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Rasmussen, Jens

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ECOLOGICAL INTERFACE DESIGN FOR RELIABLE HUMAN-MACHINE SYSTEMS

Jens Rasmussen[1]

Abstract. Recently, systematic approaches are emerging to an integrated design of the human-machine interaction promoting the perspective that system users should no longer be add-ons to the engineering design, but an integrated part of the functional design. The paper discusses the design of reliable human-machine systems from this point of view and considers the flowing issues: First it is argued that incremental improvement of system design by efforts to remove causes of human error in the past is less effective due to adaptive compensation of changes. Instead, design should be based on an explicit identification of the behavior-shaping system constraints and the boundaries of acceptable operation. Second, different approaches to modeling adaptive human-machine systems are reviewed followed by the discussion of a systematic framework to represent system constraints at several levels of abstraction. Finally, the implications for making the constraints and boundaries visible through an 'ecological interface design' are discussed and a sketch of a typology of interface formats is suggested.

INTRODUCTION

Modern human-machine systems have evolved by incremental improvement in response to technological innovations, such as new interface technology, and to operational experience, such as accidents. With respect to interface design, the evolution within the process industries has been from the traditional one-sensor-one-indicator concept typically designed by the equipment supplier, over computer based graphic displays mimicking the traditional interfaces, toward a more integrated interface design including display formats based on integration of data into higher level information matching task requirements. Still, however, interface design often appears to be an add-on by human factors and/or computer specialists following systems design.

The same picture is found within aviation. Interface guidelines for 'user-centered design' are typically organized according to equipment categories and functions (Billings,1991), interfaces are organized subsequent to the equipment design by human factors experts, and the aim is to match them to the users' performance modes and mental models.

Only recently, systematic approaches are emerging to an integrated design of the human-machine interaction. System users are then no longer add-ons to the engineering design, but an integrated part of the functional design. In aviation, several lines of development in this direction are found, as demonstrated by efforts to represent meaning (Flach, in press), approaches to the design of functional displays (Hutchins, in press; Lintern et al., this

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volume), and Ecological Interface Design for aircraft subsystems (Dinadis and Vicente, this volume). Three different lines of development seem to emerge in this context; one is concerned with vehicle control 'from the inside' (piloting), another is concerned with vehicle control 'from the outside' (flight planning, ATC), and a third concerned with the control of the technical onboard systems (power plants, fuel, hydraulics).

The present contribution reviews efforts to replace the art of interface design by a design methodology, based on findings from studies within process industries. The discussion is therefore closely related to interface design for the onboard technical systems (Dinadis et al., op. cit.) while a different intuition from studies of locomotion is underlying the contributions on the vehicle piloting issue. A promising research issue is to merge the two lines of development.

The following discussion of the design of reliable human-machine systems is divided into five parts: 1. It is argued that incremental improvement of system design by efforts to remove causes of past human errors is less effective due to users' adaptive compensation of changes. Instead, design should be based on identification of system constraints and boundaries of acceptable operation. 2. Different approaches to modeling adaptive human-machine systems are then reviewed, followed by the discussion of 3. a systematic framework to represent system constraints at several levels of abstraction. 4. Finally, the implications for interface design are discussed and 5. a rough sketch of a typology of display formats is suggested.

1. THE CONCEPT OF HUMAN ERROR AND SYSTEM DESIGN

The concept of human error is normally an important ingredient in the explanation of accidents, and errors on part of a pilot, a train driver or a process operator, are often taken to be the 'root cause' of a particular accident. Furthermore, reviews of accident cases invariably point to the role of human error and it is often stated that around 80% of industrial accidents are caused by human error.

I have elsewhere argued that it is doubtful whether the concept of 'human error' is a very reliable guide to improve design of human-machine systems (Rasmussen, 1990a). It is important to consider that commercial success in a competitive environment implies exploitation of the benefit from operating at the fringes of the usual, accepted practice - which influences decisions in management board rooms as well as by the operational staff. Closing in on and exploring the boundaries of the normal and functionally acceptable boundaries of established practice during critical situations necessarily implies the risk of crossing the limits of safe practices. Correspondingly, court reports from several accidents such as Bhopal, Flixborough, Zeebrügge, and Chernobyl demonstrate that they have not been caused by a coincidence of independent failures and human errors, but by a systematic migration of organizational behaviour toward accident under the influence of pressure toward cost-effectiveness in an aggressive, competitive environment (Rasmussen, 1993, 1994b. Similar concerns have been voiced for aviation, following de-regulation and competition from low-cost operators (Schiavo, 1997).

The fundamental design issue is not to fight the individual causes of human error, but to create a work environment for actors that makes the boundaries to failure visible and reversible. In a dynamic and competitive society faced with a very fast pace of technological change, this is very likely the only effective way to maintain operation of hazardous systems within the design envelope. A closer look at this question is important for the discussion of reliable design of systems in a dynamic society.

In the case of stable and repetitive tasks, human errors can be defined rather easily in terms of acts deviating from the instructed task sequence. In particular, this is the case for the routine operation of stable and well-structured technical equipment. During design of human-machine systems, the technical part of the system is analyzed with respect to the necessary control sequences, an operating procedure is then issued to guide operators, and an interface is designed so as to present the information necessary to cue the actions of the procedural sequence. A subsequent human factors evaluation and a test period serve to prove that the system *can* be operated that way, and later failures to do so are then 'human errors.'

However, most human-machine systems leave many degrees of freedom to the actor even if behavior during work, by definition, is oriented towards the requirements of the system. Functional objectives, that is, *what* should be done, can be well defined, whereas *when* and *how* to accomplish those objectives often leave some options open. The options from which to chose will be defined by the system and its operational conditions which create a space of possibilities for the operators within an envelope defined by the limits of functionally acceptable work performance, by limits of acceptable efficiency and, finally, by the work load accepted by the individual. Within this space of acceptable work performance, many degrees of freedom are still left for the individual to choose among strategies and to implement them in particular sequences of behavior. This freedom will be used by an actor to shift among possible strategies to match resources to local conditions (with respect to time or information available, to mental processing or memory limitations, etc.) and to optimize performance with respect to subjective performance criteria (such as cost-effectiveness, cognitive strain, cost of failure, joy of discovery, etc.).

Work planners who design operating procedures have to close these degrees of freedom to define an unambiguous operating instruction and they do so by assuming some criteria that appear to them to be 'rational' and safe. This involves two problems. One is that they are not able to foresee all local contingencies of the work context. Another is, that a work procedure is often designed separately for a particular task whereas, in the actual situation, several tasks are often active in a time sharing mode and thus pose additional constraints on the actually effective procedures which could not be known to the designer. Even for highly constrained task situations such as nuclear power operation, modification of procedures is repeatedly found (Fujita, 1991; Vicente et. al., 1994) and the operators' violations appear to be quite rational, given the actual work load and timing constraints. The general trend to optimize work procedures for more effective performance is also demonstrated by the fact that civil servants can effectively be on strike, just by "working-according-to-rules."

An important consequence of this is that a basic conflict exists between error seen as a deviation from the *normally used, effective procedure,* which typically is not known by post-hoc accident analysts, and error seen *as a deviation from instructed procedure*. One implication in the present context is that following an accident it will be easy to find someone who has violated a formal rule just by following established practice. Consequently, accidents are typically judged to be caused by 'human error' on part of an individual involved in the dynamic flow of events, that is, a pilot, a train driver, or a process operator (Rasmussen, 1994).

The actors' response to situational and subjective factors when closing the space of opportunities results in a variability of performance that can be illustrated by a space of 'Brownian movements' around the normal performance and gives performance a somewhat stochastic appearance. This space of fluctuating performance, embedded in a larger space of acceptable performance, is subject to gradients such as the pressure from management toward improved cost-effectiveness and the individual preference for the path of least resistance. From this follows by a thermo-dynamic analogy a natural migration toward the limits of acceptable performance. Sooner or later, performance will reach the limit and 'errors' will be the result.

This very adaptive behavior of actors in a human-machine system points to the need for modeling behavior at a higher level of abstraction than the usual modeling in terms of sequences of events, decisions, acts, and errors.

The problem presented by such causal models of human behavior is demonstrated by the repeated experience that efforts to improve system safety by removing causes of human error is compensated by the involved actors adaptive response (for a detailed discussion, see Rasmussen, 1990b). Causal trees obtained from accident analyses are not models of functional mechanisms, but records of particular cases and they do not reflect the actors' adaptation guided by general criteria such as effectiveness, workload, social pressure. Improvement of safety by removing causes is very likely compensated by such adaptation Many different goals and constraints dynamically shape the landscape in which the flow of events unfolds on occasion. Each causal path is a particular token shaped by higher order relational structures. Therefore, we cannot assume the trace of human behavior to be predictable. Tasks will be formed for the occasion, and we have to use higher level concepts to characterize successful as well as unsuccessful task performance.

2. Modeling Complex Human-Machine Systems

The basic conclusion of this discussion is that we have to consider two different approaches to the problem of modeling human-machine systems, one during design serving the assembling of known system elements into a system and the related human factors analysis proving that the system *can* work, and another to evaluate the functionality and reliability of the system when adaptation has taken place, that is, to judge whether the system *will* work reliably during an extended period of time. This second perspective touches on an important issue of interface design: The interface should not only support the one 'rational' operating procedure for which the system is designed, but it must be able to support operators even when they optimize work practice according to a criterion; the designer cannot know.

The two different modeling approaches to consider are the causal model created by structural decomposition and the relational model based on functional abstraction.

Modeling by Structural Decomposition

Causal models are based on a decomposition of the system into parts at a suitable level of detail and of its behavior into events, decisions, and acts. A causal model is expressed in terms of regular connections of events in time and is an analog representation including physical objects as separate elements. The great benefit from causal modeling is its immediate relationship to the material world which makes the representation very easy to update in correspondence with changes in the real world. In this way, causal models are very effective as a basis for human reasoning. When we, for instance, design a new work system, we normally use a decomposition/aggregation perspective. To serve a particular purpose, we chose among the available parts, tools, and productive processes and we select staff members having an appropriate background and education. We then aggregate these elements into a productive structure described as an assembly of elements and we instruct the actors how to operate the individual pieces of equipment. In other words, we arrange the elements in cause-and-effect chains according to their individual input-output characteristics so as to have the intended overall effect.

The problem we face in modeling systems of co-operating human actors is that humans do not have stable input-output characteristics which can be studied in isolation and we cannot develop models of human machine systems by aggregating input-output models developed in isolation. In consequence, decomposition models may well describe how operators *can* serve the system in a stable and defined context, but typically will not predict how they *will* behave in a complex and changing context.

Modeling by Functional Abstraction

When a new system is put to work, the human elements change their characteristics; they adapt to the functional characteristics of the working system, and they modify system characteristics to serve their particular needs and preferences. In other words, to understand system behavior when adaptation has taken place, we have to look at the entire system and instead of a decomposition into structural elements, we have to look at the entire system at an abstract level and here to identify the relevant functional relations. In natural sciences such functional relations are typically represented by mathematical equations as it is the case in engineering, consider e. g. the functional abstraction underlying representation of closed loop performance by control theoretic concepts.

The central issue for design of reliable human-machine systems is to apply a functional abstraction perspective and to make sure that the control loops of the system (the information channels) involving equipment as well as system users are intact. From a control perspective, this raises the following questions:

- Are objectives, intentions, and performance criteria known and communicated effectively among controllers (decision makers).
- Are they supplied with reliable information on the actual state of affairs which is directly comparable to the formulation of objectives?
- Are they capable of control, that is, do they know the effective control points and system responses?

During adaptation behavior changes from a sequence of separate acts to a complex, continuous closed-loop behavioral pattern. Variables are no longer observed individually; complex patterns of movements are synchronized with situational patterns; and interaction depends on an opportunity to perceive the state of the work environment including the boundary of safe behavior directly in the context of the current goal. A good example of this kind of model is Gibson and Crooks (1938) representation of a car driver's navigation and his perception of a 'field of safe driving.' At this stage of effective adaptation, the behavior of the system cannot be de composed according to its structural elements. This has been discussed in detail by Flach (see e. g., Flach, 1995).

Implications for Work System Design

It follows from this discussion that the design of a new work system should be focused on creation of a work space bounded by the basic system constraints. Within this space the actors should be allowed to adapt freely according to subjective criteria, such as e.g., effort, time spent, or joy of discovery. For a field study describing such adaptation in detail, see Rasmussen and Jensen, 1974.

Also Hutchins (1995a,b) observed that operators converge onto cognitively economic strategies as they discard the formal, designer specified strategies. Analyses of existing work systems to understand this behavior and to get a basis for design of new systems therefore should not be focused on decomposition into structural elements, but on a functional abstraction and separation of functional patterns and the criteria that *generate* behavior.

The most promising approach to modeling work systems at a high state of adaptation appears presently to be Gibson's (1966, 1979) 'ecological' modeling of perception-action loops. His concepts, including the attunement of an adaptive organism to the invariants of the environment and the direct perception of functional invariants and affordances for action, constitute a very effective functional representation of the systemic perception-action loops (Vicente and Rasmussen, 1990).

3. Making Visible the Ecology of Work

Operation of a system depends on purposeful changes of the state of its internal processes. Such changes are not made directly by the users. Instead, their actions serve to set the constraints of active forces within the system which then bring about the intended changes. These active forces have different sources. Some have a causal basis (laws of nature), others have intentional basis (company objectives, intentions of cooperating actors) and, finally, some have formal basis (rules and regulations). The opportunity to plan activities depends on knowledge about the internal constraints that shape the system's behavior.

It is a key design issue to create an information environment for the controllers that makes visible the ecology of work, that is, the internal constraints, and supports direct perception of the state of the world in the light of the current goals, as well as the boundaries of the acceptable performance. In a world of dynamic requirements, a map of the deep structure of a system supports navigation more effectively than route advice (i. e., procedures).

Ecology of Work

Control of a system involves operations on and through its internal constraints and can take place via the causal constraints of the physical part of a system or the intentional structure of the people involved. The representation of the behavior shaping constraints is therefore an important issue for design of reliable systems and some discussion of the nature of such constraints is useful.

To be useful for unanticipated problem situations, a representation of the sources of regularity of a work environment must identify the world of 'possibilities' which is necessary to cope with all the situations which may appear during work. This representation defines the functional inventory of the work system, that is, the functional territory within which the actors will navigate or, in ecological terms, the *affordance space*. The means-ends representation is structured in several levels of abstraction which are discussed in detail elsewhere (see e.g., Rasmussen, 1985, Rasmussen et al., 1994).

At the lower levels, elements in the description represent the material properties of the system. When moving from one level of abstraction to the next higher level, the change in system properties represented is not merely a removal of detailed information about physical or material properties but information is added on higher-level principles governing the co-functioning of the various elements at the lower level. In man-made systems, these higher-level principles representing co-functions are derived from the purpose of the system, i.e., from the reasons and intentions behind the design. An important feature of this complex means-ends network is the many-to-many mapping found among the levels. If this was not the case, there would be no room or need for human decision or choice. The focus in design of interface systems has traditionally been on providing factual information about the state of affairs in the system and about functional relations. Little effort has been spent on *intentional information* which is an increasingly important issue for system design. We will return to this issue below.

The levels of abstractions are illustrated in figure 1. The higher levels of abstraction primarily represent properties connected to the purposes and intentions governing the work system, whereas the lower levels mainly represent the causal basis of its physical elements. Consequently, perturbations of the system in terms of changes in operating objectives will propagate downward through the levels, defining the target states. In contrast, the effect of changes of the material resources, such as introduction of new equipment or break down of major machinery will propagate up-wards, being causes of change of the actual states. Now, any operator striving to control the operating state of a system will have to operate on and through the internal constraints of the system. Control involves a change of the parameters of relational constraints in order to introduce a propagation of effects ultimately bringing the system into the intended goal or target state. This control involves operation on the *causal constraints* of the physical part of a system, or on the *intentional constraints* originating in the other actors of the system or a control system. Whether one or the other mode of control is appropriate, depends on the task situation and the structure of the system.

Intentional versus Causal Constraints

The weight of the intentional constraints compared with the functional, causal constraints can be used to characterize the regularity of different work domains. The regularity of behavior of tightly coupled, technical systems has its origin in stable laws of nature. On the other hand, the regularity of many work systems depend on intentional sources such as legislation together with institutional and social practices. (For a detailed discussion of a taxonomy of work systems, see Rasmussen et al., 1994)

In the present context of reliability of human-machine systems, the focus is on tightly coupled technical systems (aircraft, industrial process plants) for which the source of regularity of behavior can be traced to the laws of nature. The underlying processes are confined and connected by the physical construction of the plant while their functional behavior is dictated by these laws. Thus predicting this behavior in response to human actions can be inferred bottom-up from knowledge about the involved physical processes. The objective functions - that is, the intentional structure or reasons for the desired functions - are often "hard-wired" in the form of a complex automatic control and safety system. The control systems maintain plant state and operation in accordance with the high level, stable design goals - such as to produce power or to transport passengers as requested by customers and to do it as economically and safely as possible throughout the lifetime of the system. The task of the operating staff is basically to ensure that the functioning of the system actually reflects the intentionality of the original design while their own personal goals have little significance.

It follows that the contents of the information presented for operators with regards to functionality must be based on these physical laws as applied to the productive processes of the particular system including the limiting conditions set by the confinement. However, providing intentional information - the *reasons* for the design - is very important to improve system reliability. In order to understand the functions and the behavior of the automated control and safety system, the operators must be familiar with the *intended control strategies* underlying this system. This is because the internal functions of an automatic control system are only the medium for processing this intentional information and, consequently, has little significance except for the maintenance crew. Unfortunately, designers of decision support systems, in process control as well as aviation, pay only little attention to the communication of intentional information to operators, pilots, or support staff. The reason for this is that the rationale for most design choices has been embedded in the minutes of meetings, in professional and company practice and in industry standards. It is often very difficult to identify and make explicit the original reasons for a particular system design feature. Blueprints and operating instructions only communicate *what* and *how*, not important information about *why*.

When it later during operation is necessary to re-configure a system because of changes in requirements or major disturbances, the lack of intentional information often hinders understanding of system behavior and prevents effective intervention. This has been observed repeatedly in process control rooms as well as flight decks. In order to provide effective support, the analysis and deliberate consideration of the path of propagation of both functional and *intentional* information through the different organizations involved in design and operation are important issues.

In addition to making visible the intention behind the actions of an automatic control system, we have the problem of making visible the intention behind the actions of cooperating actors which is a more open and general problem of 'sense-making.' It is well known from process plant control rooms and flight decks that replacement of common display and manipulation panels by dedicated computer terminals obscured operators' awareness of the activities and intentions of cooperating colleagues.

4. IMPLICATIONS FOR INTERFACE DESIGN

This discussion shows that for technical systems, the basis of interface design should be derived from the causal and intentional constraint underlying system design. The problem is not to match a display format to the mental models of the operators but to design an interface that forces operators to adopt a faithful mental model of the design constraints in a way they can *directly perceive and operate on* the constraints so as to bring the system into the goal state and/or prevent it from entering dangerous states.

In computer based control stations, direct perception-action interaction with a physical world- for which humans have adapted through ages - is replaced by operation upon a 'virtual work ecology.' As long as work conditions are stable through time, and activities can be based on an established practice with stable cue-action correlation, humans can adapt to nearly any kind of interface representation and many varieties have been developed for tools introduced in particular tasks during the history of computers, such as command interfaces, metaphorical interfaces, menu-systems, etc.

A major interface design problem appears, however, when interface systems are to be reliable for systems where control tasks are changing depending on system states and disturbances, that is, involve discretionary decision making and problem solving during rare, hazardous events. In that case, control cannot be based on cue-action correlation as specified in an instruction or evolved through practice. Then a representation of the internal functional structure of the system is required. This is the objective of ecological interfaces design (Rasmussen and Vicente, 1989, 90; Vicente and Rasmussen, 1990, 92).

Any control action activated through a work station, serves to change the internal, causal or intentional constraints to let them bring system state to the intended target. The interface should then represent the actual state of affairs in the work space in a way comparable to a representation of the intended or the useful state defined by the current goal, together with the situation dependent "affordances" i.e., the options available for action on the constraints of the internal processes as defined by the physical design or on intentionality as defined by policies, practices, or regulations.

Several different dimensions of the design problem must be considered, such as:

The *Content* of a Display

The content of the display interface should faithfully represent the constraint pattern and the actual state of the system with reference to this constraint pattern. This information can be defined at all the various levels of the means-ends network, each having its own particular formulation depending on the related source of regularity.

The specification for display content design will vary with the language used for representation at the different levels originating in the various professions involved in system design, that is, the technical system designers as well as the designers of the operating organization.

Transformation from Relational to Causal Representation

The optimal state of operation of the processes of a technical system and their coordination into functions serving a given production target are determined by quantitative mathematical relations among physical variables. The measuring and control systems are therefore designed to make it possible during operation to ensure that these quantitative relationships are optimal. That is, the fundamental basis of the instrumentation and the choice of measured variables is determined by the *quantitative, relational models underlying system design and process optimization.*

In contrast, the natural language reasoning applied by human decision makers depends entirely on a *causal model in terms of objects in a background interacting through events.* Therefore, the measured variables and the relational structure governing their interaction must be converted at the interface to a set of symbolic objects interacting through events in a virtual environment. The interface therefore should present a map of a symbolic landscape inhabited by objects -icons - representing states of processes, interacting mutually and with boundaries around territories of varying operational significance. This is important, not only to support the reasoning by an individual user, but also to give cooperating users an opportunity to point at and to discuss an external model.

This is actually the function of all engineering diagrams used for design and for explaining concepts and processes for students. For ages, the optimization of the operation of steam engines and planning of their maintenance have been based on heuristics related to pressure-volume diagrams of cylinder performance and complex control systems have been synthesized by heuristic manipulation of 'root-locus' plots. We will return to these examples later.

An important interface design issue when choosing the *form* of the presentation therefore is to integrate the raw measuring data into higher level objects, states, and events that match the conceptual language and the level of abstraction applied in the users' causal reasoning.

The *Form* of a Display

The visual coding of the display should be chosen to support the interpretation at three levels of cognitive control:

Knowledge-based reason: For unfamiliar situations, the display should serve as a faithful, externalized symbolic model to support *mental experiments*. For this reason, and to avoid conflict, the visualizations which have evolved through time for explanation of concepts to novices by illustrations in manuals and text books should be consulted.

Rule-based action: During familiar situations, the interface should allow formation of convenient, but reliable *cue-action responses*. For this, a display should integrate in a consistent way all the behavior relevant constraints in a work situation into a perceptual pattern, that is, it should include all relevant attributes with respect to effective actions. In other words, emerging cues for action should be *complete*, if not, it will very likely lead to the kind of under-specified action cues known from the traditional one-sensor-one-indicator technology.

Skill-based control: Finally, the spatial-temporal characteristics of the display should support *skill-based operation* within the work system, that is, the spatial-temporal control loops must be intact through the interface mediation. This is probably particularly important for vehicle control.

In addition to such considerations, it is important that the language used to express the content at the display surface is acceptable to the relevant user groups. Several highly developed conventions directed toward different population groups have evolved in the past for specific applications, such as research and teaching (pictures, maps, diagrams), guidance of behavior (traffic signs, icons), computer use (desk top metaphors), etc. For displays, the forms chosen for visualization should respect such established traditions to avoid conflicts.

The Content-Form Transformation Path

The path to choose from the *content* in terms of relational structure to an effective *form* in terms of a graphic structure, very likely involves several stages including different established conventions, depending upon the phenomena to be represented, the task situation considered, and the user category involved. A typology of visualization conventions and their mutual relationships is important for design and, in particular, for transfer of the results from evaluation experiments with displays and separate display elements to design improvements.

Support of Navigation in the Interface System

As Woods (1984) has pointed out, a problem in design of complex system interfaces is to support users' navigation through the many interface windows available in large scale systems. For process plants, we have found a presentation of a map of the entire means-ends network helpful (Goodstein, 1985). This is an important issue which, however, will not be discussed in the present context.

5. An Approach to a Typology of Graphic Display Formats

Designing visual displays representing the deep structure of a system in a faithful way, that is, designing a 'virtual ecology' for direct manipulation of modern systems is a very complex process. Some kind of map of the design territory based on a taxonomy of visual representations will be useful.

Whether issues related to the design of the display *content* or the *form* are predominant in the process depends very much on the nature of the task situation. Considering operation of a technical process system, such as the technical equipment of an aircraft or a process plant, determination of the necessary content of the individual displays and the integration of data into task related information and representation of the intentional structure of the control strategies is major systems engineering task which should involve the designers of the technical equipment and its control system. In the present discussion, the focus is on the process system interface, and the examples is chosen accordingly to be familiar to system engineers.

For displays in support of vehicle control, a major issue is the match of the form to the perceptual characteristics of human locomotion. In the literature, these two categories have each found their particular expression (compare the contributions of Flach and Vicente in the present volume).

To find a basis for a taxonomy, the literature on 'scientific representations'' was reviewed (Rasmussen, 1995) because the problem to represent the 'deep structure' of phenomena basically is the aim of any science. Many approaches has been taken in the various professional domains to support human activities by visualization of data and conceptual relationships.

General studies of scientific representation appear to be mostly found in social science studies of the role of representation in the social interaction in laboratories. An overview is found in Lynch et al. (1990). The general trend in the representations discussed in this literature (see e.g., Lynch, 1990) is that they show various forms of pictorial representation of a set of objects and their spatial relationships (graphic spaces) at various levels of detail (from topographic maps to electron microscopy). Scientific representation are generally derived bottom-up from primary data, following the natural science paradigm of objective integration of observed phenomena, except for some engineering representations. This may be the reason, that diagrammatic engineering representations have not been discussed in the literature on scientific representations. Even if 'mathematization' is discussed by Lynch, no discussion of abstract, graphic diagrams is presented. This trend is clear even for recent reviews of representations used in engineering, see Ferguson, 1977, 1993.

This is odd, since diagrammatic representations are widely used in engineering for 'direct manipulation' of conceptual relationships. A systematic comparison of the sources of ideas for visualization of the functional structure of systems appears to be a research need, even if already Babbage (1826) pointed to this need, and diagrammatic representations offering the potential for direct manipulation have been systematically developed for engineering use (E. g., for thermodynamics see Gibbs, 1876; and for control system synthesis see Truxal, 1955).

Means-Ends Map of Approaches to Visualization

As a start to create a basis for a comparative studies, the means-ends network of figure 1 has been used to characterize some widely used representational forms with reference to human-machine interface design.

Different representations of functional relationships are used at the various levels of the means-ends network shown in figure 1, and several conventions for visualization are therefore relevant (figure 2):

The Level of Physical Configuration and Material Form

The invariants at this level are the topography of the work system together with the material characteristics of objects, tools and systems elements available to serve processes at the physical process level. The tasks to be supported by visualization are locomotion and navigation in a topography, search for objects and parts, moving, assembling, connecting parts.

Conventions for representation of the causal aspects of the work system at this level include topographic maps, e. g., representing airport status and traffic routes, etc. At the detailed level are found architectural drawings, pictures of equipment, and in a symbolic form, engineering blue-prints of machinery, mimic diagrams of electric and hydraulic systems.

The intentional aspects include the selection and configuration of elements intended to serve particular processes, routes and trajectories in the topography to support navigation, etc.

The Level of Physical Processes.

This level represents the *physical processes* relevant to the functions of a system as they are constrained by the configuration of the underlying physical components. All purposive acts in a human-machine system serve to shape the material configuration in ways that constrain and guide physical processes so as to serve the intended functional relation between actions and their effects. Visualization should focus on the state of process variables with reference to target states and to the limits of acceptable operation. At this level visualization in the form of symbolic diagrams has evolved for particular physical processes within related engineering and natural science disciplines. Examples are pressure-volume diagrams for engine cylinders, phase diagrams for water-steam mixtures, engine-cycle diagrams for different Rankine cycle machines, phase diagrams for metallic alloys, etc.

Whether this kind of representation of process features is relevant depends on the task situation. They are very important for e. g., system designers, maintenance personnel, and process plant operators faced with system failures. For system operators such as pilots and car drivers the internal processes are more or less irrelevant, of interest are primarily the intentional aspects, that is, whether the state of the processes match the requirements of the functions to be served. As discussed in a previous section, this is in particular the case with automatic control system for which the internal processes are relevant only to maintenance personnel.

The Level of General Function.

At this level representation we find *functions* serving particular purposes and involving various different physical processes. Tasks at this level are the adjustment and coordination of the individual process systems to serve higher level purposes. That is, representation must be independent of the nature of the processes involved. Representation conventions, consequently, have to be based on recurrent, generalizable *input-output relationships*.

It follows that visualization of functional relationships have to be based on generalized representation of relationships independent of the physical implementation, that is, for technical systems usually in the form of sets of mathematical equations. Several powerful conventions for visualizing systems of mathematical representation have emerged to support causal, event based reasoning of system designers and users, such as root-locus and phase-plane representations of control theory, visualization of the solution of sets of algebraic equations in terms of analytical geometry or the solution of such equations by 'nomograms.'

Since no reference to a particular physical process and the related laws of nature is required, great freedom is left the display designer to create configural displays representing the operational and intended state and trajectory of a function together with the acceptable limits of performance.

At this level, representation of the intentional context is particularly important. Operations largely serve to make sure that a system function serves the objectives by coordinating the processes serving the function. The primary objectives normally leave several degrees of freedom open within which the operational choice depends on secondary criteria. The processes involved in the primary objective to transport passengers according to schedule leave options free to a trade-off between safety, cost, and passenger comfort. Since the coordination typically involve decisions taken by the pilot, by flight automation, and by the traffic controller(s) communication of intentions and decision criteria is very important, as mentioned by Lintern (this volume) and demonstrated by the observed 'mode errors' discussed by Sarter and Woods (1994). Creation of 'direct perception' presenting the intentional control strategy of flight automation, its reason for action, and its actual mode of intervention is an important research issue. The issue is not, as often mentioned, to 'open the black box' of automation help the pilot to understand its function, but to help him understand the *reasons* for its actions - which are not found within the box.

The Level of Abstract Functions and Priority Measures.

Priority measures, in general, are related to value carriers that obey the conservation law. Inventories of mass and energy are conserved by laws of nature, while monetary values and numbers of people are conserved by social convention. The invariant concept to be used for visualization thus is the conservation law. Typically, however, conservation laws related to several value measures are relevant, such as flow of energy, mass, monetary values and their separation by analysis of lower level variables will involve complex sets of algebraic equations.

Visualization of the actual state with reference to the intended state within the individual flow systems is often based on analogies to river structures but this will not reveal the interaction among different flow systems (such as flow of energy and energy carriers (mass)) and the significance of the parameters available for manipulation. Visualization, therefore, may be more effectively based on the conventions for visualizing relationships within algebraic equations by analytical geometry. This is the approach used by Vicente (1991) for the design of the interface system of his experimental vehicle 'Duress.'

Paths from Relationships to Visual Displays

As a guide to interface design, a typology of representations would be helpful. However, so far the issue appears to be very complex, and a 'typology' is difficult to create, considering the many independent dimensions or degrees of freedom in the interface design. An overview is suggested in figure 2, illustrating how the content of displays refer to the phenomena of the physical world at the lower levels, while visualization at the upper levels are based on general mathematical concepts and tools. Different paths to visualization are sketched in figure 3 to indicate how different domains for generalization is relevant, pictorial visualization at the bottom, physical state and process diagrams in the middle levels and general mathematical representations at the top.

CONCLUSION

For design of reliable human-machine systems, an important issue is to present to the operator the deep structure of the system to be operated at several functional levels and to make visible the boundaries of acceptable operation. Usually, display design appears to be an art, depending on the creativity and background of the designer. To develop a systematic approach to display design for safe and reliable system operation, we need research in concepts for systematic visualization of system functions at several levels of abstraction.

Development of a systematic approach to Flach's Use-Centered Design raise some crucial cross-disciplinary issues. It is not a problem that can be solved by human factors specialists, not even if they cooperate with user groups in participatory design activities. To design a display that show the margin to stall depending on the actual weather and flight conditions (Flach, 1997) requires data integration by an aerodynamic model. A basic problem is to identify and make explicit the such internal functional constraints of the system and the reasons for choice of design solutions, e. g., for control strategies. For this cooperation with subject matter experts within avionics and aircraft design is as important as cooperation with air crews.

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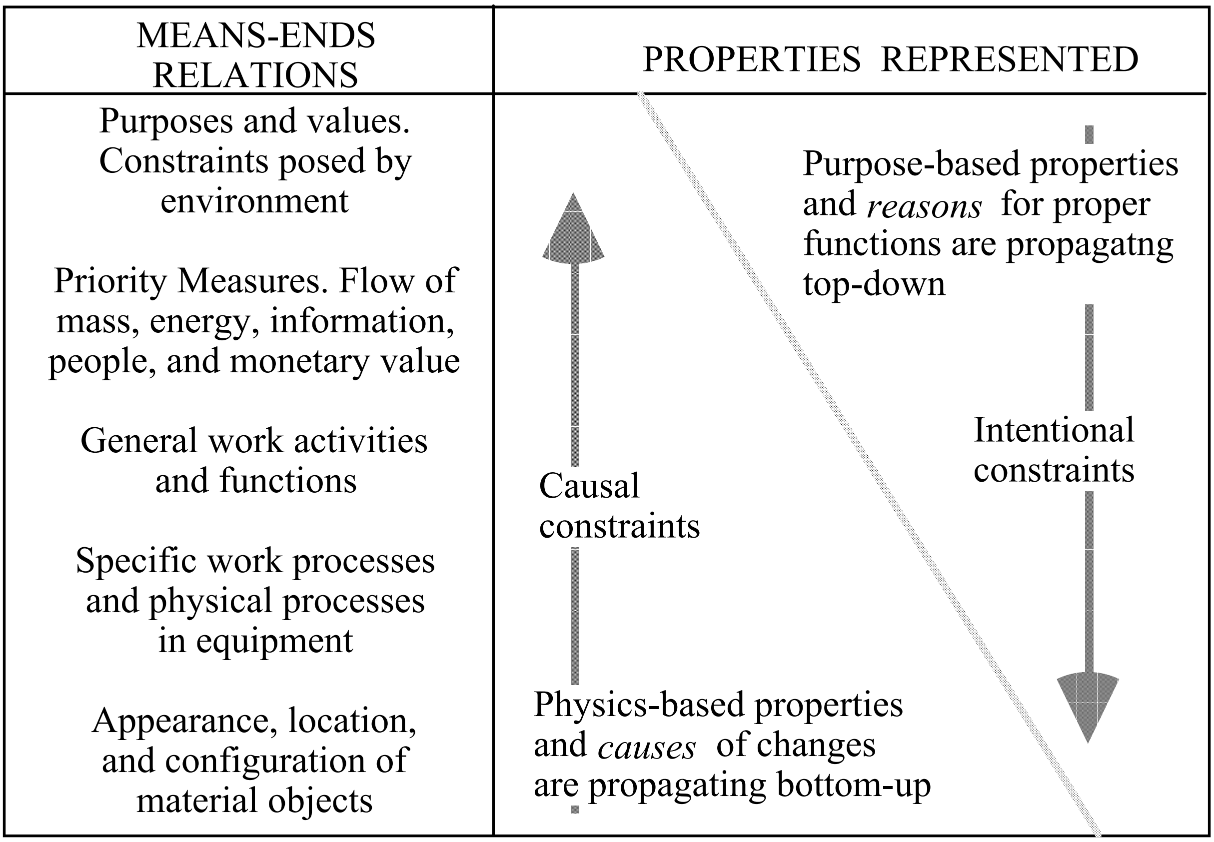

Figure 1. Any system can be described at several levels of functional abstraction adding up to a means-ends hierarchy. Lower levels are related to the physical configuration and processes. Higher levels to general functions and priority measures. Reasons for proper functions propagate top-down while causes of functional changes propagate bottom-up. The need and potential for human decision making depend on a many-to-many mapping among the levels of representation.

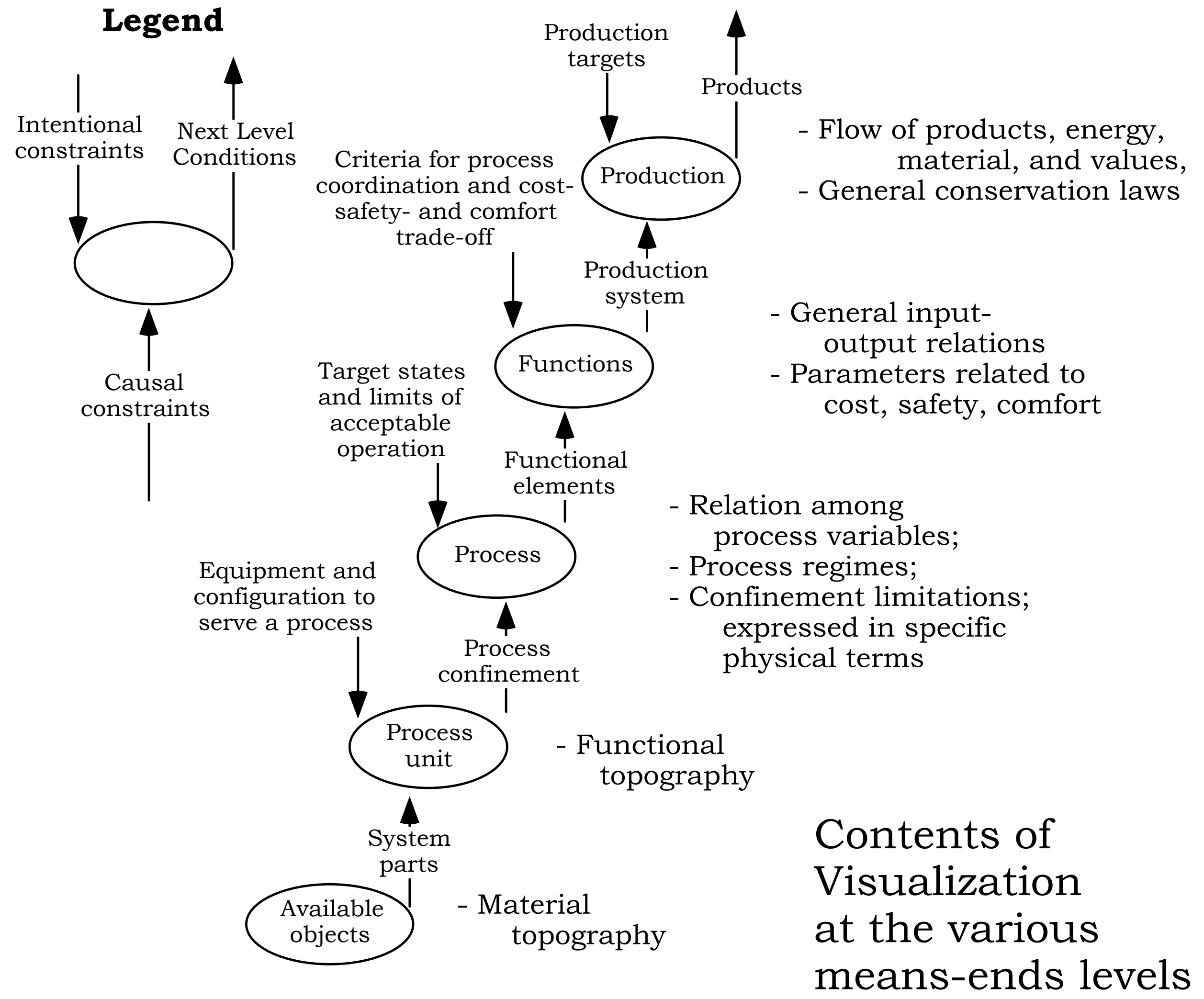

Figure 2. An attempt to map the representations relevant for human-machine interface design. The figure refers to concepts applied for process control and aircraft onboard technical systems. For piloting and vehicle control, the lower levels must be revised to represent the concepts relevant for locomotion.

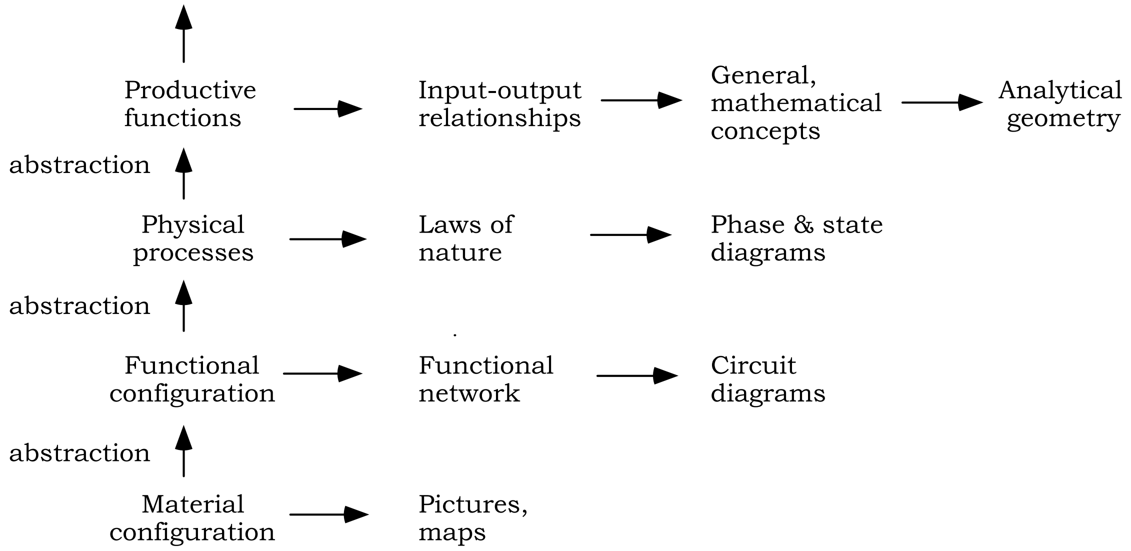

Figure 3. Different paths to visualization are relevant at different levels. Therefore, generalization of display concepts relate to different domains.