DOES ECOLOGICAL INTERFACE DESIGN SCALE UP TO INDUSTRIAL PLANTS?

Nick Dinadis & Kim J. Vicente

Cognitive Engineering Laboratory
Department of Industrial Engineering
University of Toronto
Toronto, Ontario M5S 1A4
Canada
Email: {dinadis, benfica} @ie.utoronto.ca

ABSTRACT

The purpose of this research was to determine how the principles of Ecological Interface Design (EID) could be applied to systems that are larger in scale than those that had been previously used as testbeds for evaluating EID. The focus of this initial feasibility study was the feedwater subsystem of Asea Brown Boveri's (ABB's) conventional power plant simulator. The primary outcome of this research is a prototype interface for the feedwater subsystem that is based on the EID framework. The main findings of this study are: a) a proof of concept showing that the principles of EID can be meaningfully applied to a larger-scale design problem representative of those found in industry; b) EID needs to be supplemented by more specific interface design principles; and c) it is possible to effectively integrate EID with these other design principles. Therefore, EID seems to be a viable candidate for the design of advanced computer interfaces for complex industrial plants.

I. INTRODUCTION

Many corporations are currently working on the design of advanced control rooms for their next generation of process control plants. Ecological interface design (EID) is a theoretical framework that has been developed to provide guidance in the design of these advanced control rooms. Previous research has applied and evaluated EID in the context of a small-scale but representative thermal-hydraulic process simulation. The purpose of this research was to apply the principles of EID to a larger-scale system that is more representative of the complexity of real industrial plants. A power plant feedwater subsystem was selected as the focus of the study. This paper briefly discusses the principles of EID, describes the design of an EID interface for a power plant feedwater subsystem, and identifies some lessons learned.

A. The Ecological Approach

Ecological interface design (EID) is a novel theoretical framework for designing interfaces for complex human-machine systems [6],[7]. It is based on two seminal concepts from cognitive engineering research, the abstraction hierarchy and the skills, rules, knowledge framework [3]. The abstraction hierarchy is a multilevel knowledge representation framework that can be used to develop physical and functional plant models as well as the mappings between them. It is used in EID to identify the information content and structure of the interface. The three principles of EID, each corresponding to a given level of cognitive control, are as follows:

1. Skill-based behaviour - to support interaction via time-space signals, the operator should be able to act directly on the display, and the structure of the displayed information should be isomorphic to the part-whole structure of movements.
2. Rule-based behaviour - provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface.
3. Knowledge-based behaviour - represent the work domain in the form of an AH to serve as an externalized mental model that will support knowledge-based problem solving.

For a detailed description and justification of these principles, see Vicente and Rasmussen [6],[7]. For a detailed example showing how these principles have been applied to the design of an interface for a small-scale thermal-hydraulic simulation, see [6]. In addition to specifying interface content, the principles of EID also suggest how information should be displayed in an interface. The idea is to take advantage of operators' powerful pattern recognition and psychomotor abilities. Thus, EID recommends that information should be presented in such a way as to promote skill- and rule-based behavior, allowing operators to deal with task demands in a relatively efficient and reliable manner. However, knowledge-based behavior is also supported by embedding an abstraction hierarchy representation in the interface. This provides operators with an external visualization of plant structure and dynamics which offers support during abnormal situations requiring problem solving. As a result of its unique characteristics, EID is an obvious candidate for designing computer interfaces for the type of systems that ABB is typically concerned with (i.e., complex industrial processes where unanticipated events can occur). The first step in developing an EID interface is to develop a multilevel representation of the feedwater subsystem, structured according to two dimensions: an AH progressing from functional to physical plant models, and a part-whole hierarchy progressing from the whole system to individual components. This two-dimensional problem space is graphically represented in Figure 1.

0-7803-2559-1/95 $4.00

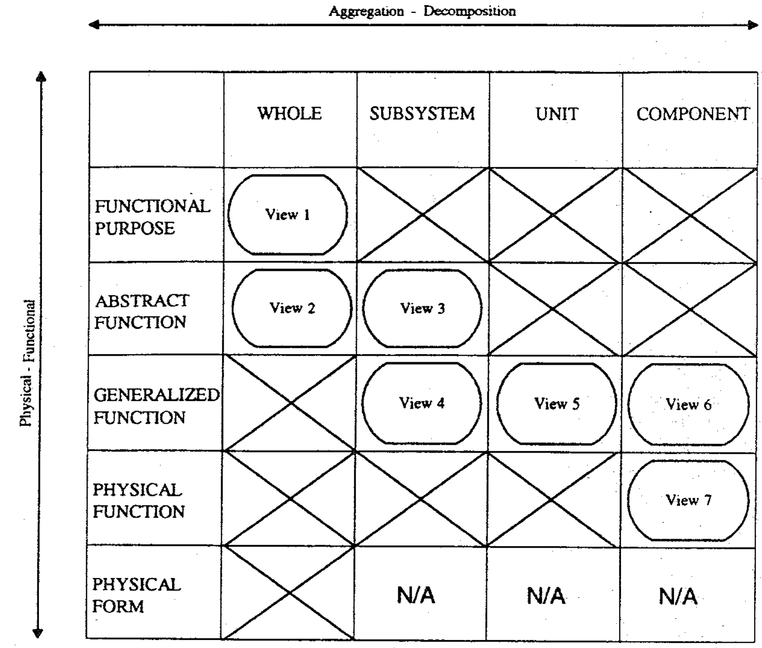


Figure 1: Representation of the Feedwater Subsystem According to Part-Whole and Means-Ends Hierarchies

II. EID INTERFACE FOR FEEDWATER SUBSYSTEM: ANALYSIS

A. Work Domain Representation

Beginning with the part-whole dimension, four levels of resolution were adopted: component, unit, subsystem, and whole. The objects at the component level are heaters, valves, and pumps. Thus, the component level of resolution is highly detailed. The next level in the part-whole hierarchy is the unit level, which consists of meaningful aggregations of components. Five objects were identified at this level: three parallel feed lines and two parallel heater lines. The next level, or the subsystem level, which is composed of aggregations of units, contains three objects identified collectively as the feedwater subsystem (composed of the three feed lines) as well as the two heating subsystems. Finally, the highest level in the part-whole hierarchy is the whole level. This level represents the entire feedwater assembly as a single object. As will be shown below, defining this part-whole hierarchy provides a mechanism for operators to change their focus of attention, moving from detailed views of the plant (e.g., component) to less detailed views (e.g., subsystem), and vice versa.

The AH, which is conceptually orthogonal to the part-whole dimension, consists of five levels of description, as shown in Figure 1 and detailed below.

B. Functional Purpose.

Objects at this level of abstraction correspond to system goals, and therefore are appropriately described at the whole level of the part-whole hierarchy. Two encompassing goals were identified for this system: to supply saturated water at a given demand temperature, and to supply a desired output flow to the boiler. At this level of representation, the entire system can be described in terms of the status of these two goals.

C. Abstract Function.

This level describes the system in terms of first principles, i.e., mass and energy conservation laws. This level of abstraction can be meaningfully applied at two levels of decomposition, whole and subsystem. With regard to the former, the whole feedwater assembly can be viewed as a mass source directly connected to a mass sink, and similarly, an energy source directly connected to an energy sink. One can decompose this representation along the part-whole dimension (while still remaining at the same means-end level), to obtain the abstract function/subsystem view of the system. The important benefit of this level of abstraction is that it allows operators to reason about the system in terms of first principles. This is particularly important under abnormal situations, since under such conditions, reasoning based on the normal functioning of physical components is unreliable.

D. Generalized Function.

Flows and storage of both heat and water are described at this level of abstraction. In this case, three levels of decomposition/aggregation are relevant: subsystem, unit, and component. The first of these accounts for the hydraulic and thermal aspects of the system. These objects are decomposed into a finer level of detail in the next view, representing the system at the generalized function/unit level. Here, many of the objects in the previous view can be decomposed into smaller parts. The same relation holds for the generalized function/component level. In this representation, the functional role of each component is explicitly represented.

At this level of abstraction, the state of the system can be described in terms of water flowrates and heat transfer rates. The advantage of having this information is that it allows operators to meaningfully reason about the system by considering its current functional state, without having to consider more concrete details about physical implementation.

E. Physical Function.

It is only at this level of abstraction that one first encounters information about the status of the physical components themselves (as opposed to the status of the functions that these components are intended to achieve). This level of abstraction is best viewed at the component level in the part-whole hierarchy. The resulting system view would be the familiar piping and instrumentation diagram (P&ID) representation of the system. Here, the status of the various heaters, pumps, and valves are represented.

F. Physical Form.

At this level, the appearance, condition, and physical location of each component are described. Because this information can typically be obtained only by a video connection to the plant components (e.g., [9]), it was considered to be outside of the scope of the present project, and is therefore not included in Figure 1. Note, however, that information at this level can be very important, particularly when faults propagate between components that are functionally dissimilar but physically proximate (cf. [1]).

III. EID INTERFACE FOR FEEDWATER SUBSYSTEM: DESIGN

A. Basic Functions

Figure 2 illustrates the prototype EID interface that was developed for the feedwater subsystem. The screen is divided into three distinct display regions, each serving a different role in efficiently communicating information to the operator:

a) Functional - This display is shown in the lower right corner of Figure 2. It contains information at the higher levels of the AH that are more relevant to the system goals.
b) Physical - This display is illustrated in the left side of Figure 2. It contains information at lower levels of the AH that are more relevant to system components.
c) Navigation/Alarm - This display is shown in the upper right corner of Figure 2. It contains information to support navigation through the physical display, as well as alarms that indicate when component values are out of their normal range.

Following the principles of EID, these three displays were designed to include all of the seven system representations identified in the previous section (see Figure 1). The fact that there are less displays than system representations results from the ability to integrate two, or more, different views of the system into a single visual form [4],[5]. For example, views 1-4 in the part-whole/AH decomposition, shown in Figure 1, have been integrated to create the Functional display, in the lower right corner of Figure 2. Each of these displays will now be described in detail.

B. Navigation/Alarm Display

The NAVIGATION/ALARM display located in the top right corner of the display shown in Figure 2, serves two behavioural goals. The first is to enhance the visual momentum [8] of the interface. The display offers an overview of the entire feedwater subsystem at the component level of resolution. Also, it shows which portion of the entire system is currently being viewed in the PHYSICAL display, which includes pan and zoom features (see below). More specifically, the teal rectangle in the NAVIGATION/ALARM display indicates the subset of the system currently being viewed in the PHYSICAL display on the left of Figure 2. This rectangle's size and position is controlled by the "sliders" surrounding the PHYSICAL display.

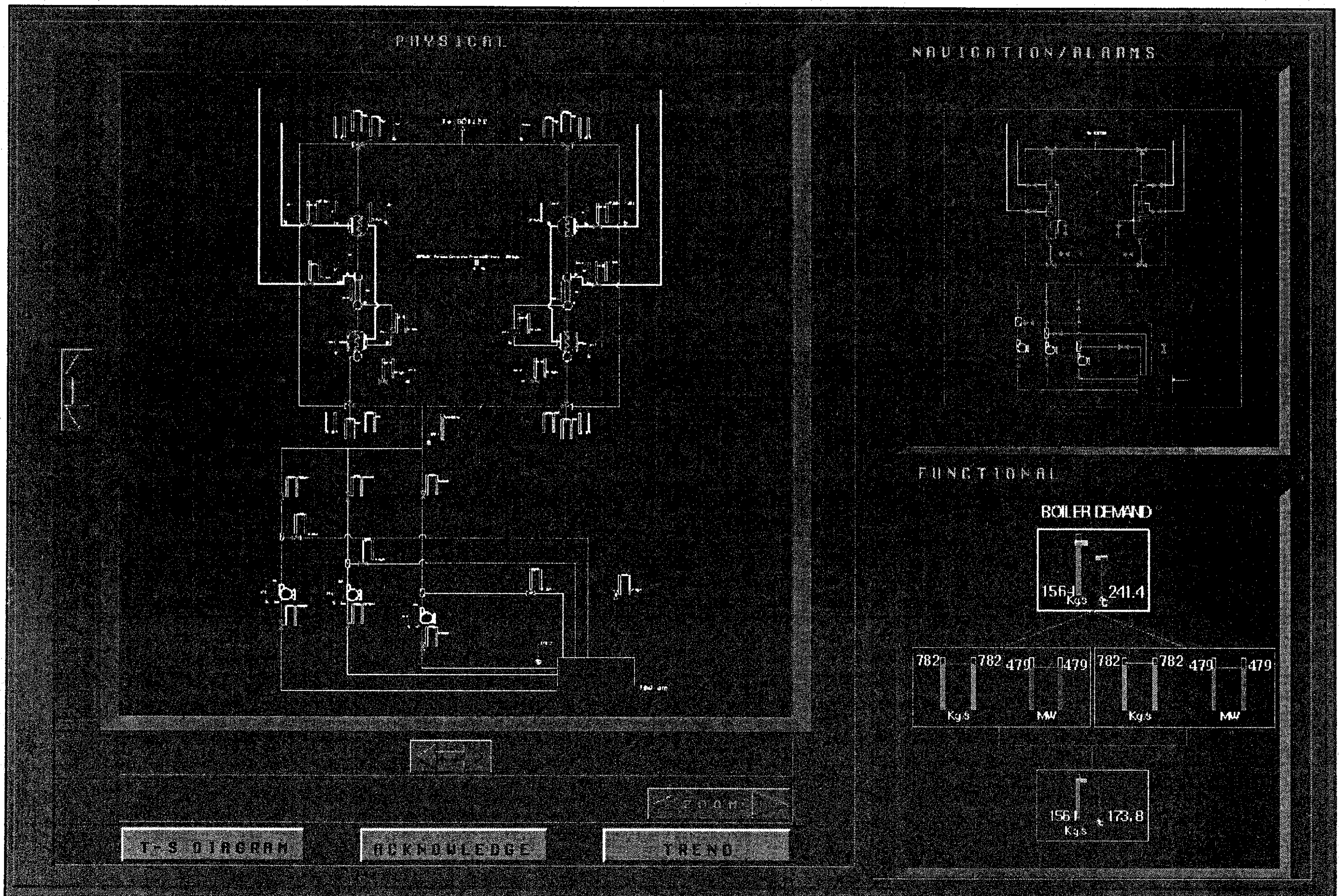
The second goal of the NAVIGATION/ALARM screen is to alert the operator as to whether anything abnormal is occurring at the component level. According to the alarm setpoints prescribed by ABB, the components' representations go from green (functioning properly) to amber (warning/caution) to crimson (hazard). These colours were chosen to be consistent with population stereotypes, and to ensure that an operator standing back from his/her screen would be able to determine, at a glance, whether a particular component was operating beyond its predetermined parameters. From this information, the operator is then able to quickly attend to a possible abnormality by zooming in on the alarmed component, determine the cause of the fault, and carry out the appropriate steps required to alleviate the problem.

C. Functional Display

The FUNCTIONAL screen located in the bottom right corner of Figure 2 is the most important, and the most innovative, in this EID interface for the feedwater subsystem. It presents the highest level goals and functions that the system must achieve if it is to operate properly (views 1 to 4 in Figure 1). Because the display is an important one, a different colour was employed for its background, causing the display to clearly stand out on its own. The four "boxes" in the display represent higher-order system functions (i.e., mass and energy which are being transported within the system). The appearance of the devices used within this view were designed so as to be consistent with the guidelines discussed in Mumaw, Woods, and Eastman [2]. Each of these boxes will now be described.

1) Flow unit box. The bottom (or Flow Unit) box contains the flow of water (in Kg/s) as well as its temperature (in ^{o}C) which passes through the feedwater subsystem. Along with the flow bar, a small yellow bar is displayed vertically along the flow meter indicating the flow production that is

Figure 2: Feedwater Subsystem Interface.



currently required from this portion of the feedwater subsystem. This facilitates determining whether or not the system is in the desired state.

2) Heater bank boxes. As indicated by the two faint grey lines leading up from the Flow Unit box, the flow of mass and energy is split into two streams which feed the parallel banks of heaters. The banks are each represented by a rectangular box of their own, and operate independently of each other, as depicted by their physical separation in the display. Since both operate in the same way, only one will be discussed in detail.

Beginning at the far left, the display represents a unit containing input and output flows to the left heater bank. Connecting the tops of the input and output flow levels is an important line which indicates the relative values of the respective flows. If the flow into the heater bank is equal to the flow out, the line will be horizontal, as indicated in the case considered. However, even if the line strays off the horizontal by just one pixel, the operator will be able to notice the effect quite easily. With this powerful perceptual cue, the operator will potentially be able to begin the problem solving process even before a warning is displayed. This is an example of the EID principle which states that the interface should contain diagnostic signs (the horizontal line, in this case) that map onto goal-relevant properties of the system (conservation of mass). Next to the flow meter is an energy unit which operates in exactly the same way, but displays flows of energy instead of mass. The impact of the two Heater Bank boxes on performance can only be appreciated if they are discussed in context with the Boiler Demand box located directly above them.

3) Boiler demand box. As the label above the Boiler Demand box states, this display represents the status of the output of the feedwater subsystem to the boiler. This is the ultimate goal of the whole subsystem, and thus has been given special attention. For example, the Boiler Demand box is larger than the others to draw the operators' attention to the overall goal state. Furthermore, the flow meter and thermometer both contain yellow "goal bars," indicating what inputs are essential to the boiler's efficient operation. In the case of the thermometer, the goal bar indicates the saturation temperature required by the boiler to produce the demanded power output. In the case of the flow meter, the required flow is indicated. As a result, the operator merely needs to maintain the levels of both the flow and temperature within the supplied "golden areas" in order to operate the feedwater subsystem properly. Again, this is an example of the EID principle of providing a one-to-one mapping between work domain constraints (the goals) and the perceptual signs provided by the interface (the salient golden areas).

If for some reason any one of the two criteria is not met, the thick white rectangle which surrounds the box changes colour to amber or crimson, indicating a warning or hazard depending on the severity of the disturbance. Even if the operator is standing well back of the screen, he/she is still able to easily notice the colour of the rectangle, informing them to attend to the abnormality.

Note that the relation between the boiler and the heater banks is also shown. Since the boiler is fed by the two heater banks, there are lines protruding from the two Heater Bank boxes which merge at the Boiler Demand box to indicate this relation.

The FUNCTIONAL display is an important aspect of this interface which best shows the advantages of the EID framework. This display offers a level of abstraction which should not only support quick fault detection, but also aid the diagnostic process as well. When used in tandem with the NAVIGATION/ALARM screen, a brief scan of the two displays can instantaneously inform the operator if the system is working properly. When a problem arises, the NAVIGATION/ALARM serves to verify the initial fault analysis made in the FUNCTIONAL view, and also eases the transition to the more familiar component level of the hierarchy available in the PHYSICAL display, described next.

D. Physical Display

The PHYSICAL display, located on the left of Figure 2, contains a detailed representation which includes the state of the components and the generalized functions that they are intended to fulfill (views 5 to 7 in Figure 1). For example, for each valve, there is a flow meter indicating the current flowrate. As mentioned earlier, this display has a pan and zoom capability. It has been designed such that the greatest zoom factor obtainable fits one component into the entire display area, and the smallest zoom factor displays the entire feedwater subsystem. It was decided that zoom factors outside the boundaries just mentioned would only hinder visual momentum by offering views that were not meaningful.

The primary difference between the PHYSICAL display and the other two displays, however, is that it is the only one to offer direct operator interaction. According to the principles of EID, operators should be able to change the state of components by acting on the display directly. As it has been currently implemented however, the only input in this prototype display is the power level indicator, arbitrarily placed in the upper middle of the feedwater subsystem display.

This display also contains information at the level of generalized function which is important in supporting operator behaviour under the entire range of operating conditions. For example, the valve settings alone are not sufficient to accurately describe a flow situation. A flow meter placed adjacent to the valve setting indicator allows for fault detection in the form of valves being stuck open, or flow meters being faulty. Thus, wherever there is a valve, the flow meter - valve setting group is placed directly adjacent to it. When the setting does not agree with the flow meter, the valve enters a state of caution and turns amber. All the components have been grouped with their measurement devices to prevent confusion.

In summary, the primary purposes of this display are to support the localization of faults that have been detected (and perhaps diagnosed at a coarse level) using the other two displays, and in particular, to support planning and compensatory activities.

IV. CONCLUSIONS

This feasibility study has shown that the EID framework can be meaningfully applied to industrial systems that are much larger in scale than the system that has been previously used to evaluate EID. The AH analysis aided in identifying the content and structure of the information that should be included in the interface. This multilevel representation, which includes both higher order functional information and lower order physical information, provides an informational basis for supporting operators during unanticipated events requiring knowledge-based behaviour. This information was then mapped onto a set of visual forms, providing a one-to-one mapping between the domain constraints and the perceptual cues provided by the interface. Operators should thus be able to easily determine the state of the system at a glance, and to rapidly and effectively extract information from the display. Finally, the design is also intended to support planning and compensatory activities by allowing operators to directly act on the display surface.

In conclusion, although empirical testing is required to evaluate the prototype described in this paper, this feasibility study has provided a proof of concept showing that the principles of EID can be meaningfully applied to industrial scale systems. Interfaces of this type will become more and more important as operators are required to deal with sociotechnical systems that are characterized by unanticipated events and complex, dynamic environments. Thus, EID seems to be a viable candidate for the design of advanced computer interfaces for complex industrial plants.

V. ACKNOWLEDGMENTS

We would like to thank Andy Sun, Andreas Zehnpfund, Klaus Zinser, and Virtual Prototypes, Inc. for their contributions to this research.

VI. REFERENCES

[1] A. M. Bisantz and K. J. Vicente, "Making the abstraction hierarchy concrete" *International Journal of Human-Computer Studies, 40,* 83-117. (1994).

[2] R. J. Mumaw, D. D. Woods, and M. C. Eastman, *Interim report on techniques and principles for computer-based display of data* (STC Report 92-1SJ4-CHICR-R1). Pittsburgh, PA: Westinghouse Science and Technology Center. (1992).

[3] J. Rasmussen, *Information processing and human-machine interaction: An approach to cognitive engineering.* New York: North-Holland. (1986).

[4] K. J. Vicente, "Multilevel interfaces for power plant control rooms I: An integrative review" *Nuclear Safety, 33,* 381-397. (1992b).

[5] K. J. Vicente, "Multilevel interfaces for power plant control rooms II: A preliminary design space" *Nuclear Safety, 33,* 543-548. (1992c).

[6] K. J. Vicente and J. Rasmussen, "The ecology of human-machine systems II: Mediating "direct perception" in complex work domains" *Ecological Psychology, 2,* 207-249. (1990).

[7] K. J. Vicente and J. Rasmussen, "Ecological interface design: Theoretical foundations" *IEEE Transactions on Systems, Man, and Cybernetics, SMC-22,* 589-606. (1992).

[8] D. D. Woods, "Visual momentum: A concept to improve the cognitive coupling of person and computer" *International Journal of Man-Machine Studies, 21,* 229-244. (1984).

[9] K. Zinser and F. Frischenschlager, "Multimedia's push into power." *IEEE Spectrum, 31*(7), 44-48. (1994).