description
Red	Excessive	None	Behind on tasks, losing track of the full picture.
Yellow	High	Very Little	Non-essential tasks suffering. Could not work at this level for very long.
Green	Comfortable Busy Pace	Some	All tasks well in hand. Busy but stimulating pace. Could keep going continuously at this level
Blue	Relaxed	Ample	More than enough time for all tasks. Active on ATC task less than 50% of the time.
White	Under-utilised	Very Much	Nothing to do. Rather boring.

Figure 1: Pictorial and Text Description of ISA Subjective Mental Workload Measure

The analysis of aircraft proximities data took account of all aircraft that fall within the attention of the controller, making the assumption that all these aircraft exert some influence on the mental workload of the controller, whether through the need for planning, intervention, or monitoring. These aircraft were considered in pairs and characterised according to distance from each other (in terms of lateral and vertical separation) and what they were doing in relation to each other (i.e. climbing, turning, straight, and level). The complete characterisation criteria are given in Table 1

Lateral Parameters → / Vertical Parameters ↓		<3 mile	→→ <7 mile	≥7 mile	<3 mile	→← <7 mile	≥7 mile	<3 mile	↗↖ <7 mile	≥7 mile
Both aircraft straight and level	<800 ft	1	2	3	10	11	12	19	20	21
	<2000 ft	4	5	6	13	14	15	22	23	24
	≥2000 ft	7	8	9	16	17	18	25	26	27
One aircraft level and one aircraft climb or descend	<800 ft	28	29	30	37	38	39	46	47	48
	<2000 ft	31	32	33	40	41	42	49	50	51
	≥2000 ft	34	35	36	43	44	45	52	53	54
Both aircraft climbing or descending	<800 ft	55	56	57	64	65	66	73	74	75
	<2000 ft	58	59	60	67	68	69	76	77	78
	≥2000 ft	61	62	63	70	71	72	79	80	81

Table 1: Characterisation Criteria for Aircraft Pairs

The characterisation is of 81 different types, corresponding to 9 different types of relationship. For each pair of aircraft the type of relationship and the distance between them was considered, and one entry made in the corresponding cell in the table. As every possible pairing of aircraft was considered, and, as there could be more than two aircraft in an encounter situation, a single aircraft could appear in several cells, and could also appear several times in the same cell. The characterisation was made every 12 seconds and totals for each two minutes (corresponding to ISA) were recorded and used in further analysis. Thus, for each controller, every two minutes an 81 cell table was produced with one related ISA value (some cells may contain "zero" values).

The data in each of the 81 cells were entered into a discriminant function analysis as the independent variable. The analysis then uses half of this data to build a regression equation to best predict corresponding dependent variable values (i.e. ISA). Discriminant function analysis was used because ISA scores are discrete values, and discriminant function analysis uses probability estimates to determine whether the result of the linear regression should belong to the lower value or the higher value.

The ability of the resultant regression equation to predict ISA is tested using the remaining half of the data, giving figures illustrating the actual number of instances of each ISA value, and the number of correctly predicted values based on the regression equation.

RESULTS

Table 2 shows the number of ISA responses recorded during the 18 exercises, split by value. Some 5% of the ISA values are not classified. In these instances, the controller has omitted to score his/her workload value, probably because (s)he did not notice the prompt. Table 2 takes no account of the different samples or the different controller, although it is debatable whether accounting for the different samples would affect the final analysis. This is because the analysis should not be affected by different samples as it deconstructs the samples into "snapshots" and bases its results on these. Half of these ISA results were then used to calibrate the regression equation to predict the whole set of ISA results.

ISA VALUE	ACTUAL NUMBER OF RESPONSES OVER THE COURSE OF THE 18 EXERCISES
1	246 (27.5%)
2	499 (55.9%)
3	87 (9.7%)
4	15 (1.7%)
5	0 (0.0%)
Not Classified (i.e. no response from controller)	46 (5.2%)

Table 2: Actual Number of ISA Responses Recorded Over the 18 Exercises

The pattern of ISA results is skewed toward the lower end of the workload scale, but this did not seem to adversely affect the analysis. This ISA data was then input, with the aircraft proximity data, into a discriminant function analysis to develop a regression equation that could predict ISA group membership. Table 3 shows the predicted group membership versus the actual group membership as a result of this analysis. This analysis input all of the proximity data, regardless of its distance parameters and the relationship characteristics.

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5
1	246	**62.6%**(154)	37.0%(91)	0.4%(1)	0.0 (0)	N/A
2	499	14.2%(71)	**82.4%**(411)	3.4%(17)	0.0%(0)	N/A
3	87	8.0%(7)	39.1%(34)	**52.9%**(46)	0.0%(0)	N/A
4	15	0.0%(0)	20.0%(3)	6.7%(1)	**73.3%**(11)	N/A
5	0	N/A	N/A	N/A	N/A	**N/A**
Ungrouped Cases	46	26.1%(12)	50.0%(23)	19.6%(9)	4.3%(2)	N/A

Overall correct ISA classification rate 73.4%

Table 3: Correct ISA Classification versus Actual ISA Classification (Whole Set)

The methodology was discussed with ATC experts who believed that the predictive regression equation may have been unduly influenced by the number of aircraft relationships involving aircraft that were a long way apart. Accordingly, a second analysis was undertaken using a subset of the cells shown in Table 1. This subset was composed of aircraft relationships which could, conceivably, increase the pressure (both in time and in complexity) on the controller to find a solution. These included any relationship under 800 feet vertically or less than 7 miles laterally and are denoted by the shaded cells in Table 1. Table 4 shows the predicted group membership versus the actual group membership for the subset of data.

Actual Group	No. of Cases	Predicted Group Membership 1	2	3	4	5
1	8	**62.5%**(5)	37.5%(3)	0.0%(0)	0.0%(0)	N/A
2	69	2.9%(2)	**95.7%**(66)	1.4%(1)	0.0%(0)	N/A
3	39	0.0%(0)	7.7%(3)	**92.3%**(36)	0.0%(0)	N/A
4	8	0.0%(0)	0.0%(0)	0.0%(0)	**100.0%**(8)	N/A
5	0	N/A	N/A	N/A	N/A	**N/A**
Ungrouped Cases	13	0.0%(0)	15.4%(2)	76.9%(10)	7.7%(1)	N/A

Overall correct ISA classification rate 92.7%

Table 4: Correct ISA Classification versus Actual ISA Classification (Subset)

The regression equation that resulted from the analysis of a subset of the data was then applied to the dataset as a whole. Table 5 shows the results of this analysis.

Actual Group	No. of Cases	Predicted Group Membership				
		1	2	3	4	5
1	246	**65.0%**(160)	35.0%(86)	0.0%(0)	0.0%(0)	N/A
2	499	6.7%(33)	**90.8%**(453)	2.6%(13)	0.0%(0)	N/A
3	87	4.6%(4)	21.8%(19)	**73.6%**(64)	0.0%(0)	N/A
4	15	0.0%(0)	6.7%(1)	13.3%(2)	**80.0%**(12)	N/A
5	0	N/A	N/A	N/A	N/A	**N/A**
Ungrouped Cases	46	%(11)	%(23)	%(10)	%(2)	N/A

Overall correct ISA classification rate 81.3%

Table 5: Correct ISA Classification versus Actual ISA Classification (Subset Generated Regression on Whole Dataset)

DISCUSSION

The results suggest that using aircraft proximity data as an objective measure of mental workload is a promising methodology. Use of the data in the Discriminant Function Analysis resulted in a correct prediction rate of 73.4%, although it is acknowledged that no account has been taken of the differences between controllers, the time of day, or the difference in the traffic samples. It was also hypothesised that much of the data used in the analysis would not affect the controller's subjective mental workload. Accordingly, a second analysis was undertaken using a subset of the data, chosen on the basis that the aircraft relationships involved could, conceivably, increase the pressure (both in time and complexity) on the controller to find a solution. The results from the second Discriminant Function Analysis showed a correct prediction rate of 92.7% on the subset of aircraft relationships, and a correct prediction rate of 81.3% when applied to the whole dataset.

To ensure the general applicability of this methodology to ATC, it is necessary to apply the methodology to other datasets. As mentioned in the *Methodology* section, one ATC sector was considered. Further sectors should be investigated in case the good rate of ISA prediction is an artefact of the sector targeted. Additionally, good rates of ISA prediction can be due to the controllers used as participants. Accordingly, further work should be undertaken using different controllers, perhaps of varying levels of experience, to ensure that ISA prediction is not dependent on the participants. Follow on work to look at the influence of time pressure (measured as a "time to impact" rather than a distance metric) on the mental workload of the controller may also result in more accuracy in ISA prediction. This line of investigation has been pursued by Hendy and his colleagues (East, 1996) with promising results. Finally, ATC is characterised by different objectives depending on the airspace, and this may influence the prediction rates for ISA. For instance, around airports the objective may be to maintain aircraft in three-dimensional flight, whereas in Area Control, the objective may be to maintain aircraft in one-dimensional flight. This may mean that different aspects of the aircraft relationship are contributors to mental workload. These differences should be explored by applying the methodology to different types of ATC.

The results show that the subjective mental workload of the controller stems from the complexity of the relationships between aircraft, of which, conceivably, only a small part may be due to the number of aircraft in a sector. This is further reinforced by the regression equation, which shows that the highest drivers for mental workload are relationships where one aircraft is level and the other is climbing or descending, and the aircraft are on convergent tracks. This result is not surprising: the mental resources that must be allocated in calculating the trajectory, to ensure minimum separation is not lost, would be considerable. However, it is surprising that, of the variables that do contribute to mental workload, the least significant contributors are relationships where aircraft are head on to each other. This seems to be due to the simplicity in solving the situation. If one or both of the aircraft are climbing or descending, the controller merely stops the vertical movement. If both aircraft are at the same level, the controller merely instructs both aircraft (in turn) to turn right a sufficient amount to ensure separation is maintained.

Most evidence currently supporting the view that mental workload is due to the complexity of the relationships between aircraft is anecdotal, as it has previously been considered too difficult to undertake an analysis of this kind (e.g. Falzon, 1982). The current study shows that it is possible to quantify the relationship between aircraft

relationships and mental workload and eliminate much of what was previously considered to be subjective variation (e.g. when the analysis has focused on the total number of aircraft under control).

One further shortfall in this study must be identified: the lack of any examples of ISA value "5". It is not the primary aim of simulations to excessively load the controller, so this was not surprising. However, subsequent simulations have provided examples of ISA value "5", and informal analyses have shown that the methodology is as successful, or more so, at prediction of ISA with the full range of values. It seems that at lower ISA values, controllers have different opinions as to what "under-utilised", "relaxed", and "comfortable mean, leading to much overlap between them. However, when controllers begin to get busy, and experience high workload, their understanding of "high" and "excessive" workload begins to reach a common definition. Thus the variability of understanding of workload shown at lower levels of workload is high, and this variability falls as workload rises.

The pattern of aircraft relationships that contribute to subjective mental workload is interesting. If aircraft are in "one-dimensional" flight, that is, aircraft are flying straight and level, controllers do not consider them to be contributing to their workload, and could accommodate a relatively large number. When aircraft are in "two-dimensional" flight, for example, flying straight but climbing or descending, or flying level but turning, there is more demand on the controller's mental resources, leading to higher workload. When aircraft are in "three-dimensional" flight, that is, climbing or descending and turning at the same time, the demands on the controller's mental resources are high, leading to high workload. When compounded with the time factor, such as is represented by the distance parameters here, subjective mental workload scores are higher.

These analyses have implications for future developments in ATC. In order to accommodate the forecast increase in air traffic, there is a need to increase the capacity of the ATC system. This may be accomplished in a number of ways: through the reduction of separation minima; through automation; through the provision of decision support tools; through the use of more controllers in the same airspace; through improving the interface; through improved training of controllers; etc. So, however, before any conclusions about future developments in ATC can be made on the basis of this analysis, further work must be undertaken to ensure the general applicability, the reliability, and the validity of the methodology reported here. The results support the importance of aircraft proximity data as contributors to mental workload, as also reported by controllers, but a thorough understanding of the implications of this data must be gained before applying it to the problem of increasing airspace and controller capacity.

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Modelling Cognitive Processes of Experienced Air Traffic Controller

Niessen, C.[(1)], Eyferth, K.[(2)] & Bierwagen, T.[(3)]

(1) Berlin University of Technology, Center for Man-Machine Systems Studies
email: niessen@zmms.tu-berlin.de

(2) Berlin University of Technology, Department of Psychology
email: keyferth@chomsky.gp.tu-berlin.de

(3) DFS Deutsche Flugsicherung GmbH, Entwicklung und Erprobung
email: bierwagen@se.dfs.de

ABSTRACT

This paper presents a model which describes the constantly changing cognitive activities of an experienced en-route air traffic controller. The descriptive model and the related computer implementation were developed in an inductive way through interviews complemented by simulation experiments with experienced and unexperienced air traffic controllers, and by means of discussion of existing human factors and psychology approaches. The main components of the model are three cycles of information processing, (monitoring, anticipation, and problem resolution), operating on different parts of the controller's picture. Because of the long qualification process also practice effects on the controller´s picture will be discussed.

Keywords
Air Traffic Control, Situation Awareness, Mental Models, Expertise

INTRODUCTION

In the long course of training and professional practice operators acquire different types of knowledge and cognitive skills to meet the specific demands of tasks in complex and dynamic man-machine systems. For various reasons it can be important to have a detailed description of the operator´s skills. Especially in the case of technological changes in order to support or to replace human skills by automatic tools, a prosepective insight into the consequence affecting performance will be helpful for future system design and training concepts. In complex technological systems with a dynamic nature, operators develop various mechanisms for internally representing the changing situation as precondition for diagnosis, planning, and intervention. Without an appropriate mental representation the operator would not be able to perform the task effectively and safely.

This paper describes the effort of the research group 'En-route Controller´s Representation' (EnCoRe, *granted by the Deutsche Forschungsgemeinschaft 'DFG', Ey 4/16-2 , Fr 375/48-2*) to gain insight in the cognitive activities of experienced operators in a dynamic man-machine system. The air traffic control domain serves as an example to study the adaptive interaction between the controller and the dynamic time-constraint environment. The goal of EnCoRe was to model the cognitive processes and the resulting representation of changing traffic situations as a basis for the continuous diagnosis of potential conflicts between aircrafts. On the basis of experimental work - interviews, simulation experiments, memory tests, and theoretical considerations, the model was developed and implemented. In addition, some of the studies focused on effects of the amount of professional experience on the mental representation of traffic situations. This paper is divided into three issues:

- theoretical context of the cognitive model,
- some empirical results, and
- the basic elements of the model.

The implementation of the model will be neglected in this paper.

THEORETICAL CONTEXT

The theoretical context of the work was influenced by models of of the human factors domain, cognitive psychology, empirical studies in the air traffic control area, and research on practice effects. The chapter starts with broad concepts that frame the topic. Then some aspects of the impact of professional practice will be reported.

Framing the Topic: Situation Awareness and Mental Models

In the case of air traffic control, we are dealing with a complex and dynamic environment, where changes in the problem state develop both with and without operators actions. Various cognitive demands for the controllers related to complexity and dynamism are for example: the coordination of multiple on-going cognitive tasks with different time scales, a recursive monitoring of the situation, and anticipation of future events. Anticipation is a main component of the diagnostic task (Hoc et al., 1995). The term 'situation awareness' describes the phenomenon of an 'up-to-date' representation of dynamic situations (e.g., Endsley, 1995; Flach, 1995). In this concept the representation of the situation does not reflect only the perceived elements, but includes also an understanding of the significance of the elements in the light of current operator goals. Also the need of anticipated situation states is underlined. Within the air traffic control domain, the term 'picture' describes a similar idea of a global representation of the current traffic situation in working memory (e.g., Whitfield & Jackson, 1982; Falzon, 1982). Another related concept, in which the notion of representation of future system states, and the processes to achieve these states, plays an important role, is the conception of the user´s 'mental model'. There are various different mental model approaches (e.g., for an overview, see Wilson & Rutherford, 1989, Gentner & Stevens, 1983). We follow Craik´s (1943) and Johnson-Laird´s (1983) basic ideas of a functional model, that parallels processes of the external world. The representation is conceived as an active construction of meaningful relations between elements of a situation, and not as an addition of perceptions. The construction of a mental model is based on the activation of schemata. Mental models in the sense of Johnson-Laird are temporary and partial: they are build up by schemata in order to serve the current functions, and will not be stored in long term memory. The model can be manipulated by drawing inferences, making predictions, understanding phenomena, deciding what action to take, and controlling the execution. This takes two aspects of the air traffic control task into account: the controller should have only a temporary representation of the traffic situation, since this situation changes, and he can not keep available all information of the situation. He has to keep the relevant information available. With this model and knowledge of past events humans are able to anticipate events by trying different outcomes mentally, instead of making empirical trials in the external world. For example, the approach of de Kleer & Brown (1983) of a mental model follow the idea of 'running the model' in order to perform mental experiments.

To construct a cognitive model of an air traffic controller therefore the following aspects had to be considered:

- the surveillance of changing traffic constellations,
- the selection of significant information that is functional to detect conflicts between aircrafts and to find conflict resolutions,
- relevant semantic relations, and
- anticipations.

The Impact of Professional Experience

It is a common assumption that the effective and safe performance of air traffic controllers is a result of a long qualification process. The impact of practice has a link to research on expert performance. Results from problem solving studies in several domains demonstrated differences between experts and novices in speed and accuracy, knowledge structures, problem representation, and perception, etc. (for an overview, see, e.g., Ericsson & Lehmann, 1996). After around ten years of daily deliberate practice the highest level of performance will be achieved. In the present context, the question was if there is an influence of professional practice on the controller´s representation after training. Especially the knowledge-based approach of expertise can lead to the conclusion that expertise is equivalent to the quantity and quality of knowledge gained through experience over years. But, in the long run, the mere number of years of experience leads not necessarily to a superior performance on relevant tasks (in comparison to less years of experience). Despite the weak relation between the mere number of years of experience and performance, the main interest was to explore influences of quantitative amount of experience on the controller´s picture. It was assumed, that in the air traffic control domain, also experienced operators are still forced to improve their skills during work to meet the increasing demands of their tasks which are related to changing technologies, and increasing traffic.

EMPIRICAL WORK

Six experiments on data selection, transformation of information, anticipation of flight constellations, and knowledge structures were complemented by interviews. (Bierwagen et al., 1997). The empirical work provided the inductive component of the modelling process. The chapter starts with some results of the interviews. This is followed by a selection of the experimental work.

Interviews

Extensive interviews with seven experienced controllers provided a first explorative functional analysis of the air traffic control task and first hypotheses about practice effects. Following the framework of cognitive task analysis (the 'decision ladder', Rasmussen, 1986), a sequence of elementary tasks, which decomposed diagnosis, planning, and intervention in air traffic control, could be identified through the interviews. As the interviews showed, the 'decision ladder' for the air traffic control task had to be modified. According to the verbal reports, the diagnosis of potential conflicts between aircrafts by experienced controllers contains stages, which are characterized by an increasing restriction and specification of the problem space. These stages are: 1. observing the situation, 2. analysing the parameters of selected aircrafts, and anticipation. The preparing steps towards an intervention and conflict resolution could be described according Rasmussen´s stages. In the first step ('observation') the experienced operator monitors the whole situation in order to get a quick overview of the complete traffic situation. The goal of conflict detection demands selection strategies during radar-screening which are guided by attention demanding features, like aircrafts located near to each other, vertical movements, incoming aircrafts, or points in the space with higher probability of conflicts (e.g., Amaldi & Leroux, 1995). According to the verbal reports, experienced controllers classify the aircrafts on the basis of these surface signals (proximity, vertical movement, etc.) into two groups: those aircrafts which have to be further analyzed (called 'focal part'), and those which are seperated safely during that moment (called 'extrafocal part'). In contrast, in this stage of diagnosis unexperienced controllers focus every aircraft. Experienced controllers analyzed the features only for aircrafts of the focal part ('analysing the parameters'), and anticipated their future states ('anticipation') in order to check for future conflicts. In contrast, unexperienced controllers analyzed more traffic information in general.

Experimental Work

The experimental work with real time simulation was based on a realistic simulation of the control task called 'En-route Controllers Representation - Programmable Airspace Simulation (EnCoRe-PluS)'. This system simulates air traffic control scenarios providing a secondary radar screen, electronic flight strips, and head-phone communication with a ghost-pilot; it also allows to set up experimental procedures and to keep logfiles of all system activities. The experimental work, presented here, is divided into two topics: 1. information selection, and recall, 2. anticipation, and conflict management.

Information Selection, and Recall

The results of the interviews showed that practice will effect the information selection and the classification of the traffic situations. For example, Shanteau´s (1992) review of studies of judgement and decision making shows that experts use the same or fewer number of information as novices, but that the information used is more relevant for diagnosis. Training studies could show that improvements in task performance can be viewed as reflecting an increased knowledge about information that has to be processed or not (Haider & French,1996). According to these authors, one important effect of practice is acquiring the skill to limit processing to relevant information. Information selection during a real time simulation, and a memory test were carried out in order to investigate if the picture of experienced controllers is based on less, but more relevant information.

In an experiment on data selection, en route controllers had to control familiar and unfamiliar dynamic airspace situations. The traffic scenarios were interactive and lasted 20 minutes. 36 controllers participated in the experiment in three groups depending on the professional experience (less experienced: AM:1 year; intermediate: AM: 7,6 years, experienced: AM:17 years). To investigate information selection, data of aircrafts on the radar screen and the flight-strip-system were masked, but could be unmasked by the controller activily. Frequencies and durations of the unmasking were recorded. The data showed, that the representation of the current traffic situation was build up under considerable reduction of information. All controllers concentrated on a few relevant data concerning the identification code, the vertical position of aircrafts in space, and flight directions. Differences between experienced and less experienced controllers were only found in the selection of time relevant parameters: experienced controllers prefered fewer but rather long-term planning data.

Results of a free recall after controlling 70 minutes of an interactive traffic scenario in a further experiment supported some aspects of the information selection study. The experienced controllers reproduced fewer aircraft features then the unexperienced, but also the most relevant (three-dimensional position in space and flight directions). This can be considered as a useful strategy: due to the multiple and permanent changing information, the controllers had to reduce only information of only temporary relevance. In addition the results indicated that positions of extrafocal (inrelevant) aircrafts were reproduced back in time, whereas positions of attention demanding objects (e.g., conflictions, and climb or decend) were reproduced correctly only by the experienced (for similar results, see Boudes et al., 1995). This bias indicates, that there is an interaction between the semantics of objects and the updating frequency: focal, attention demanding objects needed a higher monitoring frequency than extrafocal objects.

The results indicate that the controller's 'picture' is an experience-based, functionally reduced, representation of the current situation, whereby the representation is build up under considerable reduction of information and is updated recursively.

Anticipation and Conflict Management

In an experiment on conflict-management, different types of clearcut and potential conflicts were varied in a 70 minutes traffic scenario according to the *Eurocontrol Air Space Model* (EUROCONTROl, 1994). The EUROCONTROL classification has two dimensions: 1. different tracks (same, opposite, crossing), and 2. level- or climb/ decend-flight. 36 controllers had to detect and to solve the conflicts. The time to detect and to solve a conflict was measured. The data showed that all controllers did not differentiate between conflicts (separation minimum: 5 nautical miles) and potential conflicts (10 nautical miles): they intervened in all cases. This indicates that conflict detection is not based on an calculation but on fuzzy estimation. The controllers choosed always the safer way by overestimating the risk. The analysis of the proportions of detection times showed, that the more complex conflicts are, the later they will be detected. The complexity of relations rises if both objects show vertical movements and if they follow opposing or crossing courses. Conflicts between levelflights were detected earlier.

The information selection experiment, and the recall indicated that experienced controllers represented aircrafts in terms of long term flight directions. Less experienced focused more on short term planning data about aircrafts. In order to support these results, 18 experienced (AM: 15,2 years) and 17 less experienced (AM: 3 years) air traffic controllers had to perform a card sorting task. The idea was that more experienced controllers would classify the traffic situations according to features depending on an anticipation of the situation. As expected the more experienced controller showed a tendency to classify traffic situations on the basis of anticipation.

The results of the information selection experiment, the memory test, and the card sorting task showed only small long-term practice effects. This can be lead back to the above mentioned considerations about the mere number of years of professional experience as an indicator of quantitative and qualitative changes of knowlegde and skill. But there were some small differences between the less experienced and more experienced controllers concerning the amount of aircraft data available in memory and the time scale of anticipation.

THE MODEL

According to our data we constructed the following cognitive model of an air traffic controller 'Modell der Fluglotsenleistungen (MoFl)'. The modelling focused on the construction and the manipulation of the representation of aircrafts, the aircrafts´ significant features, and the semantic relations in the light of conflict detection and resolution.

The main components of MoFl are three cycles of information processing, (i.e., *monitoring*, *anticipation, problem resolution*) operating on different parts of the situation representation, called the *picture* (see Figure 1). The coordination of these processes is driven by *control procedures*. Monitoring and anticipation are diagnostic processes (conflict detection), problem resolution is the preparing step for interventions of the controller.

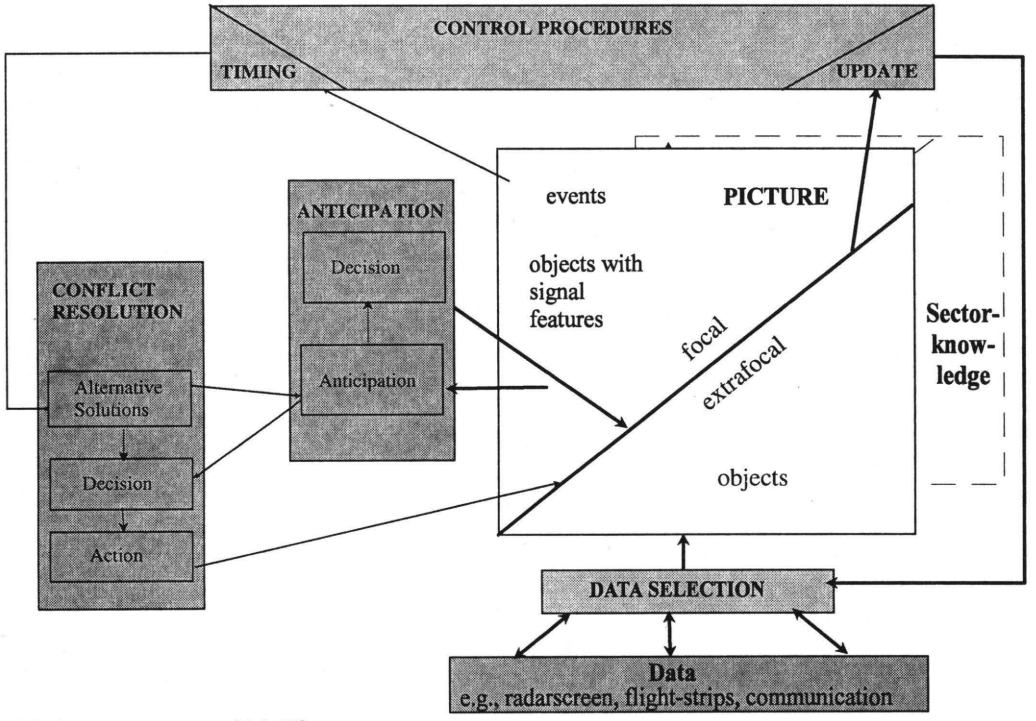

Figure 1: Main components of MoFl

The *monitoring cycle* includes *data selection* procedures and the regular *update* of the features of the aircrafts. The controller selects relevant features of aircrafts, especially the identification codes, the horizontal and vertical positions of objects in space, and in addition flight directions. These features provide an integration of objects in the represented traffic situation. We assume a preattentive perception of meaningful signals in the light of conflict detection during radar-screening. These are aircraft features like, vertical movements, incoming, proximity to other aircrafts or to points in the airspace with frequent ocurrences of conflicts. Because of these signal features aircrafts will be represented in the focal part of the *picture*. That means that they are attention demanding objects (e.g., vertical movements). Aircrafts without these features will be represented in the 'extrafocal part'. In terms of the model it can be assumed that the differentiation between focal and extrafocal aircrafts is a result of a longer qualification process: with increasing practice the representation of the traffic situation becomes more selective. In the dynamic environment of air traffic control, the objects have to be *updated* continuously. There is an interaction between the semantic of objects and the updating frequency: focal, attention-demanding objects demand a higher monitoring frequency than extrafocal objects.

The next step in the diagnosis consists of an *anticipation cycle* which operates on the focal part of the *picture*. For all attention-demanding ('focal') aircrafts or aircraft constellations, future states will be anticipated. An intentional search for further information is started. The goal of the anticipation cycle is to create new cognitive processing information about aircrafts. Depending on the result of anticipation, aircrafts with signal features can be then represented as *events*. An *event* reflects the meaning of relations between aircrafts or relations between aircrafts and airspace features in future time and space. We assume, that for the anticipation task the operator creates a dynamic mental model (see, Johnson-Laird, 1983) which includes the objects under consideration and spatial, temporal and causal relations. By constructing a model the operator can interpret (*decision*) if the future trajectories of aircrafts result in either a conflict, a safe separation, or another monitoring demand. According the experimental data it seems that with increasing practice the anticipation includes a wider range in time and space. In the case of conflict detection, the *event* 'conflict' will be created including an estimation of the time remaining for conflict resolution. Constellations which have been proofed as being safe, will be not longer in the focal part of the *picture* and they become extrafocal at this time. This indicates that at this time there is almost no cognitive processing demand, except for updating. If the operator is not sure about the potential conflict, the *event* 'monitoring' will be added to the focal part of the representation, continuing a higher monitoring frequency, and also a high demand for further anticipations. If conflicts are detected, the *problem resolution cycle* will initiate several steps to prevent an impending conflict. In a first step, the controller has to retrieve the most urgent conflict (*timing*) in order to generate or recall solutions (*alternative solutions*). Next, the operator has to check the solution that does not generate new follow up conflicts (*decision*).

We assume that for this proof a mental simulation of the solution will be run, whereby a mental model for manipulating it will be constructed (like in the *anticipation* cycle). The results of this model will be executed (*action*).

The resulting *picture* is characterized by an analogue representation of objects with references to other objects and the airspace structure, and events. Objects with signal features are represented in the focal part of the picture, objects without these features are represented in the extrafocal part. In addition, events which indicate the meaning of aircraft relations in future time and space are represented in the focal part of the picture.

Attention

In this context the term 'attention' is not used to describe a seperate mental process. It is used to describe the state of a person during performing a specific task (Neumann, 1992). The model includes three levels of activation: the extrafocal, the focal, and the anticipation level. The semantic of objects or events determines their activation level. Extrafocal objects are fuzzy represented with a few data only indicating their existence. Their activation is low. In contrast, objects in the focal part are represented with signal features: their activation level is higher. During anticipation the focus of attention is only on one aircraft or aircraft constellation because of more detailled processing. This leads to an increase of activation. The alternation of these activation levels can be described as narrowing or extending the focus of attention. According to this, either specific or global features of the situation can be processed.

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Assessing the impact of new technologies for Air Traffic Control: the human factors perspective

Patrizia Marti°, Gugliemo Casale*

°Multimedia Laboratory,
University of Siena
Via del Giglio 14,
53100 Siena - Italy
marti@media.unisi.it

*Information Technology Laboratory,
Alenia
Via Tiburtina 12,400
00131 Roma - Italy
gcasale@lti.alenia.it

Abstract

The paper describes the design methodology adopted to develop a mock-up of new advanced tools for Air Traffic Control. These tools will be operational in the Control Towers of the main European airports in the next 10-15 years. The mock-up is used to assess the impact of new technologies on the Air Traffic Control, in particular with respect to human factors issues. The methodological approach is based on Task Modelling techniques that we used for the design and the evaluation of system prototypes.

Keywords: Task analysis, Task Modelling, Design methods, Human-Computer Interaction, Air Traffic Control

INTRODUCTION

The paper presents a case study carried out within the European project ATHOS (Airport Tower Harmonised cOntroller System -TR1005 of the ECARDA Programme, CEC DG XIII) started in 1996 and still underway. The project aims at building a mock-up for the future airport tower control system in order to assess the impact of the new technologies for Air Traffic Control (ATC) that will be operational in the next 10-15 years. The project focuses on the design and evaluation of efficient and reliable controller working positions, incorporating different and complex tools in the context of future A-SMGCS (Advanced Surface Movement Guidance Control System). It moves steps towards the European ATC harmonisation and the design of the controller working positions of the "standard European Tower Control".

The problem is to assess the impact of new technologies on Air Traffic Control, in particular with respect to the human factors involved (Hopkin, 1995). Indeed, the technologies which are now in specification or experimental phase will be operational in a time horizon of 10-15 years at least in major airports. These technologies include (Page, et al. 1996):

- Data fusion on mixed data sources (radar, beacons ...);
- Air/ground data-link between controller and pilot;
- Short term accurate meteorological and wake vortex forecasts;
- On board guidance and planning tools to increase the pilot awareness of the situation and favour the understanding of the instructions of the controller;
- Advanced HCI technology concerning the display functions and the human-computer interaction.

The mock-up should simulate the interaction between controllers and new automatic tools supporting monitoring, guidance and planning activities.
In order to assess the impact of these technological tools, a significant part of the project is devoted to the study of existing and future controller working environments, including the operational and technological environments. The study concerns all activities carried out by the controllers and tools used by the controllers at

work. Three important European airports are involved in the analysis activities: Amsterdam Schiphol; Paris Charles De Gaulle; and Frankfurt/Main Airport.

INITIAL TASK ANALYSIS

The methodology adopted in the project for the analysis of the problem domain was the structured task analysis, inspired by MUSE (Lim and Long, 1994). The method was selected because it supports all phases of the design process, integrating human factors and software engineering. The process recommended by Lim and Long starts with the construction of task models of existing systems, then proceeds with the development of a Generic Task Model, until the production of a Composite Task Model for the new system. This Composite Task Model describes both user and system activities and provides a precise view of how tasks are allocated to either the computer or the users, or both of them. The construction of the Composite Task Model is an important design step, also called Design Task Modelling. In our project, we use this approach to develop a user interface to simulate the interaction between the controller and an ATC system incorporating new advanced automatic tools.

The task analysis notation that we used is inspired by MAD (Scapin and Pierret-Golbreich, 1989) and TKS (Johnson and Johnson, 1991). It consists in a graphical notation to represent task graphs, i.e., a task taxonomy representing the goal structure of tasks. This structure conveys a task/sub-task decomposition, defined in terms of temporal and logical constraints among tasks; triggering conditions; loops etc. Pre-conditions and post-conditions for task execution are specified when necessary, as well as pre-requisite and post-requisite which are tasks which need to be executed before or after a main task.
Each task in the graphs is also described in a task template collecting functional, operational, pragmatic and relational characteristics of the task. Other information about non-functional requirements of tasks like duration, interruptibility, reversibility, frequency are also specified as natural language descriptions in the task template.

Using the notation, several task models were produced during the existing systems analysis, constituting the basis for design task modelling (Marti, 1996). The produced task models served to represent the specificity of the different situations analysed and were elaborated to produce a Generalised Task Model. This provided synthesis and abstraction of the different task models, highlighting the common general structure and representing the specificity as possible elements of the activity in general.
The Generalised Task Model is a fundamental step towards the design activities; indeed it allows to produce a model which is an abstraction from the current systems with the aim of a device independent analysis of the activity.
For the purposes of the project this aspect is particularly relevant for different reasons:

- The different airports analysed: Amsterdam Schiphol , Paris Charles De Gaulle and Frankfurt/Main. At a general level the structure of the activities in the different airports shows significant similarities, nevertheless the detailed structure is very dependent on the work organisation, the topology of the airport, the traffic load, the tools used, local regulations, etc.
- The difficulty in assessing the impact of new technological tools on the activity, starting from different practices and habits.
- The objective of the standardisation of controller working positions, and the assessment of controllers' acceptance of the new organisation.
- The heterogeneity of tasks, the complexity of the data involved, the high degree of parallelism and cycles during the activity.

DESIGN TASK MODELLING

Design Task Modelling is characterised by the construction of the Composite Task Model, i.e. the model of the future human-machine system which describes both user and system activities and provides the principles for task allocation between the system and the controller (Kirwan and Ainsworth, 1992). During this phase, prototypes are produced to draw the user interface layout and to define the interaction dynamics.
In our project, Task Modelling was carried out as an iterative process: at each task analysis stage, the models were validated and refined by the controllers, taking into account completeness, accuracy, expressiveness of the model, representativity of the activities, resulting scope of the task model.
It was a participatory design process because the controllers actively contributed in the existing systems analysis, and the construction of the Generalised Task Model, providing an in-depth user oriented characterisation of the domain. Furthermore both air traffic controllers and designers involved in the project attended a course on the task

analysis process and the notation adopted, so to be able to refine and validate the models.
Task Modelling is currently used in the project for the design of an interface mock-up, and for the predictive evaluation of the system usability. The Task Model provides information about the complexity of a task (depth of sub-goal hierarchy, number of transitions or knowledge entities); possible knowledge transfers from the old system to the new one; potential errors or confusion that the controllers can face (Marti and Normand, 1997). All these information support the prediction of potential usability problems and the impact of the new technological tools on the controllers' work.

In what follows we describe how the results of Task Modelling were used to design a mock-up for the runway management task. This task is important for the Tower Controller Working Position because it implies the management of the departure sequence in coordination with a given approach sequence, planning and monitoring activities, and the handling of a lot of different and dynamic data.

THE CASE OF RUNWAY MANAGEMENT

The runway management task is part of the general activity of the Tower Controller who has to manage controlled objects (both vehicles and aircraft) in the area of responsibility, and coordinate the related hand-over procedures for assuming or releasing the object control. One of the main objective of the Tower Controller is to make the best possible use of runways for aircraft landing and take-off in safety conditions. S/He assists and controls objects moving within the area of responsibility, and issues guidance instructions (clearances) according to the aircraft constraints (including position, speed, heading, slot, wake vortices, jet blast etc.), traffic situation, meteorological conditions, airport regulations, etc.
The temporal dimension of the activity plays a key role in the decision making process. In case of traffic density in the air or on the ground, the departure sequence at the runway entry points can be long and can cause delays to the entire traffic movements. Indeed, one of the requirements of the controllers is to have a clear representation of the runway occupancy time in order to shorten the departure sequence and to manage the arrival sequence with respect to the movements on the ground. The situation is even more difficult in case of mixed use of the runways (both for landing and take-off) or in case of other vehicles crossing.
The basic automatic planning tool (currently under development) that supports the activity of the Tower Controller is the *departure manager*. Also the *arrival manager*, whose support is mainly targeted at the Approach Controller, delivers its results to the Tower Controller. Whilst the arrival manager is of interest for the Approach segment, the departure manager integrates the activities of Ground and Tower Controllers during taxiing and runway occupancy.
The usefulness of these tools is widely acknowledged by the controllers, nevertheless it is necessary to design an effective external representation of the data in order to successfully exploit the potentialities of the tools. The problem is therefore to integrate these tools in the context of the activity of the Tower Controller, providing all information needed to execute the runway management task.
On the basis of the Design Task Model, a mock-up for the runway management has been designed. The Task Model provided information about the task structure in terms of the sub-goal hierarchy, the information needed at each decision point, the object handled during the activity (strips, meteorological data, planing data, temporal data etc.), the communication needs. All these information support the prediction of potential usability problems and the impact of the new technological tools on the controllers' work.

A MOCK-UP FOR RUNWAY MANAGEMENT

Figure 1 is a sketch of a three RWYs aerodrome layout. RWY 34R is used for take-off and 16L is used for landing (mixed usage), RWY 34 L and 25 are used for take-off. They are intersecting RWYs.
This configuration presents two kinds of difficulties, in particular in case of high traffic load:

1) the mixed usage of 34R-16L requires an effective management of the RWY to avoid long departure queues (in particular if priority is given to arriving aircraft).
2) 34L and 25 are intersecting RWYs, so their management has to be integrated, in particular when other vehicles cross.

The other constraints that the controller has to take into account during the RWY occupancy planning are the estimated and the real RWY movement times, the turbulence and the wake vortex of the aircraft, the current position, speed and heading of aircraft and vehicles in the vicinity of the RWY, the other planned movements in coordination with the ground and the approach controllers.

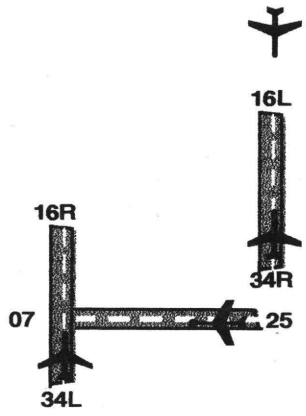

Figure 1

The Figure 2 represents the mock-up developed for the RWY management of the aerodrome sketched in Figure 1. It is the latest of a series of different prototypes and the result of an iterative process with many phases of design / evaluation with the user / redesign.
The screen of the runway management is displayed to the Tower Controller within a window on his/her information screen.

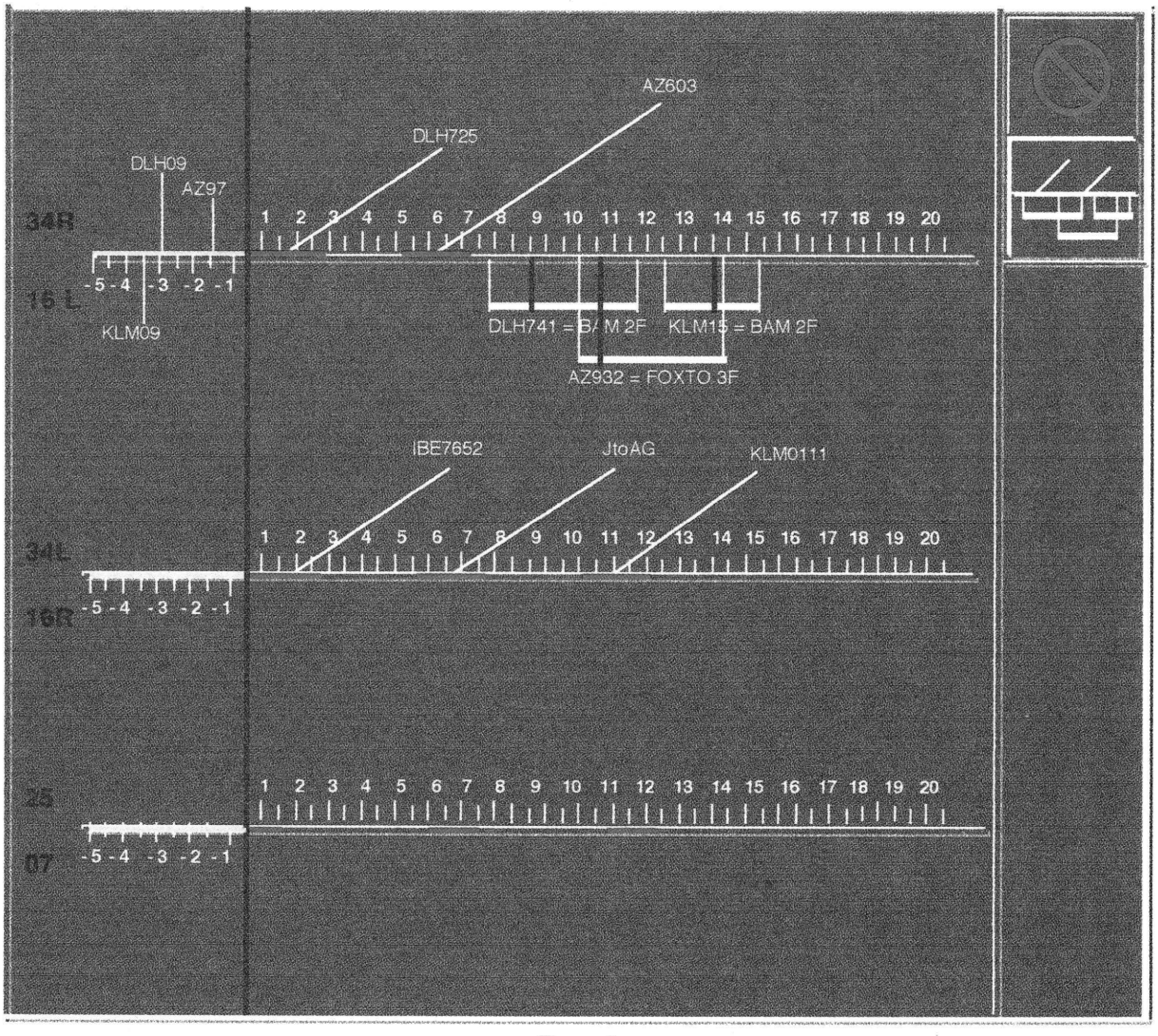

Figure 2

Each RWY is represented by a dynamic time line representing:

- the current time (the vertical black double line)
- the movements planned for the next 20 minutes (from the current time to the right)
- the movements of the past 5 minutes (from the current time to the left. The yellow line)

The callsigns on the top of the right time line represent the planned arriving flights. These callsigns are labelled to point out a priority or an emergency of the flight (e.g. sick passenger). In Figure 2 this is represented by a green icon with a P/E label.
Each callsign is associated to an estimate of its runway occupancy time (represented as a red line on the main time line). The runway occupancy time is not strictly the time in which the aircraft physically occupies the RWY, but the entire time in which the RWY is occupied to let the aircraft to land and free the RWY. This allows to manage the runway occupancy in safety conditions.
The management of the runway occupancy is integrated. For example, Figure 2 shows that even if there are no departing or arriving flights for the RWY 25, some minutes of occupancy are displayed. This is due to the fact that this RWY intersects the RWY 34L. The occupancy represented is related to the time in which the flight running on 34 L crosses the 25. This means that for some minutes also the RWY 25 is occupied, even if there are not landing or taking-off flights which affect it.
The integrated management of the runway occupancy time is particularly useful when other vehicles cross the RWY. With this kind of representation, the controller can get the occupancy situation at a glance, and manage crossing vehicles in safety conditions.

The callsigns of the planned departing flights are displayed at the bottom of the right time line. Each callsign is associated to the entry point to the RWY represented by a label and the callsigns having the same entry point are aligned on the same row. This gives an idea of a partial departing sequence by entry point (same row), and the overall sequence (different rows). Other information associated to the planned departing flights are the slot assigned (the white interval at the bottom of the main time line), and the SDT (scheduled departure time) represented by a black vertical line within the slot interval. This representation is particularly effective in case of slot overlapping: the representation of the SDT avoids confusions in the departure sequence order.

The interface is dynamic to represent the temporal evolution. When a callsign reaches the current time line, it disappears from the right time line and is displayed on the left time line. It remains there until the aircraft is identified by the system, and in any case, for no more than 5 minutes.

Other functionality of the interface are the "No crossing sign" button that allows the controller to put the sign on the RWY which is temporarily closed; and the "Change sequence" button (Figure 3) which can be used for changing the departure sequence and interacting with the departure manager tool.

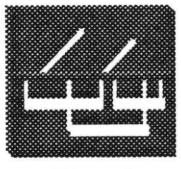

Figure 3

The mock-up has been evaluated using heuristic techniques, guidelines and walkthrough. The first results are positive and the new interface demonstrated to support effectively the activity of the controllers.
The final validation of the mock-up will take place at the end of the project. A validation plan is being defined based on usability testing in the lab with qualitative and quantitative measurements. A task-driven approach (Ravden and Johnson, 1989) will be adopted in order to exploit the results of task analysis also for the evaluation. Following this approach, a set of representative tasks will be selected, and the controllers will be required to perform each task using the prototype and to evaluate it filling in evaluation reports. Furthermore the controllers' performances during the test will be video-recorded, and the data analysed for a quantitative usability analysis.

CONCLUSIONS

This paper describes the methodological approach adopted for developing prototypes and evaluating the impact of new technological tools for ATC.

We believe that the success of the advanced technologies for ATC is strongly dependent on the design methodology adopted during the development process of the systems which will integrate these technologies. Following the principles of the user-centred design, we involved air traffic controllers in the design and evaluation activities. Indeed from the beginning of the project, the controllers were involved in task analysis and task modelling, refining and validating the models of their activities. Task models were used to guide the development of prototypes.

This approach has shown to be efficacious in obtaining positive results. Indeed the controllers had the opportunity to actively affect the design and were satisfied to see their suggestions realized. Of course, the controllers cannot substitute the designers but their knowledge is valuable to provide a user-oriented characterisation of the activity that designers can exploit to develop and refine prototypes. Furthermore the knowledge captured by task models was a vehicle to enable the communication between users and designers, who could cooperate on the basis of a common understanding of the domain and the tasks.

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FLIGHT PLANNING AS A DISTRIBUTED PROCESS

Stefana Broadbent

CB&J, Paris (s.broadbent@cbj.fr)

ABSTRACT

In this paper we present the analysis of Flight Planning activities in commercial airlines as an example of cognitive activity distributed between operators, social artefacts and technologies. We will argue that decision making in flight planning is a process of progressive adjustment of solutions to constraints and that the computer system can support this process by providing not only the means of integrating data but by allowing users to iterate on the solutions and use the output of the system's computations as a resource for further adjustments. The coupling between human, social and material components is in fact so tight, that focusing on the separate human component, as it is most frequently done in the Human Factors aviation literature, would be misleading.

Keywords: flight planning, distributed cognition, interaction.

INTRODUCTION

As many activities which involve man machine interaction, Flight Planning involves the collaboration between a user and a system in the retrieval, analysis and computation of data to reach a complex solution. We propose to look at Flight planning as a system of cognitive activity distributed between individuals and technologies. We borrow the distributed cognition notion from Hutchins (1995): "distributed cognition is a new branch of cognitive science which studies the representation of knowledge at the same time in people's minds and in the world ; the propagation of knowledge between individuals and the artefacts ; and the transformations that these structures go through when they are used by the individuals and the artefacts ". The novelty of this approach is that the unit of our analysis becomes the system composed of the individuals and the artefacts that they use. Artefacts are cognitive in the sense that they embed socially constructed knowledge, support co-ordination between individuals and shape the mental processing required to interact with them. In this respect, Hutchins (1995) introduces the concept of collaborative manipulation : " the process by which we take advantage of artefacts designed by others, sharing ideas across time and space ".

The preparation of a flight plan for a flight requires the Flight Operations department to select the best route that day, taking into account a number of factors such as the weather, the type of aircraft, the weight of the load, the air restrictions. The notion of best route is variable in the sense that while safety is paramount, the relative balance of economy of fuel and time can vary. Thus the best route can be the shortest route in terms of time one day, and the most economical in fuel consumption another day. The process of selecting a route for a flight is therefore one of combining all the existent constraints to reach a best fit solution. This process is shared between a number of cognitive actors : the navigation experts who decide the possible routes, the aviation administration who fixes the safety limitations for each type of aircraft, the accounting departments who fix the fuel policies, the dispatchers who evaluate the constraints of the specific flight, the computer system which computes the implementation of a route as a specific flight, the pilot who estimates the possibility of actually flying the theoretical flight plan.

The decision process in flight planning cannot be decomposed in a set of independent choices individually derived from the satisfaction of specific conditions. Nor can it be characterised by an initial phase in which the flight dispatchers define the requirements, gather all the relevant information and then produce a plan which satisfies the prerequisites. The decision process can be best described as one of progressive adjustment of the solution.

FLIGHT PLANNING IN COMMERCIAL AIRLINES

A flight plan is a very detailed description of an intended flight for the benefit both of the pilot and air traffic control (ATC) who will then distribute it to all organisations concerned with the flight. Flight planning is the activity of producing an ATC message compiled by or on behalf of the Pilot in Command to a set Civil Aviation Authority format and then transmitted by the appropriate ATC authority to the organisations concerned with the flight. It is the basis on which ATC clearance is given for the flight to proceed. The flight plan details the route by listing all the waypoints (aviation radio beacons or airfields) that the flight traverses; each waypoint is specified by name, co-ordinates, and radio frequency and the flight plan specifies the flight level (altitude) of the plane at that point, the fuel consumption (overall and from the last waypoint), distance covered and time passed. Three alternative destination airports, the alternates, must also be specified and other safety issues, such as en route airfields for emergency landings on long range oceanic flights. Furthermore the flight plan provides the exact indication of the amount of fuel that will be used during the flight and therefore serves as an instruction for ground maintenance for refuelling the aircraft.
In commercial airlines flight plans are prepared in the Flight Operations department by dispatchers even though ultimate responsibility for accepting the plan, rests with the pilot. Indeed both the pilot and air traffic control can reject a plan. Safety is always the primary concern, but each airline, route and even flight will have further specific constraints to satisfy: maximising payload, giving priority to fuel consumption, guaranteeing punctuality, avoiding congested airspace, these and others are some of the priorities that will vary case to case. Routes are prepared and stored by Navigation departments who calculate trajectories on the basis of airway constraints, time, overflight charges, and commercial agreements.

All commercial airlines use computer based systems to compute flight plans. In simple terms, the flight plan produced by the computer system provides a proposed best route between origin and destination, and a simulation of the flight in terms of time to fly, profile of the flight and fuel consumption. These computer systems principally use stored routes, of which there can be tens of thousands stored in the navigation database. Most systems also have a random routing facility that can calculate a route between origins and destinations for which there are no stored routes. The selection of a route has to take into account data on the specific aircraft being used (performance varies for each individual plane), on the payload for the flight, the air traffic situation, conditions in all relevant airports and of course, meteorological data. Furthermore a number of factors affect the amount of fuel to be loaded on a plane: the greater the payload the greater the fuel consumption, carrying a lot of fuel also increases the weight, prices of fuel may vary significantly between origin and destination, there may be weight restrictions for landing at an airport, winds and temperature affect fuel consumption and thus so does altitude, changing altitude is fuel costly, holding (waiting for clearance to land) consumes fuel, the aircraft must have enough fuel to reach all the alternates, etc.

PREPARING A FLIGHT PLAN

The actual task of preparing a flight plan is a joint activity of flight dispatchers and flight planning system with the additional contribution of meteorological, navigational, reservation departments and civil aviation authorities. Although there are individual differences in strategies in different airlines because of different flight planning systems and department organisations, there is a relatively common set of steps that are followed. This very simplified version of the task sequence, results from observations carried out in eight commercial airlines in Europe, Africa and the Middle East over the period of a year.

The dispatchers opens a flight request file on the Flight Plan System on which the parameters of the flight will be inputted prior to the sending off of the request to the computer system for the calculations,
The dispatchers checks the aircraft type, estimated time of departure, origin and destination and enters them in the system. Each individual aircraft has a specific performance envelop, furthermore engine types, aircraft model etc. might be relevant not just in terms of the performance of the aeroplane but also with respect to external constraints like regulations on long haul flights, acceptable runway lengths etc.
The dispatcher decides the en route and destination alternates and enters them on the system,
The dispatcher checks the surface weather of the alternates. The Surface Weather is a report of the local weather conditions dispatched regularly by each airport : it contains data like the visibility, temperature, cloud configuration, winds, rain, snow etc. all the factors that might affect the landing of aircraft,
The dispatcher checks the NOTAMs for the destination and alternates and for en-route. NOTAMs (NOTices to AirmeN) detail all the activity that might affect aircraft : ranging from military exclusion zones, military exercises, rocket launches, balloon flights, to the icing condition of airport landing strips, new radar systems in a control tower,
The dispatcher modifies the alternates if there is a problem with the weather forecast or NOTAM,

The dispatcher enters on the system any particular restriction that this flight may need (fuel, route, aircraft),

The dispatcher enters an estimated payload in the system. Payload information clearly affects the computation of a flight plan. This data will come from the reservation and cargo departments, and might not be accurate until the last minute,
A first Flight Plan computation is run,
The system computes a flight plan with the route, the expected time length of the flight, the expected fuel consumption of the flight, the flight profile, etc.
The dispatcher checks the result of the Flight Plan computation : time, route, fuel, flight profile,
If any characteristic of the flight is found to be inadequate or sed.
>From the perspective of the dispatcher, there are two types of decisions to be taken : what are the acceptable parameters for the flight and whether the produced flight plan is good. First dispatchers enter data in the system to describe the minimum characteristics of the flight, origin destination, time of departure, payload, alternates on the basis of the information obtained from other departments and various information systems. Then a plan is computed, which provides a route, a time, a fuel consumption. At this point the dispatcher must judge the plan on the basis of different criteria such as safety and economy. If the plan is not considered acceptable or if the dispatcher wants to test another alternative, the dispatcher makes an hypothesis on what factors could modify positively the plan, inputs a new set of values for some parameters and re-computes.
The two types of decisions are not independent. The amount of fuel depends on the route flown but the choice of route can be constrained by reducing the fuel burn. Therefore decisions cannot be taken individually based solely on the satisfaction of prerequisite conditions. Although, there are a number of prerequisite conditions to evaluate before selecting the values of the parameters, (e.g. the surface weather and NOTAMs for the alternates, the overall weight of the aircraft for takeoff and landing) ; satisfying the preconditions is not sufficient to select the final parameters. Firstly because there may be a number of elements that satisfy the conditions, secondly because the decisions are based on combinations of multiple factors which are interdependent.
If we take the case of the route, the minimum conditions to satisfy, are the absence of any traffic or safety restrictions on the route, acceptable weather conditions, and for some type of aircraft, the possibility of having en route landing grounds. However once these conditions are found to be satisfied, the selection of the route is then based on another set of criteria such as route length, possibility of flying at a certain altitude, overflight charges, time, airline policies. Furthermore, not all of the information is available up-front (weather forecasts are updated every six hours therefore it is best to wait for the most recent update), which implies that dispatchers must work with an incomplete knowledge basis and progressively refine the plan to include all of the affecting factors as they appear.

The number, complexity and uncertainty of the factors means therefore, that it is virtually impossible for the dispatchers to predict the outcome of the computation of the plan. Dispatchers systematically compute a first tentative flight plan to use as the basis for further adjustments. In this first calculation just the parameters that are necessary to produce a realistic plan (aircraft type, destination and maybe a set of flight profiles) are entered, while uncertain parameters like the payload, are inputted with estimated values. The flight plan produced by the Flight Planning system relates the route to the flight time and the current meteo. Any route information retrieved in the Navigation files or charts is static and not useful for evaluating the adequacy of a route for a specific flight because the routes are not put in relation with the actual meteo, and no information is given regarding the time needed to fly that route. Therefore the flight plan produced by the system gives the dispatchers information that they could not obtain by the different sources individually. The produced flight plan has then to be evaluated by the dispatcher to check whether it is the best plan given the constraints of the aircraft, the constraints in terms of possible routes, the weather conditions, and eventually adjusted to meet the constraints.

DISCUSSION

The work in a Flight Operations departments is highly collaborative (Layton, Smith & McCoy 1994), there are a number of actors involved in a flight plan : the navigation department which prepares the possible routes, the reservation department which provides the information about payload, the meteo department which provides the significant weather, and the dispatch department who prepares the flight plan. Dispatchers have the responsibility of collecting the relevant information from the different sources, entering the relevant parameters in a system that computes the flight plan, evaluating the adequacy of the result and adjusting the parameters according to the output. Since the complexity of calculation of a flight plan is enormous, the task of generating a flight plan is distributed across departments, computer systems, and pre-computed social supports such as routes and policies. Within this system, the dispatchers play a pivotal role that correspond to what Hutchins (1995) describes as : " providing the internal structures that are required to get the external structures in co-ordination with each other ".

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6 TOOLS AND PRACTICES IN PROCESS CONTROL

Communication and Coordination in Aircraft Maintenance

Michele Visciola
Quality Lab - Torino/Ivrea -Italy
e-mail:mvisciola@metriqs.com

Keywords
Communication, Coordination, Human Errors, Maintenance

INTRODUCTION

Aircraft maintenance relies heavily on the distribution of cognition in the social organization. In order to achieve good coordination results, there should be room for the construction of a shared understanding in the working environment. The study suggests that the so called "negotiation of understanding" can be hindered by the absence of communication tools useful to reduce the distance in time and space among the involved people in maintenance tasks. The modalities to transfer information from one team/person to the other play a crucial role in their coordination and management. Information is to be passed by in a proper way, so that previous' team performance will be clearly intellegible to the subsequent team/person. Communication and coordination represent also the area which deserves major attention and investigative results in the analysis of maintenance-generated "incident" cases. This study of aircraft incidents due to maintenance-generated "incidents" is based upon an analysis of 223 self-reports, coming in response to the search request of NASA's Aviation Safety Reporting System Data-Base (Search Request n. 4460-"Aircraft Maintenance Reports"). From these data I have extracted all those reports which referred to communication and coordination problems. The data are classified according to six characterizing situations, which are clustered into two main errors' case-plots. These are cases of errors due to *discoordinations* and *conflicts* in the use of communication resources, respectively.

RATIONALE OF THE STUDY

Studies on cognition in maintenance tasks have not yet achieved cogent conclusions. The "natural" approach in cognitive studies is to focus on the human errors in the maintenance operations and on their control within the maintenance organizations (see, Reason, 1997; Rankin et al. 1997). By assuming this perspective there are some advantages. First, there is a consistent ground upon which a research program might confortably rely. Second, any study aimed at improving collaboration patterns and the organization of highly complex systems can draw useful indications from studies centered on the definition and identification of situated human errors. Even though there is not an automatic link between the social and the cognitive studies, the research programs on human errors in working domains can offer a consistent bridge between them. However, the main risk of this approach is to produce too general results. In the study of maintenance organizations the more challenging endeavour is to identify the time and space constraints which bound human errors. For example, it is relatively easy to observe and to evaluate the activities on-the-ramp (i.e., when the aircraft is being surveyed for some inspection after a signalling of any unconvenience). Yet, this is in sharp contrast to most of the maintenance tasks. The great majority of maintenance tasks requires the coordinated activities of several departments, some of which external to the line organization, over a period of days or weeks. A plausible identification of the working areas and the relative timing where and when to concentrate the observations can be really time-consuming and can vanish the research's prospects of success. On the other side, any decision made a priori on this issue can reveal uncorrect without an a-posteriori confirmation on the field. Therefore, there is a methodological dilemma, which needs to be brought to a plausible solution.

One possible solution is to design a map of the areas of relevance in maintenance organizations. This solution is on the same line of research which has been exstensively proposed and discussed by E. Hutchins (1995) for the study of team collaboration in navigation tasks within an amphibious helicopter transport. The research program bridges the gap among cognitive, social and ethno-metodological studies by softening their boundaries. From this perspective a sort of hierarchical task analysis becomes necessary aiming at identifying the social structure of the maintenance organizations. Therefore, from this point ahead it should be possible to map the social distribution of cognition within the organization. Since communication and coordination are central features of cognitive activities within complex organizations, like the maintenances', it becomes possible to observe and evaluate significantly the organization by concentrating on these features. There are at least two important implications by assuming this solution. The first is that the cognitive properties of the team and, at higher level, of the organization are conceived as a whole. Human errors, for instance, are not only the expression of individual faults. It is the organization that is responsible of the results of the team behavior. The second is that the identification of human errors and their probability of occurrence in the organization can be descended from the events occurred in the communication structure. From this perspective communication is

not simply seen as a transfer of information. Communication is information propagation whose meanings are construed during as many interactions (among humans and with the available tools) as necessary to accomplish the task. These meanings are agreed through what Hutchins calls the "negotiation of understanding". I kept this concept as a central tenet of the data analysis. It is hence worthwhile to explain how I used it in this study before passing to its description.

One of the best practiced modality to reduce complexity in maintenance is to design procedures that describe how to perform a given activity in given conditions. Usually these procedures are task-driven. They do not consider for instance how to share workload in the team. They outline only the sequence of operations which fit the machines and tasks at hands. This is necessary because complex situations are mostly unforeseeable in terms of chain of events and available resources. Therefore, these procedures are able to offer just a line of conduct for a certain amount of situations. Of course, these situations are open to interferences and to error potentials. There are at least two possible conditions that will interfere with the construction of a shared meaning in the maintenance activities: They are: a) the distance at which comunication takes place and, b) the time laps between the communication acts of different actors. The error potentials are of two kinds in these conditions. They can happen as a consequence of a) *discoordination* (e.g., different teams' members undo one another's work, or different teams' members do not do what the other expects from them), and of b) *conflicts* (e.g., members of different teams work at cross-purposes and/or existing tools, procedures and manuals are not able to resolve ambiguities). We will see this simple model as applied to the analysis of aircraft incidents due to maintenance generated problems.

THE STUDY: DATA ANALYSIS

I was able to identify 132 reports which fitted to the model just outlined. This corresponds to the 59% of the 223 reports I received in response to the search request on "aircraft maintenance reports". The preliminary analysis of these reports shows that incidents are generated and can be described within six different scenarios and characterizing situations. They are the following *discoordination* cases: 1) Inaccurate Communication and Coordination (ICC); 2) Uncompleteness in operational Risk Assessment (URA); 3) Unfulfilled Procedures (UP); and the following *conflicts* cases: 4) Lacking of Adequate Tools (LAT); 5) Gaps in Existing Manuals (GEM); 6) Temporal Pressure (TP). Of course, the great majority of these 132 reports might be included in more than one characterizing situation. However, each case was dealt with according to the prevailing characterization. It is unpractical to discuss all six situations with an illustrative example in these few pages. I will just report one case of *discoordination* and one of *conflict*. These stories of errors (see, Visciola, 1993, if interested in the use of stories for engineering purposes) involved actors with different roles and having a different work location, as well as a significant time lap in the sequence of events (i.e., turn shift-over).

A "Discoordination" Case

I will shortly describe this case with the purpose of showing how the distribution of cognitive tasks in the organization requires a careful use of communication resources.

*The line mechanician of a large maintenance organization was executing a change order authorization (COA) on a wide body aircraft. This work entailed the opening of a panel on the upper surface of the wing above each engine pylon. The procedure for this COA envisaged the notation of the configuration of a fuel line installation for the engineering department (*located in another building*) and then the reinstall of each upper wing panel. Further, the procedure requested to sign off only once for the notation of the four fuel lines, and only once for the closing of all four wing panels. Since the wing panels are sealed and have numerous fasteners, their opening and the fasteners removal is a very time-consuming task. After the mechanician had started his job, his team leader suggested a shortcut to have access to the interested area. This shortcut consisted in the opening of a smaller panel on the lower surface of the wing. This panel is much easier to remove and to reinstall. Even though this shortcut is often practiced because mechanicians prefer to not disturb the large wing panels unnecessarily, it is illegal. However, the mechanician removed the small panel on the pilon number 3, noted the fuel line configuration and reinstalled the panel. The mechanician was not able to finish pylon number 4 and left a set of screws attached to the panels number 1 and 2 as a sign (*which according to the reporter was obvious to interpret for an expert mechanician*) for the next mechanician that they were not installed. He then signed off only once as per the procedure. The next mechanician was a very expert mechanician. He therefore proceeded in a goal-oriented behavior and completed the pylon number 4 by following the shorter procedure. Then he checked the small panels of the pylons number 1 and 2 and failed to observe that the first mechanician had removed the upper panels of these pylons and not the small lower panels as he had done for the pylons number 3 and 4. Therefore he*

signed off the write up and cleared the aircraft for the dispatch. On takeoff both panels separated from the wing.

The comments to this story are almost two: a) When there are sensible shortcuts to a procedure, the mechanicians do not esitate to follow them, even when they are prohibited. These violations are deliberate and are shared in the organization, as this case shows. The engineers are blamed for making tasks unnecessarily difficult and for not having first-hand experience on the job. b) The communication and the "negotiation of understanding" were very poorly supported. This is true regardless the choice of the two teams to violate the prescribed procedure. The paperwork did not allow the first technician to advise the next on the work he had done. He had to use meta-knowledge, which in this case did not work to alert the second technician.

A "Conflict" Case.

This case is brought as an example of conflicts in communication, which render the "negotiation of understanding" very difficult to be achieved in the necessary time-slot.

*The mechanician of a large maintenance organization was assigned the de-docking task on a wide body aircraft. After having removed the main landing gear pins, on the way to the nose gear this mechanician was requested by his team leader to go to the cockpit in order to assist another mechanician in different tasks, which entailed the flaps trailing edge retraction. During the normal execution of the required procedures, the mechanician got distracted (*these are the words used by the reporter) *by other objectives that were necessary to be pursued as a consequence of the change of engine number 1. This was an abnormal situation that requested more resources than those planned for the routine maintenance tasks. Of course this situation created a completely different maintenance configuration to the eyes of the mechanician. After having left the cockpit, the mechanician came back to the old de-docking task. At this time again he was requested to interrupt his job because the engine team requested the electric power necessary for their task. With a sporadic availability of electric power for the de-docking task, and after a shift change with new people, new directives and other checks being conducted, the mechanician finished his first task as per procedure. Therefore he proceeded to sign off the paper work thinking of having done a decent job. The day after the aircraft did an unscheduled landing due to the nose gear pin that was not removed as necessary.*

The comments to this story are two: a) during the solution of abnormal situations, it is easy to create overlapping conditions of work. This overlapping might cause conflictual demands for the available resources (in terms of people, procedures and tools). b) Communication resources are limited as well as the other resources necessary to accomplish the tasks. This does not necessarily mean that more communication is needed.

WHAT COMMUNICATION NEEDS TO BE SUPPORTED

The two stories just described show the advantages that can be drawn by focussing the analysis of the maintenance-generated incidents on the communication and coordination aspects of work. They show that single individuals are the error-makers, and that the communication structure within the organization makes these errors possible. In particular *discoordination* and *conflicts* are very probable causes of human errors in the activities that require many persons and roles to work together. This means that errors can be generated at different levels of the organization and it might result unpractical to reduce their occurrence by concentrating the efforts at the level where the errors are materially made. What is needed is instead an improvement in the use of communication resources within the organization. This highlights the question : "what does communication need to be supported ?". A thorough analysis of the 132 stories I have taken into account reveals that the distribution of cognitive tasks (namely, the coordination among persons and tool devices) can be very difficult. Given the existing tools and the alleged existence of gaps among manuals, procedures and the factual knowledge necessary to satisfy maintenance goals, these incidents show that the negotiation of understanding is very poorly supported. The analysed incidents show that the main source of difficulties in communicating and coordinating one's activities with the colleagues' is the interpretation of what the "other" has really done and what he/they really needs to continue on the assigned task. This analysis suggests that the distribution of cognition within the organization should be supported better. Tools are necessary for the coordination of activities and for the reduction of the conflicts among tasks-demands at the minimum necessary. In particular, the tools for the coordination should make visible the satisfaction of constraints for each significant task. For example, it should be avoided the interruption of a task at a point where its continuation can take ambiguous paths. As for the tools for the avoidance of conflicts in communication, the main efforts should be concentrated on the documentation which is consulted during the great majority of maintenance activities. Any kind of documentation (i.e., electronic, digital, and paper) should reduce possible

ambiguities in the situation assessment. The conclusion of this pre-feasibility study is that there is room for significant improvement and therefore for technological innovation in aircraft maintenance. Collaboration between different teams/persons and within different roles needs to be better supported, so that the organized system (i.e., the airline and its maintenance structure) can act as a whole even when there are limits in the explicit coordination of its action.

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Focusing the working environment during organizational changes in the processing industry

Lars Peter Jensen
Department of Control Engineering, Aalborg University, Fredrik Bajers Vej 7 C
DK-9220 Aalborg Ø, Denmark, Tel. +45 96358740, E-mail: lpj@control.auc.dk

Lise Busk Kofoed
Department of Development and Planning, Aalborg University, Fibigerstræde 13
DK-9220 Aalborg Ø, Denmark, Tel. +45 96358332, E-mail: kofoed@i4.auc.dk

ABSTRACT

The purpose of this paper is to show and discuss possibilities and problems concerning changes in the processing industry. The processing industry is characterized by fast technical development which is constantly in front of the newest technical possibilities within the area. This is manly due to the growing utilization of automation, and a direct consequence is a raising number of monitoring jobs in control rooms, at the expense of other jobs.
Because of this, we see a great potential and challenge in trying to match the new technical possibilities with new organizational structures to improve the working environment for monitoring jobs. A point in this paper is to use a change process to establish a learning culture using employee participation. Developing an "eksperimentarium" as support to this process is discussed.

Keywords
Working environment, monitoring work, experimentarium, organizational changes, participation, learning.

INTRODUCTION

Within industries with a high degree of automation, like the processing industry and related industries, there is a need for readiness, knowledge and awareness when technical or organizational changes are on the agenda, especially because safety and the working environment has to play a central role in the change process. There might be many reasons for changes, e.g. promoting efficiency, renewal of the automation systems, rearrangement of the production etc. No matter what the reasons for the changes is, it is important to have the human factor in focus for the technical or the organizational change. We find it necessary to have a holistic point of view on the possibilities and consequences of the working environment and working conditions before, during and after the changes.

Introducing a case study

In November last year we started a study of a major change process that we will follow the next two or tree years. A large Danish processing industry have to improve its efficiency in all areas, e.g. a reduction of the number of employees from 200 to 150 - 170 before the end of this century.
The manager is inspired from the ideas in Business Process Reengineering (BPR), and wants to run the change process with "open doors", and all employees are invited to participate as much as possible. The manager really wants the process to be exemplary. The working environment both during and after the change process is very much on the agenda and the management have promised that no one will be sacked. The reduction of the workforce will take place by people leaving because of age.
An international consulting company is hired to supervise the change process and their message was that they could handle a change process with no frustrations. We have been invited to study the process. We are also allowed to advise both the consultants, the employees and the management and we are able to interfere in the change process and develop as well as test or examine new ideas, which can support the change process.

The first phase of the change process

The first 3-4 month, we have by purpose been observing rather than participating because we did not want to disturb

the confusing start of the change process. Instead we have made lots of observations of the work situation in the control room. We have been to the different consultant activities during the process, and participated in all the cooperation committee meetings.
After the first period of turbulence our research approach is based on the ideas in action science; we call it dialogue research. It means that we want to give continuos feed back to the process (small reports, workshops, developmental activities, etc.), and make reflective interventions.
For different reasons the consultants haven't been able to run the process without frustrations. Especially among the operators a lot of rumours have started: About the numbers of manning, the lack of safety on job and job security, the managements' hidden agenda etc.
So now was the time for us to intervene and try to improve the working environment, suppress the frustrations, and support possibilities for participation. We decided to start en intervention with the cooperation committee. Firstly because they could be the keys to open the process for their colleagues, secondly because we thought it would be better to start with a smaller experiment, that we hoped could be used as an "icebreaker" for bigger interventions.
In May we planned and ran our first intervention, to help the cooperation committee to get "closer" to the change process. Our idea of such an intervention is to use an experimentarium as explained in the following.

EXPERIMENTS IN AN "EXPERIMENTARIUM"

We consider learning and change processes to be very connected (Busk Kofoed et. al., 1997). Therefore, to support change activities, e.g. get the background to participate in a change process, we want to establish a framework for learning and development. This framework should offer possibilities for employees from all levels and functions of the company to be in a common learning and development process, where they can benefit from each others' resources and create a common basis for the company's further development.
It is our opinion that such a framework can be made by establishing an experimentarium.
The ideas in the experimentarium are based on action learning (see the next subsection), and it is established in a 'room' which is removed from the daily life of the organization.
The purpose of the experimentarium is to give employees, managers and developers/consultants the opportunity to develop, to test new ideas, and to carry out experiments in an experimental situation.
During working with specific activities the participants are taught to see themselves and their colleagues as experts within their fields, and they also experience a common learning process. This is important to open the eyes of the different employee groups for each others resources so they can take part in a common development process - a process in which everybody in an interdisciplinary cooperation can contribute with expertise to solve problems or to create innovation. A broader understanding and knowledge of other employees'/colleagues' work may cause mutual respect, strengthen the confidence in own resources, and improve cooperation opportunities.

Learning processes

Our basic approach to learning is that learning is problem- based and that learning is based on learning in groups during a process, where reflection loops have a predominant place. Our understanding of learning processes is based on Kolb's cycle which describes experimental learning as learning taking place in a cycle with four key points: - doing - reflecting - thinking - deciding - (Kolb, 1984). Based on this and Schön's (1987) ideas about reflection in the learning process John Cowan (1996) has developed a learning method concept based on several small reflection loops - Kolb cycles (as paraphrased by Cowan: - experience - reflection - generalisation - test -) and planned reflection three times in a learning process (*for* action, *in* action, *on* action).

Method

The experimentarium with the cooperation committee was planned to pas the three reflection loops of Cowan.
We had two days, each of five hour's incl. lunch and coffee breaks to run the experimentarium, and the plan was to learn the participants to analyse a specific topic and make a conclusion of the analysis in order to suggest some further action on the topic.
The participants in the experimentarium should work in small groups (3-6 persons) with the analysis because this should supply the process of the experiment with some extra major points: the participants will learn together, everybody should be heard, mutual inspiration will have a synergic effect.

Reflection loops

In the beginning we did a short reflection *for* action loop where we tried to match our intentions with the experimentarium to the participants expectations.

At the end of day one, the group prepared a short seminar, where they presented the results so far to an "external" opponent. The role of the opponent was to place some provoking questions (facilitating questions) about why, how, who, when etc. These questions should facilitate a reflection *in* action loop.
The experimentarium ended with a final seminar where both the result of the work (suggestions for further action) and the processes of reaching it were reflected (reflection *on* action). At this seminar the opponent was also present.

Results from the experimentarium
We have run two of these experiments. Both of them with 3-4 persons, and both time the participants succeeded in making an analysis of the chosen subject, for some relevant topics. They also made some well argued conclusions and suggestions for further action. So considering the direct result/product of the exercise, the participants have learned to make fast and powerful analyses of specific topics with a little help from us.
As to the 'extra major points' to be learned during the process of the experiment, this part was even more of a success. The following list of experiences/results/skill's is more or less expressed directly by the participants in an evaluation of both experiments, 1-2 weeks after the experiments took place.
The participants expressed that they had:

- seen that they together possessed a large amount of knowledge
- experienced that their individual differences were a strength
- learned to see each other as experts on different fields
- observed that a holistic view of a topic resulted in a better analysis
- experienced some cognitive jumps
- seen that one has to analyse and assess consequences before implementing

PERSPECTIVES

Having succeeded this first experiment, we see a great potential in the ideas of using the experimentarium to establish common learning processes, that can help companies during organizational changes towards a learning organisation. When looking at the processing industry, we have found in our case study that the greatest problems came among the operators. The fact that they are working in shifts means that rumours start rather easy and are difficult to stop. It is hard to pass information, and when most of the activities in the change process go on at daytime, one third of the operators have to use their spare time if they want to get all information.
Another reason for the problems is that the total number of operators is 50% of the number of employees, which means that they have on the one side a very strong trade union, and on the other side they are a very small and not visible group at day time (there are six shifts), when the management and the administration are at work. This means that there is a polarization between shift workers and administration people, and the consequence is a lack of understanding of each others' work conditions.
What has to be done in such a situation is to find a way to remove the focus from all the negative aspects in changes towards the potentials in the new operator jobs, but of course still be aware of the problems. We think that one way to accept changes and discover potentials/possibilities could be for the operators to participate in experimentaries, where the subject to be analysed are the new working conditions.
It is our belief that this kind of experimentarium activity can overcome a lot of the actual frustration, and improve the working environment, not only at present but also in the future, because the operators and the engineering department can combine their knowledge to develop better working tasks, and at the same time obtain mutual respect.

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A Communication Program between an Auto-Startup System and Other Facilities

Jung-Soo Kim, Chul-Hwan Jung, Jae-Chang Park and Chang-Hwoi Kim and Ge-Yong Park, Chang-Sik Ham

MMIS Lab. Korea Atomic Energy Research Institute
Yu-Song, P.O.Box 105, Taejeon, 305-606, Korea
E-mail : kjs@nanum.kaeri.re.kr

ABSTRACT

In order to insure mutual communication between an auto-startup system and Functional test facility, we used the Inter-Process Communication(IPC) between the two systems and a Transmission Control Protocol/Internet Protocol (TCP/IP). The data from the functional test facility was put in the shared memory using IPC, which was then accessed by the auto-startup system through an Application Program Interface(API). Also, in order to insure mutual communication between a DCS and G2 , real time expert system, we developed a bridge-software. The data from DCS was produced using the same method , put in the shared memory using API, and the data was then sent by the bridge-software to the GSI(G2 Standard Interface) interface module of G2.

Keywords: Inter-Process Communication(IPC), Transmission Control Protocol/Internet Protocol(TCP/IP), G2, shared memory, Application Program Interface(API).

1. Introduction

Generally, we have used the TCP/IP[1] for communication among workstations. We can also use the socket function for designing the TCP/IP. TCP/IP communication is one of the communication methods using seven layers of Open Systems Interconnections(OSI).

The auto-startup system[2] is designed automatically to operate the nuclear power plant in the startup stage. This system is designed automatically to shift the plant's parameters as a method described in the general operation guide, for beginning the startup operation.

The functional test facility[3] includes a software-code which simulates the Nuclear Power Plant. This facility will be utilized for testing or for providing data for the auto-startup system or the alarm system. Also, G2, real time expert system developing tool, was used in the

role of supervisory-control. The DCS take charges of controlling each mode(including the startup operating scope) and G2 is in charge of the DCS's controller's operation. The auto-startup system consists of the DCS, G2, FTF. These systems are connected to a network. For communicating between these systems, we developed the communication program. The communication program developed in DCS-FTF is constructed to receive the necessary data at startup operation mode from the functional test facility, process this data in the DCS, and send the DCS's control data to the functional test facility. Also, the communication program developed in DCS-G2 is designed to receive the necessary data during the startup operation mode from the DCS, process this data in the G2, and send the G2's control data to DCS. For developing the communication program , in case of DCS-FTF, we used the shared memory for receiving/sending the data between two systems. In order to use the shared memory from the DCS, we utilized an API[4] software(s/w) tool. The function of the API is similar to that of the IPC[1] in other workstations. This communication program in DCS-FTF is designed for two-server processes and two client programs. The server in the functional test facility includes two processes: one is the sending process, the other is the receiving process. Also, for developing the bridge program, in case of DCS-G2, we used the shared memory for receiving/sending the data in DCS and GSI interface module for receiving/sending the data in G2. Figure 1 shows the data flow between the auto-startup system and other facility(G2, function test facility).

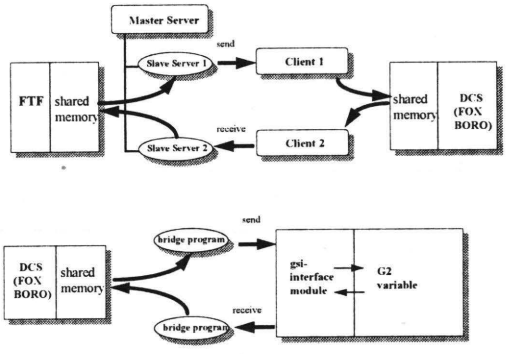

Fig 1. Data flow between automatic-startup system and other facility(G2,functional test facility)

2. Development of Communication program

2.1 The Communication Program of the Functional Test Facility

Before the data exchange, we need to know how to access the shared memory and get the data to the shared memory. The reason we used to shared memory is that we want to separate the main program in the functional test facility from the communication program and easily extract the needed data from the database of the main program using IPC's function without going through the kernel. The merit of using the shared memory is to lessen the communication load on the inside of the workstation. The function utilized for accessing the shared memory is as follow : shmget(), shmat(), shmdt(), shmctl().

The detailed role of these functions are described in the reference[4]. Figure 2. shows the comparison of the communication method of using the kernel with that of using shared memory.

After accessing the shared memory, we started the data-exchange. We design the communication program to two slave servers behind a master because we separated the sender process from the receiver process. Two process are generated by a fork function. The fork function is executed when the signal is requested to connect by the client.

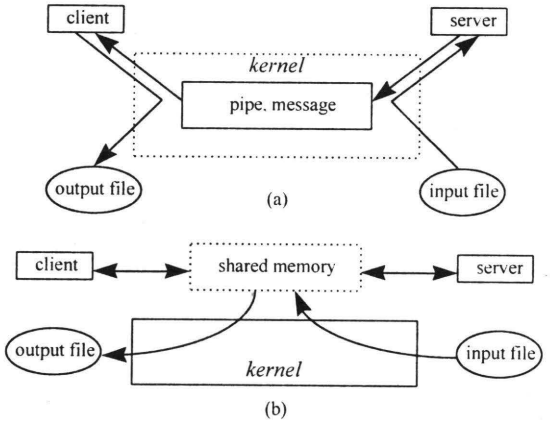

Fig. 2. the comparsion of the communication method of using the kernel with that of using shared memory

2.2 The communication program of DCS

In case of DCS's System, the access of the shared memory is different. that is, we utilize the API(Application Program Interface)[5] for accessing the shared memory at the DCS. The API s/w tool is linked between the shared memory and DCS's database. The database of DCS is, what we called, the Object Manager(OM). The OM manages all the data of the DCS. For connecting the communication program to the shared memory, we use the read/write function(readval(),wrtval()). This communication program is linked and compiled by the DCS's library function. After accessing the shared memory of the DCS, we start the data-exchange. We designed the client to two clients correspondent to two servers. The difference between client and server is that the client does not execute the fork but dose execute the two individual program i.e., one for receiving program, another for sending program, due to the characteristics of the client system. Each client program shares the shared memory at DCS.

2.3 The communication program of G2

In case of G2, we used the TCP/IP protocol for developing the bridge program. The TCP/IP protocol is provided by the kernel of G2. For communicating between DCS and G2, we developed two part, one for DCS, another for G2. In case of DCS, we developed the bridge program for communicating to G2. This bridge program is linked to the DCS's shared memory. For connecting the bridge program to the shared memory, we use the read/write function (readval(),wrtval()). This bridge program is linked and compiled by the DCS's library function and G2's library function. Another part is G2 interface module, GSI. The GSI module provide the external interface module. For utilizing the GSI module, it is necessary for the gsi-object ,G2 function, to work within G2 workspace and the gsi-object set up the connection configuration(for example, communication protocol, communication port, a point to send/receive data-exchange from DCS, etc.) Also, we defined the parameter variable from DCS. We used gsi-object-definition module. The gsi-object-definition module set the attributes of each variables.(for example, float/integer, validity interval etc.) After initializing the bridge program and setting up the gsi-object module, we started the data-exchange. We designed the operation to handle four program separately. two bridge program receiving and other program sending. One of two program is the receiving/sending of analog data. Another is the receiving/sending of digital data. Figure 3. shows the hardware configuration of ASICS(Automatic Startup Intelligent Control System) and Figure 4. shows the information hierarchy of ASICS. From Fig. 4, G2 assigned supervisory control and DCS assigned mode control/process control.

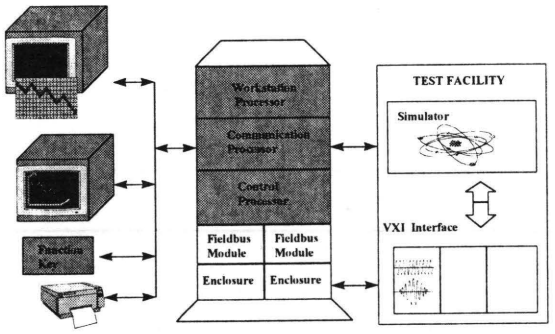

Fig. 3 Hardware configuration of ASICS

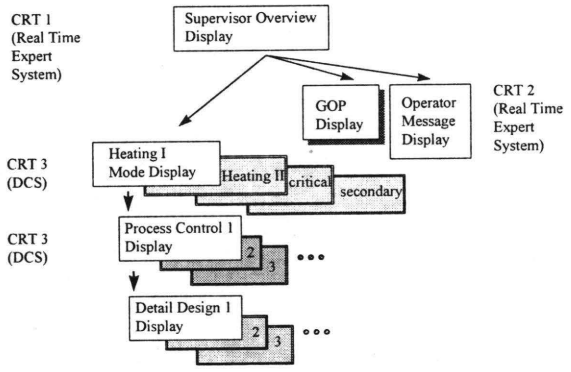

Fig. 4 ASICS Information Display Hierarchy

3. Experiment and Analysis of a Developed Communication Program

We analyzed the normal operating procedure[6] for developing the auto-startup system. As a result of analysis of the normal operating procedure, the DCS-FTF received about 400 variables(the sum of analog and digital parameter) from FTF and sent about 60 variables to FTF.

Also, the DCS-G2 sent about 300 variables(the sum of analog and digital parameter) from DCS to G2 and received about 100 variables(the sum of analog and digital parameter) from G2 to DCS.

This data was read by the communication program, one by one, and put in the DCS's shared memory, one after another, and sent to G2. The reverse procedure was used when G2 sent to DCS's shared memory and this data was changed and DCS's changing data sent to FTF's shared memory. Figure 5. shows the system overview developed at the auto-startup system(DCS). From Fig. 5, this data was received from the FTF from the communication program. Analog data in this figure display digit value and digital data display the color; for example, Pressurizer pressure is 23.95 kg/cm^2, one RCP pump is red, two RCP pump is blue(blue: off, red : on). Figure 6.displays the mode I status. From Fig. 6, temperature and pressure is controlled by G2. In case of mode I, temperature and pressure follows a P-T curve.

Each temperature and pressure controller follows a P-T curve automatically. This controller's starting signal is received by G2. Figure 7. shows the overview display of mode I in G2. From Fig.7, the upper side of this figure shows the important signal of plant and indicator(for example, mode I initializing indicator.....). The lower side of this figure displays the message board of mode I. And Fig. 8 displays the trend chart of the important variables(for example, RCS Tavg., RCS pressure, the level of PZR, the temperature of PZR, etc.) and the bottom button of this figure shows the click button of each mode.

4. Conclusion

In this paper, we developed the communication program using TCP/IP protocol and shared memory between DCS and FTF. Also, we developed the bridge program using shared memory and GSI interface module. The methods of sending/receiving the plant data in the shared memory utilize IPC function in FTF and API s/w tool in the DCS, respectively. The merit of the developed program is that this program lessens the communication load at workstation because the shared memory was used. Furthermore, the program easily accessed the

database. If we use this proposed method, it is possible to design the real-time control system. And even if we applied this program to different system , this program can be easily used because of the general protocol and method of handling the shared memory. Also, if the next Nuclear Power Plant is fully-digitalized or the auto-startup system is applied to the next generation Nuclear Power Plant, this system can used.

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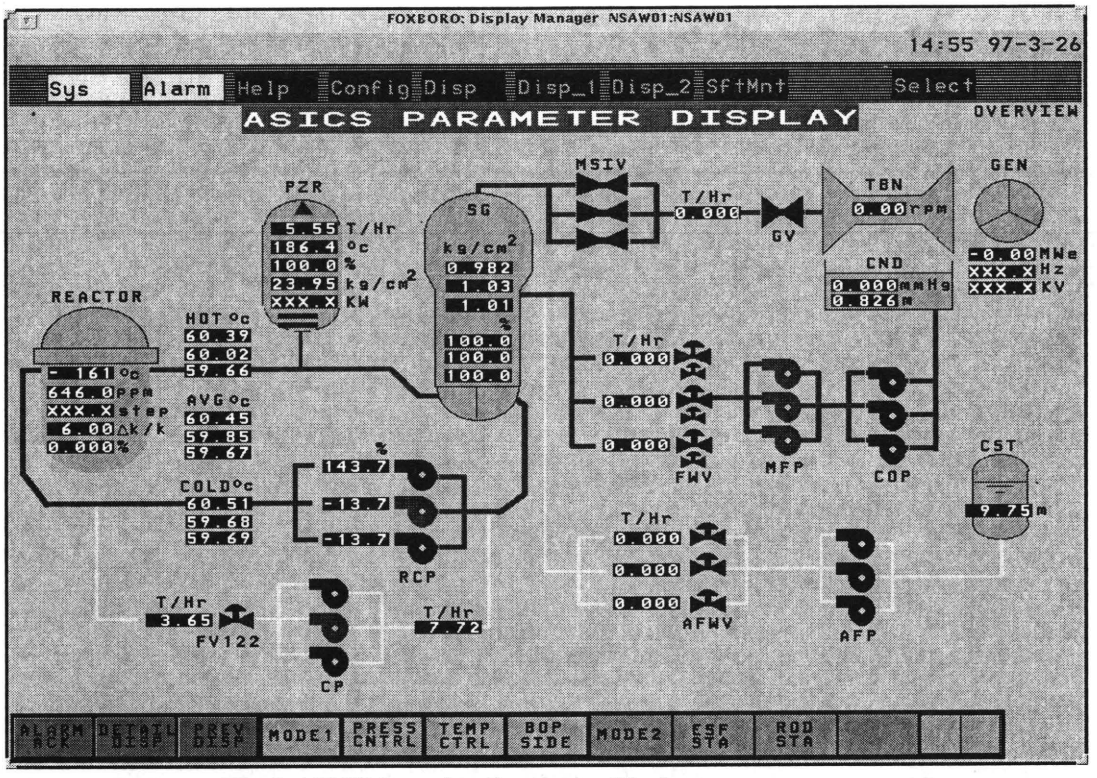

Fig. 5. ASICS Overview Parameter Display

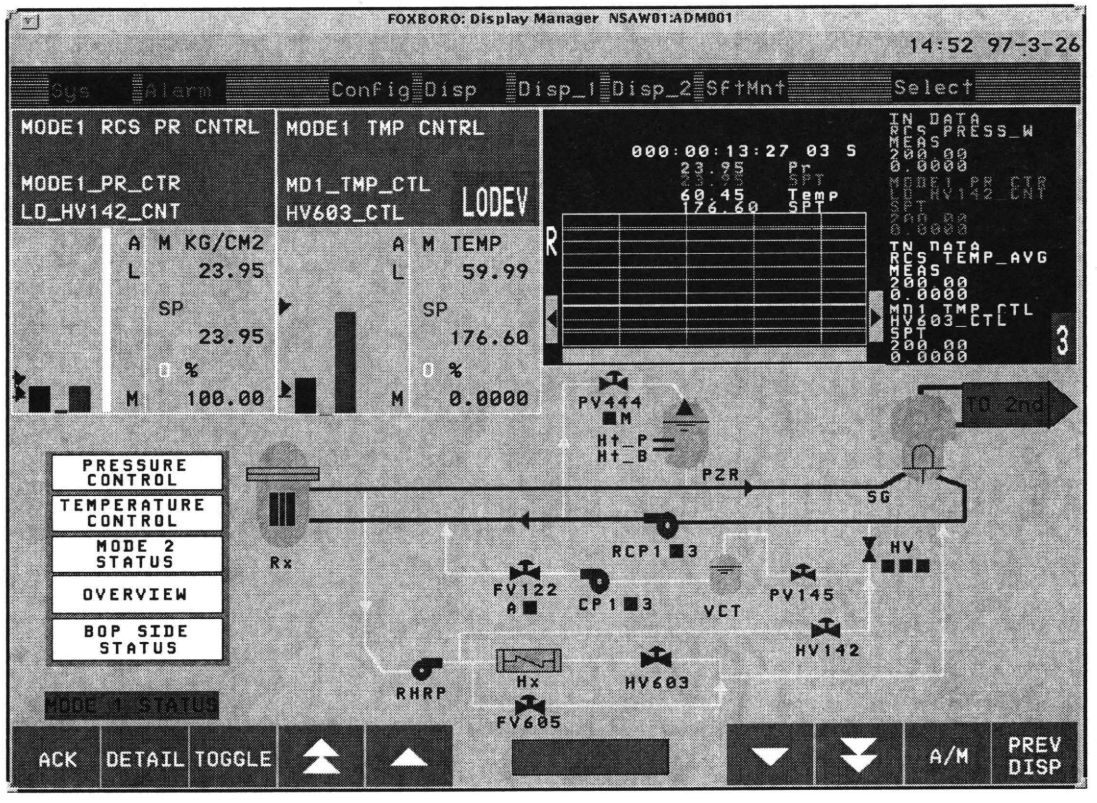

Fig. 6 the Mode I status display

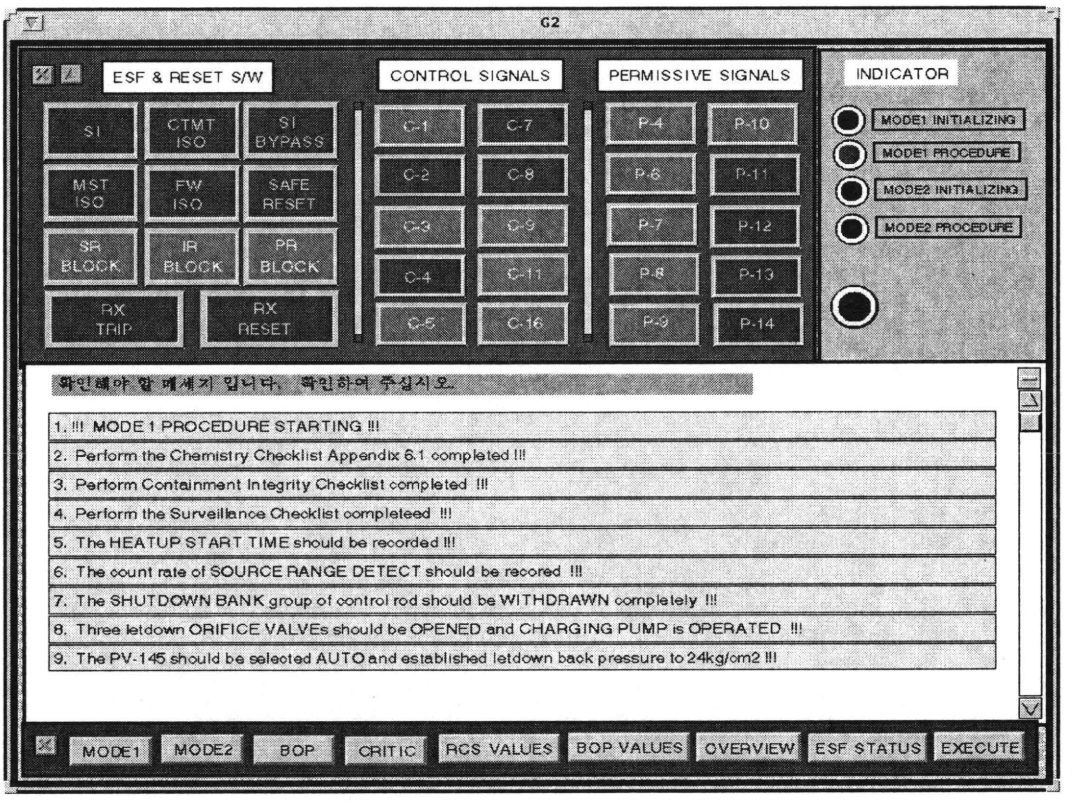

Fig. 7 the overview display of Mode I

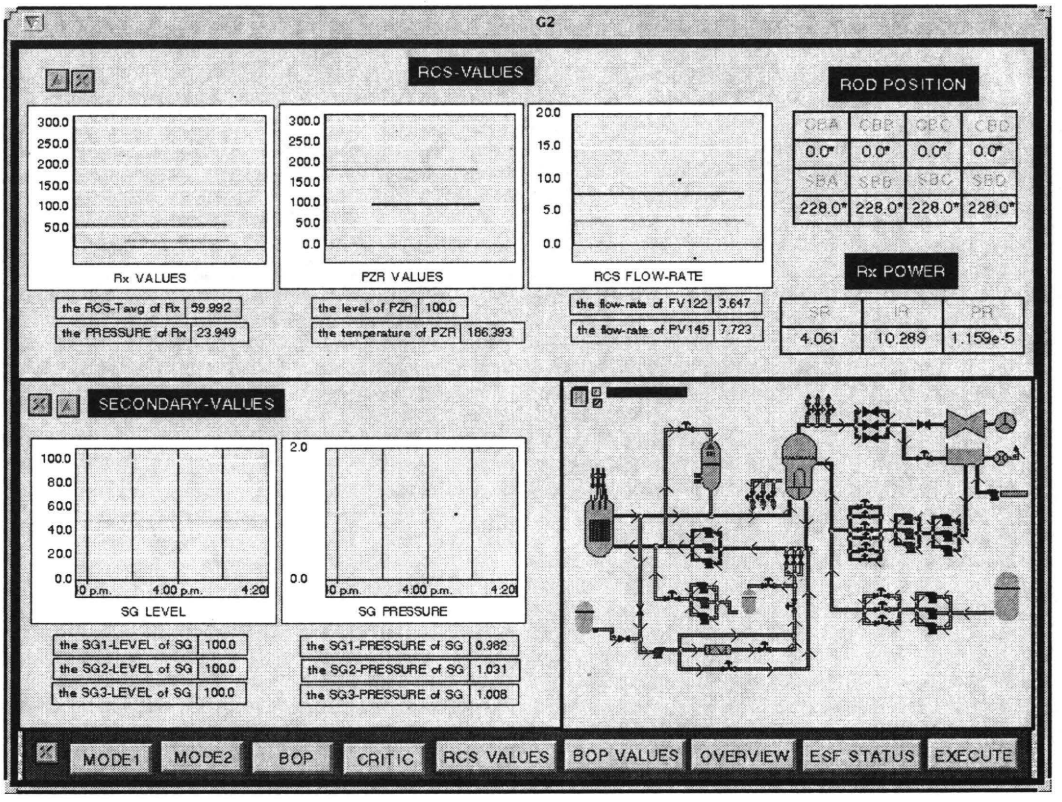

Fig. 8 the trend chart of important variables

Cognitive Science and Design Methodology: Adapting Design Guidelines to Design Practice

Sotiris A. Papantonopoulos

School of Engineering and Applied Science
The George Washington University
Washington, DC, USA
sotiris@seas.gwu.edu

ABSTRACT

Process control may benefit if the formulation of normative design guidelines is supplemented by the study of the actual practice of process control system design. Understanding how system designers work will facilitate the integration of cognitive science approaches and other ergonomic considerations in the design of process control systems. Two empirical studies of design methodology in conceptual process control system design were conducted, analyzing the design decisions and design conjectures employed. Following this analysis, a survey of two conference publications examined how design methodology is conceptualized in two cognitive science research communities.

Keywords
System design, design methodology, design conjectures, cognitive science, research communities

COGNITIVE SCIENCE AND DESIGN METHODOLOGY

Cognitive science approaches to process control aim at formulating normative design guidelines to be followed, or cognitive tools to be applied, in the design and development of process control systems and associated human competencies. Cognitive science approaches are based on disciplines such as cognitive psychology, cognitive ergonomics, and artificial intelligence.

Process control may benefit if the formulation of normative design guidelines is supplemented by the study of the actual practice of process control system design. The two branches of inquiry are interlinked. In order to develop guidelines and tools to be applied by system designers in their deliberations or decisions about process control, one should first understand how system designers actually practice the design of process control. Understanding how system designers work will facilitate the integration of cognitive science approaches and other ergonomic considerations in the design of process control systems.

This inquiry thereby links cognitive ergonomics - which mainly addresses normative questions about the design of information technology for human use - to the findings of design methodology - which studies both how designing is and might be conducted. Design methodology includes the study of how designers work and think, the establishment of appropriate structures for the design process, the development and application of new design methods, techniques and procedures, and reflection on the nature and extent of design knowledge and its application to design problems.

THE EMPIRICAL STUDY OF DESIGN METHODOLOGY

The paper presents two empirical studies of conceptual process control system design.

The starting point of the two empirical studies is the understanding of design methodology and, in particular, the structure of the design process. Design studies suggest that very early in the design process the designer imposes a limited set of objectives or one particular solution concept as the 'primary generator' for the initial

solution (Darke, 1979). Designers rely on the formulation of the primary generator to find a way of reducing the variety of potential solutions to the as yet imperfectly understood problem to a small set of solutions which are cognitively manageable. The conjectured solutions are then tested against the requirements and constraints of the problem, thus contributing to a fuller understanding, or analysis, of the problem.

Design is then viewed as a solution-focused process in contrast with a view of design as analysis-synthesis. According to this view, the designer starts by exhaustively identifying the relevant factors, then proceeds by considering the interactions between the factors and setting performance limits on those factors that could be so treated. Only then does the designer start synthesizing requirements to generate a solution, starting with clusters of related factors.

The analysis-synthesis model and the generator-conjecture-analysis model were tested by two empirical studies of process control system design.

The first empirical study (Papantonopoulos and Salvendy, 1993) involved the design of cognitive task allocation in the diagnosis of flexible manufacturing systems. Participants were solicited among the graduate students and junior faculty of the School of Industrial Engineering of Purdue University in Lafayette, Indiana, USA. The second study (Papantonopoulos, 1997) involved conceptual design and requirements analysis of an information system for real-time monitoring of satellites, performed by participants solicited among missions operators and control room system designers at NASA Goddard Space Flight Center in Greenbelt, Maryland, USA. In both studies, participants were administered scenarios describing the operation of each system and were asked to describe an appropriate operator response and to elaborate on the design of suitable automation. Verbal protocols were recorded, transcribed, and analyzed and the design decisions and design conjectures of each subject were identified.

Results indicate that the analysis-synthesis model is refuted as a design method which is used in practice.

DESIGN METHODOLOGY IN COGNITIVE SCIENCE RESEARCH

Following this analysis, a survey of the proceedings of two conferences, CSEPC96 (CSEPC96 Organizing Committee, 1996) and DIS '95 (Olson and Schuon, 1995), examined how design methodology is conceptualized in two cognitive science research communities, one in cognitive science approaches to process control, the other in human-computer interaction. The survey examined whether the research communities adhere to the analysis-synthesis model or to the generator-conjecture-analysis model.

Results indicate that the two research communities examined adhere to the analysis-synthesis model that appeared to be refuted as a design method which is used in practice.

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A computer-based cognitive tool to train spatial visualization processes

Alessandro Antonietti, Gianfranco Cordara, Barbara Colombo
Department of Psychology
Catholic University
Largo Gemelli 1 - 20123 Milano (Italy)
e-mail: antoniet@mi.unicatt.it

ABSTRACT
The poster presents the project of a computer-based program devised to train mental visualization. Such an instructional tool is aimed at developing an integrated structure of various imagery strategies and at inducing individuals to become aware of the spatial operations they are activating and to control their application.

Keywords
Imagery, cognitive strategies, training

Many experimental findings support the notion that mental visualization can play cognitive functions in memory, logical reasoning, creative thinking, and decision-making. On this ground, various imagery techniques have been devised to help people to take advantage from the spatial representation and transformation of information when they, for instance, have to store and retrieve data, solve problems, plan actions, anticipate future events, learn motor activities. These tecniques assume that individuals are able to create mental pictures and to transform them according to given instructions. This stresses the need to train subjects to visualize spatial patterns and to manipulate them mentally.

Traditional procedures to enhance spatial visualization generally consist of series of paper-and-pencil exercises which are aimed directly at improving performance but not provide instructions about how to reach good performance. Such procedures seem to share the following assumptions:
- imagery is a unique mental mechanism or ability; thus, people must be trained in such single mechanism or ability;
- even though subjects are instructed with non-ecologically valid materials, training can succeed in prompting the subsequent spontaneous transfer to everyday tasks;
- visualization skills can be induced by simply asking subjects to perform a specific mental operation a given number of times. In other words, getting some practice in executing an operation should be sufficient to learn it.

The poster presents the partial pilot implementation of the project of a computer-based program devised to train spatial visualization. The program is designed within a framework, different from the traditional one, which is more tuned into the recent perspectives in cognitive instruction. More precisely, the program intends:
- to develop an integrated structure of various imagery operations, each playing a role in a particular kind of tasks or in a particular phase of the task;
- to use materials which mimic real-life situations or to help persons to catch the correspondences existing between the training tasks and such situations;
;- to show a metacognitive sensibility, that is, to train students not only to execute spatial strategies but also to monitor their execution.

The core idea of the program is that spatial strategies should be trained so that subjects become aware of the mental operations they are activating and can control their application. Computer should facilitate this because of the possibility to "externalize" mental operations and to assist subjects in planning and carrying them out. The goal is to lead individuals to know various imagery strategies and the conditions under which each of them is adequate. In fact, it is not sufficient to give instructions about how to carry out a mental operation and to get practice in performing it. The description of a strategy should be followed by examples of its range of application. Prototypical instances of application could serve as models to be transposed by analogy to other cases. This can facilitate the transfer from the original setting in which a strategy is learned to different novel

situations.

The program, which is under construction, consists of a set of subprograms, each concerning a specific spatial operation: recognition, moving, rotation, transformation, synthesis, and so on. Each subprogram includes three sections:

-the test section, useful to assess the initial and final skill levels reached by subjects;

-the instructional section, in which some visualization strategies are described and exemplified;

-the trial section, consisting of games where the application of the strategies previously teached is requested. In this section, at each phase of the game, hints at adopting a particular strategy, feedback about the responses given, and explanation of the reasons of the mistakes are provided. Further, subjects may be asked to select the strategy to be followed, to reconstrue mental processes they activated during the task and to reflect about them, to identify real-life situations to which the visualization strategies are relevant. All these instructional devices are aimed at inducing subjects to control the process through which they form and transform their visual representations while carrying out a task.

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7 PROCESS CONTROL AND DECISION MAKING

A Zypkin-Type Stochastic Stability Criterion for Human-Controlled Nonlinear Systems

Tscheh-Kyuhn Oh
Korea Institute of Nuclear Safety
P.O.Box 114, Yusung, Taejon 305-606, Korea
e-mail:k325otk@pinpoint.kins.re.kr

ABSTRACT: A class of human controlled systems is modelled as randomly-sampled nonlinear control systems. The transfer function of human controlled systems is defined and used to derive a criterion for the stability 'with probability 1' which can be considered as a stochastic analogue of the well-known circle criterion available for related classic deterministic feedback systems. In order to demonstrate the merits of the proposed criterion a completely worked out example is given.

KEY WORDS: human controlled system, manual control, operator model, man in the loop, randomly-sampled control system, stochastic stability.

INTRODUCTION

A lot of works has been devoted to sampled-data control systems with a randomly varying sampling period[1-4]. This problem occurs, for instance, when the sampling is governed by a random process such as a sonar or radar echo[1]. Another significant example is the blood circulation system where the pump frequency of the natural or artificial heart is contaminated by the noise existing always in this system[5]. Newly emerging problems of human controlled systems from the field of nuclear power generation can be also classified as randomly sampled systems[6]. In reality, CANDU reactors are equipped with a dual computer system for the purpose of annunciation and control. However, field experiences in Canadian nuclear power plants demonstrate that even a dual computer can fail completely. The occurrence frequency of a dual computer failure is $3x10^{-1}$ events per year with an unavailability of $2x10^{-4}$ [7]. This means that an incident of "Dual Computer Failure" occurs every third year. Since the future generation of nuclear power plants would be controlled by a computer system, it is of great importance to investigate the behaviour of the operator who has to lead the plant to the safe shut-down state in this incident specific to computer controlled nuclear power plants.

Although Kuschner, H. J. and Tobias, L.(1969, [1]) have, already in the late sixties, referred to the modelling of the power plant operator as a significant applications field of the randomly sampled control system, existing criteria for the stability of such systems require, unfortunately, the explicit determination of a Lyapunov-function involving very tedious calculations. Therefore, no easy-to-use stability criterion is available for randomly sampled-data systems, as known to the author.

The purpose of this paper is to formulate a stability-criterion in the frequency-domain which can be evaluated without determination of the Lyapunov-function of the involved system. Furthermore, a model of the operator in the emergency operation is proposed. This model is strongly oriented to the queueing theory. The early results of the author (Oh, T. K., 1980, [5]) are further extended so that they can match the proposed operator model (Choi, Y. C., 1993, [6]).

HUMAN OPERATOR MODEL AND RANDOM CONCEPT

The history of human operator models is only four decades old, but a great variety of models exists already. On the basis of the qualitative three-level model of J. Rasmussen, H. G. Stassen, G. Johannsen and N. Moray (1990, [15]) classify human operator tasks as follows.

Skill-Based Behaviour (SBB); It is widely accepted that manual control tasks in stationary process conditions lead to target oriented SBB.
Rule-Based Behaviour (RBB); Procedural oriented tasks which include monitoring, interpreting and teaching a plant under supervision in stationary as well as in non-stationary are but mainly procedure oriented RBB.
Knowledge-Based Behaviour (KBB); There are also the operator tasks such as fault management and planning which are not easy to classify. They require knowledge of the tasks to be performed, but also appeal to the creativity and intelligence of the operator, hence, they lead to goal controlled KBB.

At the SBB-level many human operator models have been developed, mainly for manual control and detection tasks, such as the *Describing Function Model* (Mcruer and Jex, 1967, [13]), and the *Optimal Control Model* (Kleinman et al, 1971, [14]). It is common to all those models that the operator is so familiar with the processes to be controlled that he has to possess such a precise internal model that in the development of the human operator models the operator's accurate internal model of the processes can be utilized. It is an illusion to assume that the human operator has a precise internal model of the plant during an incident with which he is not familiar.

Therefore, it is reasonable to develope the human operator model which necessitates only a

rough internal model, if any.

Models based on the Queueing theory have originally been proposed by Carbonell (1966, [10]) for study of instrument scanning behaviour of air craft pilots and monitoring tasks (Senders and Posner, 1976, [12]). Instrument scanning and monitoring task are only a subtask allocated to a plant operator so that the queueing theory can be applied to model not the operator behaviour as a whole but merely a certain part of his behaviours.

One of the other tasks of a plant operator is the control task. In this study, for the sake of the consistency, his control behaviour will be modelled by means of the approach which is closely related to the queueing theory so far as possible. In order to alleviate the known problem of the precise internal model of the operator, the human operator model will be based on the random process which can be specified by a minimal number of the measurable characteristics such as the first and second moment of the process.

Stochastic Task Duration

In the given accident situation, the operator should control the four distinct steam generator water levels of a CANDU-type reactor. However, he cannot pay attention simultaneously to all four signals and the environments (pressurizer level, primary heat transport system pressure, etc). Hence, the operator can control the levels of four steam generators only in a sequential manner so that merely a restricted time slice of the control period can be allocated to a steam generator for the purpose of water level control. Apparently, we are here dealing with a time-discrete control system!

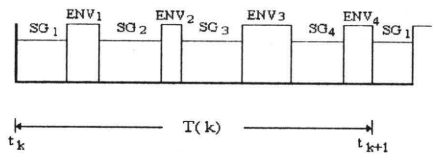

Fig. 1 A Realization of the Sampling Process of the Human Controlled Steam Generator System

The time interval between k-th control activities and (k+1)-th control activities for a given steam generator is of a considerable magnitude of order because the operator has to accomplish the control tasks for three other steam generators as well as the environmental tasks. Especially in a stressful emergency situation, the rate of forgetting will be greatly increased so that the information associated with previous task cycles remain no longer available at the beginning of a new task cycle. Therefore, every trial of a level control is nearly independent of the previous trial so that control activities in various task cycles should be regarded as stochastically independent.

At the time $t=t_k$ the operator begins with the control task for SG_1 and at $t=t_k + \tau_{k,1}$ finishes with it, where $\tau_{k,1}$ is the duration of the control task at the steam generator SG_1 in k-th task cycle. He moves under the circumstance to the environment and performs the environmental task until $t=t_k + \tau_{k,1} + \zeta_{k,1}$, where $\zeta_{k,1}$ is the duration of the environmental task associated with the steam generator SG_1 in k-th task cycle. At $t_{k+1} = t_k + (\tau_{k,1} + \zeta_{k,1}) + (\tau_{k,2} + \zeta_{k,2}) + (\tau_{k,3} + \zeta_{k,3}) + (\tau_{k,4} + \zeta_{k,4})$, the turbine operator finishes with the task associated with SG_4 and can begin with the task for SG_1 again. Also, the task cycle is reinitiated.

The duration of a task-cycle can be determined as follows: $T_k \equiv t_{k+1} - t_k = \sum_{i=1}^{4}(\tau_{k,i} + \zeta_{k,i})$

Since the operator handling the dual computer failure accomplishes, in a task cycle, a lot of tasks, he is in such a stressful situation that he cannot remember what he has performed at SG_1 a long time ago during the previous task cycle. Consequently, the behaviour of the operator in the k+1-th task-cycle is nearly independent of his bebaviour in the k-th task cycle. Hence, we have no reason to assume a strong stochastic dependence between task cycles so that the sequence of the task durations $\{T_k,\ k \in \boldsymbol{N}\}$ can be assumed to be a white process.

Probability Density Function

The sequential process of steam generator water level control tasks is a special case of the Markov process in which transitions are permitted only from state SG_i representing the control task at the steam generator i to the neighboring state ENV_i representing the associated environmental task or the subsequent state SG_{i+1}, as depicted in Fig. 2.

In detail, a transition from SG_i to SG_{i+1} means a "move" action that the operator moves his hands and eyes to the next steam generator control station. The state ENV_i and its transition has the similar meaning. Since the period of the task cycle $T(k)$ is a random variable, it must be specified by its stochastic characteristics, i.e., the state probability or the state probability density function. Because the stability criterion to be derived involves the first and second moment of system matrices, the probability density function(pdf) of $T(k)$ is needed for the determination of these moments.

Following the common notation of the queueing theory, let λ_i be the transition rate of the state SG_i at which the operator departs the state SG_i. Similarly, let μ_i be the transition rate of ENV_i at which the operator departs the environmental state ENV_i. The process will be a Markov process on the states SG_1, SG_2, SG_3, SG_4 and ENV_1, ENV_2, ENV_3, ENV_4, so that transitions are independent. The parameter α signifies the probability that the operator decides for the environmental task as the next job.

The overall system involves four equivalent stages in series. Each stage is subdivided into two states, the first state calls the operator for a steam generator level control task and the latter calls him for an environmental task just after his finished work on the previous steam generator via alarms. The fashion in which this four-stage process functions is that upon finishing his task, the operator immediately moves from the fourth steam generator or from the neighbouring

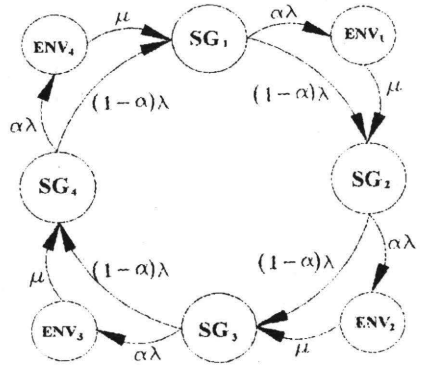

Fig. 2 State Transition Diagram of Human Controlled Steam Generator System, (source [9])

environment to the first steam generator. At least in the case illustraed in Fig. 2, pdf of the task duration can be determined by means of elementary calculations (Y. C. Choi, 1993, [6]). However, in general, pdf of the sampling process $\{T(k),\ k \in N\}$ can be extremely complicated even in a simple model. An environmental state depicted in Fig. 2 is a drastic simplification of the reality with which the turbine-operator will be confronted during an incident such as the "dual computer failure". In the case of the long-periodic task which the turbine operator has to perform in the dual computer failure, the duration of a task cycle T_k is the sum of each subtask duration $T_{k,i}$:

$$T_k = \sum_{i=1}^{n} T_{k,i},$$

where n = number of subtasks or number of states in the corresponding Markov-graph.

The environmental states consist of numerous substates so that their Markov-graph attains a remarkable size. However, as a consequence of the well-known central limit theorem of the probability theory, the pdf of the duration of task cycle converges to the normal distribution especially in the case of many subtasks ($n>>1$), independently of the distribution of the duration of its subtasks. This implies that the busier the operator is, i.e., the more complex his task is, the more precisely his behaviour can be described by the Gaussian distribution (a consequence of the central limit theorem!).

Summing up, the sampling behaviour of the human operator can be, using the standard library routines, easily implemented without additional efforts by means of the sampling process $\{T(k),\ k \in N\}$ which can be completely specified by the first and second moment.

RANDOMLY SAMPLED FEEDBACK CONTROL SYSTEM

Let us consider the nonlinear sampled-data control system of Fig. 3.

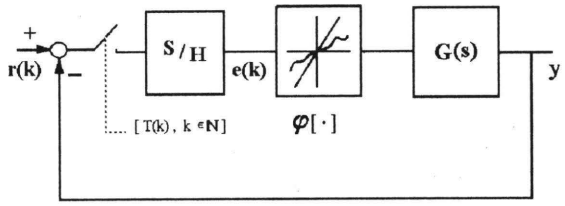

Fig. 3 Randomly Sampled Non-linear Control System

The sampler samples at a sequence of random time $\{\ t(k),\ k \in N\ \}$ and the holding intervals or sampling intervals $T(k)$ are defined by $T(k) = t(k+1) - t(k)$. The sequence of sampling intervals $\{T(k),\ k \in N\}$ will be a stationary white stochastic process.

Now, using the partial-fraction-expansion--technique;

$$G(s) = \sum_{i=1}^{n} \frac{b_i}{(s+\lambda_i)} \quad \text{with } b_i = (s+\lambda_i)\, G(s)\,|_{s=\lambda_i}$$

one obtains easily this state space representation of the control system depicted in Fig. 3:

$$\underline{x}(k+1) = \underline{\Phi}[T(k)]\,\underline{x}(k) - \underline{h}[T(k)]\,\varphi[y(k)]$$
$$y(k) = \underline{c}^t\,\underline{x}(k)$$

$$0 \le \varphi[y(k)] \cdot y(k) \le K y(k)^2, \quad \varphi[0] = 0 \qquad (3.1)$$

where $\underline{\Phi}[T(k)] = e^{-\Lambda T(k)} \in R^{n\times n}$,
$\underline{h}[T(k)] = \Lambda^{-1}(I - e^{-\Lambda T(k)})^{-1}\underline{b} \in R^n$,
$\Lambda = Diag[\lambda_1, \lambda_2, \ldots, \lambda_n] \in R^{n\times n}$,
$\underline{b}^t = [b_1, b_2, \ldots, b_n] \in R^n$,
$\underline{c}^t = [1, 1, \ldots, 1] \in R^n$.

The inequality; $0 \le \varphi[y(k)] \cdot y(k) \le K y(k)^2$ restricts the nonlinearity $\varphi[y(k)]$ to a sector in the $[y,\ \varphi\ ]$-plane, and this will be referred to as a nonlinearity in the sector [0, K] [8]. The positive real number K will be referred to as the upper bound of sector [0, K]. It will be assumed in the sequel that for all $k \in N$ the sampling interval $T(k)$ is independent of state vectors; $\{\underline{x}(k), \underline{x}(k\text{-}1), \underline{x}(k\text{-}2), \underline{x}(k\text{-}3), \ldots, \underline{x}(0)\}$. This implies that the pair $[\underline{\Phi}[T(k)],\ \underline{h}[T(k)]]$ is independent of the state vectors $\{\underline{x}(k), \underline{x}(k\text{-}1), \ldots, \underline{x}(0)\}$ again. Now, the sequence of state vectors $\{\ \underline{x}(k),\ k \in N\ \}$ in (3.1) can be easily verified as a discrete time Markov process.

MAIN RESULTS

The main objective of this paragraph is to build a bridge between the supermartingale theorem (R.

C. Bucy 1965, [2], H. J. Kuschner, 1969, [3]) and the Zypkin-criterion[8, 9]. This can be done by using the Kalman-Yakubovitch lemma (C. P. Szegö, J. B. Pearson, Jr. [8]).

It is, therefore, fundamental to the development in the sequel to put the stochastic difference equation system (3.1) into the form on which lemma 3. 4 can be applied. So, we introduce these definitions:

$$\begin{aligned}
\underline{\Phi}_m &= E\{e^{-\Delta T(k)}\},\\
\underline{h}_m &= \underline{\Delta}^{-1}(\underline{I} - E\{e^{-\Delta T(k)}\})\underline{b}\\
&= \underline{\Delta}^{-1}(\underline{I} - \underline{\Phi}_m)\underline{b}\\
\Delta\underline{\Phi}(k) &= e^{-\Delta T(k)} - E\{e^{-\Delta T(k)}\}\\
&= \underline{\Phi}(k) - \underline{\Phi}_m,\\
\Delta\underline{h}(k) &= -\underline{\Delta}^{-1}(e^{-\Delta T(k)} - E\{e^{-\Delta T(k)}\})\underline{b}\\
&= -\underline{\Delta}^{-1}\Delta\underline{\Phi}(k)\underline{b}
\end{aligned}$$

and rewrite (3.1) as follows:

$$\begin{aligned}
\underline{x}(k+1) &= \underline{\Phi}_m\underline{x}(k) - \underline{h}_m\varphi[y(k)] +\\
&\quad \Delta\underline{\Phi}(k)\underline{x}(k) - \Delta h(k)\,\varphi[y(k)]\\
y(k) &= \underline{c}^t\underline{x}(k)
\end{aligned}$$

$$0 \le \varphi[y(k)]\cdot y(k) \le K y(k)^2, \quad \varphi[0] = 0. \quad (4.1)$$

After these preparations, we give the lemma, which is based on the early work of the author (Oh, T. K., 1980, [5]) and central to the derivation of the frequency domain criterion.

Lemma 4.1

Let the $\underline{u}^t \in R^n$ be an arbitrary real vector and the symmetric (nxn)-matrix $\underline{H} = \underline{H}^t \in R^{n\times n}$ be the solution of this matrix equation:

$$\underline{\Phi}^t\underline{H}\,\underline{\Phi} - \rho^2\underline{H} = -\underline{u}\,\underline{u}^t, \quad (4.2)$$

where $\underline{u}^t \in R^n$,

$$\underline{\Phi} \equiv Diag[\,\phi_1, \phi_2, \ldots, \phi_n\,] \in R^{n\times n}.$$

Then, this condition is satisfied:

$$E\{\Delta\underline{\Phi}^t\underline{H}\Delta\underline{\Phi}\} - (1-\rho^2)\underline{H} \le \underline{Q} \quad (4.3)$$

where

$$\Delta\underline{\Phi}(k) \equiv Diag\,[\,\Delta\phi_1(k), \Delta\phi_2(k), \ldots, \Delta\phi_n(k)],$$

if and only if this (nxn)-matrix ;

$$\left[\frac{(1-\rho^2) - E\{\Delta\phi_i(k)\Delta\phi_j(k)\}}{\rho^2 - \phi_i\phi_j}\right] \in R^{n\times n} \quad (4.4)$$

is positive semi-definite.

Proof: See Oh, T. K., (1980, [5]).

Note that Lemma 4. 1 represents a necessary and sufficient condition (equivalence) and, furthermore, does not require the determination of the eigenvalues of the unknown (nxn)-matrix $\underline{H}$.

Randomly sampled data systems is often the result of random sampling of continuous-time processes where the randomness may be caused, for example, by the operator who, as a human being, can perform his control tasks only in an irregular manner. In such a case, the dynamic matrix $\underline{\Phi}[T(k)]$, especially in the diagonal form, can easily be obtained from the rational transfer function $G(s)$. Therefore, the diagonality condition of the dynamic matrix $\underline{\Phi}[T(k)]$ is fulfilled almost in a natural way.

Theorem 4.2 (Frequency-domain stability criterion),

Let $\{T(k),\ k\in N\}$ be the sampling process of the randomly sampled-data control system (4.1). If there exists a triple of real numbers $[\rho^2, \sigma^2, \delta]$ so that the following (nxn)-matrices are positive semi-definite:

1a)

$$\left[\frac{\frac{1-\rho^2}{1+\delta} - E\{\Delta\phi_i(k)\Delta\phi_j(k)\}}{\rho^2 - \phi_i\phi_j}\right] \ge \underline{Q} \in R^{n\times n}$$

1b)

$$\left[\frac{\frac{\sigma^2}{1+\delta^{-1}} - \frac{E\{\Delta\phi_i(k)\Delta\phi_j(k)\}}{(1-\phi_i)(1-\phi_j)}}{\rho^2 - \phi_i\phi_j}\right] \ge \underline{Q} \in R^{n\times n},$$

2a) all eigenvalues of the dynamic matrix $\underline{\Phi}_m$ are inside the circle $\{z \in C \mid |z| = \rho\}$:

$$\phi_i^2 < \rho^2 < 1.0, \quad i = 1, 2, \ldots, n,$$

2b) the circle condition is satisfied;

$$\bigwedge_{|z|=\rho} Re\,[\underline{c}^t(zI - \underline{\Phi}_m)^{-1}\underline{h}_m] + K^{-1} > 0 \text{ and}$$

3) the nonlinearity $\varphi[y(k)]$ satisfies the sector-condition:

$$0 \le \varphi[y(k)]\cdot y(k) \le \frac{K}{1.0 + \sigma^2} y^2(k), \quad \varphi[0] = 0,$$

then, the non-linear randomly sampled-data system (4.1) is asymptotically stable with probability one -wp1-, that is, for every positive real number ε, it holds that

$$\bigwedge_{\varepsilon\in R^+} \lim_{k\to\infty} P\{\sup_{m>k} \|\underline{x}(m)\| > \varepsilon\} = 0$$

Proof: See Oh, T. K., (1980, [5]).

The strength of the theorem 4. 2 is in being independent of Lyapunov-function $V[\underline{x}(k)] = \underline{x}^t(k)\underline{H}\underline{x}(k)$ or the unknown matrix $\underline{H}$ except the triple of the real-valued parameters $[\rho^2, \sigma^2, \delta]$ which can be determined by means of simple graphical techniques as will be shown later in the next section. The explicit determination of Lyapunov-function $V[\underline{x}(k)] = \underline{x}^t(k)\underline{H}\underline{x}(k)$, i. e., the (nxn)-matrix $\underline{H}$ is, in principle, possible but is unnecessary and requires tedious calculations.

USABILITY DEMONSTRATION OF THE DERIVED STABILITY CRITERION

Now, it will be demonstrated that Theorem 4. 2 represents a useful engineering tool. Indeed, examination of the condition 1a), 1b) and 2)

proceeds fairly straightforward so that the application seems not to be difficult.

An Example

Let the transfer function be given:

$$G_c(s) = \frac{1}{(s+1)(s+2)} . \qquad (5.1)$$

For the sake of the simplicity, the 'in the strict sense' stationary white sampling process $\{ T(k), k \in N \}$ with this probability density function:

$$p_{T(k)} = 5 \cdot I_{[0.8,1.0]}(\omega) \equiv \begin{cases} 5 & 0.8 \le \omega \le 1.0 \\ 0 & \text{otherwise} \end{cases} \qquad (5.2)$$

is chosen. Then, the system matrices of the randomly sampled system can immediately be obtained from $G_c(s)$:

$$\underline{\Phi}[T(k)] = Diag[\, e^{-T(k)},\ e^{-2T(k)} \,]$$

$$\underline{h}'[T(k)] = [\, (1-e^{-T(k)}),\ -\frac{1}{2}(1-e^{-2T(k)}) \,] \qquad (5.3)$$

Condition 1a): To examine the condition 1a) (and 1b),) the following variables are needed;

$$E\{\phi_i(k)\}\ ,\quad E\{\Delta\phi_i(k)\Delta\phi_j(k)\}$$

to build this matrix:

$$\begin{bmatrix} \dfrac{1-\rho^2}{1-\delta} - E\{\Delta\phi_i(k)\Delta\phi_j(k)\} \\ \hline \rho^2 - \phi_{mi}\phi_{mj} \end{bmatrix} \ge \underline{0} . \qquad (5.4)$$

The Sylvester's criterion can be used to test the positive definiteness of the matrix given above. Furthermore, let $F_i(\rho^2, \delta)$ be the determinant of the i-th principal minor of (5.4). As an example, the graph of $F_2(\rho^2, \delta)$ is illustrated with various values of δ in Fig. 4.

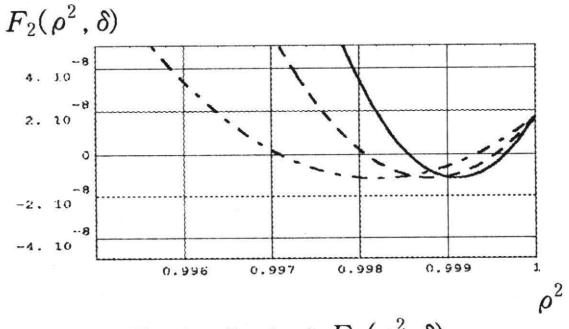

Fig. 4 Graph of $F_2(\rho^2, \delta)$

Table 1 Values of the variance $1-\rho^2$ of dynamic matrix $\underline{\Phi}[T(k)]$

δ	ρ^2	$F_2(\rho^2, \delta)$
0.2	0.997000	$0.1559*10^{-7}$
0.2	0.998000	$-0.1023*10^{-7}$
0.5	0.999000	$0.7159*10^{-7}$
0.5	0.999050	$-0.1227*10^{-7}$
1.0	0.997895	$0.2187*10^{-7}$
1.0	0.998395	$-0.3364*10^{-7}$

For the subsequent examination, the largest value of ρ^2 which doesn't make the function $F_2(\rho^2, \delta)$ negative will be taken:

Condition 1b): Taking the variables as in Table 1, the following matrix for the examination of the condition 1b) is obtained;

$$\begin{bmatrix} \dfrac{\sigma^2}{1-\delta^{-1}} - \dfrac{E\{\Delta\phi_i(k)\Delta\phi_j(k)\}}{(1-\phi_{mi})(1-\phi_{mj})} \\ \hline \rho^2 - \phi_{mi}\phi_{mj} \end{bmatrix} \ge \underline{0} .$$

As an example, the determinant of the second principal minor $G_2(\delta, \sigma^2, \rho^2)$ is illustrated in Fig. 5 with various values of δ. For the subsequent examination, the largest value of σ^2 which does not make the function $G_2(\delta, \sigma^2, \rho^2)$ negative is chosen.

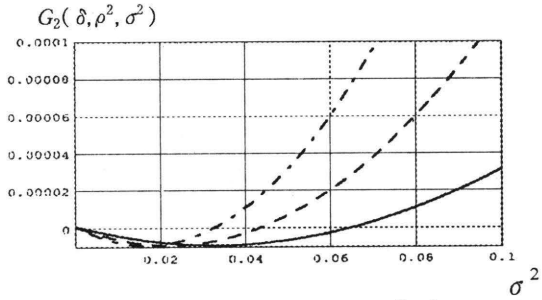

Fig. 5 Graph of $G_2(\delta, \rho^2, \sigma^2)$

Table 2 Values of variance σ^2 of input matrix $\underline{h}[T(k)]$ for various δ and ρ^2

δ	ρ^2	σ^2	$G_2(\delta, \rho^2, \sigma^2)$
0.5	0.999000	0.070	$0.12532*10^{-5}$
0.5	0.999000	0.060	$-0.25255*10^{-7}$
1.0	0.997895	0.050	$0.67967*10^{-5}$
1.0	0.997895	0.040	$-0.25242*10^{-7}$
2.0	0.997000	0.035	$0.32401*10^{-5}$
2.0	0.997000	0.030	$-0.25231*10^{-7}$

Condition 2): Condition 2) resembles the classic circle criterion and represents, apparently, a stochastic analogue of Zypkin-criterion.

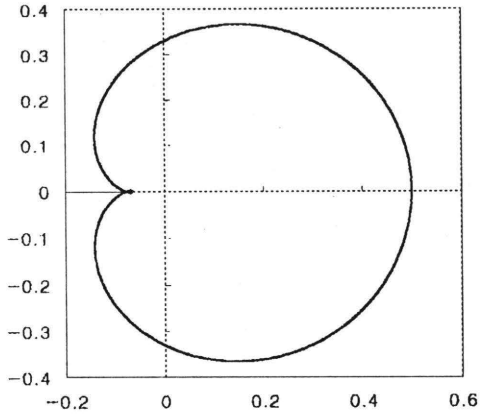

Fig. 6 Nyquist locus of the transfer function of the control system with random sampling.

The examination of this condition requires the

investigation of the complex-valued function;

$G(z) = \underline{c}^T(z\underline{I} - \underline{\Phi}_m)^{-1}\underline{h}_m$.

The upper limit of the sector interval K can be determined from Nyquist-locus depicted in Fig. 6.

Condition 3): Now, the permitted upper limit of the sector interval $K_\sigma = K/(1+\sigma^2)$ can be obtained from Table 1 and Table 2.

Table 3 The permitted Upper Limit K_σ of the sector interval [1, K]

δ	σ^2	K	K_o
0.5	0.070	7.1187	6.5300
1.0	0.050	7.0989	6.7609
2.0	0.035	7.0983	6.8583

Discussion of Results

As demonstrated in the example given above, all conditions in theorem 4.2 can be examined exclusively by simple methods.

As seen in Table 1, ρ^2 is located close to the neighbourhood of 1.0 and, therefore, the parameter $\Delta\rho^2 = 1-\rho^2$, called the variance of the dynamic matrixis (T. K. Oh '80, [5]), a very small number, in the case where the variance of the sampling process $E\{(T(k) - E\{T(k)\})^2\} \approx 0.00011$ is not substantially larger than in the demonstration. The parameter σ^2, called the variance of the input matrix (T. K. Oh '80, [5]), is also quite a small number, as seen in the Table 3. Because the complex-valued function $G(z) = \underline{c}^t(z\underline{I} - \underline{\Phi}_m)^{-1}\underline{h}_m$, called the transfer function of the randomly sampled control system (T. K. Oh '80, [5]), only needs to show a very small exponential stability degree $\Delta\rho^2 = 1-\rho^2 \approx 0.0$ the condition 2) in theorem 4.2 is not a hard requirement. It can now be seen that in the case of the randomly-sampled or human-controlled system the transfer function $G(z)$ formed out of the expectation of the system matrices has to show the degree of the exponential stability corresponding to the variance of the dynamic matrix and the upper limit of the sector interval K must be slightly reduced in accordance with the variance of the input matrix σ^2, namely, by the factor $1.0/(1+\sigma^2)$. Because the variance of the sampling process in many practical situations is small, the stability of the randomly-sampled or human-controlled system is determined mainly by the expectation of its system matrices $[\underline{c}^t, \underline{\Phi}_m, \underline{h}_m]$, hence by the condition 2) of theorem 4. 2. The stability of the randomly-sampled or human-controlled system is determined by the expectation of its system matrices $[\underline{c}^t, \underline{\Phi}_m, \underline{h}_m]$ and, therefore, can be handled as a deterministic control system with a constant sampling interval $T(k)$= Const.. Now, the stability problem of randomly-sampled or human--controlled systems can be tackled by the results of the known deterministic control theory.

CONCLUSION

In spite of the continuing efforts for the automation of the process industries, there exist some domains which will be reserved for humans even into the far future. The emergency operation during an incident in the nuclear power plants(NPP) represents one of the domains reserved for the human operator. In the existing operator models[13-14], human acts as a time-continuous controller while, in emergency situations, operators of NPP perform their complicated tasks sequentially and, consequently, operators of NPP represent inherently time-discrete stochastic controllers. Results presented in this paper give, however, a bright insight and technical tool for handling the random behaviour of human operators in the control loop quantitatively.

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A Symptom-Bookkeeping Aiding for Fault Diagnosis in Dynamic Systems

Huhn Kim[1], Wan Chul Yoon[2] and Sangsup Choi[3]

Department of Industrial Engineering
Korea Advanced Institute of Science and Technology
373-1, Gusung-dong, Yusung-gu, Taejon, 305-701, Korea
[1]hkim@cogsys.kaist.ac.kr [2]wcyoon@sorak.kaist.ac.kr [3]schoi@cogsys.kaist.ac.kr

ABSTRACT

In large-scale dynamic systems such as power plants, fault diagnosis becomes more difficult due to changing system states. Symptoms can be obscured by other symptoms or disappear as the operator proceeds with diagnosis or compensation. Such symptom-masking phenomena increase operator's memory load, constrain diagnostic strategies, and hence degrade performance. This study investigates the effects of a symptom-bookkeeping aid in a simulated sub-system of nuclear power plants. The results show that the aiding improved overall performance. Further analyses provide insights on the sources of cognitive difficulties and on the possible direction of supporting human diagnosis in dynamic plants.

Keywords
Fault diagnosis, symptom masking, dynamic symptoms, bookkeeping aiding

INTRODUCTION

In spite of the rapid progress of machine intelligence, the human still plays a central role in fault diagnosis in large-scale systems. With ever increasing degree of automation, fault diagnosis is also becoming more important part of human tasks in such systems. Therefore, the cognitive difficulties of fault diagnosis should weightily be considered in the design of the human-machine interface of large-scale systems.

Operator's cognitive difficulties in diagnosis tasks obviously depend on the complexity of problem solving that is determined by the size, interactions, and dynamics of the system (Rouse & Rouse, 1979). Wohl (1982) showed that the time to diagnose increases exponentially when the amount of information required by the diagnostic task is too large to be processed by human operators.

Besides the structural complexity of a system, the dynamic characteristics of a system may also hamper the cognitive process of human problem solving for fault diagnosis. The operator must not only run a mental model of the system dynamics, but also deal with dynamically defined symptoms. The use of such symptoms is complicated by the fact that the diagnostic meaning of a symptom is not apparently indicated by the observable form of the corresponding data. That is, the abnormal behaviour of a system should be inferred on the basis of observable sensor readings that should be interpreted in the specific context of the performed operations and thus of incurred system state changes. Observed data for symptoms may take the forms of sensor readings, changes in readings, or comparisons between readings. In contrast, a symptom as is meaningful to diagnosis may be the failure in producing an expected system behaviour through a sequence of control actions starting at a certain specific system state.

In this situation, diagnostic symptoms may change their manifestation as the operator performs actions for diagnosis or compensation. Symptoms can also be obscured by other symptoms or disappear altogether. Losing a symptom and the corresponding observation due to subsequent operations may cause a severe memory problem since symptoms are contextually interpreted and not concisely described in the verbal mode. This phenomenon is referred to as symptom masking by several researchers and found to be an important cause that degrades diagnostic performance. The loss of visibility of a symptom increases operator's working memory load and constrains diagnostic strategies (Duncan and Praetorius, 1987; Yoon and Hammer, 1988; Pawlak and Vicente, 1996).

In this study, we investigated the effects of a symptom-bookkeeping aiding (SB-aiding) on fault diagnosis of a dynamic system. An experimental simulator named AFWS-D (Auxiliary FeedWater System - Diagnosis) was

built and used as a target system. The results showed that the SB-aiding improved diagnostic performance in various measures. A post-hoc analysis sheds lights on the sources of cognitive difficulties of fault diagnosis in dynamic situation. A possible direction of supporting human diagnosis in dynamic plants is clearly suggested.

SYMPTOM MASKING AND BOOKKEEPING AIDING

One of the most frustrating difficulties stems from the fact that the observed data for dynamic symptoms are highly volatile. A symptom may be exhibited by different set of observations as the operator performs actions for diagnosis or compensation. It can also be overridden by other symptoms or suppressed altogether. Such symptom masking is one of the main causes that degrades diagnostic performance. The frequency of symptom masking will be even higher when the diagnostic actions and compensating actions are heavily interwoven, which is typical in emergency operations of dynamic plants (Lindgaard, 1995). When the corrective or compensating action is achieved, the system enters into a fault-masked state in which the operator has almost no opportunity for detecting abnormal system behaviour. For example, a pipe leak becomes obscured when the part is isolated by closing the valves surrounding it.

Yoon and Hammer (1988) observed that the operators experienced trouble returning the system from a fault-masked state to a state exposing abnormal behaviour. Reversing the actions that masked the fault in the backward order seldom recovers the original state. It is very hard for a operator to remember the observed data along with the context and the diagnostic connotation when the observation is no more visible or reproducible. Moreover, because a symptom is related to a set of hypotheses and the set is frequently held together in the memory by the symptom, symptom masking can induce hypothesis masking. Raaijmakers and Verduyn (1996) observed that the subjects tended to forget what they had checked and why hypotheses had been rejected. It was also found that experts performed better than novices in fault diagnosis by keeping the lookout for symptom masking and foreseeing impending problems (Duncan and Praetorius, 1987).

Computer aids for complex tasks need to be designed to supplement human cognitive limitations in attention, working memory, and information processing. Yoon and Hammer (1988) argued that information aiding has an advantage over more obtrusive automated reasoning in that it allows the human to remain in command in the task loop and inference strategy. Raaijmakers and Verduyn (1996) designed an information aid for fault diagnosis in a different domain and verified that the aid enhanced the performance considerably. However, an information aid, as passive as it is, must be designed to provide timely and usable information reflecting the human problem solving strategy (Yoon and Hammer, 1988; Konradt, 1995).

Bookkeeping aiding is the most basic information aiding that helps lessen the working memory load without producing any information the human does not have. Duncan and Praetorius (1987) as well as Pawlak and Vicente (1996) suggested that providing historical information may reduce masking problems. Konradt (1995) observed that, in a dynamic system diagnosis, resorting to the historical information was by far the most frequent strategy used by experts. To be effective, the information provided by a bookkeeping aid needs to be selected and represented to be readily used in the human diagnostic process. Especially, the historical records must facilitate the operator's recalling of the full implications of the symptoms (Rouse, 1978) and integrating them efficiently into current information without much additional work load.

In this study, we provided the chronology of the observed data along with the operations performed before and after the observations as the aiding information. The observation is a cue to the memory of more abstract symptoms regardless of their diagnostic meaning. The symptoms are also remembered more easily in association with the observable data than in abstract terms. The transforming between the aiding cue and the relevant information in memory can thus be minimised by keeping the forms of observations instead of abstract symptoms or hypotheses.

SYSTEM AND DIAGNOSIS TASK

The System

The Auxiliary FeedWater System (AFWS) in nuclear power plants was used as the environment for the diagnosis tasks in this study. The AFWS for two-loop PWR (Pressurized Water Reactor) contains redundant pipes, valves, check valves, pumps, tanks, and control devices (Figure 1) for safety. For the experiment, we built a simulated AFWS that was called 'AFWS-D' (Auxiliary FeedWater System-Diagnosis). In the AFWS-D, the operator opens and closes valves and turns on and off the pumps. Sensor information does not give exact numeric values, but more abstract qualitative information. For example, the qualitative information includes

only the sign of the derivatives (i.e., increasing, decreasing, or stable). With these simplifications, AFWS-D still grasps considerable practicality of diagnostic situation and strategies.

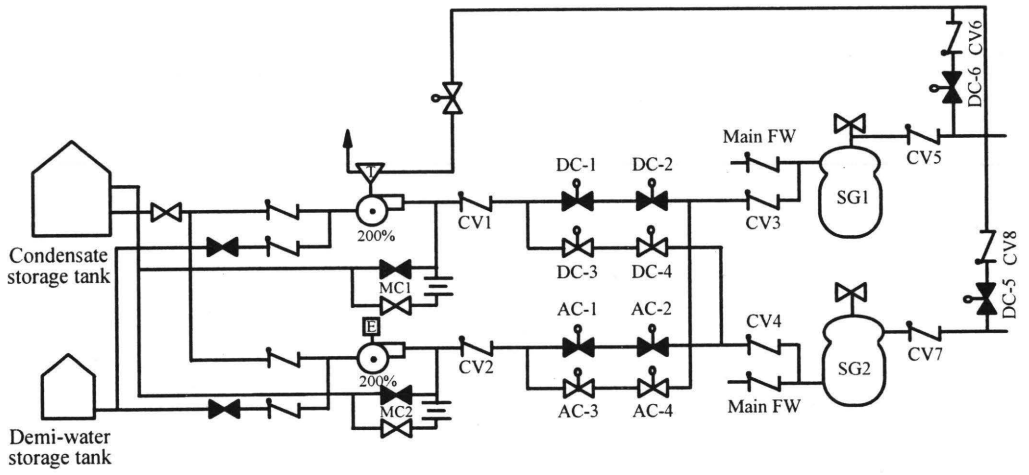

Figure 1. PWR auxiliary feedwater system

The Diagnosis Task

In AFWS-D, the operator's task is to diagnose a fault under malfunction situation. The operator must control and observe the system continuously in order to diagnose a fault because diagnosis cannot be made by observing a single scene (system state). This requirement for diagnosis in dynamic systems at times inevitably induces the symptom masking. In AFWS-D, each component has several different behaviour modes. For example, valves have modes such as normal, fail open, fail closed, and leak. The operator's diagnosis task in AFWS-D is to find a failed component and its behaviour mode that explain all the observed system behaviour.

AFWS-D Interface

The AFWS-D interface is shown in Figure 2. The AFWS schematic shows the states of valves and pumps in the AFWS. The operators are allowed to interact with the system through the interaction and schematic windows. Operators can perform control actions in the AFWS schematic, and the feedback of actions is provided in the interaction window. The sensor readings window, which is provided to mitigate the operator's working memory load, shows the observations made in the current scene. The help window shows all behaviour modes of each component. The SB-aiding window provides the operator with aiding information that will be discussed later.

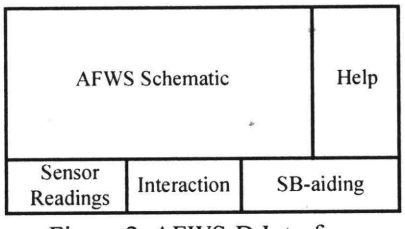

Figure 2. AFWS-D Interface

THE SYMPTOM-BOOKKEEPING AIDING

Symptom masking occurs because the system state changes as the operator takes control actions for diagnosis or compensation. Whenever a masked symptom is actively involved in the current human diagnostic reasoning, it needs to be retained in the working memory. Furthermore, when the diagnosis at a time point requires evidence from several symptoms, the currently visible symptoms and the ones in the working memory must be integrated through some common logical operations. As pointed out earlier, the content of memory contains not only the observation made but also the context of the observation as necessary to interpret it at the level of system behaviour. This means a heavy memory load as well as a severe cognitive difficulty in information processing.

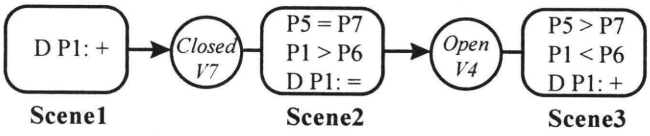

Figure 3. Dynamic Symptoms

In this system, the contextual information includes the previous state, which has been assessed by a set of previous observations, and the previous operations with their expected results in system behaviour, and finally the current observation as compared with the expectation. Since the symptom may not belong to a single static scene, it may be called dynamic or contextual. An example of such contextual symptoms are presented in Figure 3. Scene 3 has masked the symptoms in Scene 2 by opening valve V4. Instead, a new symptom may be exhibited which can only be perceived by relating Scene 3 to Scene 2 and the operation in between.

Now, the question of how such dynamic symptoms can effectively be represented by the computer should be answered. The symptoms are defined by dynamic combinations of two primitive elements: control actions and observations. Then the symptoms may be described in more abstract words that are meaningful to the current progress of diagnostic reasoning. Recording such abstract description of symptoms through overt communication will certainly be inadequate. On the other hand, the human diagostician, having once integrated the states, actions, and observations to establish a meaningful symptom, can use those elements as a cue to the memory of the abstract symptom. Even when the symptom is not immediately recalled, the operator can easily reconstruct the symptom from the elements. This consideration led us to design the SB-aiding to record the control actions and observation made by the operator and present them chronologically.

The SB-aiding provides the operator a feature by which she or he can mark scenes that are considered important and expected to be useful later. For example, the operator can mark a scene in which abnormal system behaviour is found. Using the index of the marks, the operator can review previous scenes as necessary.

THE EXPERIMENT

Twelve undergraduate students participated in the experiment. The experiment was consisted of three sessions. In Session 1 (2.5 to 3 hours), all the subjects studied training material to learn basic theories of fluid dynamics and possible fault behaviour of components of AFWS. They also learned elementary diagnostic procedures such as checking a valve leak or a pump fail-on. Then, they solved five fault problems to practice what they had learned.

In Session 2 (1 to 1.5 hours), about a week later after the basic training, the subjects returned and received a brief review of what they had learned in Session 1. Subjects were divided into two groups, the aided group and unaided group, on the basis of the diagnosis time collected in Session 1 with constraint that the sums of ordinal performance ranks for the two groups were approximately equal. The aided group were given a written instruction on how to use the SB-aiding. The instruction contained information only on the SB-aiding window, but did not include any other elements that can enhance diagnostic performance. All the subjects solved three fault diagnosis problems. The only difference between the two groups was that the SB-aiding was available to the aided group.

In Session 3 (about 1 hour), with a short break following Session 2, each subject solved five novel fault problems. Again, the SB-aiding was provided only to the aided group. These novel fault problems in Session 3 were different in nature from the ones used in Sessions 1 and 2 in that they required causal reasoning beyond simple diagnostic procedures learned or developed in Sessions 1 and 2.

THE RESULTS

Overall Effects of SB-aiding

Subjects' overall performance was measured in the amount of time to solve the novel fault problems (diagnosis time), the number of information gathering actions (IGA), and the average time to detect an abnormal system behaviour (ASB-time) after it appears.

On the average, the aided group took 48 percent less time to diagnose a fault (423.7 vs. 815.2 s, $p < 0.001$) and performed 66 percent less information gathering actions than the unaided group (11.967 vs. 34.667, $p < 0.001$). Such aiding effects appeared for all the five fault problems. The number of IGA were highly correlated with diagnosis time in both the aided group and unaided group ($r = 0.66134$, $p < 0.001$ and $r = 0.75728$, $p <$

0.001, respectively).

With regard to ASB-time, the two groups did not significantly differ although the aided group took more time than the unaided group (11.708 vs. 8.702 s, $p > 0.2$). SB-aiding certainly did not help the subjects identify the abnormal situations quickly. However, ASB-time was not correlated with total diagnosis time in the aided group ($r = 0.18505$, $p > 0.3$), while it showed a strong correlation with diagnosis time ($r = 0.58428$, $p < 0.001$) in the unaided group.

It was observed that the subjects in the unaided group tried to avoid a large deviation from an initial scene or a scene in which abnormal system behaviour happened. This strategy seemed to be employed to avoid excessive memory load as much as possible. When successive operations to observe system behaviours and to test the hypotheses overshadow a highly diagnostic scene, the subjects tended to return to the scene as soon as possible before the scene is forgotten. This interpretation is supported by the fact that the unaided group made redundant tests more frequently than the aided group. In contrast, the subjects of the aided group utilises the SB-aiding to mark and retrieve the scenes in which they observed abnormal situations or negative evidence.

Influence of SB-aiding on Symptom Masking

The above results did not explain what makes the aided group perform better than the unaided group, although SB-aiding improved overall diagnostic performance. Results from a post-hoc analysis provide such explanation. The analysis was performed on the subjects' recorded action traces and was based on a classification of the effectiveness of the subjects' actions. For example, subject's control action was classified with effective, ineffective, and masking action for evaluation.

In the post-hoc analysis, several interesting phenomena related to symptom masking were observed. In the unaided group, the subjects performed more redundant and shadowed tests that were as being ineffective. Shadowed tests refers to a test that is relevant but, being overshadowed by previous effective tests, cannot further narrow the set of competing hypotheses. Besides, after symptom masking occurred, a phenomenon called drifting was frequently observed in the unaided group. The shadowed tests during masking period (the period under symptom masking) can induce drifting. Drifting could be classified by the phases in diagnostic search strategy. During data-driven search (Yoon and Hammer, 1988), the subjects may ignore masked symptoms and pay attention to a new inefficient symptom displayed in interface. Such drifting is called symptom-drifting. Symptom-drifting hampers an effective integration of observed information and delays formation of a sound hypothesis set. Similarly, during hypothesis-driven search in which the diagnostic actions are guided by some well-specified set of hypotheses, hypothesis-drifting can occur. In this case, the subject ignores or forgets a previous hypothesis set and deals with a less efficient hypothesis set that is formed by the new symptoms. Both types of drifting were either directly related to symptom masking or excessive working memory load induced by the masking. This was verified by that the SB-aiding significantly reduced both types of drifting.

CONCLUSIONS

Symptom masking, which occurs when the operator's action changes the state of the system causing the observed symptom to disappear, increases operator's working memory load and degrades diagnostic performance. In this study, an aiding method called symptom bookkeeping aiding (SB-aiding) was proposed and evaluated for assisting the operator in fault diagnosis under symptom masking. The aiding method was intended to reduce cognitive load by providing information on the previous symptoms, which subjects should keep in working memory otherwise. The bookkeeping aid provided a chronological list of operator actions and observations that may be masked and indexed. In order to evaluate the effectiveness of SB-aiding, an experiment with a simulated Auxiliary FeedWater System (AFWS) was conducted. The experimental results showed that subjects with SB-aiding (aided group) showed better performance than subjects without SB-aiding (unaided group). A post-hoc analysis investigated the relationships between symptom masking and the effectiveness of diagnostic tests. SB-aiding also contributed to the performance by reducing the drifting cases. The experiment and the results suggest that SB-aiding can perhaps be the most basic computer support in large-scale dynamic plants.

ACKNOWLEDGEMENT

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ANALYSIS OF THE EFFECTS OF A SUPPORT TO ANTICIPATION IN THE SUPERVISION OF A LONG TIME-LAG PROCESS: THE BLAST FURNACE.

Pascal Denecker & Jean-Michel Hoc

CNRS - University of Valenciennes, LAMIH, PERCOTEC
B.P. 311, F-59304 VALENCIENNES CEDEX
{surname@univ-valenciennes.fr}

ABSTRACT

The main results of an experiment on the effect of the regular use of a computer support to anticipation on its mechanisms and supervision strategies are reported in a blast furnace situation. Regular users were more critical as regards their forecasts, more analytical, speedy, and exhaustive in their situation analysis, and shaw a more appropriate risk management strategy. In this case of knowledge-based activity developed in an uncertain situation, implications are drawn on the positive effect of the use of a support to an active elaboration of forecasts in a situation where operators were shown to usually rely on implicit expectations.

Key words: Dynamic Situation Management, Process Control, Anticipation, Computer Support, Blast Furnace.

PROBLEM AND AIM OF THE STUDY

In dynamic situations, whose evolution are uncertain and in which many factors interact, the human operator control of the process is only partial (Hoc, 1996; Woods, 1988). They constitute a vast class of work situations, in areas as diverse as industry, aerial navigation and medicine. For an efficient management, more often than not they need to bring complex operators' activities into play, and more especially reasoning activities. Reasoning, by the means of diagnosis and prognosis, contributes to a large extent to the elaboration of representations of the system, to understand it, forecast its evolution along time, and act on it.

Many studies on operators' activities in dynamic environments have clearly shown the major role of anticipation (De Keyser, 1988; Van Daele, 1992, 1993), that constitutes a distinctive feature of expertise (Bainbridge, 1988; Cellier, Eyrolle, & Mariné, 1997). When the system has long response latencies, like the blast furnace (iron production) considered in the present study, operators shift from a reactive to an anticipative mode of functioning (Hoc, 1996). More often than not, this knowledge-based open-loop regulation allows operators to efficiently manage the process upstream, by preventive actions to reduce potential risks. Nevertheless, such anticipative strategies require large cognitive resources, especially mental models to support state and evolution representations of the system, and to prevent the major risks.

The blast furnace is characterised by an *indirect* control since operators cannot intervene directly on crucial variables (the temperature of cast-iron for example) but by the means of parameters situated upstream in causal chains. Similarly, the access to the crucial variables is *indirect*, and operators must use observable parameters (symptoms) to infer covert phenomena or process descriptors (syndromes) inside the process. The process is also *continuous*, hardly discretisable, and necessitates representations in terms of evolutions rather than stable states. Finally, the *long response latencies* should trigger anticipation activities in operators, an schematic representations due to uncertainty of evolutions (Hoc, 1996).

Previous studies on blast furnace control have allowed to surround diagnostic activities developed by operators, without precisely describe anticipation strategies, because more often than not prognosis remained implicit (Hoc, 1989b), and action decisions were more directly related to observable parameters that to hypotheses on covert phenomena motivating the decisions (Hoc, 1989a). Hoc (1991) did an experiment to study the respective effects of operator expertise and situation complexity on types of processing, representations and hypotheses generated. Expertise appeared to be related to the production of more frequent forecasts and, at the same time, to a reduction in explanations after the events. On the other hand, when situation complexity increased, operators adopted a more contemplative attitude more oriented toward the understanding of the situation rather than to actions to undertake. Complexity was shown to have a negligible effect on representations and hypotheses generated, but types of processing appeared considerably modified, with a

reduction in the forecasts and, at the same time, an increase in explanations. Explanations after the events could be due to implicit expectations on the evolution of the process, since operators did not demonstrate any surprise at these times.

The analysis of verbal reports' temporal contents collected during blast furnace control (Hoc, 1996b) did not show any difference as far as expertise was concerned. Only 40% of reported clauses were temporally marked, half of them were related to evolutions, and only 17% of reported evolutions concerned the future (83% being past or present evolutions).

Finally, Samurcay & Hoc (1996) have proved the relevance of an interface allowing the manipulation of several abstraction levels according to a functional and causal hierarchical structure, comparatively to the current interface of a topographic kind with only one abstraction level. The use of this interface allowed operators to adopt a more active attitude, a more structured strategy of information gathering and hypothesis generation to causally understand the present state, and to extend their analysis of potential actions. Nevertheless, the use of this type of assistance did not produce more explicit anticipations (forecasts).

In sum, previous studies of this process control situation have provided us with interesting conclusions related to the relevance of a support to reasoning, without clearly describing and showing any effect on anticipation mechanisms. At least, we can reasonably think that expectations take place to cope with evolutions, since operators devote some time to the generation of explanatory hypotheses that could be the consequence of expectations. However, we decided to identify possible forecasting mechanisms in a situation where some support to them was available (a computer model simulating the iron temperature's future evolution on the basis of the past evolution and of action decisions). More precisely, we observed expert operators, comparing regular users of the tool with casual users to identify the long-term effect of the regular use of the tool on strategies.

EXPERIMENTAL DESIGN AND METHOD

In the experiment, we used the reproduction of a real blast furnace operation situation to be replayed by the operators. We selected four regular users and four casual users on the basis of preliminary interviews. We used a particular function of the software supporting thermal adjustment (simulation model), namely the forecasting of cast-iron temperature evolution (a major variable in blast furnace control). A homogeneous level of expertise was satisfied (training level and seniority) between the two groups. We presented the usual documents (those used in the real work situation) and curves under the usual format of the tool. The reproduced situation was a case where the blast furnace was quite stable, and belonging to the domain of validity of the model. The blast furnace operation was normal until shift handling, then a sudden decrease in cast-iron temperature was observed. Only one model entry parameter could explain the thermal state worsening, namely a decrease in an indicator of the reduction quality (the main function of the process is removing oxygen from ore to produce pure iron).

In this experiment, we studied (1) shift-handling: the analysis of the situation history and a possible action decision elaboration; (2) forecasting with no action decision: the drawing of the cast-iron temperature future trend, assuming that no action on the process is done, on a copy of the computer screen; (3) confrontation with curves: judgements produced in front of ten alternative curves distorted according to two dimensions — the amplitude and the response latency of the worsening of the reduction quality on the thermal state; (4) forecasting with action decision: a second curve production, assuming that an action is done; and (5) confrontation with actual future: the comparison of the actual evolution (integrating actual crew's decisions, close to the subjects' decisions: action on coke) with the evolution simulated by the model.

Cognitive activities were coded on the basis of inferences from verbal and non verbal (observable) behaviours, under the control of a "frame-model" to describe these activities. In the present experiment, the verbal protocol analysis bore on the cognitive architecture (the frame-model) proposed by Hoc and Amalberti (1995) for dynamic situation management. This cognitive architecture comes from other diagnosis models, especially the Rasmussen's "step-ladder" (1986), but differs by its non-sequential nature. It relies on the central notion of a continuous updating of a current representation of the situation to enable decision-making. It assumes a parallelism between different cognitive regulation levels based on skills, rules, or knowledge. At the same time or on a time-sharing basis, operators must maintain a valid plan (planning and replanning, in the long or medium-term) integrating not only their own actions, but also the spontaneous process evolution, and give priority to the short-term control of the process.

All the protocols collected were transcribed and coded. The coding was done with the help of the MacSHAPA software (Sanderson *et al.*, 1994) which is an interesting support to protocol encoding, without imposing a particular theory. Inferences realised from verbal protocols covered four classes of activities (Figure 1): information gathering, information gathering management, diagnosis, and action. Each class was decomposed into predicates corresponding to elementary activities, and arguments coding the representations used and transformed by these activities.

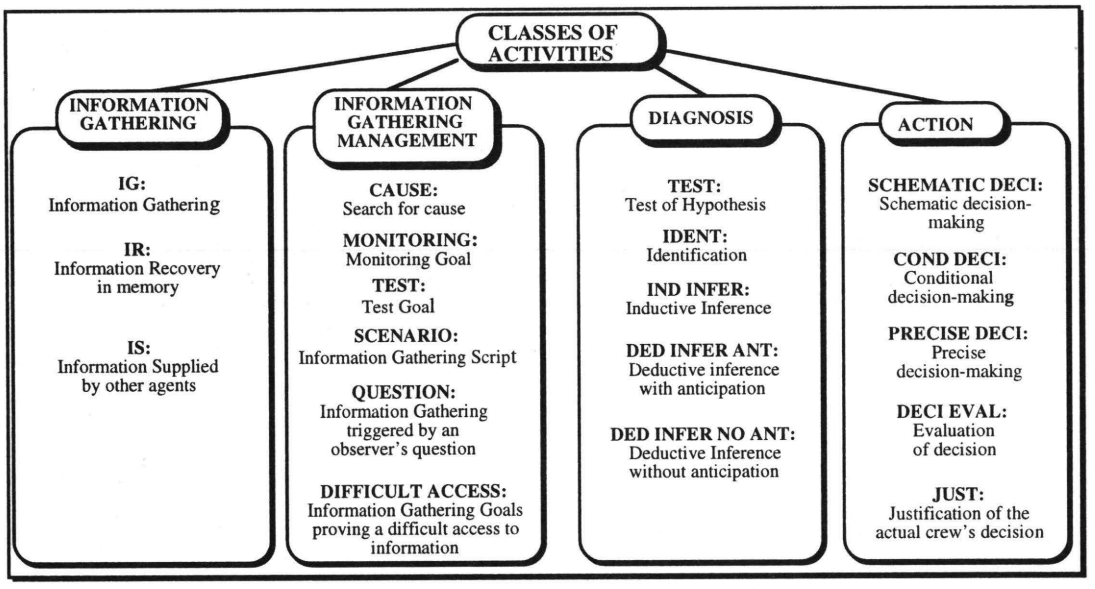


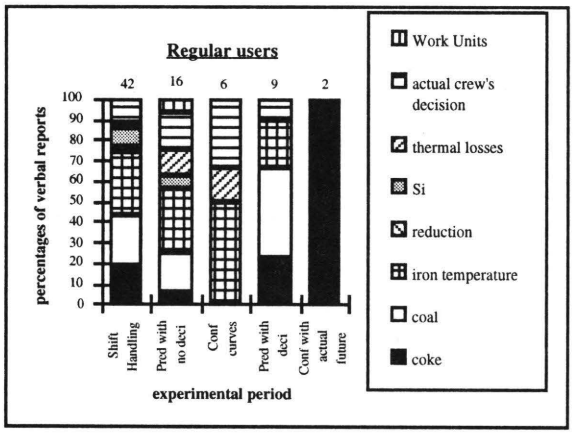
Figure 1: Classes of activities for coding protocols.

RESULTS

The present paper is devoted to the analysis of the verbal reports collected during the five experimental periods. Other results are available, especially the verbal reports during the preliminary interviews (context of use of the tool), clinical data collected during the experiment, errors committed when questioning the proposed curves or when drawing curves. From these other sources of information, we can say that the curves were carefully examined or drawn, with frequent return to the other measures. Obviously, the operators proved their ability to precisely formulate forecasts rather than showing a guessing behaviour. Here we will propose four kinds of interpretation of the differences between the regular users and the casual users, and give some evidence for them. Regular users are (a) more critical as regards their forecasts, (b) more analytical and exhaustive in their situation analysis, (c) more speedy in doing it, and (d) more efficient in risk management. Evidence will be given by comparing distributions over argument values or individual predicates for each experimental period, between the two groups of operators, for the four classes of activities (Figure 1).

Critics of the Forecasts

For each experimental period, Figure 2 displays the distributions over the values of one of the arguments of the information gathering predicates — the type of object considered. However, the set of values is restricted to some parameters of the model, that were reported by the operators during the preliminary interviews as the most relevant to thermal adjustment. Here, we will focus on the confrontation with curves (third experimental period) where the two groups of operators adopted two different strategies. Regular users took for granted that the model's forecasts are very often approximate and they were used to see some discrepancy between their own forecasts and those of the model. Hence they read the global trends of the curves rather than precise values. However, in the experimental situation, where the curves were largely distorted, the operators checked their situation analysis, either searching for the possible causes of distortion in the situation history they could have missed (possibly unnoticed actual crew's actions or increase in thermal losses which can announce a decrease in iron temperature) or extrapolating from the past iron temperature's evolution. Figure 2 shows that only the regular users reported these three parameters. On the contrary, casual users took the model's forecasts as precise and correct data. When the curve was not in accordance to their forecasts, they assumed that an entry parameter was changed in the model before drawing the curve (fictitious action on coke). In addition, they tried to check a possible effect of the recent evolution of 'Si'. But this evolution is only correlated with a short-term iron temperature evolution, not to a long-term evolution as shown by the curve. Only casual users reported these two parameters (see Fig. 2). Hence, regular users were able to use the model to check their situation analysis (mutual control), whereas casual users did not really check their causal forecasts. Hence, regular users were more critical as regards their forecasts than casual users.



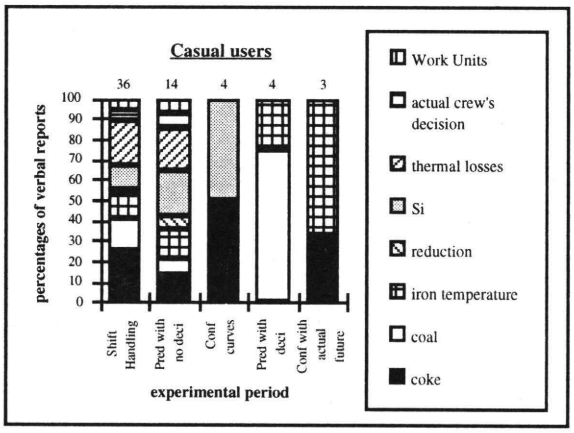


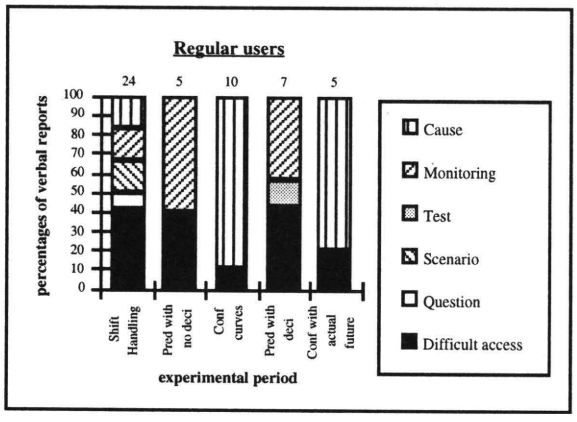
Figure 2 : Percentages of parameters reported by regular users and casual users (total frequencies above).

Quality of the Situation analysis

Now, we will return to the Figure 2, but focusing on the fourth experimental period (forecasting with action decision). Here we can see that regular users considered more parameters to forecast (actual crew's actions and coke) than casual users. In this way, they combine the effect of their own action (on coke) more exhaustively with the actual crew's actions and the general context (long period of low coke proportion in the charge). They were also more exhaustive (more parameters considered) during the confrontation with curves (third experimental period). They were more analytical since they considered the actual crews' actions more often than the casual users whatever the experimental period (apart from the fifth), using these actions to produce precise calculations. Hence the quality of the situation analysis was better in regular users than in casual users.

Speed of the Situation Analysis

For each experimental period, Figure 3 shows the distributions over the information gathering management predicates, that is the activities underlying the information gathering goals. During the two first experimental period (shift-handling and forecasting with no action), casual users verbalised more frequent information gathering goals motivated by the development of information gathering routines (scenarios) than regular users. Such scenarios correspond to preliminary routines preceding a more specific analysis of the situation. In addition, we can see that regular users did not report any scenarios during the second experimental period (the preliminary analysis was finished) whereas casual users continued. It is the same for goals motivated by the understanding of the situation ('cause'). Regular users did not report any goals of this kind during the second period contrarily to casual users. They had finished their situation understanding. Obviously they reported this kind of goals during the confrontation with curves or with the actual future since the task forced them to do that. Hence regular users were more speedy than casual users in analysing the situation.



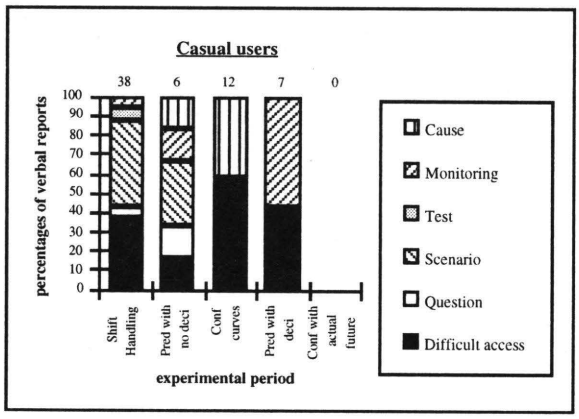


Figure 3: Percentages of types of processing underlying information gathering goals by regular and casual users (total frequencies above).

For each experimental period, Figure 4 shows the distributions over the diagnosis/ prognosis predicates. During the two forecasting periods (second and fourth periods), regular user reported more frequent prognoses (deductive inference with anticipation) and less frequent understanding hypotheses (inductive inference: hypotheses on the possible causes of phenomena). This observation confirms that regular users took the lead over casual users in situation understanding.

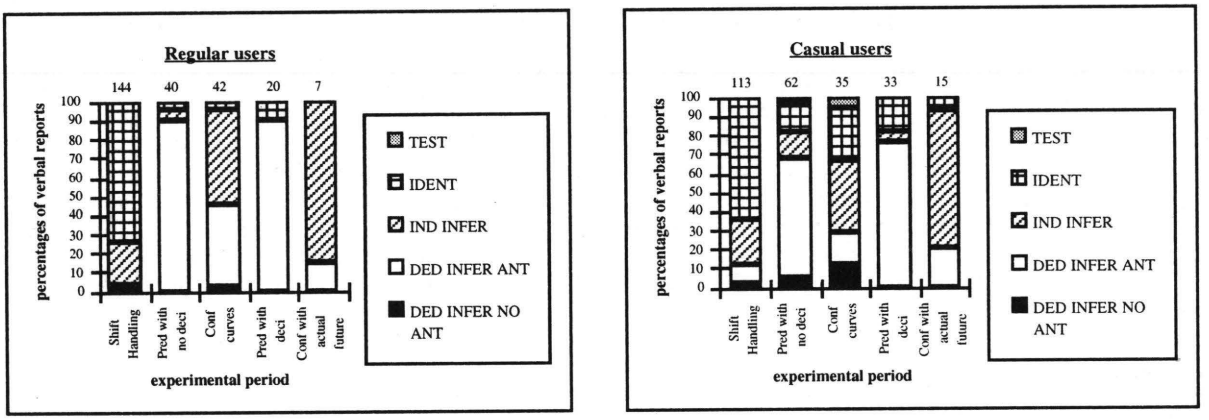


Figure 4: Percentages of types of processing concerning diagnosis and prognosis by regular and casual users (total frequencies above).

Risk Management

During shift-handling (first period) and forecasting with no decision (second period), Figure 3 (information gathering management) shows that regular users reported more frequent monitoring goals than casual users, that could be related to a better risk management strategy. For each experimental period, Figure 5 shows the distributions over the action predicates. For the same experimental periods (first and second), we can see that casual users reported more frequent precise (and conditional) decisions than regular users, that could be related to more risk taking. At the level of the global decision-making strategy in this situation, in all protocols there was a temporal sequence of decisions to be made. At first, operators decided to implement protective actions with weak effects, but dealing with quite certain risks. After that, decisions were schematic to deal with uncertainty and were made more and more precise as the situation is developing and the uncertainty reducing.

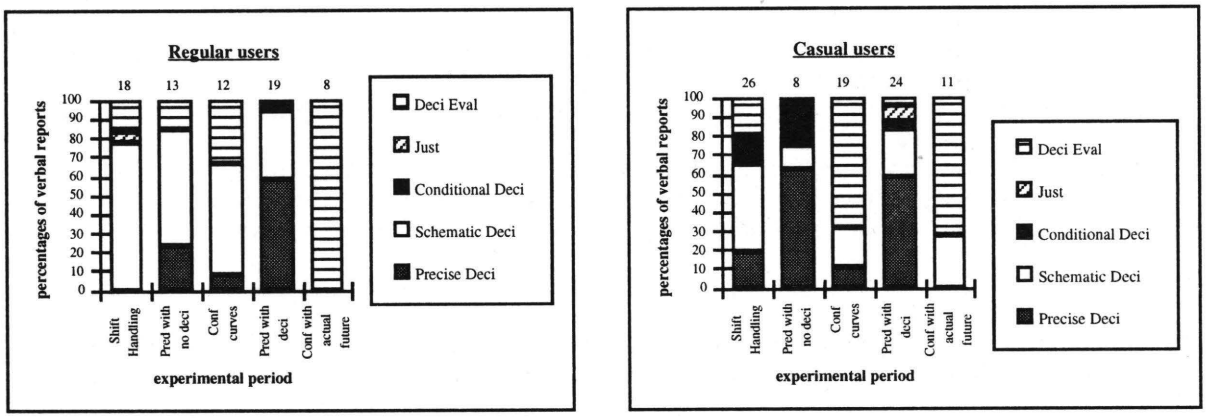


Figure 5: Percentages of types of processing performed in interventions on the process by regular users and casual users (total frequencies above).

CONCLUSION

After a series of experiment showing that blast furnace operators (supervising a long response latency process) paradoxically make little use of explicit anticipation (forecasting) and content themselves with implicit anticipation (expectation), this experiment shows two facts. On the one hand these operators are able to precisely develop and question forecasts in the context of the use of a computer support to anticipation, although

they do not do that spontaneously. On the other hand, the regular use of a computer support to anticipation can improve the strategies in the long term. Hence, the cognitive cost of the forecasting activity in an uncertain situation can be counterbalanced by a benefit in strategy efficiency. Regular users are more critical as regards their predictions, more analytical, speedy, and exhaustive in their situation analysis, and show a more appropriate risk management strategy.

However, in this situation, operators were in a position of "active" users of the tool, since they had to draw or question curves. This could play a major role in strategy efficiency when using a computer support. Besides, preliminary interviews had shown that regular users generally made use of the computer tool to check their forecasts rather than to get forecasts passively. This "active" use has important implications on the success of human-machine cooperation since it creates a "mutual control" situation where each agent can be "debugged" by the other (Roth, Bennett, & Woods, 1988). Now, we are planning an experiment on an experimental platform where operators will be able to cooperate with the computer tool during decision elaboration, which can take several hours (although easy to compress in a simulation). They will be able to enter their action decisions and access to forecasts of the possible effects. To investigate the potential use and benefit of this computer support, we plan to compare two kind of situations: "active" (forcing operators to draw a forecasting curve before accessing to the computer) and "passive" (free access). We expect better results in the first kind of situations than in the second one.

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Decision making and dynamic risk management

Janine Rogalski

Senior Researcher CNRS
COGNITION & ACTIVITÉS FINALISÉES
Université Paris 8-CNRS, 2 rue de la liberté, F-93526 Saint-Denis Cedex 2
e-mail : rogalskij@univ-paris8.fr

ABSTRACT

Managing dynamic environments often requires decision making under uncertainty and risk. In an experimental study on dynamic risk management, two scenarios --transposed from effective situations-- were compared. The possibility of risk occurrence wa not quantified as a probability, and both situations required decision making under uncertainty. A scenario with qualitative and irreversible consequences (child's death) and high uncertainty exerted high demands in risk assessment (risk representation) and action elaboration. It was compared with a less open situation. They appeared to be independent: this could be explained by differences in assessing risk before decision making. "Experimental" (naive) subjects dramatically differed from "operative" subjects (professional fire-fighters): This questionnes the ecological validity of research with experimental subjects.

Keywords
Dynamic environment, risk assessment, decision making, ecological validity

INTRODUCTION

Managing dynamic environments often requires decision making under uncertainty and risk management. It is particularly the case in open dynamic environments, when situations are weakly modelled, with few--if any--systems of control and command, and with a high level of risk (forest fire, chemical accident, floods, earthquake..). As situation is evolving with its own dynamics which interacts with actors' actions, decision making under risk can be characterised as "dynamic risk management". Issues about competence and training professional fire-fighter officers for such situations lead us to design an experimental study on the specific point of dynamic risk management. Two scenarios were contrasted from the point of view of their spatio-temporal characteristics; both naive subjects and professionals of risk management (fire fighter officers) were involved in the study for the methodological issue of the validity of laboratory studies. Before presenting the experimental study, we will introduce the perspectives we have been using in designing the scenarios for studying dynamic risk management, and in analysing our experimental results with regards to target real situations.
Schematically, two main lines of research can be contrasted concerning decision making and risk management. In the line of the theory of decision, decision making is considered from its rational point of view, as a problem of optimisation. The reference in modelling decision making is the expected utility (EU) theory proposed by von Neumann and Morgenstern (1947), where decision making is considered as a reasoning process of choice between alternatives dealing with uncertain events. In this framework assessing probabilities of outcomes and evaluating values for gains or losses provides the core of decision tasks analysis and experimental designs (Cohen, Jaffray & Said, 1987). Theories of decision making under risk -derived from or opposed to--the standard normative model of expected utility theory were tested through a wide set of experimental studies, often based on the paradigm of "lotteries". They were designed for a better understanding of what Simon (1955) has called "limited rationality", and to design descriptive models fitting with empirical evidences about effective decision making (Cohen & Jaffray, 1988). From a pragmatical point of view one main issue was decision support systems. A survey of trends of decision science from an AI point of view can be found in (Pomerol, 1996); Camerer & Weber (1992) proposed a review of developments in research on ambiguity and subjective expected utility. In a similar line, approaches in terms of heuristics and biases (Kahneman, Slovic & Tversky, 1988) contrasted effective human capabilities with the image of "rational man" using laws of probability theories, with the aim to improving judgements by decision makers.

Another line of research, mainly present in cognitive ergonomics[1], considers decision making in dynamic environment as a "continuous process aiming at dynamic control of the state of affairs in a work domain" (Rasmussen, Brehmer, & Leplat, 1991, preface). It covers the whole range of activities from defining actual state (situation assessment), to implementation of decided actions and control of results, in individual or collective work. We proposed to schematise decision making as a time-dependent loop, extending Rasmussen's ladder (Rogalski, 1991, p.300-302). In case of distributed decision making in open dynamic environment management , commanders or managers are in charge of the elaboration phase, while implementation is mediated by other actors. Limitation of resources (for time and means for action) interacts with risk for presenting decision makers with complex dynamic decision making. Assessing risks and defining appropriate ways and means to face the whole set of possibilities while limiting negative consequences, appeared as a crucial component of competence, for both individual and group decision making (Rogalski & Samurçay, 1991; Samurçay & Rogalski, 1993). However data obtained in real situations or in training sessions had let open the issue of the role of risk characteristics on performance and activity. An experimental study was designed for contrasting two type of risks analysed as games against nature[2]. the risks differed in the quantitative / qualitative nature of their respective occurrence and consequences (in terms of the first perspective on decision making). Results will be discussed both from this point of view and from the second perspective centred on the activity developed in situation analysis and elaboration of actions for coping with different types of risky situations.

DYNAMIC RISK MANAGEMENT. SITUATION ANALYSIS AND ELABORATION OF ACTIONS.

Open dynamic situations can be compared along two dimensions: the nature of their evolution, and the characteristics of dynamic risk they are presenting. Several types of dynamic situations have to be distinguished:
-Situations whose evolution can be calculated with more or less precision (for instance: quantity of hydrocarbon lost due to a pipe-line break, fire spreading without fire jump, evolution of a chemical cloud under stable wind);
-Situations involving hypothetical evolution (such as a fire jump in a Mediterranean forest fire or an explosion in an oil tanks farm fire);
-Situations both involving various possibilities for initial state, and hypothetical evolution (it is the case when loosing the position of a person, an aircraft, or a ship).
For comparing situations with regards to the characteristics of risks involved, we will now precise the risk definition used from here in the paper: A risk is an event, specified by two attributes : its occurrence and its outcomes (negative consequences).
-1) Its occurrence is neither sure nor impossible; it is more or less plausible and can or cannot be probabilised[3];
-2) its outcomes may be uni-dimensional (as loosing money) or multidimensional (loss of money and stuff destruction), involving quantitative or qualitative issues (lost money versus injured people).

Experimental studies in classical decision theory mainly deal with probabilised occurrences and quantitative issues, or search for how people evaluate and probabilities and outcomes and take them into account for their choice for designing analytical models. As we needed data for qualitative risks, we designed two scenarios both involving non probabilised risks, respectively with quantitative versus qualitative outcomes .
Concerning situations where uncertainty was both affecting initial state and evolution, observations made in training sessions and in real situations showed that a frequent trend was to give priority to the most plausible states of the world instead of the most critical possible consequences, or to waste resources (for time or means of action) to decrease uncertainty. The two scenarios were designed to allow subjects such types of strategies.
The issue of validity of such scenarios for decision making on the field will be discuss, after presenting the main results in terms of what decisions were performed. Analysing results from five field studies of different populations of experienced decision makers, including fireground commanders, Klein found that "relatively few decisions are made using analytical processes such as generating a variety of options and contrasting their

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[1] While discussing the classical theory of decision making as a normative standard, both incomplete and conflicting with results in everyday experience, cognitive science approaches referring to the theory of mental models (Johnson-Laird, 1993) remain on the line of decision making as a reasoning process linking information gathering and choice between alternatives (Legrenzi, Girotto & Johnson-Laird, 1993).
[2] This study was developed with Renan Samurçay, in collaboration with Anna Gody and Patricia Antolin
[3] We are adopting here a "technical" point of view, independantly of any choice about bayeasian or frequentist models for human evaluation of probabilities.

strengths and weaknesses. There are differences between the types of prescriptive decision guidance offered by analytical and by recognition-based decision models--decision support systems designed to improve recognition-based decision making would focus on situation assessment more than option comparison." (Klein, 1989). The situations from which our scenarios were transposed are not at all current in the activity of fire-fighter officers (at the evidence they are not familiar to naive subjects). Hence fore we hypothesised that analytical processes would be involved in "target" real situations and in our transposed ones. However, we can anticipate on the results for supporting Klein's claim that the focus would be on situation assessment more than option comparison in "The lost child" scenario. In fact, this situation involves spatio-temporal parameters which are critical for possible initial states and for evolution assessment and define constraints for possible actions.

THE LOST CHILD SCENARIO: AN EXPERIMENTAL STUDY

The "lost child" scenario was designed for analysing cognitive processes in decision making in the case of risk for which neither the plausibility nor the consequences could be quantified. The them was transposed from real situations of searching for lost people. It was compared to a scenario involving a risk whose consequences were quantified (referred to as Hydrocarbon Fire). There were two key points in dynamic management in the case of "the lost child" scenario. Firstly, both information provided by the scenario (text and imap) and general knowledge had to be used to inferring properties of risks in terms of plausibility and consequences. Moreover, the situation required to articulate spatial and temporal dimensions, concerning interaction between the dynamics of possible movements of the lost child and the dynamics of people acting as rescue means.
A series of experiments based on this scenario was developed for answering two main questions:
-1) Should subjects professionally involved in dynamic risk management perform differently from naive subjects? The answer to this question presents methodological consequences for experimental research.
-2) What could be the determinants on dynamic risk management, in terms of variables of the situation, characteristics of the subjects, conditions in task performing (such as specification of sub-goals).

Methodology

The Subjects
Two categories of subjects took part to the experimental study: "naive" subjects and "professional" ones.
a) Naive subjects were university students:
-Psychology students (first to third year at the university, N=88) were asked to perform the task in the framework of a curse on problem solving;
-Scientific students (first year of university, oriented towards mathematics, physics and chemistry, N=117), performed the task as a problem concerning general reasoning, in the context of a comparison with their psychology colleagues.
b) Professionals were fire-fighter Officers (at a level equivalent to engineers) attending a training year in a professional school for job adaptation[4]. They differ in initial background and experience in the professional domain.

The Task
The task was a decision of organising actions for searching a four-year old child who disappeared from a children holiday camp, in April with cool weather. Subjects were presented a written text and a schematic map[5]. They were asked to propose and write down a strategy for managing this situation.
The temporal context imposed limits for action: Two hours only remained before night. The spatial context was in rural zone with several possibilities for the child to be gone. From information given in the scenario, it could be inferred if the various possible sites were more of less plausible. Consequences of being gone to the possible places differed in severity due to the possible evolution of the situation both from the point of view of the child state and the possibilities for future research.

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[4] We thank the Direction, instructors and trainees of the Ecole Nationale Supérieure des Officiers Sapeurs-Pompiers (ENSOSP) , of the Institut National d'Etudes de la Sécurité Civile for their welcome and cooperation.
[5] It is quite usual for professional firefighter officers to have to process this kind of non-organized information in managing emergency non-routine situations.

Three variants were used concerning requests made to subjects, giving a somehow different orientation to their activity (V2 and V3 were used only with professionals):
-V1: expressing goal, strategy and decision justification;
-V2: specifying possibilities and risks, before expressing goals, strategy and decision justification;
-V3: specifying possibilities and risks, after having expressed goals, strategy and decision justification.

In the Hydrocarbon Fire Scenario (HF), subjects have fight a tank farm fire, due to an explosion. They can taking the shortest way (using a bridge) ensuring to save almost all tank farm but taking the risk of a total loose, as there was no certitude about the bridge state). They can take a longer way, being sure of the success of action, but loosing half of the tank farm while conserving the other half. In all cases these choices were coherent with means anf time latencies. Depending on temporal parameters differing in two variants of the task, it was impossible (V1) or not (V2) to make a decision conditioned by information about the state of the bridge.

Data analysis
Data were analysed for the LC in terms of a classification of the choices expressed by the subjects depending on how they took into account the main risk and the spatio-temporal constraints. For the HF scenario, choices were Certitude (of the results of action); Risk taking; Sharing means : subjects decided to send the appropriate number of fire means by the shortest way and simultaneously the remaining -- and unsufficient-- means by the other way, and finally conditional action (searching for information on the bridge state before deciding for action).

Results
They concern: 1) the effects of the subjects' operativity (naive versus professional subjects), for the two scenarios. (Table 1 for LC scenario; Table 3 for HF scenario); 2) the effects of activity orientation on performance (variants in LC) on the performance of professionals. Evaluation of risk and centration on the main risk (variants 2 and 3 of LC) were dependent. Finally, there was no systematic individual orientations towards risk taking or risk avoiding : responses to LC and HF were independent whatever the subjects and the variants.

Role of the Nature of the Scenarios
Surprisingly, the effects of the subjects' operativity were greater for the --apparently--less technical scenario: The Lost Child. Moeover, choices expressed in the two scenarios by the same subjects (47 psychology student with V1, 97 professionals with the V1 variants and 93 with the V2 variants) were statisticaly independent.

Effects of operativity
There were no differences between more or less experienced professionals concerning the centration of action on the main risk. Statistical comparisons between sub-groups (a year vs four or five years of professional life) gave similar results for variant 1 and for variant 2. Similar results were found for the "Hydrocarbon Fire" scenario (although it was more technical, at least at a surface level). Hence, we will give globla results when comparing professionals and university students, and variants in each scenario.

Table 1. Distribution of the centration on the main risk in terms of consequences to be avoided in terms of per cent subjects, in variant 1 for three types of subjects: psychology students, mathematics students, fire-fighter officers.

	University students Psychology	Mathematics	FF Officers
CENTRATION on the main risk	**18.2**	**40**	**66**
respect of time/space constraints	*05.7*	*06*	*26*
no precision or explicit time/space error	*12.5*	*21*	*31*
static option (avoiding the worse)	-	*03*	*10*
OTHER	**81.8**	**60**	**34**
Number of subjects	88	117	97

There were dramatic differences both between naive and professional subjects. A majority in the professionals were centred on the main risk (nevertheless only half of them expressed choices certainly avoiding the worse).

Psychology students were dominantly sharing means on a lot of possible places, and/or not taking into account the constraints on means and time.

Table 2. Distribution of the performances of naive subjects (psychology students) and of professionals (fire-fighter officers) on the HF scenario, depending on the variants of the task for the later (results in per cent).

	Psychology students (Variant 1)	Fire-fighter Officers (Variant 1)	(Variant 2)
CERTITUDE OF THE RESULTS OF ACTION	19	43	14
RISK TAKING	24	04	02.5
SHARING MEANS between options	52	43	43
CONDITIONAL CHOICE	-	-	29
other answer or no decision	05	10	10
Number of subjects	47	97	113

Sharing means was the dominant choice, both for naive and for professional subjects. The main difference lied in taking risk: 24% of the students were taking risk (choosing the shortest, uncertain way). Professionals choose the certitude of action (V1) and/or the certitude of information before action(V2) as often as they shared the means.

Effects of Task Variation on Professionals' Performance

From Table 2, it appeared that allowing the possibility for searching for information, in the "Hydrocarbon fire" scenario, oriented the choice of almost 30% of the professionals. However it was to the detriment of the choice of the (other) certain choice, not to the detriment of sharing means, with involved in fact risk taking, due to severe time constraints. Orienting activity through questions in the LC scenario did not modify the professionals' choices, as shown in Table 3.

Table 3. Distribution of the performances of professionals on the LC scenario, depending on the variants of the task (results in percent).

	Variant 1	Variant 2	Variant 3
CENTRATION on the main risk	**66**	**67.5**	**63**
with respect of time/space constraints	*26*	*24*	*26*
no precision or explicit time/space error	*31*	*23.5*	*30*
static option (avoiding the worse)	*10*	*19*	*07*
OTHER	**34**	**32.5**	**37**
Number of subjects	97	93	43

There was a quite limited effect of variations of the task requirements in terms of expressing risk assessment in the LC scenario, even ifasking for risk assessment (possiblities of locations and nature of the related dangers) before defining an action, seemed to a slightly better account of time and means constraints.

DISCUSSION AND CONCLUSION

Decision making and dynamic risk management was studied in an experiment involving naive and professional subjects, in two scenarios involving risk in a different manner. These two main variables had an effect on the observed performance (in terms of proposed actions and justification of the decided strategy). Performances appeared as "resistant" to tasks variants, for the two types of su bjects. Decisions of actions expressed in the two scenarios were independent, whatever the type of subjects.

Analytical decision making models can not account for this independence, nor for the nature and differences in subjects performance. In fact, these models are oriented towards an analysis of decision making *stricto sensu*, where subjects have to choose between predefined options with known issues, while our experimental scenarios involved different processes. In the case "Lost Child" scenario, subjects had to construct a model of the situation. Assesssing risk in terms of plausibility and possible consequences was then a critical point. From this

situation analysis, subjects had to elaborate solutions instead of choosing between options. TheLost Child scenario presented a case of decision making *lato sensu.*^ In the "Hydrocarbon Fire" scenario, risk and consequences were predefined, and the options were strongly constrained.

The groups of "experimental" subjects (students) and "operative" subjects (fire-fighter officers) differed for both scenarios, particularly for the less technical and more open one, involving more complex processes of decision making *lato sensu*. We postulate the existence of two types of cognitive processes in decision making. A top-down process consists in searching for the main features of the situation, involving the most serious consequences, and deciding actions in order to avoid these consequences. A bottom-up process first consists in elaborating "local solutions for local risks" ; the set of local solutions might be more ou less --if at all-- adapted to the spatio-temporal constraints of the dynamic situation, which were very high in the Lost Child scenario.

Several -non independent- factors might intervene to explaining differences between naive and professional subjects: general previous background, knowledge and training, composition of groups with regards to gender, spatial competencies. The later could--at least partly--explain individual internal differences between professionals. Specific professional experience seemed not to be one of these factors as beginners and soon experienced professional performed in a quite similar way. Whatever the reasons of the observed differences, a methodological conclusion has to be drawn: Results from "experimental" subjects have a limited ecological validity, and cannot be used as a basis for training purposes. More research is needed for understanding relationships between processes in dynamic risk management and previously acquired competences

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A Hybrid Approach for Operator Support in Process Control

Karl Reinhard Kimmel

Forschungsinstitut für Funk und Mathematik (FFM)
Neuenahrer Straße 20
D-53343 Wachtberg-Werthhoven
e-mail: kimmel@fgan.de

ABSTRACT

From the known deficiencies of the classical knowledge-based techniques and of neural networks a prototypic hybrid modelling approach was derived under the objective to obtain a working system for the concrete environments of process control. The essential feature of this approach consists in the fact that knowledge is shared among the two implemented paradigms. This is accomplished by a special kind of symbolic process description, such that it can serve as an isomorphic „substratum" for the neural network part. That way both paradigms exist in parallel, independently of each other, according to the underlying idea to maintain the specific advantages of both lines of thinking. The common units in both paradigms can represent both concepts and conceptual relations. The specific solutions are presented and shortly outlined by a simple example.

Keywords

Hybrid systems, neural networks, knowledge-based systems, human operator modelling, process control.

INTRODUCTION

The finding that the large majority of accidents are undoubtedly the result of a combination of factors which contain a certain amount of inadequate or faulty human behaviour motivates a sustained need for the development and implementation of assistance functions for process control. Hence, the interaction between operators and the plants which they control has become a central topic of the design and safety analysis. This problem may be tackled by design and development of advanced intelligent decision support systems for process control.

There have been presented a lot of proposals developed for this kind of tasks along various lines of thinking. One of these concerns symbol-processing knowledge-based systems, another one the re-emergent "subsymbolic" neural network paradigms. This paper will try to briefly present an approach consisting in the combination of two specially elaborated approaches from the field of the two paradigms, and to try to give an understanding of its real advantages as well as to address some hopes that might be connected with it.

THE MODEL APPROACH

The classical symbol-processing knowledge-based systems use an explicit symbolic task representation which they process by symbolic manipulation. They encode their task-environment knowledge in symbolic structures and use it for the control of their behaviour in order to reach of their goals. Rules correspond to the (more or less) verbalisable knowledge and often the used symbols correspond directly to notions in human language. Even when human reasoning processes do not always run symbolically, can these symbolic systems be considered as models of concious human information processing, since they use symbol structures and rules for the representation of concepts and abstract categories, which characterises concious human reasoning.

On the other hand hold parallel distributed processing (PDP) networks *per se* certain features significant for cognitive phenomena by their physiological inspiration, their content-addressability, and what is usually called generalisation and approximated performance. Since for the intelligent accomplishment of certain tasks obviously many things have to be kept in mind simultaneously mechanisms that allow the simultaneous interaction of various information aspects are required. In this view PDP offers to a certain degree a new quality of information processing which cannot be achieved by serial processing on a von Neumann architecture with the same adequacy.

Recently both symbolic as well as connectionistic approaches have been established as methods for cognitive

modelling in AI and Cognitive Science. From the understanding of specific strengths and weaknesses of both paradigms a new sight emerges, which stakes on their combined use, exploiting their specific strenghts, rather than discussing again and again, why the one or the other line of thinking is superior. Since the domain of hybrid systems is a research area only few reports are to be found in literature. In the following it is tried to make a contribution by an approach which could be used in the process control domain. A hybrid architecture integrating knowledge-based and neural network paradigms based on a unified knowledge-representation concept is presented.

UNIFIED KNOWLEDE-REPRESENTATION CONCEPT

Knowledge bases can be realised with various different data models und structuring possibilities, which are equivalent in many respects. But despite this it turned out that object-orientented tools (as e. g. LOOPS; Bobrow & Stefik, 1983) are most convenient for the construction of knowledge bases in the process domain. In this section we will shortly present a representation concept, which is characterised by three features, shown in Fig. 1 and outlined rapidly in the sequel.

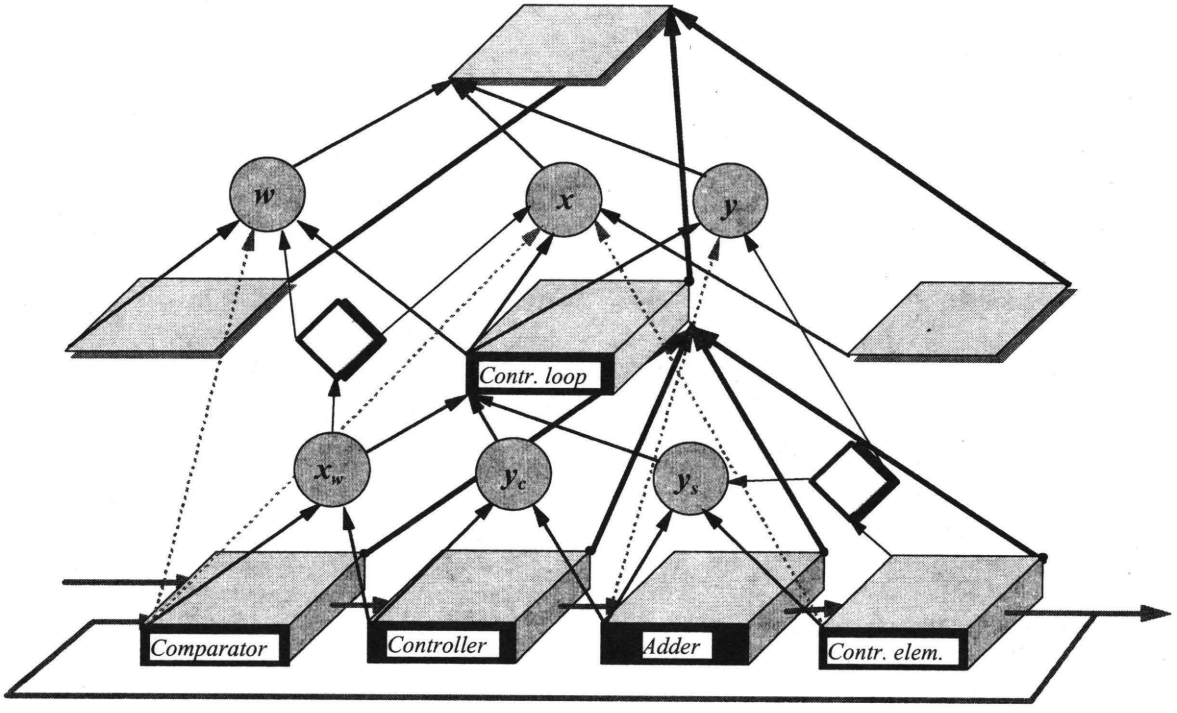

Fig. 1: Unified knowledge representation concept

1 Hierarchic representation of plant components. The description of the whole process requires the representation of knowledge of different kind. Herewith consists a first (natural) step in the representation of the component hierarchy [V] (i. e. the decomposition of the whole plant in functional groups, subgroups, etc., concrete objects being to be found at the bottom of the hierarchy, whereas more abstract objects are oriented towards the top). In knowledge-based system terminology all of these items can be seen as plant objects. The arrows from the sub- to the super-objects in Fig. 1 have the interpretation "IS-PART-OF". Structural dependencies of the process complexes are realised non-associatively; information about the location of components is received by access on the implicit bookkeeping of the structure (*Subs, Supers*). This holds also for the elements not belonging to the proper drive, as instrumentation, measurement, and control systems, which are usually described separately.

2 Representation of system states. The component hierarchy contains no information about the kind of interaction between the components (i. e. their interconnection via the system states) on the different levels. The question how these system states are to integrate into this hierarchy led to the decision to implement them as self-contained units and attach them to the components of the hierarchy, cf. the "spheres" in Fig. 1. This re-

presentation form can be called *extensional,* as opposed to the usual intensional description with predicates.

For the attachment of the system states into the component hierarchy certain rules have been developed, which we address only shortly. We simply note that hierarchisation is a sheer human mental construct and each process in fact consists of a network of components, influencing each other by means of state variables. Due to the hierarchisation process it can be that certain variables connect several system component nodes in the hierarchy. This is indicated in Fig. 1 by the dotted lines. Consequently the process components are described by the set of their super-objects being variables. This set can be derived by a simple system oper ation.

Another important aspect as to a complete process description concerns the *influence direction* of the process states. Since this feature cannot be derived from the structure graph **V**, all process components and variables are provided with the attributes *Input/Output* or *From/To,* respectively. These attributes are set with their appropriate values, i. e. component objects contain variable names and vice versa. This feature is not shown in Fig. 1. For the retrieval of further describing features the general "world description" can be accessed.

From Fig. 1 we see, that a purely hierarchic component decomposition first of all does not enable the description of feedback structures. But by the *external* implementation of a structured scheme results that contains a describing variable (the control variable x in the example indicated in Fig. 1 as an output of the structure), which is also input of a *component* of the feedback loop. This is the circumscription of the graphical feature of feedback which enables the system to "perceive" the feedback property of such structures by means of the internal bookkeeping functions of the object hierarchy.

3 Rule attachment. The introduction of the state variables in the structured process hierarchy, was also motivated by the idea to link the (originally unstructured) production rule set into the hierarchy. By the predicates in their clauses the rules represent connection links between the process variables and components, respectively. These links can be realised as associative pointers from the variables or components, respectively, to the rules. In Fig. 1 these links are symboliseded by the thin arrows, the production rules by the upright standing squares. The successive pursuit of such connections in the knowledge representation graph enables then repeated inference operations and any substructure can be named and provided with a functionality description, ultimately resulting in improved system functionality. Consequently it follows from this representation concept that inferences do not require any search processses. This also holds true in case of "ignorance", i. e. the system always "knows what it does not know"; it does not search for informations not contained in the knowledge base. Older concepts for the increase of effectivity, as grouping by "context" or " importance", respectively, have thus become inherent.

A SUBSYMBOLIC MODEL APPROACH

The linking of the rules across the state variables leads to implicit, *structurally* represented metaknowledge. The shown concept represents a so-called "deep model", i. e. a model containing knowledge about structural and functional dependencies, which can be taken for the justification of the surface knowledge. The presented concept belongs, among others (see e. g. Früchtenicht et al., 1988; Dilger & Womann, 1984; Kippe, 1986; Struß, 1988; Stairmand & Kreutzer, 1988), to the range of what is called "associative models". However, in the literature it is discussed that associative knowledge-based techniques, despite their successes, still cannot simulate the abilities of experts. So experts cannot only solve routine problems, they are also not helpless with novel problems, can often resolve seeming contradictions by considering additional knowledge, can ask behind and justify their rules, overlook the fringe of their special domain, can estimate their own competence, and - most important - learn by experience. Davis (1982) showed that many of these problems could be solved (at least partially) by an explicit description of causal models of the application domain. Such models can be considered as systems of mutually interacting objects, with attributes that characterise their state. Often the behaviour can be derived from the physical (geometric) structure or a functional description on a lower level of abstraction.

A qualitative simulation machine

We begin the presentation of the subsymbolic model approach at the above structured process description (Fig. 1). Such a model concept is "connectionistic" and we introduce into this structured high-level symbolic description the dynamic view of parallel distributed processing (PDP). This requires the realisation of neurons

as autonomous units which locally hold information about the activation potentials and their mutual influencing. Variations of the neural activity do not occur as a result of prescribed computer processes, but in fact by the parallel unit interaction. The processes that cause such changes are interpreted as logical influences, which is supported when the activation value range of the units is limited.

Model mechanism. Object-oriented programming is well suited for the realisation of dynamical systems with these features. A certain process is then formed by the dynamic behaviour of this object set and the values of these state variables are treated as real (or logic) variables, tied together by physical (or qualitative) laws. Such "programmes" in form of interacting self-contained units locally contain the various procedures ("messages") for the mutual synaptic influence of the neuron-objects and memories for the respective ("eigen"-)values. The realisation of this PDP approach was carried out in a LISP environment on a serial computer, requiring the creation of a control instance for the parallel activiation-spread among the neurons. The processes are driven and maintained by the eigen-activities of the neurons, accomplished by use of so-called "active variables" for their activation levels (AL). The spread process in such networks runs autonomously after its start by a sustained activation "injection", until it is stopped by an external supervisor.

From the above demand to integrate the symbolic and subsymbolic parts of the model it is derived that the subsymbolic model is established in the space of the symbolic entities of the description hierarchy. This is accomplished when we assign to the variable-objects a function as neural processors. This makes the set of the variable-objects of the (symbolic) description hierarchy the *single* neural layer of the subsymbolic processes (a network strucure belonging to the autoassociator class). The objects in the description structure have then both a symbolic and a subsymbolic function; here the two paradigms are tied together. The goal to create a logic image of the problem domain (a simulated ship propulsion unit) is achieved. Based on the locally representing system states, it can be seen both as a qualitative isomorphism to the physical process and to the symbolic process description, or as Pinkas (1995) states it: the network **is** the model.

It remains the problem to establish the connectivity among the neural units. Hereto three principles shall hold: *(1)* Excitatory and inhibitory synaptic connections between the units are allowed.[1] *(2)* The units are always connected pairwise (if they are connected at all) with the same connection type (i. e. either excitatory or inhibitory). *(3)* The weight distribution is symmetric, as e. g. for Hopfield (1982) networks. The question, which *kind* of connections is to be established between the single units is answered by the evaluation of the physical relations among the represented state variables. The synaptic influences between the neurons which determine the activation values are the logical-qualitative analoga of the physical relations. A difference to the general structure scheme of the autoassociator consists in the lack of a full connectivity (see Fig. 2 below). The connectivity at hand has rather the character of "receptive fields" - a consequence of the physical equations.

The *a-priori* invention of inhibitory connections (according to the givens with real neurons) means, that a certain "a-priori knowledge" is introduced into the system. This measure facilitates the learning task considerably. In conjunction with the demanded symmetric weight distribution there emerge interesting features, which we can address only shortly. Smolensky (1986b) showed that in restricted state spaces there is a non-linearity due to the restricted neural activations, leading to *natural competition* of interpretations in overlapping patterns. Thus the advantage of inhibitory connections consists in the preference of the stronger hypotheses as against the weaker ones in the solution process.[2] A system of this network type realised in the way described, is called "Qualitative Simulation Machine" (QSM). It solves problems by completing certain externally applied partial patterns. (This is another kind of inference as opposed to symbolic inference indicated above.) Whether the single neurons play the role of inputs or outputs is task-depending.

Example: Control Loop

For the sake of a clearer understanding of the above explications about the approach we consider a simple control loop with an active element as an example (Fig. 2a). The describing equations of the system (equ. (1) - (4)) with a total of 8 parameters are given in Fig. 2d. The resulting neural net is to be seen in Fig. 2b. In the ca-

[1] It is supposed without loss of generality that the feature neurons can process incoming excitations of both signs, restricted to [-1, +1]. An activation value of -1 is interpreted as "smaller", of 0 as "unchanged" and of +1 as "greater".

[2] In a linear system the network state can receive a distributed neural as well as a distributed conceptual interpretation. In the superposition of conceptual patterns the weights of the pattern vector show the confidence of the system into the corresponding conceptual hypothesis.

se of the application to descriptions of process models these applied partial patterns represent certain qualitiatively formulated questions to the system, and the generated rest pattern represents the (qualitative) answer. An example for such a question to the system in Fig. 2 would be:

"What happens, if W is held constant and Y increases?"

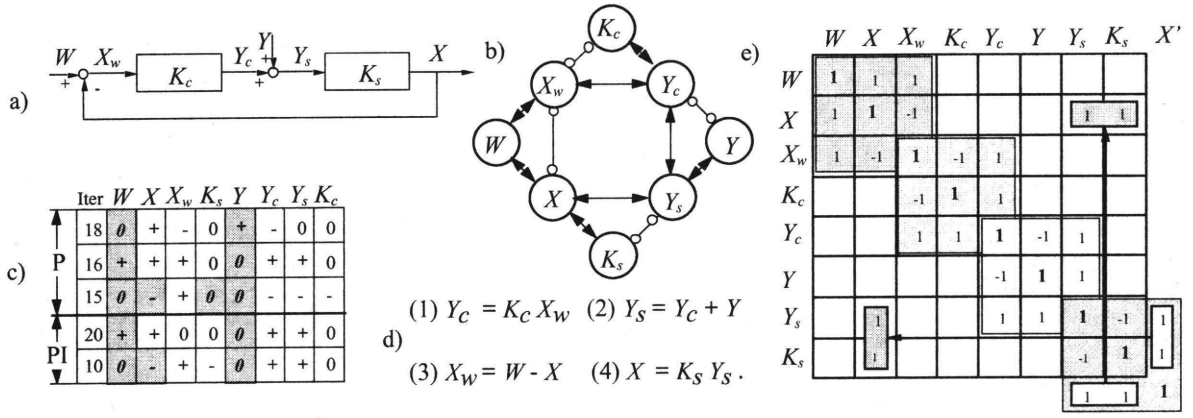

Fig. 2. Example: Control loop. a) Schematic, b) network, c) simulation results, and e) weight matrix.

This question is brought into the system, by translating the predicates in the condition part of this question into activation values and "injecting" them into the network (i. e. that the units for W und Y are "clamped" to their respective values. Then the system starts a qualitiative simulation. Some results are given in Fig. 2c, the bold symbols in the figure symbolise the task, they are those which are clamped according to the respective task. The normally drawn items represent those values the state of which shall be found. In the first time interval the activation in the network spreads in parallel from Y (in the example corresponding to the first line of table 2c)) to Y_C and Y_S, these units are activated, they forward their activation in the next time interval on the cells connected with them, and this proceeds step by step in the network. The system response (the completed pattern) is achieved when the neural spread process has become stationary.

A deterministic Learning Rule

One view of learning is, that the weights $\{w_{ij}\}$ in a network constitute a generic model of the environment, such that the activity patterns on the units with a freely running network are the same as those received when the environment clamps them. We consider the following bilinear expression for a non-equlibrium state:

$$\Delta S = \Sigma_{ij} \; w_{ij} \alpha_j \alpha_j .$$

In this equation we can interprete a_j as the differences $(o_{pj} - t_{pj})$ between the actual neural activation of neuron j with pattern p and the corresponding target value. $w_{ij}\, a_i$ designates the input to cell j from the other cells connected. We call S (neural) ***entropy.*** Based of this equation a Hebbian learning rule can be derived. We note that the weights are to be changed symmetrically being a first hint on the symmetry of the weight matrix **W**.[3]

DISCUSSION AND CONCLUSION

It should be noticed that the reproduction model can answer imprecisely posed questions, just as it can answer well-formulated ones. With insufficient information there will be several states of highest *entropy* of which the model will select one. It does not fail because of "lacking information", necessary for the "firing" of some rule. When inconsistent information is given, then no available state will have an entropy as high as that of the answer to a well-formulated question, nevertheless those answers, which violate as few relations as possible,

[3] By use of principles of thermodynamics of irreversible processes it follows for a model which is isomorphic to the considered process that the above equation for non-equilibrium states is closely linked to the thermodynamic entropy of the system. From the findings of L. Onsager (1931) follows the symmetry of the weight matrix **W**.

will have the highest entropy, and therefore one of them will be selected; a contradiction will not lead to an "arbitrary conclusion". The mechanism enables the model to solve well-formulated problems as well as to find the best answer to ill-formulated problems without any modification. Moreover there is a direct influence in network reasoning. When single conditions are changing during the reasoning process, the net can adapt and satisfy the changed conditions. The "rules" are really context-sensitive and not stored in big compiled "chunks".

An essential feature of problem solving with the presented approach (compared to the symbolic approach) is its use of implicit productions which are not stored, precompiled, and fed by an inference engine; they rather result dynamically from the common action of the knowledge entities, when they are needed. All stored patterns can be recombined in a completely new manner. This leads to the imagination that productions were precompiled, though the specific condition/consequence pair appeared never before. And, since they are generated on-line by the parallel action of all entities, the extent of the production set depends exponentially on the number of represented states. However, the exponential explosion of the compiled productions is only virtual. In this scheme only the functional relations and dependencies have to be learned or established, respectively. An approach similar to the presented model with one neural layer is given by Smolensky (1986), describing how a stochastic machine for the simulation of the environment (*simulation machine*) can be derived from a harmony network.

It was shown, how a subsymbolic model can be based on and integrated into a symbolic model. In the sense of a given definition it can be seen (to a certain extent) as a *unified* architecture, sharing knowledge in both forms. At the present stage some problems are solved with the symbolic system and others with the neural net. The information transfer between both paradigms is accomplished by transformation of the given problem into a form appropriate for the particular modul. The processing algorithms of both systems run independently of each other, and in principle could even run in parallel. It has to be tested, whether the approach works in systems, larger than the implemented propulsion process (i. e. whether it is *practicable* when many individuals participate). Further developments of this approach should mainly concern the relations and roles of symbolic rules and subsymbolic (implicit) "rules".

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Methodological Considerations in Analysing Anaesthetists' Habits of Action in Clinical Situations

Ulla-Maija Klemola and Leena Norros

Department of anaesthesia, Otolaryngological Clinic, Helsinki University Central Hospital, Haartmaninkatu 4, 00290 Helsinki, Finland. Ulla.Klemola@pp.kolumbus.fi

Technical Research Centre of Finland, Automation, P.O.Box 1301, 02044 VTT, Finland. Leena.Norros@vtt.fi

ABSTRACT

By exploring the meanings the anaesthetists' attach to their activity we demonstrated a new conceptual framework to the activity. Habit of action refers to the ways the actor organises his actions in order to construct adaptive interactions with the environment. The activity of eight expert anaesthetists was videotaped during anaesthesia on two occasions. The anaesthetists were also interviewed. Additionally all clinical data were recorded during the anaesthesia. Using an ethnographic methodology we constructed an interpretative link from the observations of the activity to our theoretical terms. The constructed criteria provided us a basis to give a concrete description of the anaesthetist's habit of action.

Keywords: Situated action, naturalistic decision-making, ethnographic methodology, habit of action, anaesthetist's activity

INTRODUCTION

The theme of the conference, time and space in process control, is in this paper considered in a broad sense as to refer to the situational nature of our research object, human action. With this interpretation we want to draw attention to the recent trend in the decision-making research and man-machine interface studies - both central areas of interest for us. Within these disclipines there appears to be wide interest to study action in real-life settings. A new paradigm, the naturalistic decision-making paradigm, is emerging out of the commonly shared need for redefining decision-making as a research object (Klein et al. 1993, Cannon-Bowers et al. 1996, Zambok et al. 1997, Hollnagel 1993). Within this developing paradigm there is considerable general agreement of what the new object of research, naturalistic decision-making (NDM), is in comparison to the traditionally studied choice decisions. The methodical diversity in these studies however, indicates that the concept NDM has been interpreted in many different ways. It also shows signs of the great challenges in the development of adequate contextual methods to explore the object.

There are, of course, many practical difficulties in studying decision-making in real environment. The methodological problems, such as the definition of the unit of analysis, generalisation of results, reliability of methods etc., seem, however, even more difficult, because they deal with the underlying philosophical questions concerning the nature of human mind and knowledge. Harré and Gillet (1994) suggest that adoption of a non-representational point of view to human cognition offers a more fruitful starting point for explaining cognition as an intentional activity. The authors argument that while it is obvious that we have a possibility to conceptually handle the objects of our environment in our thinking, it can be claimed that mental activity is not essentially an inner set of processes. Instead it can be conceived as a range of moves or techniques defined against a background of human activity and governed by informal rules. It is the meanings attached to the objects that are significant, and they become visible in the way concepts are used to organise actions. The inquiry of human activity should focus on revealing different habits of action constructed by actors to help them to deal with the world. The ecological content of the concept of habit of action is emphasised by pragmatist philosophers such as John Dewey and Richard Rorty (Rorty 1991).

According to the adopted approach, interpretation and empathy is more significant than prediction or control in understanding human behaviour. Consequently, the self-reports of the people one is studying become very important.

THE UNDERLYING CONCEPTUAL PERSPECTIVE TO THE ANAESTHETIST´S ACTIVITY

We have chosen to study the anaesthetist´s activity as an intentional enterprise explained through meanings attached by the actors to their activity. Our approach emphasises the actors´ role in explaining, and, in addition, the context as a fundamental constituent of the meanings.

In our previous interview study (Klemola & Norros in press), based on accounts given by the anaesthetists, we developed a conceptual framework to the anaesthetist´s activity, in which orientation had a central position. The Galperian concept of orientation (Galperin 1979) refers to the framing of the problem in a situation demanding action. Orientation indicates the logic according to which the task situation is taken into account by the actor. Therefore orientation can be assumed to have a major influence on the course of coping with the situation. (Norros 1989, Norros 1995, Norros 1996). In our study, the contextual definitions of orientations were based on the anaesthetists ways to frame the object of their activity, the patient in anaesthesia. Consequently, two distinct anaesthetic practices became evident. The one was guided by the objectivistic orientation which reflected traditional medical thinking. The other was guided by the realistic orientation according to which the patient's uniqueness and the uncertainty of anaesthesia were recognised. This orientation implied a new approach to the practice in order to cope with the ever-increasing uncertainty of anaesthesia process. Moreover, the differences in orientations became evident in the respective habits of action, especially regarding the use of situational information.

The subject's framing of the task situation can also be inferred on the basis of the subjects' habits of action, which refers to the ways the actor organises his actions in order to construct adaptive interactions with the environment, and it can be specified through analysis of observations concerning the actors' utilisation of the task and situation specific resources, and explanations he gives to his performance in a real task performance (Hukki & Norros 1994, Klemola & Norros in press, Hukki & Norros submitted).

STARTING POINT TO THE PRESENT STUDY

As it was found out, orientations are expressed by the anaesthetist through the conceptions concerning the object of activity and the task situation. Through using the concept habit of action we urge not only to take distance from the cognitivist clarifications of the subjects' internal processes, but also from detailed behavioristic descriptions of the sequence of acts. The concept of habit of action, given a central position in our vocabulary, provides us a means to focus on the inferential basis of decision-making under the demands of specific task situation.

THE METHOD OF ANALYSIS

Studying the habits of action of anaesthetists involves insight on the situated, contingent character of actions, their dependency on the particular, clinical circumstances where activity is constructed. Moreover, to discern the meaning of particular actions it is necessary to find out the rules and logics the actor was following at that point. The methodical constraints set by the above requirements are described by Hutchins and Klausen (1996). They point out that when mappings from the observed events to terms of theory cannot be taken as obvious, or when mappings cannot be justified with "operational" definitions, it is necessary to provide an interpretative bridge from the structure of the recordings of activity to terms of theory, in our case habit of action.

The activity of eight, previously interviewed expert anaesthetists was videotaped during anaesthesia on two occasions. In addition to the video recordings providing a chronological representation of the course of actions, the anaesthetist of the research team documented the administration of drugs, observations of monitors, and other procedures accomplished by the anaesthetist, and also available values of measured parameters of the patient during the course of anaesthesia. She also wrote, immediately after the studied anaesthesia, an account of the course of anaesthesia.

Based on these recordings, our challenge was to capture the fleeting circumstances of a clinical situation that constituted our observational basis for the subsequent scrutiny. In the first step of the analysis a combined representation of videotaped recordings and clinical data was accomplished. Creation of the representation is theory laden activity based on contextual knowledge. Especially in a highly specialised area, like anaesthesia, such a task can be accomplished meaningfully only by someone who shares the conceptual framework of the actor, and therefore this task was carried out by the domain expert of the research team (Heritage 1984). In addition to this representation also the actors own accounts of the anaesthesia were available because several interview question were presented at different phases of the course of anaesthesia.

The next phase of analysis comprised of defining the central functional, time-dependent phases of anaesthesia, because they each fulfil a specific function based on the intentional logic of the anaesthetist´s activity. The actions were conceptualised through focusing on the interactions between the expert using his material resources of activity, monitors and drugs, and the patient with his physiological potentials. In order to accomplish an understanding of the sequence of actions, such as use of information and giving drugs, they were represented in a chronological graph. Then, based on our theoretical conceptions we made interpretations concerning the anaesthetists' actions and, finally, achieved criteria to differentiate between habits of action.

ANAESTHETIST'S HABITS OF ACTION

The analysis of the observations revealed us that only the combination of different documents of our material provided us adequate basis to see the significance of particular actions and to interpret the character of observed interactions between the expert, material resources and the patient. In constructing the conception of the anaesthetist's habit of action we identified elements expressing the anaesthetist's possibilities for inferences and actions in relation to the goals of anaesthesia as they are manifested in each of the functional phases of anaesthesia. By exploring the anaesthetist´s actions and his accounts concerning the logics behind them we observed differences in the habits of action. The criteria we used for differentiating the habits of action express our theoretically based assumptions of features that contribute to an appropriate fulfilment of anaesthesia activity. This conceptual framework and the results of the analysis will be presented in the following.

There are several conflicting demands during the anaesthesia that the anaesthetist has to take into account and strike balances between them. The conflicts we mean are the following. In addition to general anaesthesia, anaesthetic agents may cause undesired effects, especially cardiovascular and respiratory depression at the most manifest after anaesthetic induction. Thereafter, a dynamic balance has to be maintained between the depth of anaesthesia and surgical stimulation. Undue stimulation may cause physiological changes as detrimental as those by undue depression. Moreover, a dynamic balance has also to be achieved between different anaesthetic agents, if general anaesthesia is supplemented with opioids and peripheral muscle relaxants. These are the fundamental constraints the anaesthetist must take into account when accomplishing an anaesthesia.

In this study our aim is to explore possible different solutions the anaesthetists may construct in order to carry out this complex task. Our basic hypothesis is that the physiological state and the potentials of the patient are vaguely determined with regard to anaesthesia. During the different phases of anaesthesia the anaesthetist can through his practical actions specify his knowledge through following the patient's responses to anaesthetic induction and endotracheal intubation. We assume that meeting the above mentioned global demands of anaesthesia is related with the way and extent the anaesthetist uses this possibility.

The above assumption was used as the basic theoretical criterion for differentiating habits of action in relation to the concrete actions of the anaesthetists. The objects of evaluation represent the anaesthetist's possibilities for inference and action reflected in his use of available material resources in each of the functional phase of anaesthesia. Within each object of evaluation the concrete criteria for differentiating habits of action (*) are defined.

Preoperative evaluation of the patient

In the preoperative phase the anaesthetists creates anticipatory insights of the forthcoming anaesthesia during which he/she has the possibility to acquire information of the patient through different information sources. The relevant objects for evaluating the habit of action in this phase of anaesthesia are:

1. Use of different sources of available preoperative information
   (records, interviewing, clinical and other examinations)
   * scarce
   * moderate
   * extensive

2. Evaluation of the patient´s physiological state regarding anaesthesia
   * statement of diagnoses
   * subjective evaluation of the severity of diseases
   * interpretation of preoperative information from the perspective of the patient´s physiological resources

3. Evaluation of physiological state as a constraint to own activity
   * no constraints to the activity, "routine anaesthesia"
   * rules based on classifications of diseases or age, otherwise "routine anaesthesia"
   * a specific description of the principle to guide drug administration according to the patient´s unpredictable physiological response, otherwise "routine anaesthesia"

Transformation of the patient´s homeostatic state by inducing anaesthesia

This phase in anaesthesia is a transition from the patients's normal homeostatic state into a new one in anaesthesia. After anaesthetic induction it is especially the cardiovascular and respiratory depression that become manifest, creating constraints for the anaesthesia. At the same time the transition stage provides possibilities to acquire information of the patient's thusfar unknown physiological potentials.

1. Use of available information during administration and administration of anaesthetic agents
   * no interplay between information and administration of drugs, doses based on weight
   * search for the patient´s individual sleeping dose by following the level of consciousness
   * in addition to following consciousness, deliberate search for changes in the physiological parameters as determinants for the optimal sleeping dose

2. Use of information obtained after stimulation caused by laryngoscopy and intubation
   * no adequate observation of cardiovascular intubation response
   * deliberate notice of arterial pressure, heart rate and S-T changes immediately after intubation

3. Evaluation of the patient´s physiological state after transformation phase
   * no changes in the evaluation as compared to that performed preoperatively
   * stating the observed changes in parameter values and relating them to own actions
   * interpretation of the patient´s physiological state based on the changes during transformation phase

Maintenance and regulation of the transformed homeostatic state

In this phase a dynamic balance has to be maintained between the depth of anaesthesia and surgical stimulation taking simultaneously account of the optimal physiological limits of the patient. Moreover, a dynamic balance has also to be achieved between different anaesthetic agents, if general anaesthesia is supplemented with opioids and peripheral muscle relaxants.

1. Maintenance of balance between anaesthetic level and optimal physiological limits
   * minimising depressive cardiovascular side-effects at the cost of anaesthetic level
   * maintaining balance with relevant means

2. Maintenance of balance between anaesthetic level and surgical stimulation
   * reactive way to maintain the balance
   * anticipatory way to maintain the balance

3. Regulation of physiological state

   a. Use of information
      * reactions to vital limits in spite of the expressed optimal limits
      * reactions based on trends
      * sensitivity of regulation seen as reactions to incremental changes in the parameter values

   b. Choice of drugs and doses
      * drugs administered with expected mean accuracy
      * drugs administered on the basis of previous responses of the patient or the demands of the patient as expressed by the actor

CONCLUSIONS

On the basis of this conceptual framework we could distinguish three different habits of action. In the first, situational information was used insufficiently leading to course of anaesthesia in which information and actions were not in concert. In the second, information was used to control the process within generally accepted limits and with mean accuracy. In the third, information was used as communicative tool to construct a cumulative interpretation of the patient´s physiological potentials.

It was evident that the last habit of action with its adaptivity to the demands of the patient provides means to cope with uncertainty of anaesthesia process caused by inaccurate knowledge of the patient´s physiological potentials. The patient´s physiological state is always incompletely determined regarding anaesthesia, especially in patients with disturbed homeostatic control mechanisms. However, the changes at anaesthetic induction if used to construct an interpretation of their meaning, may specify one´s insight on physiological potentials of the patient. Taking advantage of this possibility was characteristic to the last, adaptive habit of action. Regarding our previous results it seems that the first two habits correspond to the objectivistic and the last one to the realistic orientation described by us.

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8 INDIVIDUALS AND PROCESS CONTROL

Operator Behavior Model with Learning Mechanism

Seiichi Yoshimura and Naoko Hasegawa

Human Factors Research Center
Central Research Institute of Electric Power Industry
2-11-1 Iwato Kita, Komae-shi
Tokyo 201 , Japan
+81 3 3480 2111
yoshi@criepi.denken.or.jp, naoko-h@criepi.denken.or.jp

ABSTRACT

One effective method to analyze the causes of human errors is to model the behavior of human and to simulate it. The Central Research Institute of Electric Power Industry(CRIEPI) has developed an operator team behavior simulation system called SYBORG(Simulation System for the Behavior of an Operating Group) for analyzing human errors. An operator behavior model which composes SYBORG has no learning mechanism and the knowledge of a plant is fixed, therefore, it cannot take actions when unknown situations occur nor learn anything from the experience. However, considering actual operators, learning is essential. In this paper, Q learning with 1/f fluctuation was proposed as a learning mechanism and simulation was conducted. The results showed the effectiveness of the learning mechanism.

Keywords
Human modeling, human errors, Q learning, 1/f fluctuation

INTRODUCTION

It is necessary to analyze not only the behavior(actions and utterance) but also the cognitive process of an operator and the decision making process of an operator team when understanding the human factors problems correctly. CRIEPI has developed a simulation system called SYBORG(Yoshimura,et al.,1994) which is for analyzing an operator's cognitive process and an operator team's decision making process.

The operator behavior model can take appropriate actions within its knowledge. However, it cannot take actions when unknown situations occur. Thus, the knowledge of the model is fixed and nothing is learned from the experience. However, considering actual operators, learning is essential because they enhance their ability to cope with the unknown situations by learning the features of the situations and corresponding operations.

Reinforcement learning is noted in this paper as a learning mechanism of an operator behavior model. The learning is reinforced by a reward which is given to a specific operation. Reinforcement learning is a concept which has originally been used in psychology and some trials to apply the concept to machine learning or artificial intelligence have been conducted from 1950's(Samuel, 1959, Michie, et al.,1968). Recently, it is used in technological application such as robot control. There are two main methods in reinforcement learning, one is Q learning proposed by Watkins(1993) and the other is TD(Temporal Difference) method proposed by Sutton(1988). Comparing the two learning methods, The former is thought to be similar to actual operators

because they consider that plant state and operation is a pair. Thus, Q learning is adopted as a learning mechanism in this paper.

Q learning has a mechanism that a high reward is given to an appropriate operation and a low reward is given to an inappropriate one, thus, only appropriate operations are selected in the learning process. This mechanism seems to be reasonable, however, it has such a problem as mentioned below, i.e. the result of learning may not be the most appropriate solution, in other words, it may be a local one. In this case, the most appropriate solution exists somewhere. In order to prevent a learning from falling into such a local solution, it is necessary to provide a wide view in selecting an operation. 1/f fluctuation, which is a universally observed phenomenon in the nature including human beings, is noted in this paper as a candidate for providing a wide view.

This paper describes (1)the outline of SYBORG, (2)how to model the learning mechanism of an operator behavior model and (3)some simulation results and discussions.

OPERATOR TEAM BEHAVIOR MODEL

SYBORG consists of an operator team behavior model, a plant model and a human machine interface(HMI) model. The operator team behavior model includes three operator behavior models, i.e. a leader(shift supervisor) and two followers(reactor and turbine operators). They think respectively based on plant information through HMI and make a team's decision by communicating each other through the human human interface(HHI). Finally, they operate HMI based on the decision. The plant model is a simplified Boiling Water Reactor(BWR) which can simulate about 20 malfunctions. The scope of simulation is from 100% steady state to reactor scram. The human machine interface model includes numerical data of a control panel of the simplified BWR plant.

MODELING OF LEARNING MECHANISM

Basic Concept of Q Learning with 1/f Fluctuation

The basic concept of Q learning with 1/f fluctuation is shown in Fig.1. In this mechanism, an action with the highest evaluation value for a pair of plant state and corresponding action is selected. The evaluation is done by Q function, where, neural networks are adopted as the function because the plant state is defined by so many parameters that calculation, e.g. by a table, needs much time. Finally, 1/f fluctuation is applied to the evaluated values of all actions including the selected one. Outputs considering 1/f fluctuation are thus decided. As the data of 1/f fluctuation, the intervals of heart beat are adopted in this paper. The outputs considering 1/f fluctuation are defined as follows;

$$Qf = (1.0 + Rf) \times On$$

where,

Rf: Random numbers whose maximum values are less than the intervals of heart beat

Qn: Outputs from neural networks

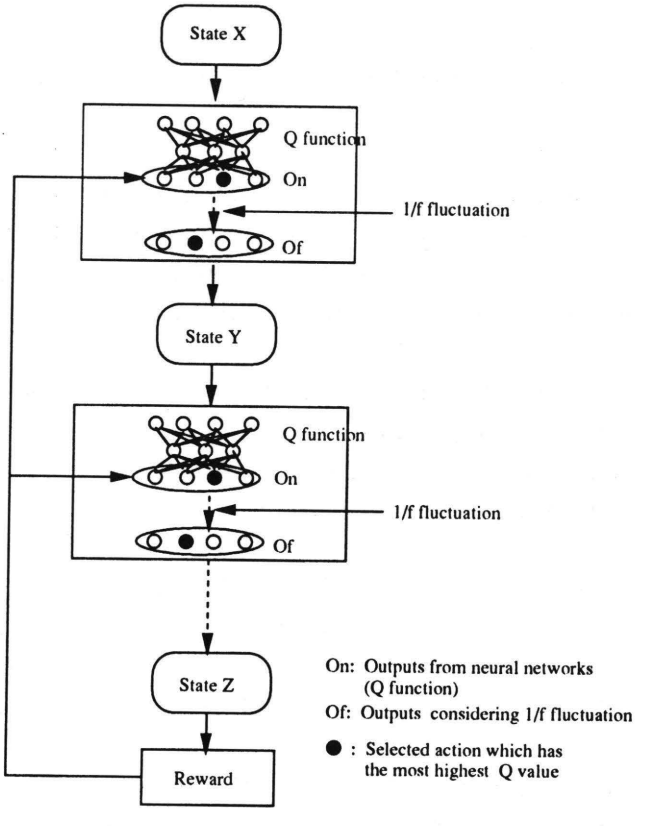

Fig.1 Learning Mechanism

The same procedures are repeated in the following action selections. After a plant state becomes final(state Z) , rewards are given to the previous actions.

Knowledge of Operator Behavior Model

An operator behavior model has knowledge of plant dynamics and actions(operations) for BWR when a safety relief valve(SRV) is stuck opened. The knowledge is as follows;

Alarms

The model has 13 knowledge of alarms, e.g. "SRV leak", "Suppression chamber temperature high" and "Reactor water level low low low", etc.

Parameters

The model watches 8 parameters, e.g. "SRV temperature", "Suppression pool(SP) temperature" and "Hotwell(HW) water level", etc. then anticipates the development of the parameters. After feedwater and condensate pumps are tripped due to "HW water level low low" alarm, it watches reactor water level, and then anticipates the development of reactor water level in the same way.

Operations

The model has 2 kinds of knowledge of operations. One is knowledge of operation which is done immediately when an alarm is activated, it is called an "immediate" operation. The other is knowledge of operation which is done to prevent the next alarm from being activated by watching the corresponding parameter, it is called an "urgent" operation which is done when the corresponding parameter reaches a landmark value. The model has 13 knowledge of operations such as "Reactor output decrease", "SRV manual open" etc. including "non-operation". As for the landmark values, the model has the knowledge of SP temperature, HW water level, SP water level and drywell(DW) pressure. Three kinds of values, i.e. small, medium and large, are considered in each parameter.

Q Function

Q function is described in neural networks which consists of 3 layers. The inputs to the networks are alarms and parameters. The outputs from the networks are operations and landmark values, i.e. the operator behavior model learns appropriate operations and landmark values, by watching the alarms and parameters. The hidden layer is divided into 3 parts. One is for operations, another is for landmark values and the other is for both operations and landmark values. Learning is done by back propagation and teaching data are the rewards.

Rewards

Rewards are given to the previous operations. However, the immediate operations are fixed as an operator behavior model's knowledge regardless of learning. Therefore, the concept of "arbitrary" operation is introduced in this paper. The 13 operations mentioned above are selected as the arbitrary operations which can be placed between two alarms and the maximum number is supposed to be three. On the other hand, as for the urgent operations, rewards are given to the landmark values. Rewards are given in proportional to the elapsed time from an operation to the next and that from an operation to the next alarm.

Plant Model

A simplified BWR plant simulator is used in SYBORG. However, there is no need to use such a precise simulator in this paper, therefore, a qualitative plant simulator on SRV stuck open is constructed on a personal computer together with the learning mechanism by giving

a. qualitative trends of concerning parameters(e.g. SRV temp.: 0.542℃/sec., SP water temp.: 0.03℃/sec., etc.)
b. relations between operations and parameter changes(e.g. Reactor output decrease operation: SRV temp. decrease, SP water temp. increase, etc.).

SIMULATION RESULTS AND DISCUSSIONS

The learning mechanism is simulated using SRV stuck open event. SRV leak alarm is firstly activated in this event, then immediate, arbitrary and urgent operations are successively selected. Finally, reactor scram occurs due to DW pressure high trip alarm. Rewards are given to arbitrary and urgent operations. Thus, the elapsed time between the first alarm and the final is expected to be elongated. In fact, the learning effect is enhanced as learning proceeds. However, no effect of introducing 1/f fluctuation is found. The critical operation which prevents reactor scram in this event is stand-by DW cooler operation. Therefore, the number of selection for the operation is compared between with and without 1/f fluctuation. The results are shown in Fig.2. The figure indicates that the stand-by DW cooler operation is more selected with 1/f fluctuation than without.

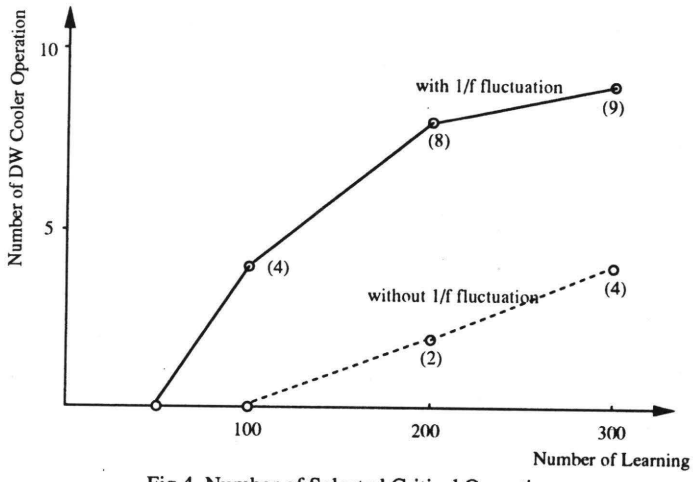

Fig.4 Number of Selected Critical Operation

On the other hand, as for the landmark values, there are three in the urgent operation(stand-by DW cooler operation), i.e. DW pressure=0.11Kg/cm^2(small), 0.12Kg/cm^2(medium) and 0.13Kg/cm^2(large). The operation is conducted at DW pressure=0.12Kg/cm^2(number of learning: 100times) and DW pressure=0.11Kg/cm^2(number of learning: 200, 300 times) with 1/f fluctuation. The results indicate that 1/f fluctuation selects appropriate landmark values to prevent a reactor scram as learning proceeds. However, no clear relation is found in the case of without 1/f fluctuation.

CONCLUSIONS

Q learning with 1/f fluctuation is proposed as a learning mechanism of an operator behavior model in this paper. The effectiveness of the learning mechanism is thought to be made clear by the simulation using SRV stuck open. Though no effect of 1/f fluctuation is found in the elapsed time to reactor scram, it is thought to be proved by making the operation time longer or making the arbitrary operation more frequent.

In this paper, learning is done for arranging or selecting existing knowledge. However, considering actual learning of plant operators, creation of new knowledge is essential. Therefore, such a learning frame is successively to be studied.

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Design of a New Interface for The Supervision of a Nuclear Fuel Reprocessing System

Manuel LAMBERT, Bernard RIERA and Grégory MARTEL
Man-Machine Cooperation Team
Laboratoire d'Automatique et Mécanique Industrielles et Humaines (LAMIH)
(Laboratory of Industrial and Human Automation and Mechanics)
Université de Valenciennes et du Hainaut-Cambrésis
BP 311 Le Mont-Houy
59304 VALENCIENNES-Cedex, FRANCE

{Manuel.Lambert, Bernard.Riera, Grégory.Martel} @univ-valenciennes.fr

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ABSTRACT

The work of development of a new generation interface has been carried out at the LAMIH of the University of Valenciennes in collaboration with the LAG ("Laboratory of Automation of Grenoble") of Grenoble (FRANCE) and the LIA ("Laboratory of Advanced Computing") of Marcoule (FRANCE), a department of the CEA ("Atomic Energy Commission"). Starting from a numerical simulator of a nuclear fuel reprocessing system composed of two pulsed columns and belonging to the CEA of Marcoule, the LAMIH has realized the supervisory interface of this process by integrating an original alarm filtering system developed by the LAG, based on fuzzy reasonings.

Keywords: Supervision, continuous process, dynamic model, Mass-Data-Display, causal graph, functional analysis, information synthesis, fuzzy reasonings.

INTRODUCTION

The traditional supervision systems present some already known faults. To simplify, it is possible to identify two situations which have two opposite causes: sometimes the supervision operator can be saturated by an information overload, whereas, some other times, an information underload can deteriorate the operator's mental model of the supervised process. These situations are normally due to the operator's tendency to wait for the alarm to act, instead of trying to foresee or anticipate abnormal system's states. Since human information processing capacities are limited, when human operator (HO) has to face with an alarm cascade, it becomes difficult to avoid or manage interpretation and/or action failures. Moreover, there are some aid supports which minimize operator's attention and so his anticipation capabilities.

To avoid these perverse effects and to make operator's work more active, future supervision has to be human centered, that is it has to take into account and integrate cognitive capabilities of HO such as perception, anticipation and reflection capabilities. Our objective is to provide the operator with the sufficient degree of information to realize the different tasks required during the supervision activity (monitoring, detection, diagnosis, localisation). The supervision system we have developed is based on concepts that have not been often employed in the traditional supervision systems and that should aim at favorizing a more active and intelligent activity of the operator through a better use of the information coming from the alarm filtering system.

The first paragraph reminds briefly the actual challenges of supervision and the basic principles of the workshop of pulsed columns. In the second paragraph we describe the basic concepts of the MDD and of the causal graphs representation. Then, the next paragraph deals with the design steps related either to the monitoring views (MDD concept) or the hierarchic diagnosis views (causal graph concept). Finally, the advantages of this type of interface are evoked in the conclusion where we present the first results of an experimental assessment realized with professional operators at the CEA of Marcoule in february 1997.

GENERAL RECALL ON THE SUPERVISION

The Classification Of the Supervision Tasks

In general, supervision consists of commanding a process and supervising its working (Millot, 1988). Moreover, to achieve this aim, the supervision system of a process must collect, supervise and record important sources of data linked to the process working so as to detect the eventual dysfunctions and to warn the HO. When aiming at the optimization of the criteria linked to the respect of production security and economy objectives, the HO must supervise the process states and act in such a way as to maintain it as near as possible to its nominal working point. The induced tasks are generally decomposed into three main classes (Rouse, 1983): the control, the follow-up tasks of normal working, the transition tasks linked to the running changes, the default detection tasks, the diagnosis and the resumption tasks of defaults. According to Moray (Moray, 1986), a supervisor operator realizes a monitoring task when he supervises the whole of displayed information without executing any action which may change the system state. From this definition and according to the Rouse's classification, the monitoring tasks gather the monitoring tasks and the follow-up tasks of normal working on one part, and the default detection tasks on the other. In the following of the paper, our classification will include the monitoring tasks as intended by Moray and the diagnosis tasks as intended by Rouse.

The monitoring tasks need a global vision of the process to allow an efficient supervision whereas the diagnosis tasks need a hierarchic vision to obtain views less or more restricted of the process. Or, the today supervision systems composed of many synoptics (P&I diagrams) do not reply to the specificities of these information needs.

THE PRESENTATION OF THE USED CONCEPTS AND OF THE STUDIED SYSTEM

The design step of a supervision system starts with an analysis step of the process and its command which allows one to constitute a rough database as exhaustive as possible. From this database, the designer must create a second database, as reduced as possible, taking the data sufficient for the understanding of the process state by the HO. It is this second database which will constitute the information content of the interface. To obtain it, some functional analysis techniques which represent the process in normal working can be applied. In the last years, as a consequence of the computerization of industrial systems, the HO is become a bottleneck in the information flow. More and more information revolves around these systems and overloads rapidly the human information processing capability. So, it becomes necessary to select rigorously the information through the main techniques of information reduction: filtering, synthesis and agregation of information.

The MDD Interface

The concept of a MDD interface appeared at the end of the 80ths and is characterized by the presentation on a single display of all the data allowing a supervision operator to supervise a process (Beuthel, et al., 1995) (see figure 1). Each variable is symbolically represented and at least one of its intrinsic characteristics, such as its shape or its colour gives a picture of the temporal evolution of its state. In theory this visual representation should support the operator to achieve as fast as possible a global vision of the process state and to detect fastly all anomalous process deviations.

Types of representation / Characteristics	Mass-Data-Display	Causal Graph
Type of tasks	**Monitoring**	**Diagnosis**
Principles	- Symbolic data display - Massive data presentation	- Causal representation of the process =>Nodes = pertinent variables => Oriented relations = causes to effects links between the variables
Representation	1 stick = 1 variable — normal / abnormal Working mode	The variable X influences the variable Y (X) → (Y)
Theorical interests	- Several hundreds variables by screen => exhaustive vision of the process state - Visual attraction => easier detection	- Simple description of the working of the process - Representation adapted to the cognitive strategies developped by the HO during the diagnosis steps

Figure 1: Presentation of MDD and causal graph representations

The Causal Graph

A causal graph of a process is a graph whose nodes represent all variables and the oriented relations between these variables the causal links (Dziopa, 1996) (see figure 1). This representation constitutes a good support for the supervision operator because the causal links between the variables are susceptible to facilitate the different types of cognitive reasonings coming into play in diagnosis processes. Moreover, to allow the HO to access different points of view according to the Means/End and Whole/Parts description axis, the views dedicated to the diagnosis follow a hierarchic pyramidal disposition.

Principles Of the Pulsed Columns Workshop

This workshop is composed of two pulsed columns head to foot and their system of alimentation (see figure 2). Each pulsed column ensures the separation of the couple Uranium-Plutonium of the fission products which are considered as wastes. The uranium, plutonium and fission products are originally dissolved in an acid solution. The first column, the extraction column, receives this loaded solution (var 1) from which the uranium and the plutonium are extracted thanks to an organic solution (var 3). The acid solution denser than the organic solution is put at the top of the column whereas the organic solution is put at the base. Within each column, a pulsation pressure (var 11, var12) increases the chimical exchanges making a more efficient emulsion. At the base of the extraction column, the aqueous outflow (var 7) contains only the residues. At the bottom, once the organic solution overflowing (var 4) which contains in addition to the uranium and the plutonium some traces of fission products is recuperated, it is sent to the second column, the washing column. Thanks to the supply of an acid solution (var 6, var 8) and to the action of a pulsation pressure (var 12), the already described physico-chimical processes take place; the aqueous outflow (var 2), which contains the residual fission products, is reinjected in the extraction column. Finally the organic solution overflowing of the second column (var 10) contains only the uranium and the plutonium.

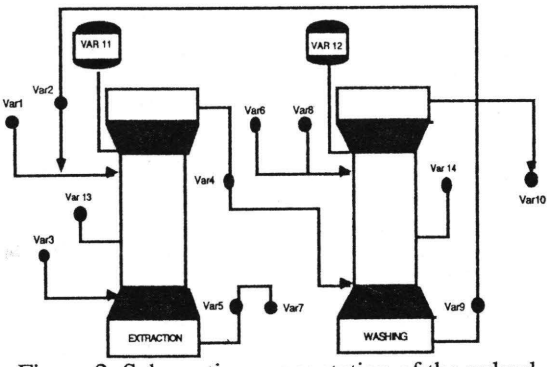

Figure 2: Schematic representation of the pulsed columns workshop

THE DESIGN OF SUPERVISION INTERFACES

Design of Monitoring Views: Application To the Functional Analysis

For the design of the MDD views (see figure 3), we have applied two techniques of Functional Analysis to the pulsed columns workshop: the functional tree (Zwingelstein, 1995) which allows one to identify and to organize the functions of the system hierarchically and the SADT (IGL Technology, 1989) which allows one to represent the flows of matter. Their combinated application supplies a structuro-functional model of the workshop under normal working. As for the MDD symbol, each variable is represented by a quadrilateral whose two attributes, size and color, reflect respectively its importance and its state (see figure 3). This symbol owns a range of colors with progressive contrasts (from green to red through the yellow) which is representative of the state of the residue (i.e. of the difference in absolute value between the actual value called measure and the theorical measure called model). These different values are generated by a numerical simulator of the pulsed columns workshop: the model corresponds to a normal working whereas the measure to an abnormal working i.e. when there is an abnormal behaviour of the process at a given moment in the simulation. In actual fact, the green means that the variable is in a normal state (value of the residue null or near to null) whereas the red color translates an abnormal state (significative value of the residue). The panel of colors (30 colors) between these two colors allows one to translate, in a very gradual manner, the whole states from the normality to the abnormality.
The MDD color as others information issued from the system of fuzzy alarms filtering, comes from an algorithm based on fuzzy reasonings developed by our collaborators of the LAG. Briefly, the state of a variable is established through the study of its instantaneous value and its evolution in the past (via its derivative). 9 possible qualitative behaviours (1 normal et 8 abnormals) function of the couple "instantaneous value/derivative" have been defined. These behaviours called primitive states, are shown at the figure 5. In fact, when a variable follows a normal behaviour (value of the residue null or pratically), the value of the membership function associated to the primitive state 5 tends towards 1 (see figure 5). The states 2,3,4,6,7 and 8 correspond to a

suspect situation although the states 1 and 9 correspond to a serious situation. Then, to deduce the corresponding MDD color, an agregation function supplies, from the values of the 9 membership functions, a value between 0 and 1. To this value corresponds so a nuance within the 32 available colors. In fact, the colour (from green to red) charaterizes the gravity of the variable state by the means of an analysis of the shape of the residue. The next paragraph presents the diagnosis views, based on hierarchic causal graphs which should allow the HO to isolate the source of a dysfunction.

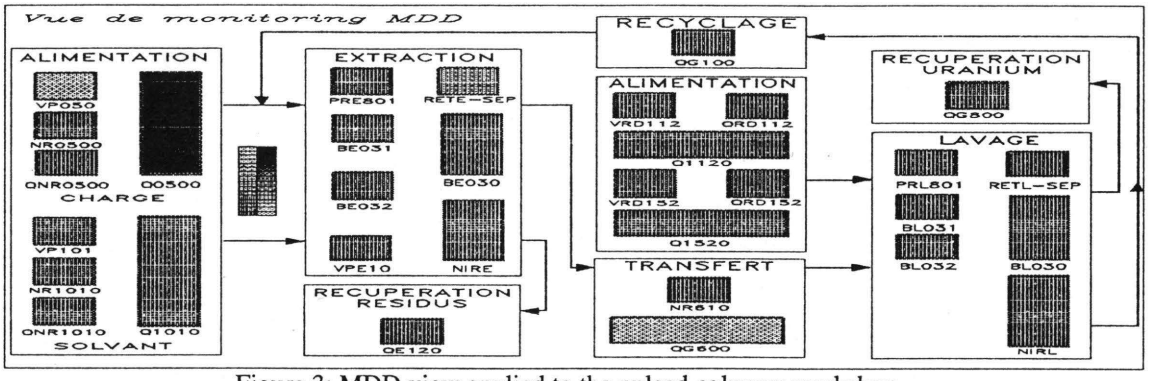

Figure 3: MDD view applied to the pulsed columns workshop

Design Of Diagnosis Views Based On Causal Graphs

For the design of the diagnosis views, two points have been considered: their general organization and their contents. Because of the information density which characterizes the complete causal graph of the workshop, an information reduction has been applied. To translate it at the level of the interface, a hierarchic organization in 3 levels has been adopted: The superior level (level 2) supplies a General view of the process, the intermediary level (level 1) a Median view and the inferior level (level 0) two complementary views of the process, the Extraction and Washing views. This pyramidal organization allows a gradual progression of the information contents between the different levels (see figure 4). As for the MDD representation, each variable is represented by a node composed of two entities: an exterior crown resuming the MDD color of the monitoring view and an interior disk, containing a symbol representative of the shape of the residue called "drift indicator". This symbol corresponds to the 9 primitive qualitative states already seen in the previous paragraph (see figure 5). To display one of these 9 symbols, the value of the corresponding membership function must be at least superior to a beforehand chosen threshold (in our case, 0.9).

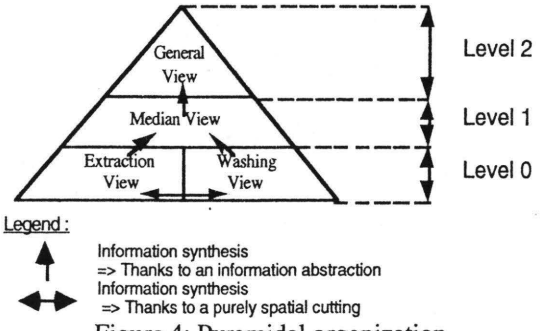

Figure 4: Pyramidal organization of the diagnosis views

To determinate the causal graphs associated to each level, we use two decomposition axis, the Whole/Parts and Means/End axis. A first decomposition following the first axis allows one to decrease the information content thanks to a simple structural cutting of the complete causal graph into two sub-graphs (the graphs "Extraction" and "Washing" of the level 0). These two sub-graphs constitute the two views of the level 0 of the pyramidal organization, the Extraction and Washing views (see figure 4). Then, we use the Means/End axis. This axis with a variable abstraction degree allows one to obtain models which describe with more or less details a same part of an installation. This decomposition is first applied between the inferior and median levels and secondly between the median and superior levels. That allows one to obtain two causal graphs with increasing abstraction degree.

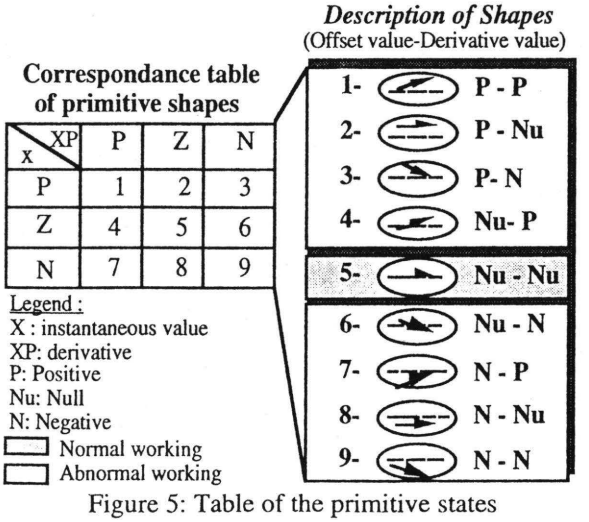

Figure 5: Table of the primitive states

Hence, from the complete causal graph, an information filtering following the criteria of production (balance of matter flows), security and economy (stability of performance indicators) leads to the realization of the causal graph of the view with a medium abstraction degree, the Median view. Finally from this view, an information filtering following only the criterion of production (balance of the matter flows) reduces the number of information to constitute the causal graph of the most abstract view, the General view (see figure 6).

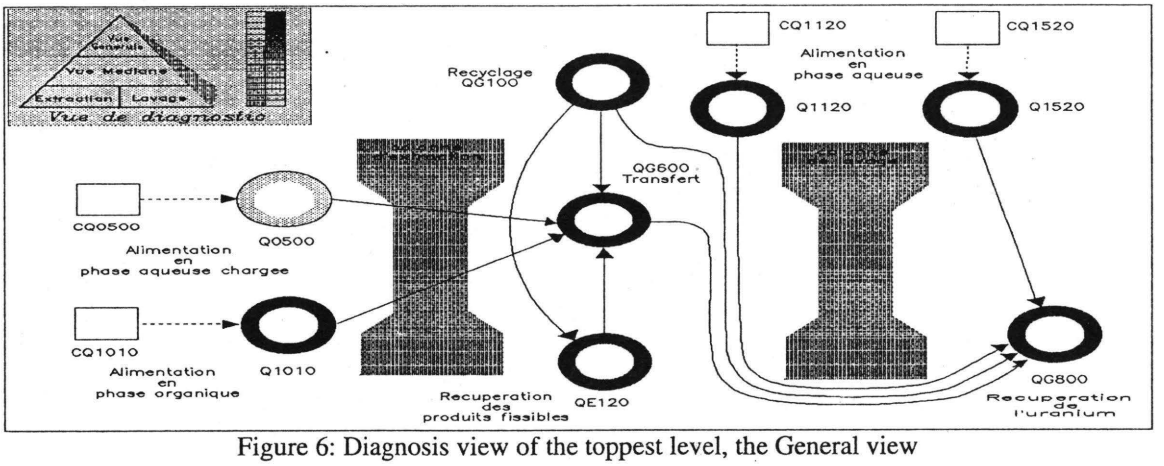

Figure 6: Diagnosis view of the toppest level, the General view

CONCLUSION

In this paper, we briefly presented the today problems of the supervision and so put in evidence the challenges to solve in the future. Indeed, a design approach of a supervision system based only on alarms condemns the HO to remain too much dependent on these alarms. We propose so an approach more centered on the HO. This means that we have to provide him with the means to develop a more active behaviour face to events. To reach this goal, the HO must be provided with tools which allow him to estimate at each moment the process state. For that, since the monitoring and the diagnosis tasks require specifical information, we decided to treat them separately and to apply two distinct concepts: the MDD concept for the monitoring tasks and the causal graph concept for the diagnosis tasks. So we designed a MDD view dedicated to the monitoring using symbolic information with a low agregation power generated by an advanced alarms filtering system. In this view, the functional structure, the respect of the logical links between the functions of the process, and the representation of the variables states following a visual dynamic have to contribute to make more active the work of the HO by allowing him to detect, as rapidly as possible, the defaults. For the diagnosis tasks, the hierarchic views composed of causal graphs aim at allowing the HO to reflect more easily in terms of causes to effects relations and to dispose of different points of view of the installation. All concepts presented in this article have been tested by the means of an experiment led at the CEA of Marcoule with professional operators. These works should allow one to obtain more detailed results on the efficacity of the new concepts applied to the supervision that we have just presented in this paper.

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How does design support task tools in complex environment? Studies in Air Traffic Control.

A. Bellorini, [1] C. Cacciari, [2] R. Nicoletti, [3] and F. Vanderhaegen [4]

[1] Joint Research Centre, EC,
21020 Ispra (VA) - Italy
Email: anna.bellorini@jrc.it

[2] Department of Psychology, University of Bologna, 430127 Bologna - Italy
Email: ccacciari@psibo.unibo.it

[3] Institute of Psychology, University of Urbino, Urbino - Italy
Email: R.Nicoletti@bib.uniurb.it

[4] LAMIH, University of Valenciennes
Le Mont Houy BP 311, 59304 Valenciennes Cedex - France
Email: vanderhaegen@univ-valenciennes.fr

ABSTRACT

This paper presents a human oriented approach for designing task support tools for system control and supervision. This design is presented following three main dimensions: task, human operators and machine. The task dimension embodies the objectives to be achieved during the control of a given system. The human dimension includes the interaction between human operators that is required to perform the task. The machine dimension includes all technical instrumental tools provided by the working environment. The three dimensions are described and analysed through three applications in the air traffic control domain.

Keywords

Task support tools, Human oriented design, Air Traffic Control.

INTRODUCTION

A human oriented design of task support tools is presented in this paper following three main dimension that define a system: task, human and machine. The task dimension embodies the objectives to be achieved during the control or the supervision of a given system. The human dimension includes the interaction between human operators that is required to perform the task. The machine dimension includes all technical instrumental tools provided by the working environment. These three dimensions are interactive and dynamic: human capacity increases with experience and decreases with workload, while machine capacity evolves with technology.

This paper focuses on the application of these three dimensions to the air traffic control for the design of task support tools. In the air traffic control domain, the organisation of human tasks conforms to rules and procedures that are needed to achieve an optimisation of flight safety, flight economy, and fluidity of traffic flow. The human dimension includes also the sharing of the task between human controllers and pilots. The machine dimension is the set of instrumental tools that human controllers use during the management of their tasks. These tools display information (e.g. radar screen, flight strip, weather condition on TV screen) or transmit verbal communication (e.g. radio, telephone, intercom).

This paper presents three related ways for assessing the relevance of human oriented factors, notably in tower control, in approach control and en route control. The first part focuses on the analysis of mental representation of the tower controllers and pilots task. The second part deals with the management of the tasks supported by

verbal communication between approach controllers. The third part consists of an experimental approach of task support in en route control.

THE TOWER CONTROL TASK AND MENTAL MODELS

A study in a tower control was conducted in which eleven tower and radar controllers were interviewed. The aim of the study was to investigate the mental model of the tower controller's tasks. A further set of ten interviews that used an adaptation of the structured interview techniques employed with tower and radar controllers was conducted in which pilots, as users of tower control activities, were asked about the ways in which they mentally represent the tower and radar control activities.
We investigated the mental models underlying: (1) the tower and radar controllers' tasks, i.e. the ways in which both the controllers represent and evaluate their work, and (2) the ways in which pilots mentally perceive the tower and radar controllers' tasks.

According to Cannon-Bowers, Salas and Converse (1993), mental models are clusters of knowledge, shared by the members of a team. Such structures make possible the development of tasks in co-ordination and are useful to anticipate the behaviour of other members (Klimosky & Mohammed, 1994). Shared models are cognitive structures that allow the human operators to behave as a team, to face emergencies and to deal with abnormal situations.

The management of safety in air traffic control environments is based on several aspects, among which is the operator as an individual (his/her internal mental and physical states, cognitive processes and communication capacities) and his/her being part of a team and of an organisational system and culture. A work group is a well performing team when it optimises the ratio between resources and results, and when it shares a consistent mental model of its tasks.

Tower and radar controllers indeed have a fairly articulated mental model of the requirements and capacities underlying their tasks. Based on the content analysis of the interviews we carried out, we found that such a mental model revolves around two main dimensions: tower control as a team-based activity and tower control as a cognitive enterprise. Interestingly enough, pilots share this twofold representation as well. In addition, pilots stress the relevance of the procedural aspects of tower control. Tower and radar controllers mental representation of their work is generally more articulated than that possessed by pilots, showing once again that the difference between levels of expertise in a field also implies a more detailed capacity of task analysis for experts.

The study of interactions between humans is helpful to build a controller mental model. The second field study takes into account a part of those interactions. It aims at modelling communication in co-operative work.

HUMAN INTERACTION BETWEEN APPROACH CONTROLLERS

The data we discuss are based on a field study in air traffic control. During the field study a data collection has been realised followed by the analysis of the communication exchange between human controllers in the management of the approach control task (Bellorini et al., 1995). The approach control task is characterised by a high need for co-operation between human controllers. The communicative exchanges between controllers are aimed at defining common objectives and shared strategies, and to anticipate problems, solve conflicts, explain intentions, and take decisions. The analysis of the communications between human operators enables a more thorough understanding of task and workload distribution, in particular in the management and fault diagnosis, and the identification of the factors that affect human performance.

From the data analysis it is observed that the following situations can increase the human operators workload: (1) high density of communication and overlapped communication; (2) high traffic conditions in terms of complexity, volume or holding; (3) the appearance of unexpected situations or conflicts.

The human operators under high workload experience a decrease in their performance, the main effect being on co-operation due to a lack of time to dedicate on the explicit communication and negotiation for co-operation. It is a matter of fact that the safe and efficient conduct of air traffic control depends on the exchange of information.

The human operators under high workload conditions cannot manage the communication exchange efficiently. In presence of workload, a breakdown it is observed on the communication flow between human controllers. Different solutions to cope with these situations are applied, based on task sharing and workload distribution. For example, the human controllers decompose the task into sub-task giving a priority to the safety rather than to the flight economy and fluidity of the traffic flow (Bellorini, 1996).

The introduction of task support is mainly based on the workload distribution and the errors and/or the "automation surprises", where the automation takes an unexpected action, are the results of a mismatch between the properties and the abilities of both human operator and machine (Woods, 1994).
In order to increase efficiency and safety, an important role seems to be played by the development of systems that support the exchange of communication.

Moreover, communication problems due to an overloaded situation, for example, can be solved by allocating tasks to an automated system. This approach which aims at using competencies of machine in order to maintain the reliability of human operator, it is developed on the last study.

HUMAN-MACHINE INTERACTION TO SHARE EN ROUTE CONTROL TASKS

The en route control study is an experimental feasibility of task sharing between human and machine. Then, it focuses on a part of the air traffic control task organisation: the tactical tasks which can be performed by both human and machine. Tactical tasks consist of detecting possible conflicts between planes (a conflict appears when two planes transgress minimum separation norms), of solving conflicts and supervising the whole traffic. The human dimension is represented by a radar controller and the machine dimension is an expert system called SAINTEX which is able to take in charge a part of tactical tasks. Indeed, it is able to supervise the traffic and to detect all conflicts but to solve only conflicts between two planes changing the direction of one plane. In order to increase sector capacity by regulating the controllers' activity and maintaining an optimal global performance, a project, called SPECTRA, consists of providing controller help to action, i.e. sharing dynamically tasks between a radar controller and SAINTEX. Two types of dynamic allocation management are then integrated in the SPECTRA structure: a manual allocation in which the human is in charge of task allocation with regard to subjective criteria, and a automated allocation in which allocation decisions are based on objective criteria related to task difficulty (Vanderhaegen, 1997).

The interaction management between task, human and machine dimensions is made through dialogue screens in order to avoid co-ordination conflicts and allocation conflicts between both human and machine. In both manual and automated modes, conflicts that SAINTEX can solve are indicated by a specific colour on a dialogue screen which displays flight plane strips and a radar view which displays on-line the evolution of the planes. In manual mode, the deadline for the conflict to become non-solvable by SAINTEX as well as the deviation order it proposes are displayed on the strips of the conflictual planes. Initially, the control of all planes is allocated to the radar controllers. If they feel overloaded, they can select a conflict and transfer it to SAINTEX. They can take a conflict back again, but if the order deadline given by SAINTEX is over, the conflict cannot be allocated to SAINTEX anymore. On the other hand, in automated mode, allocation criterion is based on task demand assessment which characterise the functional task difficulty. When this difficulty exceeds a maximum level, shareable conflicts are allocated to SAINTEX in order to decrease the task demand. When it is possible to allocate a conflict to SAINTEX, the solving strategy is displayed on the corresponding strips and SAINTEX takes in charge the control of these planes until the conflict is over.

Qualified controllers and air traffic control engineers have performed different experiments on SPECTRA. The main results are promising. Indeed, depending on subjective and objective data obtained, both manual and automated dynamic task allocation modes are useful for loaded traffic control and supervision, in terms of decreased workloads and improved safety. Qualified controllers prefer the manual mode which allows them to feel fully responsible for the entire traffic control, whereas engineers prefer the automated mode because it frees them from the task sharing management. On the other hand, qualified controllers perform best with the automated mode which obliged them to take in charge fewer conflicts, whereas engineers achieved the best results with the manual mode because they gave more conflicts to SAINTEX. Despite different uses of the abilities of the machine, both manual and automated modes permit the adaptation of the task sharing, related to the human's need for assistance during the management of the tactical task.

CONCLUSION

The paper has presented different ways to study the task, the human and the machine dimensions for designing a system. The task dimension is the task organisation, the human dimension is the task management by humans and the machine dimension defines the implication of tools on this task management. Therefore, sub-levels can be considered into these three design dimensions and interactions between them have to be identified.

A human oriented approach is presented in three different domains of air traffic control. The first one concerns the task organisation of tower control as it is mentally represented by controllers and pilots. The second domain is considered in the light of the interactions between humans for the task organisation of approach control. The last one presents the task organisation of en route control implicating a radar controller who manages tactical tasks and who is assisted by a machine. Therefore, these studies analyse a part of the global air traffic control task organisation in order to characterise the task management related to both human and machine dimensions. They aim at specifying the dynamic task distribution among humans, between human and machine and at identifying which tasks can be supported by the machine. These three approaches have to be matched to analyse the integrity of air traffic control system organisation.

Generally, actual supporting task tools do not take into account the whole system organisation i.e. they are designed through studies focusing only on a part of task, human or machine dimensions. Design requirements need the definition of an integrative approach and methods development for task supporting tools. This approach includes the integration of task, human and machine dimensions.

Related to the last dimension (i.e. machine dimension), the study of both task and human dimension has to orient the design of two kinds of instrumental tools: (1) passive tools which aim at supporting communication flow and interaction between human operators and machines, and (2) active support tools which aim at releasing humans from specific situations (e.g. overload, stress, emergency) and at helping them to take decisions. Studies on mental representation modelling, such as communication modelling between humans are then helpful in order to identify assistance requirement and to design model-based task support tools and to determine sufficient criteria to validate the efficiency of these tools.

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Memory Performance and Diagnostic Processes in Air Traffic Control

Nicole Boudes */, Paola Amaldi */** & Jean-Marie Cellier ***

* Laboratoire Travail et Cognition
Maison de la Recherche
Université Toulouse-Le-Mirail
5, allées Antonio Machado
31058 Toulouse Cedex, France

** Centre d'Études de la Navigation Aérienne
7, avenue Édouard Belin BP4005
31055 Toulouse Cedex, France

[boudes, amaldi]@cenatls.cena.dgac.fr
cellier@cict.fr

ABSTRACT

The objective of this paper is twofold: a) identify strategies that expert operators develop to focalize on the relevant information in a dynamic environment and b) relate information seeking behavior to diagnostic contexts. We have investigated these questions in the domain of Air Traffic Control through the design of two studies. For the first study operators were asked to perform a memory test and in the second they were asked to explicitely identify the information they needed to diagnose the presence of conflicts between aircraft. Results suggest that the unit of traffic representation is a network of inter-related airplanes, rather than individual aircraft and that conflict detection is a process guided by a set of knowledge structures, called *detection frames*. Both studies emphasize the use of environmental information to develop time management strategies. Concluding remarks concern implications for the design of a decision support system for air traffic controllers.

Keywords :
Air traffic control, time management strategies, detection frame

INTRODUCTION

We are interested in investigating the nature of some aspects of memory performance involved in selecting the relevant information for diagnosis. A central task faced by controllers is to select the data leading to the detection of potential future conflicts (i.e., lack of standard separation between aircraft) and to the choice of the most effective solution. By "effective" we mean that the selected plan of actions has to simultaneously satisfy several, sometimes conflicting, constraints. We shall present some elements concerning the information seeking activities in dynamic environments.

Information filtering strategies

Across different applied domains, a number of previous works highlighted the existence of a selected attention mechanism oriented towards some specified sources of information. Not all of the available data are processed by the operators. The filtering activity reflects the meaning assigned by the operator to the information selected at a given time (Iosif, 1969).

De Keyser (1990) claims that the perception and recognition of the useful data are accomplished by a cognitive filter allowing one to focus on the problem space relevant to the currently active operators' objectives. Two components defining such a filter are introduced: a statistical-inferential filter, oriented by probabilistic knowledge about the occurrence of future events, and a semantic filter related to the operator's objectives. The fact that the search for relevant information is carried out in a dynamic environment should also be taken into account. To our knowledge, the temporal framework characterizing the development of the filtering activity is never been learned explicitly. The major difficulties to anticipate a system evolution in a near future as well as in a distant future, has been however emphasized by several studies (Boudes, 1997 ; Boudes, Amaldi, Cellier & Leroux, 1995 ; Mariné, Cellier & Valax, 1988). Their findings showed that the accuracy of estimation degraded as a function of the delay of the estimation interval.

Two studies were carried out within the frame of an extensive project concerning the design of a decision support system for air traffic controllers called ERATO (En Route Air Traffic Organizer) (Leroux, 1993). In the first study, controllers were asked to carry out a (memory) recall task that would reveal the effect of focalizing attention only on

a portion of the available data sets, and the second study aims at eliciting strategies developed by controllers to identify conflicting aircraft.

STUDY 1: MEMORY RECALL TASK

Methodology

The data analyzed come from a study concerning how people anticipate traffic development (Boudes, 1997). Sixteen expert operators managed a heavy simulated air traffic scenario. The simulation was unexpectedly stopped to allow people to carry out a number of tasks. For one of them, we asked controllers to estimate future aircraft positions at different time horizons, using a schematic map of the sector and without any access to traffic data. Operators were given a list of eight aircraft, however, they could, if they wished, position additional airplanes. The presentation order of the aircraft changed to avoid presentation biases. The callsigns of the presented aircraft were the following: ACF5111, ITBY, DIBAL, FBJMG, MON1789, CYP455, GBJMA, DLH514. We might refer to this as the "imposed" list of aircraft.

A few remarks are appropriate here concerning the characteristics of the task. First of all, the diagnostic activity is a continuous process during the control of dynamic situations. In air traffic control, diagnosis is often achieved through anticipation of future events. Controllers have to detect in advance the future occurrence of a loss of standard separation among aircraft, (what we define as "conflict") to be able to take preventive actions. The two main constraints are a frequent lack of the necessary information and a limited time available to make decisions ("Is there going to be a conflict or not?"). Therefore, the outcome of the diagnostic processes depends partly on the status of these two interacting factors.

Broadly speaking, one of the goals of air traffic control is to verify that aircraft follow their flight plans in a conflict-free trajectory. In addition to that, however, in the sector under study, aircraft had to be sequenced to achieve a safe landing. Sequencing is a very constrained task, as aircraft have to be managed in a progressively reduced space given the very limited number (usually one at the most two) of landing runways available at each airport.

A third characteristic relevant here, concerns the controller-pilot radio contact which is usually established shortly before the aircraft enter the sector, although the aircraft is visible on the radar image beforehand. Such event mark the time at which the aircraft is actually under control in a given sector. When the simulation was interrupted the CYP455, DLH514 and the GBJMA were not yet in the frequency.

Results

Results showed that the rate of recall of the aircraft from the imposed list, went from 100% to 13% (figure 1).

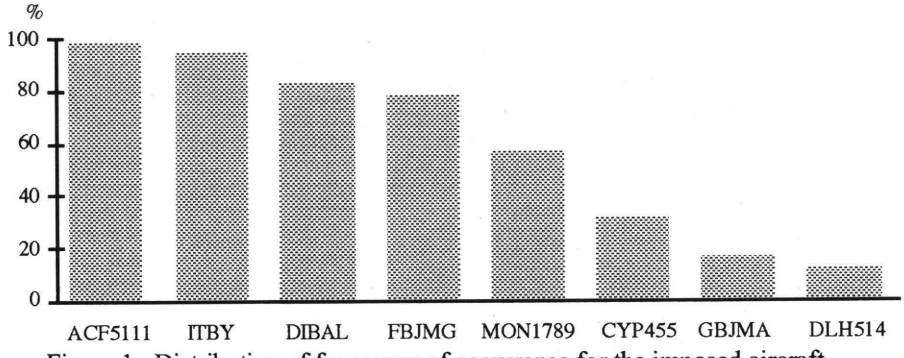

Figure 1: Distribution of frequency of occurrence for the imposed aircraft.

In addition to that, controllers spontaneously recalled some aircraft that, by not being members of the imposed list, were named "additional". About 40% of the positioned aircraft were additional. Figure 2 shows the distribution of the most frequently spontaneously recalled airplanes.

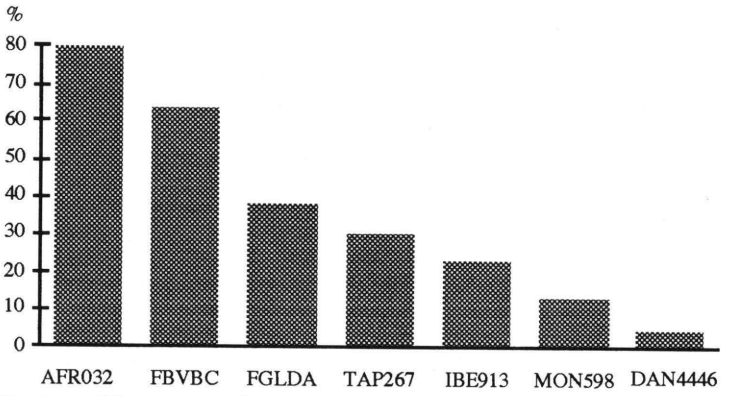

Figure 2: Distribution of frequency of occurrence for the most significant "additional" aircraft.

One question raised by the observed performance was: Why controllers did remember those aircraft (imposed and spontaneously recalled)? Can we extract enough compelling evidence from the data that would justify the results we get? Given the enormous amount of work carried out to study memory, can we assemble a theoretical model that explain why did controllers remember (and perhaps why they did not, when that was the case)?
As already noticed, the rate of recall varied. Concerning the aircraft from the imposed list, three of them were cited less than 30% of the cases. Those were the airplanes that were not yet in the frequency at the time of the interruption (CYP455, GBJMA and DLH514). On the other hand, not surprisingly, we found that one of the most cited aircraft, the ITBY, was involved in several conflicts. It had to land in Paris and several events were in its way preventing each time the controller to take the step necessary to get the aircraft closer to the objective.

Next, we carried out a protocol analysis to establish the existence of associative links between the imposed aircraft and the additional ones. In what follows we shall discuss only some of the links that we found.

Associative links
A first observation was that controllers did mention the existence of conflicting links among the two sets of aircraft, those coming from the imposed ones, and the spontaneously recalled ones. Controllers expressed the existence of a link among two, three or four airplanes contained in the identified sets. The links among aircraft as expressed by controllers are shown in the figure 3.

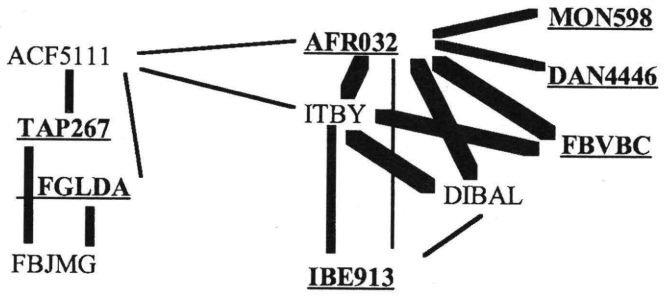

Figure 3: The most frequently expressed links among aircraft.
Aircraft in bold and underlined are additional aircraft and the remaining are from the imposed list.

The strength of the links indicate the probability that aircraft would be recalled together. The five strongest associative links were established among four aircraft (**AFR032**, ITBY, **FBVBC** and DIBAL). The last two were often mentioned as they represented an obstacle to the achievement of the main objective by the first two aircraft: be ordered in a sequence to land. The fact that these particular configuration was unique to these aircraft at the time the scenario was stopped, suggests that it strongly affected the probability of these aircraft being clustered together by the majority of controllers interviewed.
The analysis of the verbal protocols led us to group all of the aircraft into four overlapping sets, as shown in figure 4.

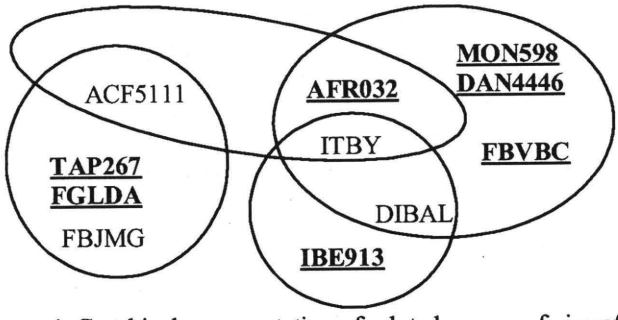

Figure 4: Graphical representation of related groups of aircraft.

Some of the links comes from the diagnostic activity. In some cases the airplanes recalled have been the object of a clear-cut diagnosis: the conflict was detected along with a resolution. When that occurred, we might state that the present environment uniquely specified the content of the activity ("what shall I do and when"). But in many other cases, the information available at anyone time was not enough to achieve a definite diagnosis. To that aim, controllers had to manage an additional resource which is *time*. We found that some of the links among aircraft expressed different time management strategies. In particular:
a) some aircraft were clustered because controllers did not have enough information to diagnose the presence of a conflict;
b) some aircraft were grouped together as they needed to be monitored just in case one of them would slightly deviate from the tolerated space-time "envelope";
c) the expected outcome of a control action had to be further verified to make sure that the conflict was really over.
To summarize, in those cases where the present available information was insufficient to specify the development of traffic, controllers showed to use time as a resource in at least three ways: 1) to obtain the lacking information; 2) to monitor for the occurrence of possible "disturbing" events et 3) to obtain feed-back on the outcome of an action.

The above analysis shed some light on the different information seeking strategies developed by the controllers to deal with the various diagnostic outcomes. It also show that aircraft were not represented as individual points: rather, the patterns of meaningful interactions among the airplanes were used by controllers to recall the positions. The next study aims at further investigating on the nature of information filtering strategies in the context of a diagnostic task.

STUDY 2: ELICITING INFORMATION SEEKING STRATEGIES

Methodology

Forty-four expert operators from the five French Air Traffic Control Centers were individually interviewed while watching an already played simulated air traffic scenario. Each time the scenario was stopped (about 5 times), the controller was asked one by one, to focus on a reference aircraft and list the conflicting airplanes as well as those that needed to be monitored. Verbal protocols containing explanations about identified traffic problems, were recorded and later analysed.

Results and discussion

First of all, conflict detection is a "principled search" guided by general heuristics that direct controllers' attention to pertinent features (i.e., climbing/descending) of the traffic and those portions of the space where conflicts are most likely to be detected. The process is iterative as the application of these heuristics generates a space that needs to be further refined through the use of contextual flight parameters and inferential knowledge about likelihood of future development.

We observed different types of diagnosis which we grouped into five broad categories ("certain", "conditional", "possible", "neighboring sector" and "rejected") that reflected as shown in study 1, the degree of reliability of the available information but also the time horizon chosen by the controller as well as the solution accepted (for more details, see Amaldi & Cellier, 1997).
Finally, a certain variability in conflict detection was found: about 30% of the interferences were not detected by the majority of people. To explain this variability, we have integrated a number of factors into the notion of *detection frame*. A frame is a type of knowledge structure that, like scripts and schemata, are evoked to explain how people organize incoming information to make sense of the current situation (Tversky and Kahneman, 1982; Klein, Orasanu, Calderwood, and Zsambock, 1993). In our domain we found that, depending on the frame

adopted, different kinds of problem formulation, different selection of information and ultimately, different diagnostic outcomes would follow. A detection frame includes the knowledge activated by the individual which is brought to bear to select specific goals and strategies to carry out the diagnostic process.
Four broad dimensions have been found to characterize a frame as they directly affect the outcome of the decision process. These dimensions interact to affect each other particular values. They are: a) temporal horizon considered; b) development of alternatives; c) integrated versus sequential problem solving, and d) resources management strategies. Space does not allow us to detail these dimensions here (see Amaldi & Cellier, 1997).

IMPLICATIONS FOR DESIGN.

The richness and variety of the diagnostic process showed in study 1 and 2, seems to warrant a certain caution towards aiding systems that mean to replace conflict detection and resolution activities by presenting the operators with already-made solutions. The risk is one of "forcing" operators to adopt a certain frame implied by the automatic resolution. In fact, the proposed solution might be "technically good" but violate some of the parameters specified in a particular frame adopted by operator in that particular circumstance. Findings from study 1 showed that people are more likely to focus their attention on aircraft related in certain ways. A system that presents a list of problems that controllers need to take into account, might prevent them from falling into some sort of tunnel vision.

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TEMPORAL DISPLAYS FOR FIGHTER PILOTS

Dan Strömberg
Defence Research Establishment (FOA)
Box 1165, S-58111 Linköping, Sweden
danstr@lin.foa.se

Jens Alfredson
SAAB AB
S-58188 Linköping, Sweden
Jens.Alfredson@saab.se

ABSTRACT

The first part of this paper presents cognitive aspects on temporal displays. In the second part, the results of an evaluation of three temporal display approaches, aimed for pilots, are shown. The same set of objects were shown on both a temporal display and a spatial display. Comparisons between the temporal displays were made concerning association, readability and resolution.
Keywords: Temporal displays, displays, cockpit, aircraft.

INTRODUCTION

Aircraft pilots rely on displays for their environmental information, both stationary states and dynamic processes. Possibilities to fulfil the need of displaying future states are provided when dynamic processes are represented in computer based displays (Woods, 1995). Future states could be presented to the operator by the use of predictive displays (Stokes 1997). Such displays can represent both spatial and temporal information.

Temporal displays is a class of tools that visualises possible future *action* and *event* schemes to participants in processes and games where temporal facts are important. Examples of such actions schemes may be found in the monitoring of industrial processes and in traffic situations. Temporal displays may then be used to show to an operator *what* and *when* different and important actions might occur in the future. In order to be understood by the operator, the temporal aspect of future possible actions must be shown in a way that fits well with the symbolism and the mental models that is otherwise used in the system. Visual representations of possible future actions of importance to aircraft pilots will be analysed in this paper.

In a game with several participants, each actor may perform a set of actions that has importance both for himself and other participants. Think of the action of shooting a missile from one aircraft to another one! Such an action is initiated by one actor but - we assume - it can be observed by other actors as well. Each participant of such a game wants to be prepared not only to actions that can be initiated by himself, but also to actions that can be initiated by other actors.

VISUALISATION OF TEMPORAL FACTS

The visualisation of the temporal description of a future action in a dynamic environment is a non-trivial task. For an actor that has to control or observe a large number of possible actions, only a few facts of each actions are relevant. If the actions can be ordered according to the importance that an operator assigns to an action instant, then it may be relevant to visualise more details of important actions than of less important ones.

In one common graphical representation of time information, the interval-based approach, time is represented along the x-axis and each action is shown in graphical form as a horizontal bar parallel to the x-axis. Each time bar represents the interval during which a future action is predicted to endure. In real time applications with small (i.e. a few seconds) time predictions, the set of displayed action bars moves steadily towards the left as time goes by. The internal relation between the time bars changes if and only if the predicted time to a subset of actions changes, e.g. as a result of an action that is initiated by the operator. An uncertainty of the start and/or end time

points of the action may cause a time bar to cover a longer period than the expected length of the corresponding action. This graphical form is advantageous if the operator wants to know which events that may occur during a certain future time period. It is more space-consuming than some other forms. See figure 1.

Other common graphical representations of the time period during which a particular action is predicted to occur are marks on an analogue circular clock-like display and the textual displays showing the digital figures for the number of minutes and seconds that remain to the start and end time point of the action respectively. Still other displays use speed bars, circle sectors or other contours around aircraft symbols on a two-dimensional spatially oriented display, where all objects are shown as seen from a satellite. Contact of two contours represents there the possibility of an event and the distance between the contours represents the time that remains to the start of that event. It is also possible to represent time-to-action on a two-dimensional display as the distance of an object to some fixed point on the display. Temporal visualisations may also be based on texture, colour, thickness or filling of symbols used to represent objects or other mechanisms already shown to the operator.

THEORETICAL FOUNDATIONS

The time is assigned specific properties in temporal logic, which is a non-traditional mathematical-logical theory, see e.g. (Bäckström, 1994). In such theories the temporal extension of the truth of a statement is often represented either as time points or as time intervals indicating the time during which a statement is true.

A temporal display is an instrument for an operator to read and understand the possible sets of events - the different actions schemes - that may occur in the future. This information inference concerning the temporal knowledge is known as the third step and final step of the situation awareness activity (Endsley, 1995). The first step is perception of single elements and the second step is their aggregation to situational entities.

COCKPIT APPLICATION

The set of actions indicated here concerns aircraft manoeuvring in air-to-air combat. Relevant subsystems include weapon systems and sensor systems.

The shooting of a missile is a potential event associated with an interval for the time during which a missile launch is to occur in order to hit a target. The operation is initiated by an pilot in a combat situation. The actor of the target wants to avoid the missile. Both actors use temporal data to predict the possibility of a hit. In terms of time intervals this can be expressed in the following way: Each actor tries to minimise - and delay the start of - the time interval during which the other actor can attack, while he tries to maximise - and start earlier - the time interval during which he himself can attack. In order to achieve these goals, each actor strives to plan (i.e. select and schedule) and accomplish a set of preparatory actions that brings him closer towards the goal, and the time-oriented reasoning can be applied to these actions as well.

The formulas that compute the possible time intervals for a launch operation depends on factors such as position, current speed, maximal speed, direction, altitude and turn performance for both aircraft, together with maximal speed and turn performance for a potential missile. The distance to an opposing aircraft is an important factor, since a missile has a maximal travel range. Several different launching events are of interest, based on different assumptions. One is that the two aircraft approach each other nose-to-nose. Another assumption is that the target continues it's current direction after launch, and a third assumption is that the target tries to escape by a sharp turn. The procedure that computes time intervals for the event under these different assumptions depend on data which may be derived not only directly from the sensors. The performance data, for example, must be derived in other ways. The derivation of data from the sensors is of a course crucial task in these calculations.

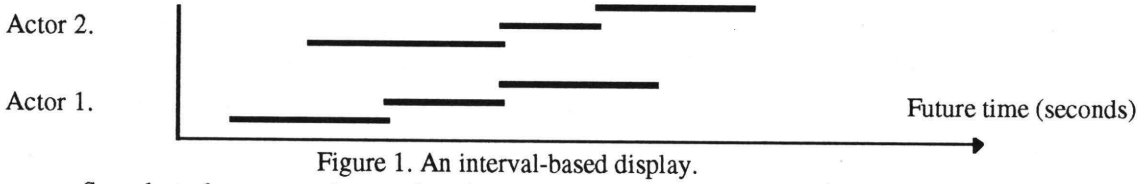

Figure 1. An interval-based display.
Snapshot of an event scheme where two actors might perform three events each.

METHOD

An experiment was done with the goal to compare concepts for temporal presentations. The results is supposed to be a basis for studies where the advantages with temporal presentation can be compared with spatial displays.

Display Approaches

An experiment was done in order to evaluate a number of display approaches for temporal displays. We wanted to compare some factors concerning the interpretation of visual representations of temporal facts, and the degree of resolution of temporal facts in these displays. Only one type of action, aircraft-to-aircraft collision, was predicted. The risk of collision was to be evaluated by a population of test persons.

Though important, we did not in this experiment compare spatial and temporal displays. No real cockpit displays were used. The graphical representations were fixed images with no dynamics. Some displays approaches were excluded from the experiment due to secrecy reasons.

Three different display approaches were compared, the interval-based approach, the point-based approach and the symbol-based approach. The first one, the interval-based approach is described above. In display approach two, the time point oriented display, only the start point of each event is mapped along the horizontal time scale. Each event is represented by a special event depending symbol that marks a point on a time line. The events which can be initiated by one actor against another one are represented with one line at a discrete point along the Y-axis. This display requires less height than the interval oriented display, but the specific details that separate the different events must be shown.

In the third display approach, the symbol-oriented approach, the temporal information is graphically included in the aircraft symbols of the spatial display. Due to the limited space for time-oriented graphical information at this display - some 5 millimetres each - some temporal facts must be excluded and the rest must be made small. A graphical mechanism must be invented in order to visualise the growth of time. The size of a circle may be used for that - a larger circle may, for example, visualise a smaller remaining time than a smaller circle.

Apparatus and Measured Factors

Workstations used during the experiment were of type Silicon Graphics Indigo2. As screens were used 20-inches Sony Trinitron tubes showing 1280*1024 pixels. The distance between screen and test person was approximately 50 cm.

Four simple scenarios were used in the experiment. In each scenario the own aircraft meets two other aircraft that may collide with the own ship. Each aircraft is characterised by four parameters, position, altitude, direction and speed. In each scenario only one aircraft parameter had different values. Each scenario is shown both at the spatial and at a temporal display. In the temporal display the time parameter shows time to collision.

One factor of interest in temporal displays is the pilot's capability to associate each object in the temporal display with the same object in the spatial display. This is called the *association* factor. One way to associate objects is to order objects in each one of the two displays according to their collision risk. This is the basis for one of the questions to the test persons. Another factor concerns the possibility to read data from the temporal display only. For that reason, a question was posed concerning which object on the temporal display that was most dangerous. This is the *readability* factor. A third factor concerned the resolution with which time could be read. This is the *resolution* factor, which was searched in another question.

Test persons we selected arbitrarily among undergraduate students at the campus of Linköping University. The test population was divided into three groups consisting of 20 persons each, one group per display approach.

Experimental Procedure

The goal of the experiment in terms of scenarios and display approaches was to evaluate the difference between the three temporal display alternatives, concerning the factors for association, readability and resolution.

Prior to the test, the test persons got a 30 minutes instruction during which examples were shown and questions posed in order to make sure that all persons had achieved a full understanding of the test.

Each test person was shown all scenarios but only one temporal display approach. Each scenario was displayed for five seconds, at a time point decided by the test person. After each display, the test person had free time to answer the three questions. Pre-printed alternatives were given for all questions.

The questions:
1. Pair each one of A and B with one of x and y by connecting them with lines. A/B x/y
2. Mark with a ring the most dangerous target. A B
3. How long is the time difference between A and B? 10 20 30 40 50 60 70 sec

RESULTS AND EVALUATION

The number of correct answers in each display approach is shown in table 1. The maximum number of correct answers per question and display is 80, since each question was asked once per scenario and test person, i.e. 4*20 times per display.

	Question 1	Question 2	Question 3
Display 1	74	74	38
Display 2	66	74	36
Display 3	80	76	13

Table 1: Number of correct answers.

Comparison Between the Displays

Statistical analysis (χ^2 test with continuity correction) of the data from the three questions showed no difference between display 1 and display 2 on the 95% significance level (For example, for Question 1, Display 1 and Display 2: $\chi^2_{Q1D1D2}=2.80 < \chi^2_{.95}=3.84$). The data from question 2 showed no significant differences between any of the displays (for example, $\chi^2_{Q2D2D3}=0.1 < \chi^2_{.95}=3.84$). Data from question 1 showed significant differences between Display 3 and any of display 1 and display 2 (for example, $\chi^2_{Q1D1D3}=4.33 > \chi^2_{.95}=3.84$). Also, data from question 3 showed significant differences between display 3 and any of display 1 and display 2 (for example, $\chi^2_{Q3D2D3}=14.2 > \chi^2_{.95}=3.84$).

CONCLUSIONS

The evaluation shows that the point-based display approach and the interval-based approach show similar results on the test population. The smaller space required for the point-based display approach gives this alternative the first place in an evaluation, if the association problem can be discarded. The symbol-oriented display approach gives less good temporal resolution but much better association.

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Mental Processes in Air Traffic Control - Implications for the Design of Future Systems

Dirk Schäfer[1], Genia Grundmann[2], Fred Volker Schick[1]

[1] German Aerospace Research Establishment (DLR), Institute of Flight Guidance, Germany.
E-mail: dirk.schaefer@dlr.de
[2] Technical University of Berlin, Institute for Aeronautics and Astronautics, Germany.
E-mail: grundman@ilrserv.fb12.tu-berlin.de

ABSTRACT:

The use of 4D Trajectory Planning Tools and digital Data-Link connections in a future Air Traffic Control (ATC) environment will be discussed. First, an overview on cognitive processes during the work of ATC Controllers will be given. We then report on experiments carried out to evaluate the benefits of these new systems. The results indicate that supporting high-level planning processes offers substantial performance benefits. Replacing the vocal communication with Data-Link seems to affect Controller's workload positively.

Keywords
Air Traffic Control, 4D Trajectory Planning, Data-Link, Performance, Workload

INTRODUCTION

A steady increase in air traffic has been reported over the last decades and will continue in the future. Air Traffic Control (ATC) services have to deal with an increasing number and density of aircraft. Considerable efforts are therefore required to enable the controller to deal appropriately with the increasing air traffic while improving or at least maintaining today's standard of safety. An efficient way of improving the overall system performance and reducing operator's workload is to delegate at least some of the working tasks to an automated system. The operator's physical and mental resources can be released from boring routine tasks, leaving him more time to concentrate on non-routine tasks and decision-making. Unfortunately, this approach contains many pitfalls, and badly designed automation often deteriorates system performance rather than improving it.

New ATC tools should therefore be designed as assistance systems, supporting rather than replacing the operator while keeping the situation clear to him. Tools that are capable of facilitating the working process must be designed according to the operator's needs. This emphasises the importance of knowledge about the mental processes involved in the work of Air Traffic Controllers, which has become a rewarding subject of psychological studies. Current efforts to support ATC controllers with automated systems primarily focus on two new technologies: 4D Trajectory Planning and data transmission via digital Data-Link. Concerns have been raised about the impacts these new systems may have on Air Traffic Control. This paper sketches cognitive processes during the work of Air Traffic Controllers, describes tests carried out to evaluate the benefits and drawbacks of 4D Trajectory Planning and Data-Link, and discusses some of the results of these experiments.

AIR TRAFFIC CONTROL AS A COGNITIVE PROCESS

Air Traffic Control consist to a large degree of high cognitive tasks, such as visuo-spatial representation, abstract thinking, and mental arithmetic. Most of these tasks are time-critical and require high communication skills. Cognitive science approaches can contribute to understanding the involved processes and thus facilitate and appropriately support at least some of these tasks. Cognitive psychology has identified three major constituents involved in human interaction with the environment. The *sensorium* obtains information from the environment. The *memory* with its knowledge base and procedures processes the information and infers an appropriate action. The *motoric system* interacts with the environment by executing the action. Besides, the *motivation systems* influences goals and decision-making. System designs that respect such models and the corresponding attributes of human behaviour enhance the performance of the overall human-machine system.

As Air Traffic Control involves information processing on a comparatively high level, a cognitive model of information processing is highly rewarding, so that cognitive functions can be supported appropriately. A model of human performance as proposed by Rasmussen in [Rasmussen, 83] identifies three levels: *skill-based*, *rule-based* and *knowledge-based* behaviour. According to the level of experience an operator developed while using a system, his performance seems to be bound to different mechanisms and he seems to use different sources of information. Frese and Semmer, 1979, developed a taxonomy of errors based on information processing theories. In contrast to Rasmussen's model they identified one additional level called *Abstract Thinking*. At the level of abstract thinking the generation of heuristic rules and the regulation of meta cognition takes place. Analysing errors that occur while using a technical system helps to understand and deal with the underlying problems and thus to improve the human-machine interaction.

Air Traffic Controllers are highly trained. Unforeseen new situations that would require meta cognition or knowledge based problem solving are comparatively rare. Most of the situations ATC Controllers encounter during their work can be solved in a rule-based way, i.e. rules or procedures exist that have been developed in earlier situation of a similar kind. The actual traffic state has to be observed in order to estimated the future positions of aircraft and to foresee problems that might occur. A flight profile for each aircraft must be planned that is efficient and conflict free to other aircraft's routes. Clearances must then be derived to ensure the aircraft comply with these flight paths or to avoid conflicts in the near future. The clearances must then be transmitted to the aircraft via voice communication, which happens on a routine basis.

ADVANCED TOOLS IN ATC AND POSSIBLE IMPACTS ON CONTROLLER BEHAVIOUR

4D Planning and Support Tools

In order to guarantee safe separation between all aircraft at any time and to enable the aircraft to fly on economically optimum routes, the flight profiles of all aircraft in the sector have to be co-ordinated in time and in space. Co-ordinating routes and extrapolating future aircraft positions requires a fair amount of higher level cognitive resources which involve mental arithmetic. Computer-based systems generally perform faster, more accurate and more consistently in numeric tasks. The extrapolation of future aircraft positions and the planning of flight profiles may therefore efficiently be supported by computer systems. 4D Trajectory Planning Tools can be used to derive flight profiles for each aircraft, optimised with regard to flight time or flight distance, arrival sequence at airports, weather and operational limitations of specific aircraft types. In case the calculated profiles are not conflict-free, or one or more aircraft can not comply with it, the trajectories must be modified and the planning process repeated until a viable combination has been found. The planning tool may then derive the control advisories necessary to guide the aircraft along the trajectories and propose the trajectory as well as the corresponding advisories to the controller.

The Use of Digital Data-link

Data-Link is a digital radio connection between aircraft and ground stations for the transmission of parameters such as aircraft status, clearance parameters, and trajectories. Although a technical standard has not yet been defined there exists some common understanding about the requirements for a future Data-Link. Data-Link may be used to replace the vocal pilot controller communication. Voice communication is a major source of errors and overloaded channels already have become a limiting factor for airspace capacity. This problem may be addressed with a communication interface which allows the controller to interact with the aircraft trajectories via direct manipulation in a graphical way and transmit the inputs to the aircraft via Data-Link. If the ATC systems and the aircraft are capable of 4D Planning entire trajectories may be transmitted via Data-Link. A trajectory may be negotiated between airborne and ground computer and proposed to both pilot and controller. On the airborne side this would require some new Flight Management System (FMS) functions.

EXPERIMENTAL STUDIES IN AN ADVANCED ATC ENVIRONMENT

The PHARE PD/2 Experiments at DLR Braunschweig

Several European research establishments are currently participating in the Programme for Harmonised ATM Research in Eurocontrol (PHARE). PHARE focuses on a co-ordinated effort to develop new ATC systems and concepts in Europe and to test and evaluate these systems in simulations, named PHARE Demonstration. The second PHARE Demonstration (PD/2) was carried out at DLR's Braunschweig research facility in early 1997.

Eight ATC Controller teams from eight European countries participated in the simulations, totalling to more than 100 hours of simulation. As the major interest lay with the effects of the new systems on handling arrival traffic, PD/2 simulated three working positions in the *Extended Terminal Area* consisting of Approach and adjacent Enroute sectors. In the Approach sector the working positions of *Pick Up* an *Feeder* were simulated. Aircraft that enter the Approach airspace first contact the Pick Up controller for radar vectors to the ILS and are then handed over to the Feeder for final guidance onto the ILS. In order to investigate the co-ordination between the controllers of the Arrival sector and the adjacent Enroute sectors, one additional Enroute sector was simulated .The scope of the PD/2 experiments was twofold.'On the one hand the effects of supporting the controllers with ground-based 4D Planning tools were being evaluated. On the other hand the additional benefits of having an increasing proportion of 4D FMS / Data-Link equipped aircraft following their trajectories in a nearly automated manner were being assessed. Three Organisations (ORG) were defined:

- ORG 0 served as the reference scenario. The aircraft were controlled in the traditional way without trajectory planning tools and the clearances were issued via voice on radio lines. A present-day arrival sequence planning tool was available as it has been in operational service at Frankfurt airport for nearly ten years now.
- ORG 1 implemented a 4D Trajectory Planning tool that calculated optimum flight profiles for each aircraft including both time and space in order to meet the optimum arrival sequence and the scheduled times. The planning tool derives and displays the control advisories necessary to guide the aircraft according to the trajectories. To implement the proposal the controller has to issue the control advisories via voice communication. No additional functionality on the airborne side was required in ORG 1.
- ORG 2 30% and ORG 2 70% used the 4D Trajectory Planning tool already used in ORG 1 plus an additional functionality to transmit the clearances proposed by the planning system via digital Data-Link, avoiding voice communication other than init call and handover clearance for these aircraft. As the capability of Data-Link and following 4D routes would require additional airborne functionality, the introduction of such a system would be a gradual process. The ORG 2 scenarios therefore included a percentage of 30% and 70 % respectively of aircraft capable of this functions whilst the other aircraft were controlled with the assistance of the 4D Trajectory Planning tool but with traditional voice communication.

Each of these configurations was tested in a medium traffic scenario and a high traffic scenario. Data recorded during the experiments includes performance and operator workload. Performance data provides objective figures upon which to judge the benefit the use of the new systems has on the performance of the overall human-machine system and includes figures such as number of landings per hour, separation, mean flight time per sector and precision of delivery at the Approach Gate. Workload data includes objective workload, such as number of instructions given per aircraft and subjective workload figures such as SWAT (Subjective Workload Analysis Technique) and NASA TLX (Task Load Index) ratings. Questionnaires and debriefings were used to asks the controllers about their appreciation and impression of the usability of the new systems.

Studies at the Technical University of Berlin

The focus of a set of experiments at the Technical University of Berlin was to identify impacts of the use of Data Link, especially the effects of voiceless communication between aircraft and ATC, on workload and usability. Previous interviews with controllers showed wide interest in Data Link due to highly updated and accurate information continually transmitted from the aircraft to the ground. Deep uncertainty, however, was expressed about the substitution of voice communication. The main fear was that voiceless communication would be less flexible and lead to higher workload due to inappropriate ways of interaction with the system. Therefore, a detailed task analysis provided the basis for a task oriented HMI design. Kind and sequence of actions were kept mainly constant, necessary alternative ways were developed by a step by step Rapid Prototyping process. In this way a GUI was developed which displays a 4D picture of selected flight paths and allows to manipulate it with regard to flight level, heading, speed, and time over fix. An additional tool allows to negotiate the new profile with the aircraft or gives simple instructions in time-critical situations.

Thirty-two subjects participated in the experiment in teams of a co-ordinator and an executive controller. All subjects were professional air traffic controllers with a licence for en-route sectors with similar experiences and training. The reference group of eleven teams controlled the traffic in a conventional way. The remaining five teams worked with the new voiceless simulation system (experimental group) and a smoothly adapted ATC

philosophy in which aircraft fly on computed most economic flight profiles. All subjects encountered a set of 53 aircraft in a simulated en-route sector in one hour, which is equivalent to current sector capacity. The controllers were asked to describe the errors at different performance levels and evaluate the system with the ATC Human Factors Checklist [Cardosi and Murphy, 1995]. The controllers completed a NASA Task Load Index (TLX) questionnaire immediately after the experiments.

EXPERIMENTAL RESULTS

Results of the PHARE PD/2 Experiments

Performance

Figures 1 and 2 serve as examples for the performance data that has been recorded during the experiments. These figures are used to judge upon the effects that the new systems have on the performance of the overall human-machine system. Figure 1 indicates that the number of landings per hour at the airport can significantly be increased using the 4D Planning system (ORG 0 to ORG 1) while no significant difference is reported between scenarios in which the Data-Link is used (ORG 2) versus scenarios in which it is not used (ORG 1). Figure 2 depicts the mean flight time in the Approach Area (Pickup and Feeder). Again, the introduction of 4D Planning significantly improves the situation while use of Data-Link has no significant effect. A significant improvement when introducing 4D Planning was found with most of the performance figures.

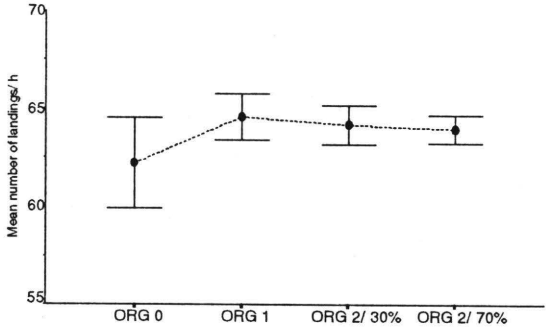


Figure 1: Number of Landings.

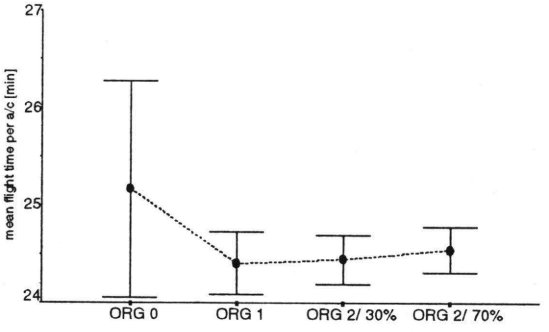


Figure 2: Mean Flight Time.

Workload

Figures 3 and 4 show an example for data that has been recorded as an indicator for workload. These figures depict the mean frequency of ATC instructions per minute. The introduction of 4D Planning shows a significant decrease in the workload of the Pick Up, which has been exceptionally high, whereas the workload of the Feeder remains mostly constant. This indicates that the Pickup Controller can be released from some workload partially by an enhanced co-ordination between Pickup and Feeder. The co-ordination between Enroute controller and Pick Up is also affected: the workload for the Enroute controller even increases slightly from a very low level. As the goal is not to reduce workload as far as possible, but to keep it within limits sensed appropriate for comfortable working, this, in total, has to be judged as a benefit. Data-Link and 4D FMS eases the situation for both working positions: the workload of both Pick Up and Feeder decreases significantly. Other workload indicators indicate the same tendency. The results of the subjective workload assessment show a good correlation to the objective workload data.

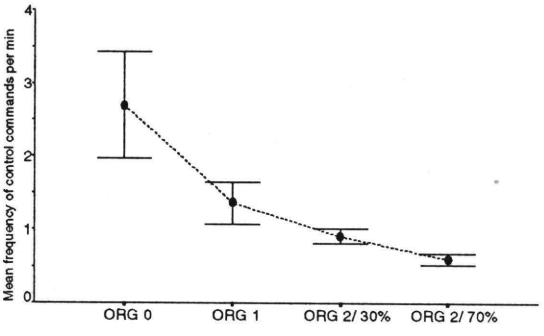


Figure 3: Number of ATC Instructions (Pickup).

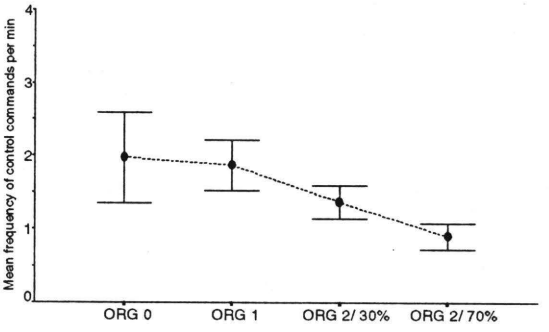
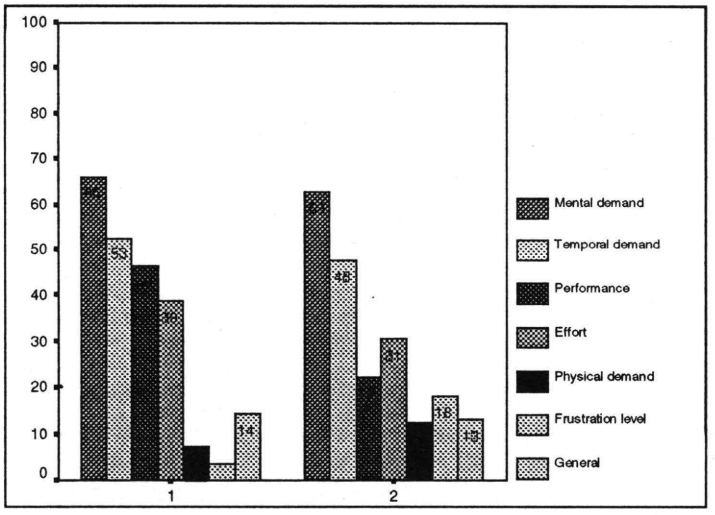


Figure 4: Number of ATC Instructions (Feeder).

Results of the Studies at the University of Berlin



The NASA Task Load Index indicates a significant reduction in subjective workload in the Data-Link scenario group (U-Test Mann & Whitney: $p < 0,05$). Figure 5 indicates the total results in each of the six scales. The decrease in *temporal demand* and *performance* are significant as well as the general workload calculated from all of the six scales. The times required for the communication between controller and aircraft were measured as an indicator for objective workload. However, the experiments with voice communication and with communication via the Graphical User Interface didn't show differences in transmission time for simple messages.

Figure 5: The NASA Task Load Index ratings recorded at the Berlin experiments.

CONCLUSIONS

The results of our experiments indicate that significant performance improvements can be achieved in supporting ATC planning processes with a 4D Trajectory Planning system. The workload, subjective and objective, of Air Traffic Controllers may also be reduced. The use of Data-Link for the automated, voiceless transmission of trajectories and clearances significantly reduces the workload, even more if at least a certain percentage of aircraft is equipped with 4D FMS systems capable of flying the aircraft on a 4D flight path.

Estimating future aircraft positions and planning flight paths happens at a mostly *rule-based* and *knowledge-based* level and involves intensive mental capacity. Supporting this process by computer-based systems can free mental capacity and, due to exact calculations, produce more accurate results. From this point of view it is not surprising that 4D Planning systems help to improve the overall performance of the human-machine system and reduce operator's workload.

The transmission of control advisories in a vocal communication process is fairly routined process which does not require a high degree of mental activity. Supporting or replacing it with Data-Link can not be expected to free a high amount of cognitive resources. However, reducing frequency congestion and abolishing the need to scan the pilot answers helps to disburden the controller. From that perspective a reduce in operator's workload had to be expected due to the introduction of Data-Link systems. This effect could be expected to be more obvious with the introduction of aircraft equipped with 4D FMS functionality and thus capable of flying on negotiated 4 dimensional trajectories.

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Planning Process Control In Uncertainty

Iain S. MacLeod and Linda Wells
Aerosystems International
West Hendford
Yeovil, Somerset
BA20 2AL, UK
Tel: + 1935 443000
Fax: +1935 443111
iain.macleod@aeroint.com

ABSTRACT

Military aircraft direction and control is in many forms and exists in an uncertain environment that is more variable, dynamic and potentially hostile than that associated with industrial process control. Both industrial and military process control involved planning. However, in contrast, military proactive planning is more complex and is a rehearsal for expected dynamic changes to the mission. Associated changes to mission process control are managed by skilled reactive planning, all mediated by information feedback and situational awareness. The burgeoning complexity of airborne system design and its control suggests the future design and adoption of electronic assistants as advisory aids to aircrew performance in process control.

Keywords
Planning, Control, Uncertainty, Complexity, Information, Feedback, Military, Systems.

MAINTENANCE OF THE AIM

The first principle of war is 'Maintenance of the Aim'. The aim of all military is encapsulated in mission plans and their timings. A primary goal of mission planning for all airborne military operations is the accurate achievement of a planned Time On Target or Time On Task (TOT) or Estimated Time of Arrival (ETA). However, timings of plans are influenced by the clocked time of engineered processes, the timely and effective use of these processes, and the aircrew anticipation of the time required to complete mission tasks with the aircraft and its associated systems. As a result, aircrew control and direction of aircraft related processes must be planned and actioned to result in the aircraft being at the right place, at the right time, and in the configuration required for the achievement of the mission objectives.

In the military context, aircraft and their systems are frequently and deliberately operated at extremes of their operating envelope and in environments where the uncertainty of the environment, uncertainty being the level to which the environment thwarts aircrew understanding and anticipation of the environmental state, is dictated by factors outside the aircrew control. For example, aircrew have no control of the weather and its dynamic affects on system operation, though weather forecasts allow anticipation of the probable weather conditions, and no control over enemy hostilities, though military intelligence and success in battle can allow anticipation of the level of hostility to be encountered. Experience, knowledge, and high expertise promote aircrew Situational Awareness (SA), maintenance of process control, and a capability to react to unexpected events.

PLANNING PROCESS CONTROL

All process control is planned proactively as a means of anticipation and rehearsal for performance of future control related activities. In industrial processes the procedures evoked for such planning are normally well established. In contrast, military proactive planning is performed pre-flight knowing that the plan will normally need to be changed during flight; this planning acts as a flight rehearsal and as a template on which to base the conduct of necessary in-flight reactive planning throughout the mission. 'Maintenance of the Aim' requires a flexibility of operation to equate the vagaries of the operating environment, to meet particular requirements of the operational situation, the context of that operation, and to cater for any hostile actions against the aircraft.

In addition, both the planned control, locations, and product of military operations may be spread geographically, change with time and at different rates. Thus, ever changing and dispersed military activity has associated processes that are in contrast with general industrial processes. Industrial processes have fixed control and production centres that may be distributed but have production loadings that are generally predictable.

The co-ordination of planned processes is also essential to the success of military operations, the changing nature of the operations requiring dynamic adjustment of processes by the involved parties to maintain a joint aim towards a planned objective. This co-ordination involves high quality communication between the different parties. In industry, good communication is also essential but is less fraught with noise as most of the subject processes can be ably predicted.

In contrast to military customs, most industrial processes are operated within legislated tolerances to ensure minimum risk to operators and safe system operation. The unpredicted events affecting industrial processes are normally catastrophic failures of a system caused by either a breakdown in the system or operator failure to follow procedures. In many cases the alarms in any system are false caused by noise from imperfect In-Built-Check-Out-Systems (IBCOS) and/or Built-In-Test Equipments (BITE).

FORMS OF MILITARY CONTROL PROCESSES

There are many interacting control process involved in the planned performance of an aircraft mission. Control processes can be argued to reside in four forms in military aviation, namely:

Cognitive Control

The human cognitive processes in control related to their knowledge, perception (visual, auditory, haptic), awareness and understanding of the situation and context, and anticipation of future situations.

Equipment Control

Control of internal aircraft equipments / avionics. This area is the traditional area of concern for engineering safety studies of systems.

Sensor Control

The control of aircraft sensors (radar, Infra Red, Electro Optics, Laser, Electronic Surveillance) to aid the perception, interaction, and operation within the 'real-world' environment.

Weapons System Control

Direction and control of aircraft flight and the effective use of the aircraft weapons and defence suite.

Discussion on Forms of Control

Cognitive and Equipment Control can be argued to apply to any work settings whether they be industrial or military. However, Sensor and Weapons Control are essential for operations in the military flight environment. The four control processes are obviously interrelated with Cognitive Control being the process supplying the direction to the other processes and, depending on the level of system automation, also a degree of control over the other processes. As an example related to Weapons Systems Control, with Fly-by-Wire control of an aircraft flight the aircrew will be denied manual control of the flight under certain flight manoeuvres that are outside the limits of their Cognitive Processes to control.

The interaction between the four main forms of control processes is complex involving high degrees of expertise and an associated SA (MacLeod, I.S., 1996 & MacLeod, I.S., Taylor, R.M. and Davies, C.L., 1995). SA may be considered as an integral property of 'open skills' (Poulton, 1957) associated with the management and control of perception. In an ever changing military flight environment, a loss of awareness of the mission and flight situation can lead to unplanned control actions, the operator 'out-of-loop' with relation to feedback from all the forms of process control, and eventually if there is insufficient aircrew expertise to initiate recovery, unpredictable and random actions may result (See Hollnagel on 'Scrambled' cognitive control - Hollnagel, E., 1993 and Phillips, E.H., 1995). Figure One is a model of interactions between the four postulated forms of military control processes. All process are dynamically interrelated.

THE IMPORTANCE OF INFORMATION FORMS TO FEEDBACK AND CONTROL

The maintenance of plans for control of military processes depends strongly on feedback of particular types of information, the different values expected of information in different control situations, the errors possible through mistaken identity of the information form, and the appropriateness of the information presentation to the task in hand (MacLeod, I.S., 1995) . Some of the information forms most pertinent to the control of dynamic military processes are:

- Ephemeris Information — Information with a short term value e.g. aircraft speed, direction.
- Collateral Information — Supporting information to the performance of a mission often in the form of map and planning information, information on enemy capabilities and intentions.
- System Information — Information on the state of system processes e.g. BITE.

- Environmental Information — Information on the mission environment obtained by system sensors or through operator senses e.g. missile warning.
- Expertise — Information / knowledge related to cognition.

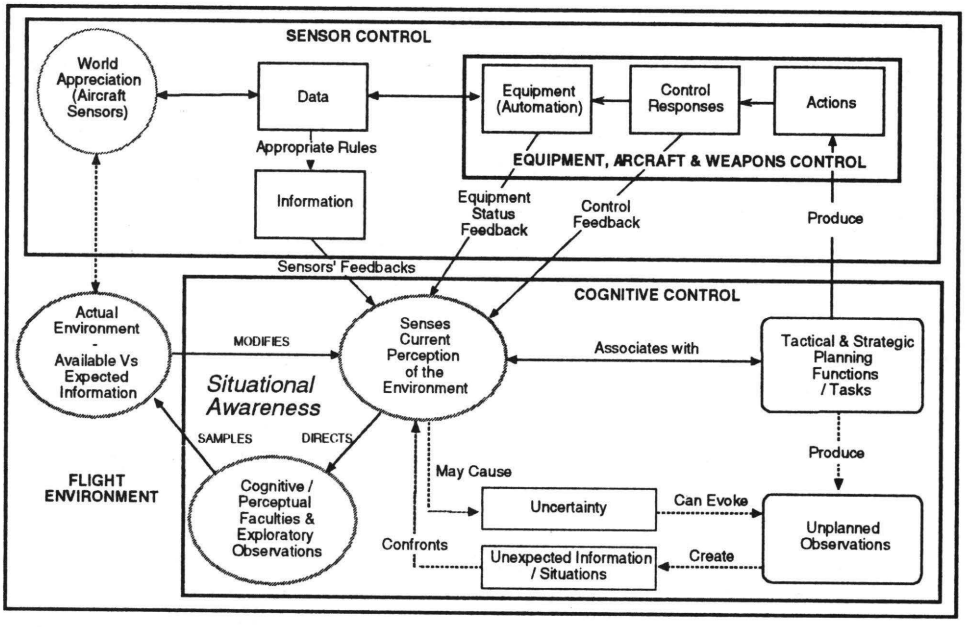

Figure One: Model of Interactions Between 4 Forms of Military Process Control
(Acknowledgements to Neisser, U., 1976 and Hollnagel, E., St Lary Lecture Notes, 1995)

The use of the wrong form of information for specific tasks can cause confusion and have critical consequences to the maintenance of SA and the associated performance of a mission. There have been many examples of the use of flawed flight planned information (Collateral Information), rather than actual real-time flight information (Ephemeris Information), this incorrect usage of information causing loss of the aircraft. For example, maps provide a medium for mission rehearsal and can be used to provide a record of the mission conduct for the purposes of debriefing and assessment. As previously argued, both proactive and reactive mission planning and rehearsal are essential for the maintenance and achievement of mission goals. Planning with the aid of maps enables decisions to be brought forward on the mission time-line to a far greater extent than can be achieved through cognitive processes alone, for example mental simulation and practice (Taylor, R. M. and MacLeod, I.S., 1995). However, maps are static depictions of the world, created at a particular time and for a specific purpose. There are innumerable cases where the incorrect use of a map, for example where the map scale depicts insufficient terrain and height information for low level flight, has almost led to aircraft collision with the ground. There are fewer recorded cases of actual ground collisions resulting from incorrect map usage. With the increasing use of VDUs to display all forms of information, often mixed in one display, the presentation of information at the wrong time and place must be carefully considered as poor presentation has been shown to cause 'mindless behaviour' (Langer, 1992) producing human error.

INFLUENCES ON EFFICACY OF CONTROL PROCESSES

The main underlying influences affecting industrial processes are the balance between monetary profit and Health &Safety requirements. The operator tasks in industry are normally scoped by regulations to be within an argued sphere of competence and, with the possible exception of certain unrehearsed forms of emergencies, the operator should always be operating within an agreed plan and well established procedures.
In the military the influences affecting control processes vary between peace and war. Consider the differences between the control processes applicable to the successful completion of an aircraft mission and those involved in the safe completion of a mission. In peace the loss of aircraft or life are generally deemed to be unacceptable both with relation to the political consequences (public / government opinion) and the monetary consequences (replacement of aircraft and aircrew is expensive). However, in war the successful completion of a mission takes precedence to the monetary consequences of the loss of an aircraft, but not over a balanced usage of the

available air assets. Further, the adverse political consequences in war resulting from an unsuccessful mission can be far greater than those involved in the loss of aircraft assets, losses in this case only exacerbating the problem.
The above differences between peace and war can be argued to influence peace time recruiting of aircrew. In peacetime safe flight is paramount and the aircrew should be so selected and trained. However, in war the successful completion of a mission may be paramount. Thus it can be argued that not only are a different body of aircrew needed for peace and war, but a different set of rules and associated amalgam of control processes.

FUTURE TRENDS

Increasing questions on aircrew ability to control complex system processes, and also maintain SA, is suggesting support from machine advisory assistance (Amalberti. R., Deblon, F., 1992 and MacLeod, Taylor and Davies, 1995). Such support requires that some form of cognition can be logically functionally specified for the machine in such a way that the resulting design allows the machine to proffer advice complementing and assisting human cognitive functions within system control (MacLeod, 1996).
Control theory has long been capable of specifying the dynamic control changes required to direct the necessary machine processes to adapt to changes caused by environmental influences or operator inputs to the machine processes. The seminal work by Ashby (1956) on cybernetics introduced the idea of homeostasis in Man-Machine Systems (MMS); adaptive control to maintain a stable and required man-machine system state. However, a MMS that includes an Electronic Crewman (EC) will involve a control loop whose homeostasis relies on a sharing of cognitive aspects of EC / operator teaming including the team application of pertinent knowledge, expertise, and Situation Awareness. Such a loop would have to reliably perform its required control functions to gain acceptance for its adoption or certification: in other words it must do what it is required to do in a variety of situations and in a sufficiently consistent manner to allow confidence in its acceptance.
An EC would have to be continually developed (trained). Changes in any one of the first three of the above processes could affect the veracity of the whole EC / operator team - as might a change of operator. Therefore, the examination of all of the above processes would need to be iterative and the findings applied as refinements to the MMS throughout the EC life-cycle, this generating unique problems in aircraft EC certification.

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TEMPORAL AWARENESS AND COGNITIVE TRADE-OFF IN A SIMULATION OF A PROCESS CONTROL TASK

Vincent Grosjean
Ergonomics and Industrial Psychology Department
I.N.R.S. (National French Institute for Safety and Health)
54550 Vandoeuvre France
e-mail : grosjean@inrs.fr

ABSTRACT
this paper presents an experiment where operators have to deal with various parallel asynchronous processes. We were interested in the level of " temporal awareness " developed by the operator. By temporal awareness, we mean the ability of the operator to build a representation of the situation including the recent past and of the near future. The hypothesis was that this ability is linked to others elements of performance. We were also interested with the effects of an aid aimed at supporting the building of temporal representation. The experiment showed that this support system was poorly effective, but that the presence of a temporal awareness proves to be a good indicator of the number of some categories of errors.

KEY-WORDS
Process control, simulation, anticipation, human error, support system.

AIM OF THE PAPER
The present study is concerned with the notion of "cognitive trade-off" developed by Amalberti (1996). This notion means that, in a complex working situation such as process control, the human operator is confronted to a set of goals that could be partially in conflict one with the others. In order to decide what to do in a particular situation, the operator should have made (at least implicit) choices, should have prioritise the various goals. These choices take various criteria (subjective consecutive workload, evaluation of various risks, etc.) into account, and will determine a global strategy (the cognitive trade-off) that characterises the way the operator gives sense to the situation.

The underlying idea of this concept is that the various indicators of performance that one can use to characterise human activity (notably the nature and frequency of his errors) should be interpreted in relation to the particular cognitive trade-offs adopted by the operator, and that it makes no sense trying to understand these indicators in abstraction of these trade-offs. Starting from this point of view, Amalberti argues that human errors should be analysed taking into account the specific trade-offs adopted by the operator. Consequently, he says that it is not realistic to try to improve a situation by providing supports systems that are aimed at avoiding a particular kind of errors, without understanding the meaning of these errors. A more clever way to reduce errors would be to identify the cognitive trade-offs and to try to encourage the safer ones.

To adopt such a way to improve the situation it is necessary to have some hypothesis related to the characteristics of " safer " cognitive trade-offs. The idea presented here is that one important axis of this cognitive trade-off lies in the elaboration of a temporal awareness (Javaux 1993) of the situation at hand. The notion of temporal awareness is close to the notion of situation awareness developed by Sarter and Woods (1991)in the context of aviation. It relates to the fact that the pilot is aware or not of the context in which he is. When an incident occurs, if the pilot has a good situation awareness, it will not be necessary for him to build a representation of the current situation before coping with the problem. In the contrary, if he is not aware of the situation, there is a risk either that he wants to solve the problem without knowing enough of the situation, either that he spends to much time to build his temporal awareness before acting. Javaux (1993) restate this notion in the temporal context, underlying the role of a good awareness of the temporal context (present, near past and future events). So to say it simply, an operator

will have a good level of temporal awareness if he has a precise idea of the recent events and of what will occur next.

The work related here assumes that an important aspect of the cognitive trade-off of the operator is the temporal awareness, i.e. the fact that he has built a representation of the temporal context when facing to a particular problem.

The experiment related here is centred on a double hypothesis :

- 1° the elaboration of a temporal awareness is an essential part of the adopted strategy (cognitive trade-off), as such, it underlies the appearance of contrasted patterns of behaviour and performance ;
- 2° the degradation of the temporal awareness could be considered as an initial sign of (a global) performance degradation.

Practical consequences of this hypothesis for safety and reliability will be discussed in the presentation.

The experiment uses a micro-world. We developed a micro-world were the main task was to control simultaneously various parallel simple processes. The interest of such a simulation laid in the fact that the building if temporal awareness could be examined in itself. In other types of situations, the building of a temporal awareness could often hardly be separated to others aspect of the understanding of the situation. For instance, temporal aspects are often confounded with causal and spatial aspects.

EXPERIMENTAL SITUATION

The micro-world reproduces some cognitive characteristics of real situations, in particular their multi-objective nature. This allows subjects to adopt various cognitive trade-offs, corresponding to different way to balance the various goals. The micro-world is based on a latex process control task, where the operator has to control many parallel production lines. To control a single production line, the operator must undertake rather simple manual actions at precise moments of the production cycle. These simple manual actions alternate with fixed duration autonomous phases. During these autonomous phases, the operator has nothing to do for this line. Hence, the main source of complexity of the task is to know when to go to a specific line of production in order to minimise the latencies between autonomous phases and manual actions (see figure 1). Elaborating a temporal awareness of the relative temporal positions is one possible strategy (cognitive trade-off) to cope with this difficulty. Another possibility is to zap permanently from one production line to another. We assume that in the first of these two case, the operator had a better temporal awareness than in the second.

On the computer, the various production lines are presented on various computer views. So in order to find out about the current phase of one production lines, the operator must either call the corresponding view (on the computer supporting the micro-world), or use an aid (if available, see later in this paper), either refer to his mental representation of the situation. This aid presents a graphical representation of the temporal status of all the production lines. So it could be seen as a way to reduce the usefulness of the construction of a temporal awareness.

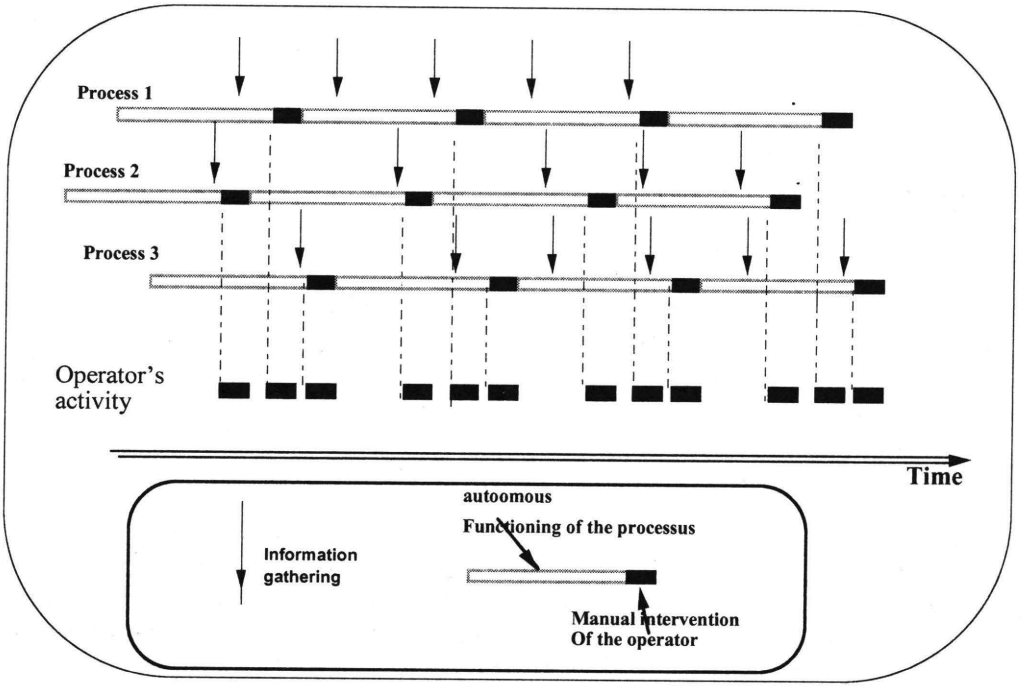

Figure 1 : dealing with multiple parallel processes

PARTICIPANTS

Participants were 24 student volunteers in their last year of chemical engineering training (two different schools with two different levels of diplomas).

Half of the participants worked with the aid, and half without.

EXPERIMENTAL TASK

After a training session, participants were asked to control a system with five production lines working simultaneously. There were six scenarios of varying temporal complexity The last two could be viewed as perturbed situations.

Three factors were taken into account : presence or absence of the aid, scenario at hand (including scenarios related to a perturbed situation) and nature of the cognitive trade-off (presence or absence of temporal awareness, see hypothesis 1).

The presence of temporal awareness was deduce from the information gathering behaviour. We assume that if the operator had built a temporal awareness, he will less frequently consult the view presenting a production line when no action is requisite. In the contrary, the operators who haven't built such an awareness will have to consult the view more frequently, as far as the could not rely on their mental representation of the temporal positions of the various lines.

The different levels of training were considered as a potentially perturbing variable.

DATA COLLECTED

Every single action of the participants were automatically gathered by the computer. In order to make comparisons amongst subjects, the protocols were truncated at the shorter size. In order to make comparisons between scenarios, weighting were applied.

Indicators of the Development of Temporal Awareness

To determine if the operator developed a temporal awareness, the strategies of information gathering and the links between information gathering and requisite actions were examine. Criterion were determined. These elements are considered as indicators of the temporal awareness on base on the fact that an

operator who has built a temporal awareness of the situation will less frequently consult the view of a line when no operation is required. The number of view (and aid) consultations will then be lower for this operator than for an operator who don't develop such a strategy.

Performance Indicators

Various kinds of errors were collected, corresponding to various kinds of goals present in the task . The taking of rest periods (number and length), the respect of temporal constraints, indirect indicators of the hierarchy of the goals present in the task (see full paper), the nature of knowledge build through the task were also gathered.

SOME RESULTS

Effect of the Aid

The effects of the temporal support system were contrasted in terms of performance. There are more differences in the nature of errors committed than in terms of their absolute frequencies. The fact that the operator uses this tool or not has no influence on the kind of cognitive trade-off adopted. There is no difference in the data gathering strategies connected to the presence of the aid.

The analysis of the perturbed scenarios showed that the presence of the aid cannot be used to predict the evolution of performance when the subject is faced with perturbed situations. Furthermore, when confronted with such perturbed situations, the frequency of use of the aid goes down.

Effects of the Scenarios

The effects of the two scenarios corresponding to perturbed situations will be analysed in more detail in the presentation.

Development of Temporal Awareness

Results showed that the variability of information gathering strategies was very important. For the same scenario, some operators consulted 5 times more the view when no action was requisite than other.

Effects of the Development of Temporal Awareness (as Indicator of Cognitive Trade-Offs)

This factor proved to be a good indicator of the pattern of performance; much better than the presence of the aid or the level of training of the subjects (not presented here).

The subjects who developed a temporal awareness committed fewer errors. It is true for the errors connected to cognitive activities (mistakes) but not if we consider only a specific category of slips (Reason 1990).

The ability to arrange goals in a hierarchy, as well as the ability to develop rest periods is better for those subjects. So when conflicts between goals become more important, the operators who have developed a temporal awareness seems to react in a more safer way.

Nevertheless, it seems the use of this indicator as predictor for the behaviour when facing perturbed situations, such as those corresponding to the last scenarios of this experiment, should be undertaken with caution.

CONCLUSION

Temporal awareness seems to be a good indicator of the pattern of performance. As such it could be use to characterise the cognitive trade-off adopted by the operator.
So being focused on the temporal dimension of the operator's adaptation to the situation proves to be an interesting point of view to "give sense" to the complex pattern of the behaviour of operator in process control situation.

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9 DESIGN FOR PROCESS CONTROL

Cognitive Space of Operator's Knowledge

Kazuo FURUTA
Dept. of Quantum Engineering & Systems Science
The University of Tokyo
furuta@q.t.u-tokyo.ac.jp

ABSTRACT

This paper is to propose a generic model of operator's knowledge on plant systems and his/her tasks. The model consists of four cognitive subspaces of fundamental knowledge: configuration, causality, state and goal spaces. The four subspaces are interrelated with each other, and connections between knowledge entities of different subspaces also form operator's knowledge. A concrete example of knowledge representation is shown for a model plant, and the relation between the new model and other cognitive models are discussed.

Keywords
Plant operator, cognitive behavior, knowledge model, knowledge representation, abstraction hierarchy.

INTRODUCTION

Many models of knowledge that plant operators have on plant systems and their tasks have been proposed, but most of them deal with a specific aspect of cognitive behavior at a specific level, such as symptom-based diagnosis or action planning by goals-means analysis (e.g. Newell and Simon, 1972). Cognitive models proposed so far are much more generic, but they are organized based on process rather than knowledge to be used (e.g. Rasmussen, 1976; Reason, 1990). A generic view of operator's knowledge, however, is necessary not only for understanding operator's cognitive behavior but also for designing good operator support tools.

We have already proposed a knowledge model with two layers of task hierarchy (TH) and qualitative causality (QC) to develop an intelligent training support system (Furuhama, Furuta and Kondo, 1995). In the previous model, the TH layer represents teleological knowledge on plant operation organized by goals-means relation, while the QC layer represents indifferent knowledge on physical mechanism of the target system. The two layers are interrelated and the QC layer can provide etiological justification for each knowledge element on the TH layer.

This model was successfully used for construction of trainee's knowledge model in a training support system (Furuhama, Furuta and Kondo, 1996), but the model contains just the aspect of action planning in cognitive behavior; it is insufficient as a generic model. It is also a drawback of the two-layered model that knowledge on system configuration, which supports the knowledge on the QC layer, is not considered. This paper is to present a more generic model of operator's knowledge on plant systems and his/her tasks.

CONCEPTUAL MODEL OF OPERATOR'S KNOWLEDGE

The new model to be proposed in this paper consists of four cognitive subspaces of fundamental knowledge: configuration, causality, state and goal spaces. A conceptual view of the model is shown in Figure 1 and features of these four subspaces are compared in Table 1.

Configuration Space

The configuration space describes the structure, topology, shape and other physical properties of objects: the whole system, subsystems, components, and parts. It is hierarchically organized by whole-part relations, and it includes various views of the system at different levels of granularity. An operator will see macroscopic arrangement of the whole system, and he/she can also see the microscopic structure of each component if necessary. A graphical representation is suitable to formally represent device topology and the whole-part hierarchy, which are the principal knowledge of this space. This space is very similar to design description of

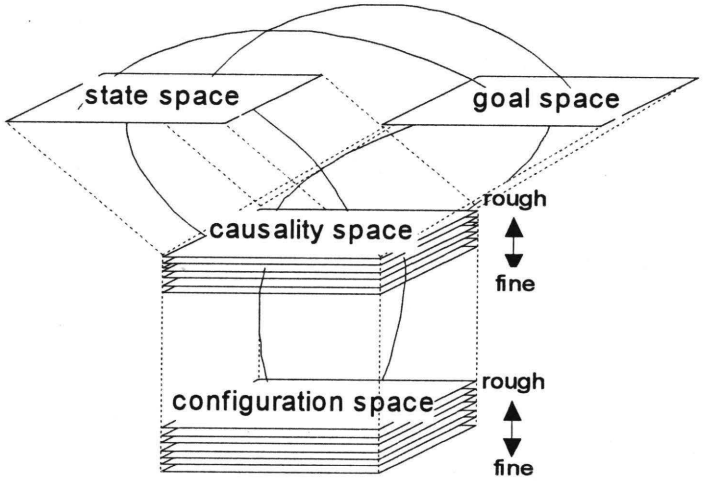

Figure 1 Conceptual view of operator's knowledge model.

Table 1 Features of four subspaces in the knowledge model.

Subspace	basic entity	basic relation	formal representation
configuration	physical object	connection, arrangement, whole-part	graph, frame
causality	attribute, parameter	cause-consequence, equality, inequality	graph
state	state of attribute	connotation, specific-general	topological space
goal	function, task	goals-means	graph, partially ordered set

the system, but it represents operator's subjective but unintentional view of the system configuration rather than complete and formal design description.

Causality Space

The causality space describes physical mechanism of system behavior, such as cause-consequence relations between system parameters, conservation laws of mass and energy, or various types of qualitative/quantitative constraints. Causality is not a real concept of physics and the knowledge of this space does not exactly coincide with physical laws. Causality however represents human's naive recognition of physical laws, and some heuristics are known to derive the former from the latter (Iwasaki and Simon, 1986). An operator can understand and predict system behavior by mental simulation based on such naive recognition. The space includes various views of the system at different levels of granularity, which correspond more or less to those of the configuration space. A graphical representation such as a cause-consequence diagram will be useful for a formal knowledge representation of the causality space. An equation, which can be represented as a tree, is another candidate of representation, but it is much more theoretical and normative than a cause-consequence diagram.

State Space

The state space represents operator's interpretation on system states that are worthwhile for operational purposes. Each system state can be connoted by a particular set of symptoms: observable states of attributes. An operator uses symptoms to recognize a system state by matching symptom patterns with the real condition. The state space is organized by general-specific relations. A general state is connoted by a few and ambiguous symptoms, while a specific state by many and concrete ones. A topological space of symptoms can be a formal representation of this space.

Goal Space

The goal space represents goals-means relations of system functions and operator's tasks. A system function here means some behavior of the system that is implemented to achieve a designated goal, and an operator's task means some set of well structured actions that is expected to achieve a designated goal. The both are almost the same concept from a viewpoint of human-machine complex, and the only difference is which of human and machine is in the role of achieving the goal. The goal space is hierarchically organized, and a graph or a partially ordered set can be a formal knowledge representation of this space. The hierarchy however is parallel to the viewing plane in this space; it is different from the configuration and the causality spaces, where the abstraction hierarchy is perpendicular to the viewing plane.

The four subspaces are interrelated with each other, and connections between knowledge entities of different subspaces also form operator's knowledge. The configuration space is the foundation of the causality space. For example, a connection of components defined in the former can provide justification to a cause-consequence link defined in the latter. A similar relation also holds between the causality space and the goal space, between the state space and the causality space. A goal in the goal space is specified by a particular state of the system, which is then related to some system parameter in the causality space.

Among the four spaces, the configuration and the causality spaces representing physical principles are almost independent of human expectations, while the other two are teleological. The former two correspond to so called deep knowledge in AI literature, while the latter to shallow knowledge. Since the teleological spaces are empirical or prescriptive, they cannot cover all aspects of the etiological ones, and knowledge in the latter provides justification to that in the former.

When an operator faces a familiar or within-design-basis situation, he/she can recognize the current state of the system by similarity matching using knowledge of the state space and then plan his/her action by goals-means analysis using knowledge of the goal space. It corresponds to rule-based behavior in the SRK taxonomy. If an operator faces any unfamiliar or beyond-design-basis situation, the teleological knowledge must be powerless, but he/she may still be able to cope with the situation using knowledge in the causality space and the configuration space. It corresponds to knowledge-based behavior.

IHS EXAMPLE

In order to present a more concrete image of the model, an example of knowledge representation is given below for a model plant, an Indirect Heating System (IHS). The example given here is neither complete nor sufficient for a practical purpose, but it is enough for explanation.

Let us assume a system to heat up some fluid indirectly with circulated hot water as shown in Figure 2. The system consists of a heat exchanger, tank with a heater , pump, five valves, flow sensor and controller. The water heated up in the tank is circulated through the primary loop by the pump, and heat is transferred to the fluid supplied to the secondary side of the heat exchanger. The flow rate of the hot water is controlled automatically. A graph like Figure 2, which shows connections between the major components, can be a representation of the configuration space of IHS. The configuration space of IHS also includes other representations, such as the floor plan of the components, the inner structure of the pump, the circuit diagram of the flow controller, etc., and physical attributes are attached to these representations.

The causality space of IHS can be described as a cause-consequence diagram of system parameters as shown in Figure 3. For example, the flow rate in the loop is positively affected by the openness of Valve-C, 1, 2, and the

pump speed. In the heat exchanger the amount of heat transferred is positively affected by the inlet temperature of water, and then it negatively affects the outlet temperature and so on. The direction of affection is not originated from physical laws but from heuristics. Nodes of system parameters as well as causality links are related to physical entities in the configuration space. The positive link, for example, between the pump speed and the flow rate is due to the fluid path between the pump and the piping at the flow sensor; an operator can predict that if the boundary of the path breaks the causality link may no longer work. An operator can thereby hypothesize a wider range of system behavior using interrelations between knowledge on configuration and causality than by mental simulation using the causality space alone.

Figure 4 shows an example of state space description for IHS. The symptoms observable in case of a pump failure are listed on the left of the figure, and those in case of a flow controller failure on the right. The both failures are specific categories of a primary loop failure, and the symptoms common to the specific failures, such as "*flow rate is not normal*", are the symptoms representing the general failure. The symptom patterns are explainable by knowledge in the causality space. The cause-consequence diagram on the left of Figure 3, for example, suggests that a pump failure affects the pump speed and then its effect propagates to the flow rate but it does not to the openness of V1, V2 and the pump power supply; the diagram can explain the symptom pattern for a pump failure.

Figure 5 shows an example of knowledge for the goal space. The nodes as rectangles stand for abstract tasks or functions, while rounded boxes for concrete actions or functions. The top goal of "*heat up fluid-2*" is decomposed to three subgoals : "*circulate fluid-1*", "*heat up fluid-1*", and "*keep fluid-1 inventory*". The first subgoal is decomposed further to three subgoals of "*provide driving force*", "*make flow path*" and "*regulate flow rate*", and finally to specific actions. The functions of hatched nodes are assigned to machines, and some of them do not correspond to any dynamic actions but to static plant configuration like "*hold fluid-1*". Nodes in this space are linked with nodes or a partial structure in the causality space. A node of "*circulate fluid-1*" is, for example, connected with a node of "*flow rate*", "*open V1*" with "*openness of V1*", and so on. The cause-consequence diagram on the left of Figure 3 therefore provides the justification for the goal structure below this node and the corresponding operation procedure.

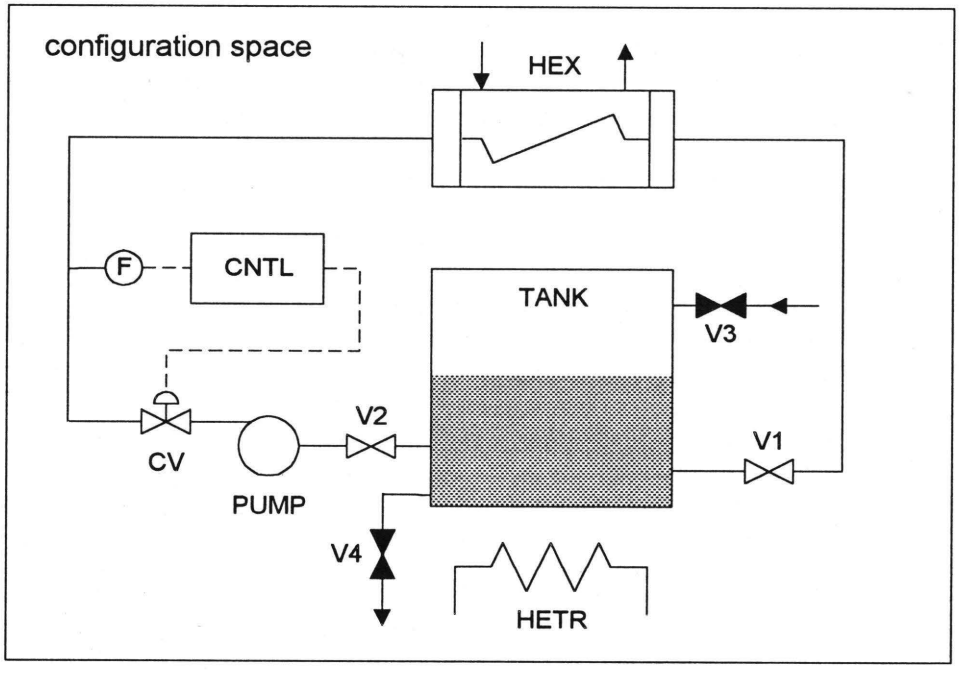

Figure 2 Example of knowledge representation for configuration space of IHS.

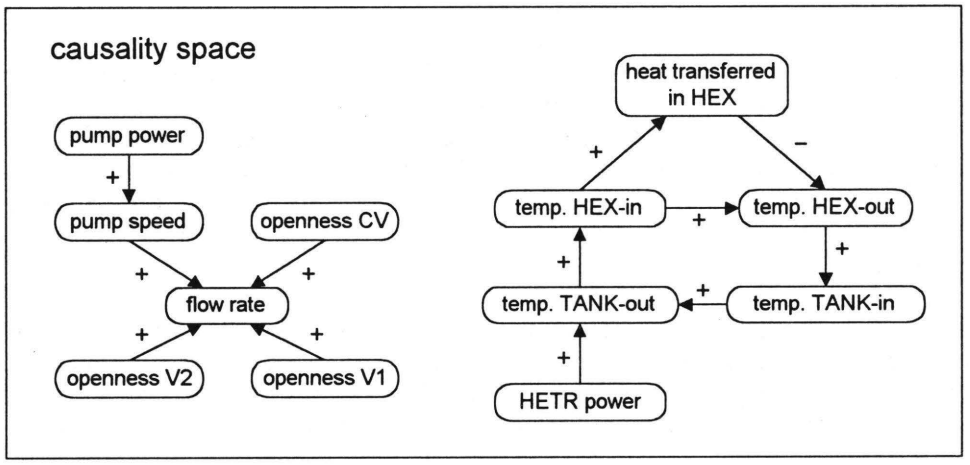

Figure 3 Example of knowledge representation for causality space of IHS.

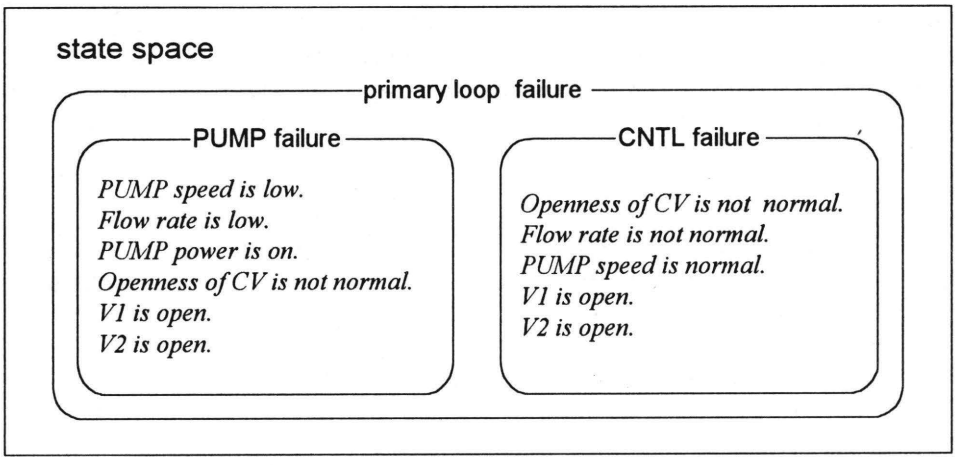

Figure 4 Example of knowledge representation for state space of IHS.

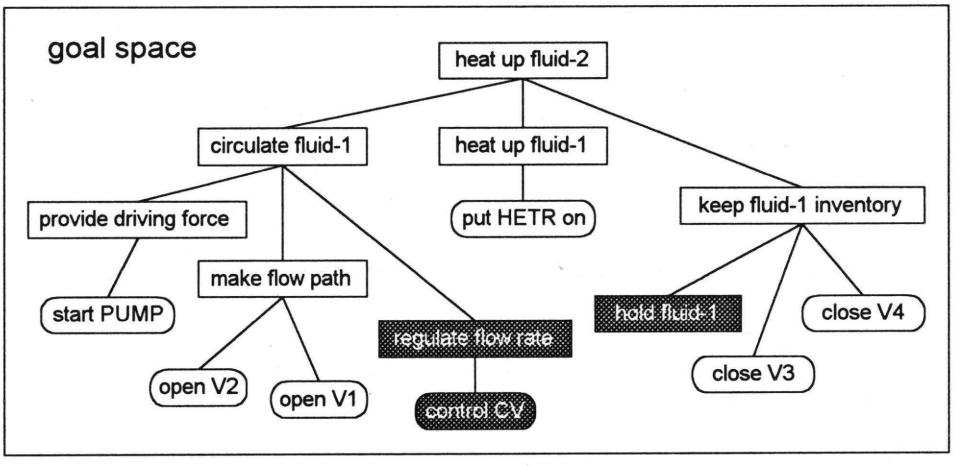

Figure 5 Example of knowledge representation for goal space of IHS.

COMPARISON WITH OTHER MODELS

The knowledge model of this work is similar to but different from some other models already proposed, for example Rasmussen's Abstraction Hierarchy (AH) (Rasmussen, 1986). While AH is a view of the system, the model of this work includes views of both the system and operator's tasks. In addition, the notions of system state and causality are not clearly separated from functions, and physical form and configuration appears at the lowest level in AH; it makes distinction between teleological and etiological knowledge ambiguous. The author however thinks it important to distinguish the both knowledge, because it contributes to understand or support operator's behavior in unfamiliar situations.

In the Multi Level Flow Modeling (MFM) of Lind (Lind, 1982), system behavior represented as flows of mass, energy and information is distinguished but interrelated with the goal structure of the system; it is possible to derive unprescribed operation procedures from MFM (Larsen, Kjaer-Hansen and Lind, 1993). The representation of system behavior, however, is teleological, since it is organized by system functions.

CONCLUSION

A generic model of operator's knowledge on plant systems and his/her tasks has been proposed. The model structured as four subspaces of configuration, causality, state and goal includes various types of knowledge used on both analysis and planning aspects of operator's cognitive behavior. The structure and the feature of each subspace is explained, and then an example of knowledge representation is given for the IHS plant. The new model is expected to provide a good basis not only for understanding cognitive world of an operator but also for designing operator support tools.

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A modelling concept to support complementary design of dynamically complex systems

Ph. Moscoso*, T. Wäfler, A. Windischer****

*Institute for Operations Research, **Work and Organisational Psychology Unit,
Swiss Federal Institute of Technology Zurich (ETH), 8092 Zurich, Switzerland,
e-mail: moscoso@ifor.math.ethz.ch

ABSTRACT

A prototypical solution of a process planning and control system for an automated work-cell which is realised in practice is analysed. The key concept relies on an agent-based control using simulation. The major problems during introduction into an existing manufacturing process are discussed with regard to the fact that decisions concerning function allocation between human and technical system are crucial for the design of such systems. Consequences for the technical and organisational integration of the work-cell are pointed out. Finally a general modelling concept to support complementary design of planning and control systems is outlined.

Keywords

Process model, function allocation, planning and control, simulation, complementary design.

INTRODUCTION

Increasing structural and dynamic complexity of production processes led to the realisation that an exact prediction of process states can not be guaranteed. Consequently, new process management systems are needed considering unsteady-states as normal and even a presupposition for organisational learning. There are different concepts to reach this goal. Technology on the one hand and the human on the other might be considered enablers of dynamic process control. Whereas some approaches follow the idea of artificial intelligence (e.g. through virtual agents), others try to empower human intelligence by providing human operators with job characteristics that permit them to gain experience in process control. In our work we bring these two approaches together. We consider production processes including their management tasks as sociotechnical systems comprising human and technical operators. Together they have to cope with increasing structural and dynamic complexity in respect of productivity, reliability and safety of the production processes. A successful mastering of this challenge doesn't only depend on independent abilities of human operators and technical equipment but also on the quality of the mutual interaction. The function allocation between human and technical subsystem is therefore a crucial question in the system design. Frequently used criteria like economic and technical feasibility and allocation to the presumably better performer have proven to be insufficient in respect to optimal interaction between human operator and technical subsystem. A complementary approach taking into account differences in strengths and weaknesses of human and technical subsystems is suggested. Their adequate interaction provides a performance impossible to human or technical systems alone (Bailey, 1989; Bainbridge, 1982; Grote et al., 1995a). Complementary design requires tools for modelling and prospective design for both operator jobs and technical systems. Allocation decisions have to take into account technical, organisational and human considerations in an integral manner (cf. e.g. Ulich, 1994). A (re-)design of a production system implies its description for which an aggregate model is helpful. The set of variables represented by a model as well as its interaction is defined by both the modeller and the modelling technique. Comparing different design solutions (e.g. by computer simulation) only those variables represented by the model are considered in deriving design scenarios. The effect of variables that are not represented by the model (e.g. the human operators motivation) are neglected. Criteria for complementary system design must therefore be incorporated into design processes and modelling concepts in order to reach complementarity in the system design.

We carried out a case study in this problem area. A highly automated work-cell for semi-conductor assembling was analysed and modelled using two different concepts: KOMPASS and HIDES. These were developed at the Work and Organisational Psychology Unit (IfAP) and the Institute of Operations Research (IFOR) respectively at the Swiss Federal Institute of Technology (ETH). The goal was to derive a modelling concept to support the complementary design of process planning and control systems. The first step was the integration of the KOMPASS-criteria into a conceptual framework for the HIDES-modelling of the planning and control process of the work-cell and is presented in this paper.

THE HIDES APPROACH

For the planning and control tasks of the work-cell a distributed problem solving approach was implemented using the discrete event simulator HIDES (Highly Interactive Discrete Event Simulator). HIDES-models are based on a meta-model which comprises one physical and one logical level. In the physical level, the static structure of the system and the dynamic sequence of the physical events are represented. The relationships are modelled as a directed graph with two types of nodes, stations and queues. A third important model element are resources introduced as abstract elements that can be allocated dynamically containing information about their availability and their behaviour. The logical level comprises the control of the system, together with the information flow which is necessary for this purpose. HIDES allows the building of hierarchical models with different levels of abstraction and therefore supports top-down modelling. Formulated planning problems are distributed to several virtual agents, which are the dynamic extension of the control concept of the logical level. Each of these agents supports a clearly defined task and has its own specific problem solving strategies. Agents have information about the problem area they are responsible for and they can request services of other agents. Simulation is used by the agents to determine the future consequences of their decisions. For the work-cell application the agent- based HIDES approach has been used in two different fields. During development it allows to clarify the effects of new modules and to estimate their efficiency in advance. For production it enabled to implement an intelligent and adaptive planning and control system for the work-cell. In operation events from the work-cell are permanently forwarded to the agents. The agents compare the actual state of the work-cell with the planning data and take appropriate actions if necessary (Lüthi et al., 1996).

THE KOMPASS APPROACH

The design heuristic KOMPASS (complementary analysis and design of production tasks in sociotechnical systems) aims at supporting complementary design by providing design criteria and a moderation aid leading a design team through a discussion of design philosophy, design criteria, and the actual development and evaluation of design options (Grote et al., 1995b, 1996, 1997). It provides guidelines for the analysis and assessment of existing systems and a heuristic for system design. A participatory approach is envisioned, such that future system operators are included in the design decisions as early as possible; although, participation and the use of expert design criteria should be balanced. The KOMPASS-criteria concern job design on three levels: sociotechnical system, individual work task and human-machine-interaction. Design goals aimed at are, for example, local control of variances and disturbances (e.g. through independence of organisational units) and intrinsically motivating job design (e.g. through complete tasks).

THE WORK-CELL AS A PRACTICAL EXAMPLE

The work-cell supports three process steps. On the die-bonder the electrical devices are picked from a wafer and glued on a metallic strip (the leadframe). The strips are filled into magazines. That semi-finished product goes to an oven where the glue is dried. Afterwards the electrical connections (gold wires) between the device and the leadframe are made on the wire-bonder. The transport of magazines within the work-cell is automated and performed by a robot.

The (static) scheduling problem is the following: given is a set of lots. Each lot is defined by its product type and the lot size (number of devices). For a given lot size it is easy to calculate the number of magazines that will be necessary to transport the material for this lot. Since all the material in a magazine is moved as a whole within the work-cell, the number of magazines (per lot) that are distributed to each wire-bonder is taken as one decision variable and the question we have to answer is: in which sequence should the lots be started on the die-bonder and how many magazines per lot should go to which wire-bonder ?

This scheduling problem is more complicated as it appears at first sight. Depending on the user of the work-cell different optimisation criteria and several different restrictions may be addressed. In addition, solutions calculated for static scheduling problems may become obsolete in a dynamic environment. Planning and control has to be flexible allowing the integration of new equipment types to the work-cell and supporting the integration of new process steps. The time to search a solution has to be short and the information to deal with could be fuzzy (e.g. „this lot has high priority“).

THE NECESSITY OF A MODELLING CONCEPT TO SUPPORT COMPLEMENTARY DESIGN

The introduction of the first generation of work-cells in the Asian region, showed three major problem areas with regard to the integration of the work-cell with its internal planning and control system into the existing manufacturing process:

- the technical integration into the shop floor,
- the conditioned acting of operators due to their different cultural environment and
- the social integration into the work organisation within the factory.

Hence the consequences of decisions of function allocation between human and machine as well as the organisational structure of the production process of the entire industrial operation, must exert a more deliberate influence on the design of the work-cell. The level of automation, i.e. the opportunities human operators have to organise and intervene must be adaptable to match the available qualification of the staff as well as the cultural environment. An automated planning and control system supported by simulation should not limit this flexibility. Furthermore if the simulation is used to determine the most expedient design for the work-cell with the customer on site the consequences of different levels of automation must be considered too. Simulation applied to support planning and control as well as complementary system design needs a modelling concept that represents all relevant parameters and relationships. This seems to be the most difficult part, because the selective input taken into account forces to reduce the complexity and therefore implies the risk of neglecting fundamental aspects of the system. As a consequence, even the recognition of major problems could not be guaranteed. On the one hand, the modelling concept must be capable of transparently recording the structural complexity of the closely intermeshed process steps in the work-cell and specially their relationships with the corresponding environment, for technical as well as for organisational aspects. On the other hand, it must appropriately describe the dynamic complexity, in our case the throughput of different batches processed simultaneously and the dependence of previous and following processing steps. The different strategies for reducing the production lead time will serve as an example for the modelling problem addressed.

If for example, several different product types are to be processed, a point which must be taken into account is that the resetting period for the individual components and hence the production speed for the work-cell depend very heavily on the sequence of product types. Correspondingly this sequence determines the distribution of the resetting over time for which an operator has to be available. Because of the high complexity of the production process, the operator will often be expected to solve unforeseen events, e.g. missing of needed resources or sudden failures of peripheral components. Consequently, operators try to change the automatic generated planning proposals in a way that fits their needs better. If the human - according to the principles of complementary design approach - is considered to be an important resource able to provide a specific contribution to successful system performance (e.g. flexible reaction, creative problem solving) he must have the opportunity for both the acquisition of the required qualification as well as the development of motivation. Qualification and motivation are highly related to working conditions and job design (cf. e.g. Ulich 1994). As long as the design of the technical system leads to working conditions and job design as accidentally generated by-products the prerequisites for complementarity are not or at best accidentally met. Therefore it is essential for modelling concepts to support designers in the realisation of complementary design. An integration of the conceptual framework for the HIDES approach to system modelling and the KOMPASS approach to complementary design will be presented in the following section.

A CONCEPTUAL FRAMEWORK FOR COMPLEMENTARY MODELLING

For the mentioned purpose of supporting complementary system design we developed a systemtheoretical framework where processes are the center of attention. The concept of designing processes is coming to occupy an increasingly central position in industrial practice because of an improved perception of the difficulties related to the dynamic complexity. The difficulty of dealing with time calls for a deeper investigation of processes as an abstract concept abandoning pure structural descriptions to understand them in their dynamic context. The development of the conceptual framework for modelling comprises two basic aspects:

- specification of the fundamental dimensions of system design in order to guarantee a complementary design.
- definition of criteria which allow the evaluation of different design options.

In this research we focused on these two main goals.

The proposed concept for modelling will be presented using two activities of the planning and control process within the work cell as an example. The first activity represents the task of choosing lots to be processed from a given set. The second activity consists in planning the production sequence for the chosen lot. Activities are elementary processes which on an aggregate level constitute again a process. Therefore a process is an ordered sequence of connected activities which determines a transformation. Processes consist of sources, transformations and sinks, and are part of an open, dynamic sociotechnical system. To orient the behaviour of the system, goals and purposes must be defined. The purpose concerns the functions of the system related to its environment whereas the goals specify the intended characteristics of behaviour (Ulrich 1970). For the realisation of goals and purposes a performance potential is needed. This must be provided by the resources of the system. The objects processed by the system use the resources to increase their value in the sense of the formulated goals and purposes. The relations with the environment are represented by sources and sinks (see Fig.1, So and Si). The amount, the arrangement and types of relations between the elements (i.e. resources, processes, and objects) constitute the structure of the system. It is necessary to distinguish between a static and a dynamic view of structure which is formed during a process. Together they link the order in time and space needed to enable the system behaviour (Krieg 1971). In addition, the structure is in a complementary relation to the process. Structures

enable processes but are also result of processes. The system behaviour is determined trough the relations among its elements and with the environment.

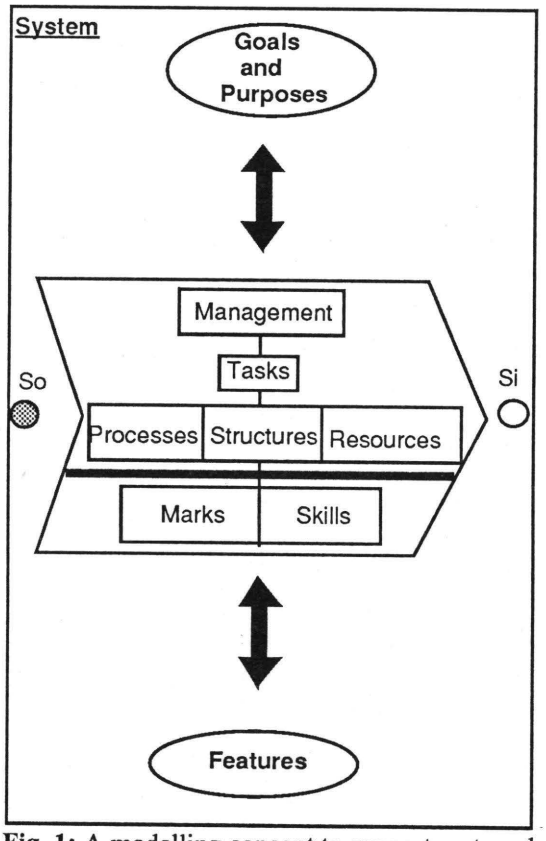

Fig. 1: A modelling concept to support system design

A conceptual framework for modelling of planning and control systems must allow to model and analyse the process with its relationships to all other system elements. Therefore a feature-catalogue is defined (Fig. 1). The chosen set comprises seven dimensions: management, tasks, structures, processes, resources, marks and skills. Whereas marks and skills are consequences of the system design, management, tasks, structures, processes and resources are dimensions of system design. The former are dependent, the latter independent variables of system design. In the management dimension the framework for the specification of tasks is determined. Together with the tasks dimension the management concept establishes the base for the design of processes, structures and resources. The structure is given through the relation between the processes, the resources as well as between processes and resources. This modelling concept serves as a conceptual framework for HIDES supported design. The physical level in the HIDES approach refers to the structures, the logical level to the processes and the agent-level to the management and tasks dimensions. As well as HIDES the described modelling concept allows to model in different levels of abstraction, for top-down as well as bottom-up modelling. The conceptual framework presented in Table 1 is defined through the following modelling dimensions:

Table 1. Descriptive dimensions of the modelling concept

The management dimension describes the capability of the system for a goal and purpose oriented self-control and consists of three levels:

- normative: specification of standards and values as well as determination of goals and purposes of the system
- strategic: specification of the relations with the environment and the system development
- operative: co-ordination of subsystems and stabilisation of perturbances

The tasks dimension consists of two levels:

- the primary task is given through a determined purpose and is the reason that the system was created
- secondary tasks are defined to preserve and control the system

Processes consist of sources, transformations and sinks:

- sources describe the objects to be transformed by the process and the system load by the environment
- sinks describe the objects transformed and the demand-patterns of the environment
- transformations describe the transformation of objects from an initial state at time t to an end state at $t + \partial$

Structures describe the relations between the elements of the system. Two views are distinguished:

- the static view describes the hierarchical organisation of the system
- the dynamic view describe the procedural organisation which is constituted during a process

Resources describe elements of the system that can be allocated and contain information about their availability and their behaviour. There are five aspects of resources described:

- multifunctionality, flexibility, autonomy, degree of interdependence and degree of virtualisation (i.e. independence of time and space)

Skills describe the capacity and the possibilities of the system to reach determined goals and purposes as well as to survive in a given environment. There are eight skills described:

- capability for: communication, competitive advantages, structural and dynamic reaction, synergism, realisation, learning, efficiency and effectively

Marks describe quantifiable system characteristics. There are seven marks described:

- throughput, stock size, capacity load, accuracy of delivery time, lead time and quality

Models of work systems according to these seven strictly descriptive dimensions still abstract from the peculiarity of humans. If at all they appear as a resource among others without consideration of their specificity. It is clear that models incorporating concepts like these do not support complementary system design. This is where the KOMPASS-criteria are taken into account. They concern the interaction between humans and technical system as well as between humans. The criteria are both descriptive and normative. Whereas the descriptive aspect should support multifunctional design teams in considering the human-human as well as the human-machine interaction the normative aspect provides designers with indications of how to meet psychologically founded demands for complementary system design. The criteria presented in Table 2 concern three levels of job design (cf. Grote at al.,1997):

Table 2. KOMPASS-criteria for complementary design

Work system

- Task completeness: processing depth, functional integration, complexity of production processes
- Independence of work system: buffers, flexibility of work flow, local quality control
- Fit between regulation requirements and regulation opportunities: type and extent of system variances and disturbances, task interdependence/form of co-operation, flexibility of co-operation form
- Polyvalence of work system members: proportion of tasks for which operators have complete competence and skills, not necessarily responsibility
- Autonomy of work groups: joint decision making regarding internal and external co-ordination, internal personnel management and continuous improvement within the work system
- Boundary regulation by superiors: ratio between superiors' internal and external co-ordination tasks

Human work tasks

- Task completeness: tasks including preparation, planning, execution, controlling and maintenance/repair
- Planning and decision making requirements: planning and decision making required with respect to content of work, equipment, workflow and results of work tasks
- Communication requirements: requirements for communication and co-operation based on common planning and decision making
- Opportunities for learning and personal development: possibilities for using existing qualifications and acquisition of new skills
- Variety: requirements for dealing with different materials, procedures and tools, types of products, and persons
- Transparency of work flow: transparency regarding the integration of own work tasks into overall work flow
- Influence over working conditions: opportunities for controlling jobs, working hours, distribution of work tasks, and production goals
- Temporal flexibility: planning horizon, temporal coupling regarding jobs and production process, time pressure
- Absence of hindrances: informatory and sensomotory hindrances, interruptions

Human-machine system

- Dynamic coupling: availability and use of technically provided options regarding time, place, work procedures, and required cognitive effort
- Process transparency: opportunities for forming and maintaining mental models of the general nature and temporal structure of production processes and of required interventions, process feedback modalities
- Decision authority: distribution of decision authority regarding information access and process control between human operator and technical system
- Flexibility: variability of function allocation between human operator and technical system and distribution of the respective decision authority

The KOMPASS-criteria concern all five independent variables of system design (i.e. management, tasks, processes, structures and resources). On the management dimension at least the commitment for complementary system design must be given. A reasonable definition of the work system's task as well as its division into meaningful tasks for humans according to KOMPASS-criteria concern the tasks dimension. Finally the definition of interaction between humans as well as between humans and technical systems according to principles of complementary design affects the linking of processes and resources to structures.

Coming back to the initial example of the two activities of the work cell, we briefly explain the modelling concept, by analysing the consequences of a given environment on the planning process. The enterprise was interested in the question, why the automated planning and control did not lead to a shorter duration of the as-

sembling process. In analysing the normative level of the management dimension two opposite goals became apparent. While the engineering division demanded a maximum capacity load, the assembly manager wanted a minimum lead time. For the strategic level of the system again two opposite positions were found. The assembly manager was advised to reduce his stock. Because the main value of the chip was added within the previous production system the assembling process had to follow a push principle. The sequence of lot assembling was determined by the previous system and differed from the sequence demanded by the retail department. Consequently the assembly manager could only fulfil the orders by having a stock. In a next step the operative level of the system was analysed. An effect of the mentioned push principle was a strong dependence from previous perturbances. In addition the choosing of a lot to be assembled on a work-cell, was not within the responsibility of the operator. The allocation of lots was decided by a dispatcher for all work cells. By using the automatic planning system of the work cell operators had no influence on the sequence in which the magazines of the lots were processed on their work cell. This management characteristics of the assembly system implied important consequences for the tasks dimension. The tasks assigned to the operators were reduced to assist the work-cell when breakdowns happen, on the one hand by the determination of lots by the dispatcher, on the other hand by the determination of the magazine sequence by the automatic planning and control system. Task completeness and transparency of process was not given. Operators had no possibility of improving their mental model of the assembling process and to gain experience. If they were asked for manual reassignment due to unforeseen events they were often not able to predict the consequences of their decisions. Consequently in the skills dimension a bigger reaction-time was needed in case of unexpected events and competitive advantages were lost because of delays. To summarise, the organisational structures allowed almost no planning scope within the cell during regular production (e.g. when no failures occur).

CONCLUSIONS AND PROSPECTS

The presented case study has outlined the necessity of a modelling concept to support complementary design. To describe the structural and dynamic complexity of sociotechnical systems the human peculiarities must be taken into account. Therefore the formulated descriptive concept was complemented with the KOMPASS-criteria. However, the criteria presented are not to be understood in the sense of leading to one straight forward solution, but as part of a modelling concept, which enables the reflection of decisions and the proper use of simulation during a design process within a team. Further research based on more case studies will allow to improve the concept and to formulate a general methodology for computer-supported complementary system design.

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Design and evaluation of decision support for integrated ship operation

José Kerstholt and Peter Passenier
TNO Human Factors Research Institute
The Netherlands
email: Kerstholt@tm.tno.nl

ABSTRACT
Research is reported in which it was investigated how a single person would handle multiple disturbances in a ship control task and whether performance improvements could be attained by adequate support. Our results indicated that one of the main reasons for suboptimal performance was that the majority of subjects tended to focus on only one single disturbance at a time while ignoring the rest of the system, including alarms that indicated additional disturbances. Performance could be improved by training and decision support. In the training experiment, performance increased when subjects had received an integrated training. Additional performance improvement was acquired when subjects were given an interface that provided them with 'on-line' support for the diagnosis process.

Keywords: supervisory control, cognitive lockup, diagnosis, training, support

INTRODUCTION

During recent years there has been an increased use and acceptance of automation onboard ships. The various vessel functions such as navigation, machinery control/monitoring, cargo handling/monitoring, communications and fire detection, have increasingly been concentrated into the bridge area. The initial motivation behind these changes has been the desire to reduce operating costs by reducing the crew number. Today's requirements for a more efficient bridge operation have made the 'integrated bridge' an accepted reality. However, the true integrated bridge is not just a traditional ship with a few extra VDU's and control panels, but there is a need to address the complex interaction between equipment, control systems, computer hardware/software and the human operator.

Due to technological developments the watchkeeper's role is increasingly being reduced to that of a supervisor. In such a situation the operator supervises multiple systems concurrently, only occasionally adjusting set-points. The interaction with the systems under control mainly occurs at a high level. For example, the operator may indicate that a route should be taken that minimizes either time or fuel costs. The actual control of the various functions are carried out automatically and these specific actions are mostly unknown by the operator.

Under normal conditions, automation will reduce workload. Because many functions, mainly at a routine level, are automated the operator can fully concentrate on planning and decision making functions. Still, even though the number of functions to be carried out by humans are reduced, new cognitive demands are posed on the operator, especially when intervention is needed after the occurrence of unexpected events.

One of the main characteristics of unexpected, critical situations is the presence of time pressure. In dynamic environments, time pressure is defined by the rate in which the system changes towards some negative consequence (Kerstholt, 1994, 1995). In fast changing situations, the operator needs to act quickly in order to prevent negative consequences to materialise.

Before an appropriate action can be taken the operator first has to assess the actual situation, but because many automatic control actions are not perceived by the operator this may become a critical element in accurate task performance. Problems around situation assessment (SA) have mainly been investigated in the context of aviation (Adams, et al., 1995; Salas et al., 1995). The installation of glass cockpits in commercial aircrafts can be regarded as a major technological initiative toward managing human workload (Adams et al., 1995). In glass cockpits a limited number of cathode-ray tubes replace the hundreds of gauges and instruments while flight management computers manage information presentation and have taken over the control of many functions that were previously assigned to the aircrew (Adams et al., 1995). However, the main complaint due to the automation of a great part of the process is the increased perceived distance to the aircraft and the environment (Wiener, 1985). Because of the automation the operator has less overview of what exactly is going on at a detailed level. In an experimental study, Sarter and Woods (1994) identified the main problems that occurred in pilot-automation interaction and they concluded that most of the observed difficulties were related to lack of mode awareness (manual or automatic mode) and to gaps in mental models of how the various automated modes

work and interact. These problems occurred primarily in the context of nonnormal time-critical situations, for example, aborted takeoff, disengagement from an automatic mode during approach for collision avoidance, and loss of the glide slope signal during final approach. In the case of the aborted takeoff, 65% of the pilots were not aware that the autothrottle system was in charge of thrust control. Consequently, they did not disengage the autothrottles in order to have full manual control of the throttle setting. In the debriefing, 15% of these pilots could describe the active mode settings and the system activities during takeoff but their knowledge was inert; they had not been capable of applying this knowledge to the ongoing situation.
Another problem often mentioned in the context of supervisory control is the fact that the operator is deprived of experience in dealing with the system. In general, laboratory research has indicated that people perform rather poorly in dealing with dynamic systems. They ignore feedback delays (Brehmer, 1992; Diehl and Sterman, 1995), they focus too much on requesting information that will reduce their uncertainty concerning the cause underlying declining system performance (Kerstholt, 1995; in press) and they insufficiently consider the dynamic development of their environment (Eisenhardt, 1989; Hogarth and Makridakis, 1981). However, in real life people seem to perform rather well in dealing with complex dynamic systems. Fire fighters are able to directly recognise a situation and consequently to select the appropriate action (Klein, 1993) and pilots can adequately manoeuvre ships through restricted waterways (Schraagen, 1994). This expertise seems to have been acquired by learning the relations between input and output signals through many years of experience. Or, as put by Schraagen (1994) "pilots' expertise seems to consist more of using specific references in a particular area than in being able to predict accurately a ship's movement". Problems that are met in supervisory control tasks will mostly be unique and an operator will therefore not learn to recognise the situation, but he or she must first diagnose the situation by actively requesting information before an appropriate action can be applied.
Our research focused on decision behaviour in such nonroutine situations, that is, when multiple disturbances occur that cannot be directly recognised but that have to be diagnosed and solved within a limited time span.

DIAGNOSIS PERFORMANCE IN CRITICAL SITUATIONS

In order to investigate how operators respond to a nonroutine situation in a ship control task, we developed an experimental task in which four ship functions needed to be supervised: navigation, propulsion, electricity and cargo (Kerstholt, Passenier, Houttuin and Schuffel, 1996). Due to dependencies between system components a fault could propagate through the system and it was predicted that a critical situation would result when multiple disturbances would occur at the same time. In such a situation the watchkeeper needs to divide his attention between monitoring overall system performance and diagnosing a disturbance at a more detailed level. As negative consequences would result when no action was taken the disturbances had to be dealt with under time pressure.
A simulation was developed in which the functions were represented by simplified process-diagrams. The overall performance of the subsystems could be deduced from a specific signal: GPS position for navigation, thrust for propulsion, mains power for electricity and temperature for cargo. Whenever this overall value would deviate from its required level the operator could conclude that a disturbance had occurred in the subsystem. For example, when it was noted that the ship had deviated from its planned track it could be due to, amongst others, the GPS, to the course control unit or to the hydraulics. In order to deduce the exact cause, symptom information could be requested. Each cause resulted in a unique symptom pattern. When the subject thought he knew the underlying cause for decreased system performance, the suspected component could be reset, which could restore system performance to its normal level.
Another action that could be taken by the subjects was termed a 'global reset'. A global reset simulated a stabilizing action. Such a stabilizing action would not solve the disturbance but would give the operator some extra time to diagnose the disturbance.
Because of the dependencies between systems a fault could affect several components. Each disturbance in the propulsion system, for example, would also cause a deviation in the stability and the course control unit in the navigation subsystem. This implies that when the subject would perceive a disturbance in the propulsion system, it would be wise to check the propulsion system first.
In all experiments we used as subjects students from maritime training curricula. In order to obtain a homogenous group they were all in their second year.

Cognitive lockup

In general, the results of our experiments showed that most of the subjects dealt with multiple disturbances sequentially, providing support for 'cognitive lockup': rather than dividing attention between problem solving and monitoring the rest of the subsystems, subjects focused on the diagnosis of one single disturbance at a time (Kerstholt et al., 1996, Kerstholt and Passenier, 1995a). They finished the disturbance first encountered, before switching to another disturbance. While diagnosing a single disturbance they completely ignored auditory alarms

that signalled additional disturbances. This finding implies that subjects lost the overview of the system when dealing with a disturbance.
However, across subjects large individual differences were found. Some subjects were better able to deduce a cause from a requested set of symptoms than others and a small proportion of the subjects was also able to keep an overview of the system. The best performing subject, for example, used the folowing strategy: When he was working on the second disturbance two auditory alarms went off, informing him that there was an additional disturbance in another system. He reacted to this information by interrupting his ongoing diagnosis process to first stabilize the subsystem in which an additional disturbance had occurred. This way he ensured that overall system performance could be kept within safety limits. By giving the stabilizing action in the third subsystem, he created extra time to solve the disturbance in the third subsystem.

Effort accuracy trade-off

A common observation in technological environments is the great number of alarms going off at regular intervals. Many of these alarms turn out to be 'false' however, meaning that, despite the alarm, the system is working properly. In order to see how the presence of false alarms would affect human behaviour we carried out an experiment in which two conditions were distinguished: one in which signals indicating deteriorating system performance were always 'real' and one in which part of the signals turned out to be 'false' (Kerstholt and Passenier, 1995a). The results of this experiment showed that subjects took less samples of the various subsystems when false alarms were possible and dealt with real disturbances less accurately (Kerstholt, 1995; Kerstholt and Passenier, 1995a).
This result can be explained by the common finding that people make trade-offs between accuracy and effort. By simulating various decision strategies, Payne, Bettman and Johnson (1992) showed that particular simplified decision rules came up with fairly accurate decisions, but with a considerable reduction in effort. They compared these strategies to actual decision making behaviour and showed that subjects performed very adaptively. Subjects did not always select the best option, but when both accuracy and effort were considered the best strategy was generally chosen, that is, the strategy that led to a reasonable solution, but with only a little amount of effort.
For a situation in which false alarms occur it can be stated that subjects may often invest effort in information search and diagnosis that turns out to be in vain. As a consequence subjects reduced their effort level, they checked the systems less often and were slower at responding to a disturbance, but at the expense of less accurate performance.

INTEGRATED TRAINING

The finding that people can be caught in cognitive lockup not only holds for laboratory tasks such as the one we have used in our experiments. Decortis (1993), for example, analysed the strategies of experienced and inexperienced operators when dealing with incidents in a complex control task. In general, she observed in this study that, compared to novices, experienced operators could maintain an overview of the systems under control. They tried to prevent the propagation of a fault before diagnosing it in more detail and they generally took more selective actions. Similar observations have also been reported by Patrick (1993) and Lee and Moray (1992). Thus, comparisons between experienced and inexperienced operators suggest that lack of knowledge may be one factor underlying cognitive lockup.
Having knowledge of the working of a device in terms of its internal structure has generally been found to improve performance (Bibby and Payne, 1993; Kieras and Bovair, 1984; Zeitz and Spoehr, 1989). More specifically, Kieras and Bovair (1984) and Zeitz and Spoehr (1989) suggested that knowledge of how a system works helps by enabling the user to infer how to operate the device.
The training that subjects had received in our first experiments taught them the workings of the subsystems in isolation. Thus, even though these subjects knew about the dependencies between the subsystems, they were explicitly told about it, they may not have had a device model of the complete system. Particularly with regard to cognitive lockup it seems highly important to have a clear representation of system dependencies to be able to predict the propagation of the fault through the system.
In order to test whether performance would be improved when subjects had a representation of the system as a whole, we designed a training curriculum in which all subsystems were taught in relation to each other (Kerstholt and Passenier, 1995b). In this training subjects saw all four subsystems on one screen. For each disturbance the symptoms were colour coded and subjects had to indicate the underlying cause. By providing the subjects with the structure of the complete system, together with the symptom pattern for all disturbances, we assumed that they could build up a representation of the symptom patterns for the entire system.
The performance of the subjects who had learned the systems in relation to each other was increased by 20%. In the condition in which the systems were learned in isolation, subjects solved 70% of the disturbances correctly,

and in the integrated training condition this percentage was 90%. Even without explicit instruction, subjects who had received the integrated training used a more systematic problem solving strategy. They not only gave more stabilizing actions, compared to the control group, but also applied these actions relatively more to the systems that were dependent on other systems. Thus, these subjects were better able to keep an overview of all systems under control, and could anticipate on fault propagation by their knowledge of dependencies between subsystems.

All subjects had received three series of trials which allowed us to see whether the two groups showed differential learning curves. When the control group would, for example, build up a representation of the system during the experimental trials we would expect their performance to increase more rapidly than the performance of the integrated training condition. The results showed, however, that the differences between experimental groups remained constant across series of trials. This suggests that practice alone is not sufficient for improved performance, but that a fundamental understanding is needed of the relations between all system components.

DECISION SUPPORT

In the training experiment we showed that performance improved when subjects were given an integrated training. In this experiment, however, there was a close match between the knowledge that these subjects had acquired during the training phase and the disturbances that occurred in the experimental trials. In reality disturbances will not directly match this knowledge and there will be a probabilistic relationship. In a subsequent experiment we therefore made the relations between symptoms and causes more opaque, requiring a more explicit reasoning process of the subjects. In this experiment we investigated whether performance could be further improved when subjects were given on-line support in their fault-finding behaviour.

Experimental results of Raaijmakers & Voorkamp (1993) showed that diagnosis performance was highly correlated with the availability of knowledge of the process. In a follow-up study (Raaijmakers & Verduyn, 1996) a form of diagnosis support was tested that aimed at making relevant causal relations available for a specific alarm situation. With this way of information structuring they showed a significant improvement of diagnosis performance. The support can be considered as an information aid: the operator makes the diagnosis with, at his own discretion, the use of a support tool. Based on this result we designed an interface that would support the subjects in requesting the relevant information.

In the support condition subjects received support at two levels: at a global level, which allowed them to keep an overview of the complete systems, and at a local level, in order to identify the disturbed component in a specific subsystem. At the global level of support subjects received the following information on a computer screen:

1) In one window they were given feedback about their own timing behaviour, i.e. for how long did the subject look at each of the subsystems, and they were given preview information about the time left until an 'autoshutdown'. An autoshutdown basically meant that the problem was not solved within the available time.
2) A second window depicted the structure of the complete system. The relations between the components, across subsystems, were indicated by arrows. Furthermore, the program also indicated whether additional disturbances were likely by a colour coding of dependent components. For example, if there was a disturbance in the propulsion subsystem, it could also affect the performance of the navigation subsystem, due to a coupling between the propulsion system and the stability and course control unit of the navigation subsystem. If a disturbance had occurred in the propulsion subsystem, the components stability control and course control were colour coded in the navigation subsystem. This way the subjects were supported in keeping an overview of the complete system, in particular in relation to the dependencies between system components.

From this overview screen the subject could indicate which component he would like to inspect in more detail. Suppose this is the course control unit in the navigation subsystem. By clicking on this button he would see on an additional screen the detailed diagram of the navigation subsystem. On this second screen not only the diagram was shown but also a table that indicated the relations between symptoms and causes. The component to be checked was put in the first row of this table. The rest of the causes were ordered according to the similarity of their symptom pattern with the component to be tested. This way the subject could easily compare both symptom patterns, facilitating the selection of the most diagnostic information.

The experiment showed that the subjects who had received the support diagnosed 20% more disturbances correctly than the subjects in the control condition. Whereas the control subjects managed to solve 70% of the disturbances within the available time, the supported subjects attained a percentage of 90%. This kind of support can therefore be helpful to the operator in dealing with complex, multiple fault situations.

CONCLUSIONS

When something unusual happens in a supervisory control task, such as a disturbance in an automated system, the operator will be required to divide his attention between the problem under consideration and keeping an overview of the process as a whole. Our research has shown that humans are not good at doing these tasks simultaneously (Kerstholt, Passenier Houttuin & Schuffel, 1996; 1995; see also Boer, 1995). It was shown that people had a tendency to focus on a single disturbance, and even ignored auditory alarms that indicated additional disturbances. This so-called 'cognitive lock-up' can lead to serious consequences in case multiple problems occur that all need the operator's attention. That this tendency is not restricted to laboratory situations is illustrated by the following example from aviation (cited in Boer, 1995):

> In 1972, the crew of EAL flight 401 concentrated all mental capacity on a fault in the landing gear system. An unintended disengagement of the altitude-hold feature of the autopilot escaped attention; the ensuing gradual descent escaped attention; the low-altitude alarm escaped attention, a remark of the air-traffic controller failed to restore attention to the situation. The plane crashed 4 minutes after the disengagement of the autopilot, killing most people aboard.

Auditory alarms are therefore not in all cases sufficient to guide an operator's attention to system faults when they are engaged in a diagnosis task. As a consequence it is highly recommended to embed the support that is given to the operator in the actual task environment, i.e. through an adequate interface design. The interface that we have designed for our specific task environment supported the operator at two different levels of behaviour: at a global level, by providing information on system dependencies, and at a local level, by aiding the operator in his search for the most relevant information. As shown by the experimental results this kind of support may significantly improve performance.

However, in making decisions, or allocating attention to subtasks, people are not only led by their desire to attain accurate task performance, but they also take the effort that is required into account. An important motivational drive for behaviour is the outcome of an (implicit) trade-off between effort and accuracy (Payne, Bettman and Johnson, 1992). In general, people will accept a less accurate decision when the decision process will save considerable effort. In one of our experiments we observed that the presence of false alarms affected this trade-off by increasing the effort that may be fruitlessly spent. As a result, people will be more reluctant to respond to an alarm directly, but they will wait to acquire more information whether the alarm is false or not. As a consequence, however, performance will be suboptimal in critical situations, as the operator may be too late for an effective control action in the case of disturbances (Kerstholt, 1995; Kerstholt and Passenier, 1995a). In general, it is recommended to reduce the number of false alarms as much as possible, of course without increasing the probability that a 'real' event is missed. One solution to this problem is sensor-fusion.

Another implication of this result is that the natural trade-off between accuracy and effort should be taken into account when developing procedures. In general, it can be predicted that when procedures require much effort to apply, and the reduction of risk is only marginal, people will abandon the procedure and use heuristics. These heuristics will save effort, but at the expense of the increased risk.

Responding in process control is optimally performed by using open-loop strategies. This strategy, however, becomes available only after the process is well-learned. The ironical situation occurs that, just because most functions are automated, operators are deprived of the experience that they need to take over control, or solve problems, in critical situations (Bainbridge, 1983). Yet, because of the complexity of the situations and the potential serious consequences one would in fact like an expert to deal with it.

Knowledge of a process or a system is generally formulated in terms of a developing mental model. This mental model is a hypothetical construct that accounts for three levels of process control behaviour:

1. It guides the monitoring process. Through the knowledge of the process the operator is able to interpret the numerous bottom-up signals provided by the system.
2. It is used for the compensation process. The operator uses his or her knowledge of the relations between certain variables as a basis for corrections when the expected pattern does not correspond to the observed one.
3. It is used for the anticipation process. Through knowledge of the goals and planning scheme the operator can think of control actions in anticipation of future system responses.

The internal model seems to be rather specific. Kessel and Wickens (1982) found that experience with fault handling in the autopilot mode did not transfer to an increased performance in the manual control mode. Furthermore, performance did also not improve when subjects had an understanding of the general scientific principles underlying the process. In contrast, however, having knowledge of the working of a device in terms of its internal structure has generally been found to improve performance (Bibby & Payne, 1993; Kieras & Bovair, 1984; Zeitz and Spoehr, 1989). In our training experiment it was indeed shown that performance significantly improved when subjects were taught the working of the subsystems in relation to each other (Kerstholt and Passenier, 1995b). Thus, effective control is based upon a deep understanding of the structure and causal

relationships between the various system components, and training should therefore be directed towards acquiring this knowledge. Some practical guidelines can be found in Schaafstal and Schraagen (1996).

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VIRTUAL CONTROLS

Steen Weber, Henning B. Andersen, Thomas Bove & Johan Trettvik
Risø National Laboratory
Roskilde, Denmark

Abstract: The use of touchscreen based virtual controls has become an interesting option in the design and development of simulators for training aviation pilots in procedural tasks such as pre-start chekclists and engine start. In this paper we report experimental results that concern design and training aspects of the virtual controls. Risø National Laboratory has carried out a transfer of training experiment aimed at assessing the training transfer capability of a touchscreen based control panel as compared with a standard control panel. While the study revealed indications that subjects trained on a touchscreen panel performed slightly slower than subjects trained on a real panel, no difference in their rates of error was found during test trials. In order to make the controls easy to learn and to operate Risø has also examined objective and subjective effects of two central interface features. We have termed the features "Enhanced Feedback" and "Expanded Circular Movements". The first results from two experiments confirm the importance of these features in the design of virtual controls.

Keywords: Transfer of Training, Touchscreen, Virtual Controls, MMI-features, Enhanced Feedback, Expanded Circular Movements.

1. INTRODUCTION

Touch screen technology has improved significantly in recent years enabling users to operate touch screen based controls with much greater precision and reliability. In turn, this development has spurred increasing interest in applying this technique to replace conventional control panels for certain applications. Conventional control panels contain "hard" controls, e.g., switches, dials or handles which give operators tactile feedback. In contrast, a touch screen based control panel contains virtual controls - that is, graphic pictures of controls shown on a computer generated display. Users may then operate virtual controls by sliding their fingers across a transparent touch sensitive surface on top of the computer display. As the user "moves" the control, the picture of the control will change and this change will normally be accompanied by appropriate sounds ('clicks' and 'tocks') which correspond to auditive feedback emitted by real controls. The chief drawback of touch screen based control panels is that they fail to give users tactile feedback - a user cannot "feel" the position of a control, nor feel the resistance when he or she changes its state. So, for normal applications - such as control panels in airplane cockpits, ship bridges, or control rooms - hard controls are nearly always preferable. On the other hand, virtual controls have a significant advantage by being extremely easy to re-configure: it is quick and inexpensive to re-configure layout, position and even type of control on a touch screen based panel.

In areas such as simulator training and interface design, re-configurability of control panels has a great attraction. Yet, the adoption of virtual controls in these areas has been slow, since there have been doubts about the training effectiveness of virtual controls. Thus, it has been expected that users who have been trained (in a simulator, say) on virtual control panels and who are then transferred to an operational environment with conventional control panels would show more errors or perform more slowly

2. TRANSFER OF TRAINING EXPERIMENT

The experiment aimed at comparing transfer of training between real controls and corresponding virtual ones. We selected a specific and relatively short procedure taken out of the training syllabus of a commercial aircraft (SAAB 340) and had two panels constructed, one being a near-physical replica of the relevant subsection of the overhead panel of this aircraft and the other being a CRT-based touchscreen version of the same subsection. The study then examined how subjects taught to perform the target procedure on the two types of panels performed when tested on the real panel. The prior expectation was that trainees taught on the virtual panel would either commit more errors or spend more time than real-panel trainees when both groups

subsequently were tested on the real panel.

Results

Training Trials: While there were no overall differences between the two groups when we compared their performance (by errors or time) across the set of training trials, there was an interesting significant difference for the very first training trial: the number of error-free subjects among virtual panel trainees for training trial 1 was 21, while only 10 out of the real panel trainees scored an error free performance ($p<0.013$; Fisher's exact test).

Test Trials: Times during test trials. The times logged and used for data analysis do not include time spent for correction of errors. There was a significant difference in medians of time in the very first trial between the two panel groups ($P < 0.05$, Mann-Whitney). Median time per trial for the group trained on virtual panels was 83.4 seconds and for the real panel group 75.4 seconds. Significant practice effects on time were found between first and second 'slow' trial for each of the groups (virtual panel trainees: $p < 0.001$ and real panel trainees: $p < 0.001$, Wilcoxon matched-pairs signed-ranks test) and for both groups between first and second 'fast' trial (virtual panels trainees: $p< 0.001$ and real panel trainees: $p< 0.05$). No other significant effects - including interaction effects - were found cf. figure 1).

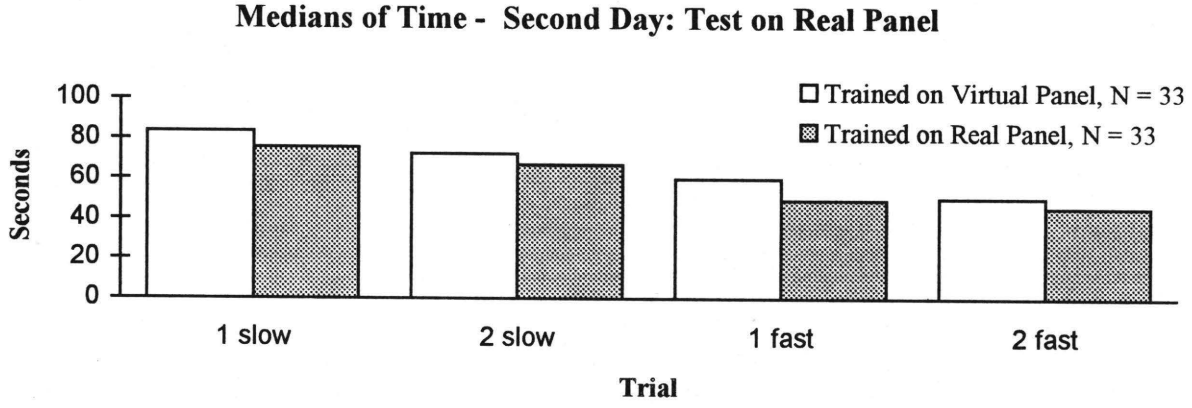

Figure 1

Errors during test trials: No significant error differences were found between the performance of subjects belonging to the two groups. Thus, the primary null-hypothesis cannot be rejected (see fig. 2).

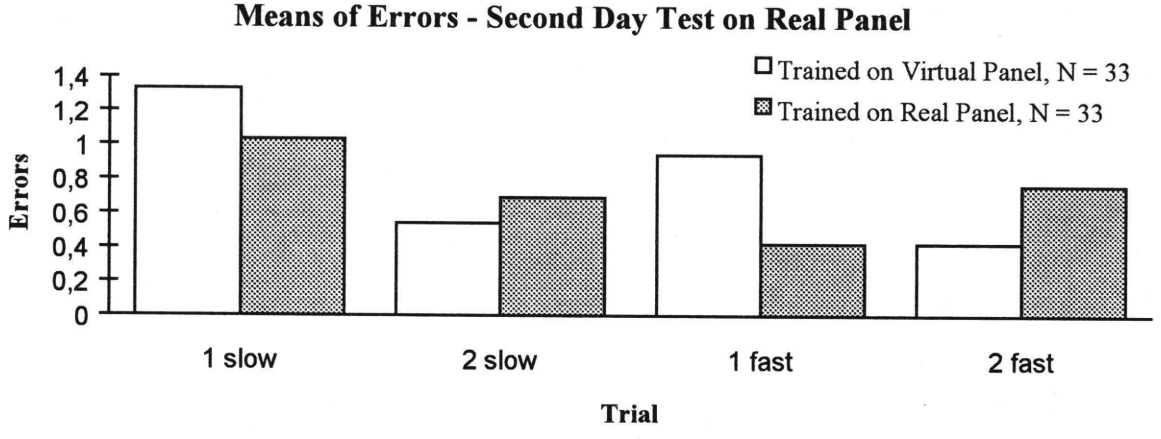

Figure 2

3. MMI-EXPERIMENT[1]

In two experiments we examined objective and subjective effects of MMI-features which informal observations had shown to be of importance in optimising the operation of the virtual controls. In the two experiments we have examined the features that we will refer to as "enhanced feedback" and "expanded circular movements. The "enhanced feedback" is a feature that provides the user with extra substitute feedback, replacing the tactile feedback received when gripping a dial. Enhanced feedback provides sound and/or change of colour when the user picks up a control and is expected to make it easier for the user to know whether he has picked up a control. The "expanded circular movement" is a feature that allow the user to operate a control outside the graphical area after having picked up the control and thereby require less fine-motoric precision when the user wants to change the state of a control. In the following we report the experimental results of the effects of these two features.

1. Enhanced Feedback

We have examined the effects of incorporating "enhanced feedback" in the design of the virtual controls as a means to compensate for the lack of tactile feedback. In the experiment 40 persons were randomized into two groups that were asked to operate six different types of controls that are representative for the controls found in real cockpits. One group had enhanced feedback when picking up a control and the other group had no direct indication of picking up a control. Their performance (that is, pick-up times and pick-up errors) were logged in a computerfile. After the experiment both groups tried various MMI-configurations (that is, no feedback, only sound, only graphics and both sound and graphics) and subjective attitudes were elicited in a questionnaire.

Results

Subjective measurements: In figure 3 is shown the results from the questionnaire regarding the subjects preferred type of feedback. As the figure shows, the majority of the subjects finds the enhanced feedback - either as graphics or sound and graphics - as very helpful. We have tested the results to see if there were any significant difference between the groups by the use of "Chi-square Goodness-of-fit test". Both when comparing all the four groups and when comparing only two groups differing in whether they preferred some or no feedback the results show a significant difference (the estimated P-values for the two tests are less than 0,00001 and less than or equal to 0,001, respectively).

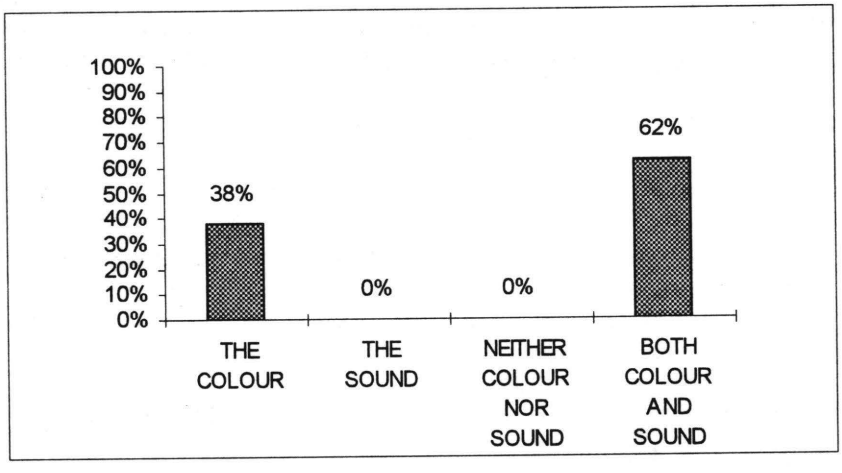

Figure 3: Preferred type of feedback

Objective measurements:

Regarding the performance parameters, we have examined if we could find any objective effects of the enhanced feedback. In figure 4 is shown the average pick-up time and errors for the two experimental groups.

[1] The design of the experiments is described in detail in Bove et al. (1997).

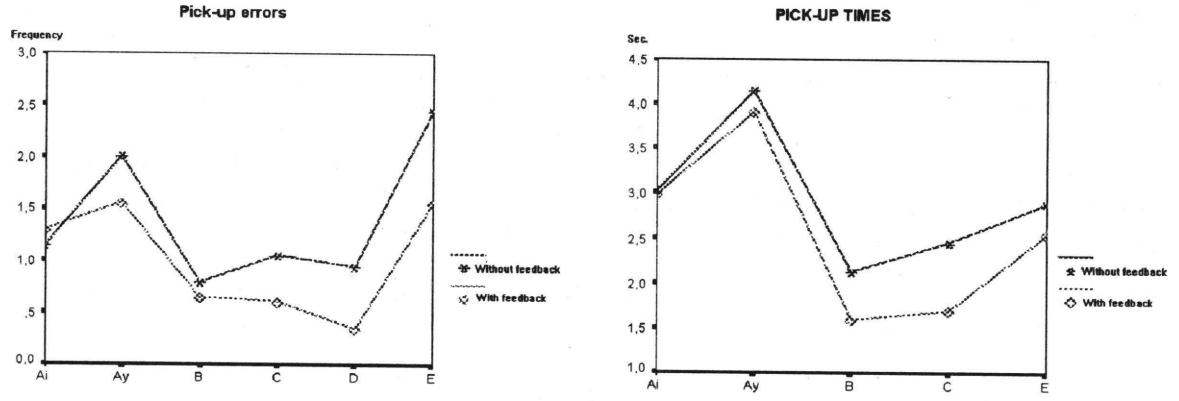

Figure 4: Pick-up errors and times for the groups with and without enhanced feedback

As the figures reveal there is an overall tendency that the group receiving feedback makes fewer errors and is faster than the group without feedback. We have examined the results by using a 2 x (6) mixed and a 2 x (5) ANOVA, respectively[2]. The results from the mixed ANOVA shows a significant main effect of feedback on the pick-up errors (p=0,043). In respect to the pick-up times the effect does not reach the significant level (p=0,11). The mixed ANOVA for the two performance parameters does not show any interaction effect. This means that the effect of the enhanced feedback is not restricted to particular controls.

In summary, the overall impression from the experiment regarding the enhanced feedback feature is that it is a feature that the users find valuable as a way of compensating for the lack of tactile feedback. In addition, there is a robust and uniform tendency that the users' performance is better when they get enhanced feedback.

2. Expanded Circular Movements

In this section we report the experimental effects of the expanded circular movement feature. The subjective results are based on the experiment described in the previous section. To examine any objective effects of the expanded circular movement feature we carried out a new experiment where we had four subjects to operate a dial control both with and without this feature[3]. For each configuration (that is, with and without expanded circular movement feature) they were asked to carry out dial instructions written on the touchscreen as fast and as accurate as possible. The time available for each configuration was fixed (480 sec.).

Results

Subjective measurements. We were interested in knowing whether the users found the idea about being able to move their finger out in broader circles after having picked-up a dial control as a good and intuitive design solution. We therefore asked the subjects about the way they would prefer to pick-up the small wheel on the double dial control. The results are shown in the figure 5.

[2] The reason that we only have five groups - and not 6 groups - for the pick-up times is that the log-file did not register the pick-up times for control D due to a technical error.

[3] In addition to examining the effect of the expanded movement feature we also examined another MMI-feature, namely *hysteresis* positioned as wheel spokes between touch-active areas. The results of this feature will be studied further and will be described in a future publication by the authors.

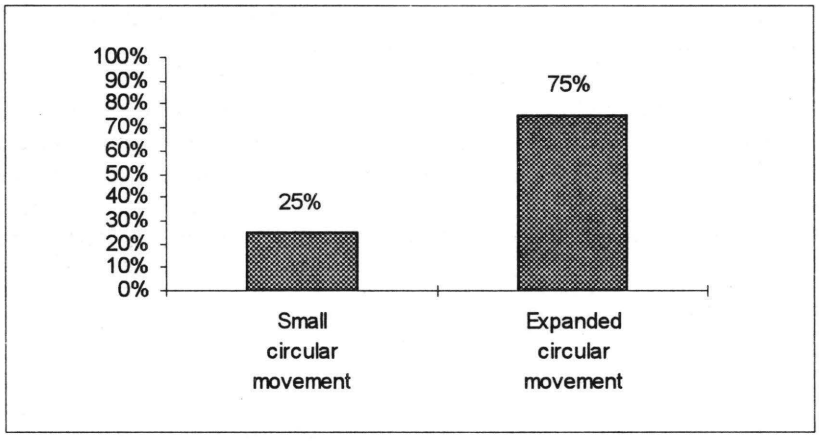

Figure 5: Preferred way to operate the small wheel on the double dial control

A large majority of users preferred to use the expanded circular movement feature - conf. fig. 5. The result has been analysed by the use of Chi-square Goodness-of-fit test and is highly significant (P-value is 0,00225). This result substantiates our intuition that the expanded circular movement feature is an important way to make the operation of dial controls easy.

Objective measurements: As a consequence of the large majority preferring the expanded movement feature we chose to examine the objective effects of this MMI-feature. The results from the experiment is shown in figure 6

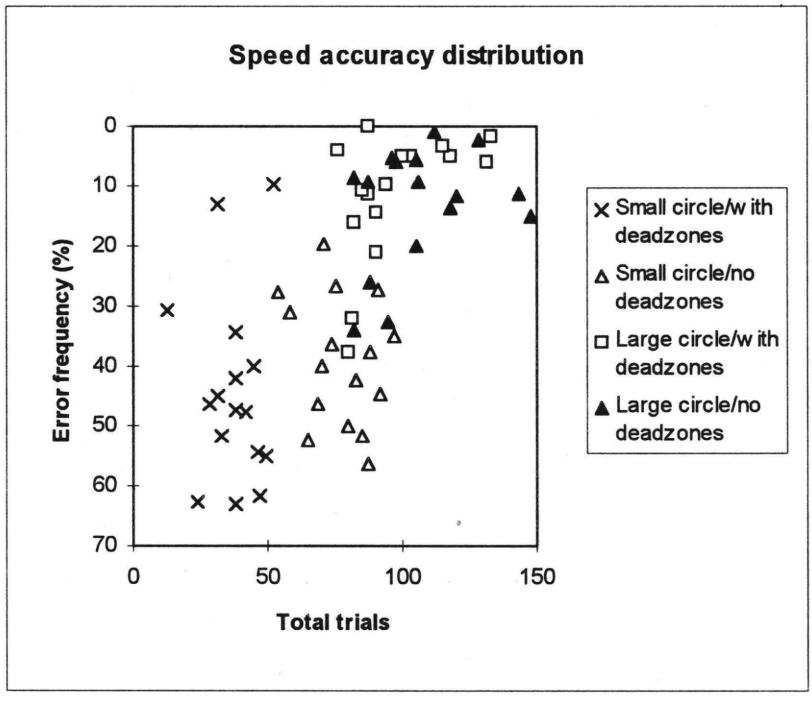

Figure 6: The speed-accuracy distribution as a function of two variables - small vs. large circular movements and with vs. without hysteresis or "dead zones"

As can be seen in the figure the trials where the subjects were not allowed to move the finger out from the graphical area of the dial control the performance results are located in the lower left corner of the speed-accuracy area. This indicates that they only completed a small number of trials and that they made many errors. In contrast, the trials where they subjects could move outside the graphical area of the dial control the

performance results were located in the upper right corner. This indicates that the group with the expanded circular movement feature, in general, completed many trials and only made few errors.

In summary, both the subjective and objective effects of the "enhanced circular movement" feature clearly indicate its operational advantage. The results from the questionnaire showed that a very significant part of the subjects regarded the expanded circular movement feature as a useful and intuitive way of operating the virtual controls. In addition, the test results clearly showed that subjects with the enhanced circular movement feature performed faster and more accurate than without it and thereby verified the importance of this feature in the design of virtual controls.

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VIALE MARX, 15 - 00137 ROMA

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