A DIRECT PERCEPTION DISPLAY FOR RULE-BASED BEHAVIOR: SUPPORTING POWER PLANT STARTUP WITH A “LATTICE” DISPLAY

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Research over the last decade on interface design has suggested that “configural” or “direct perception” displays provide better support for complex operator tasks than single-sensor single-indicator displays. In this paper we focus on the development of displays to support the human operator role in nuclear power plant start-up procedures, which involve rule-based behavior. During start-up operators construct a functioning plant. This process can be characterized as climbing an “abstraction/aggregation hierarchy” from initiating low-level physical functions, combining them into generalized and abstract functions until the plant fulfills its functional purpose (Rasmussen, Pejtersen, & Goodstein, 1994). We introduce a graphical interface based on a visual lattice representation of the abstraction/aggregation hierarchy for nuclear power plant startup which should (1) provide constant feedback through the lattice display about the level of abstraction/aggregation achieved, (2) provide feedback about system state through direct perception displays, and (3) promote the correct sequence of actions. We describe the theoretical background for our work, provide illustrations of the “lattice” displays, and discuss the exact sense in which the interface is and is not an instance of “Ecological Interface Design.”

INTRODUCTION

Traditional Single-Sensor, Single-Indicator (SSI) displays are poorly matched to the cognitive needs of operators, especially for large and complex systems. Research over the last decade has suggested that “configural” or “direct perception” displays provide better support than SSSI displays for complex tasks (Bennett & Flach, 1992). A theoretical framework for designing such displays known as Ecological Interface Design (EID) (Vicente & Rasmussen, 1992; Rasmussen, Pejtersen, & Goodstein, 1994) is becoming more widely accepted as the basis for supporting skill-, rule-, and knowledge-based behavior in continuous process control. Our focus in this paper is nuclear power plant (NPP) start-up procedures, which are usually heavily weighted towards rule-based behavior. During start-up operators “construct” a functioning plant, which can be described as climbing Rasmussen et al.’s (1994) “abstraction/aggregation hierarchy” from initiating low-level physical functions, combining them into generalized and abstract functions until the plant fulfills its functional purpose. In this paper we propose a graphical interface based on a visual “lattice” representation of the abstraction/aggregation hierarchy for nuclear power plant startup which should (1) provide constant feedback through the lattice display about the level of abstraction/aggregation achieved, (2) provide feedback about system state through direct perception displays, and (3) promote the correct sequence of actions. We describe the theoretical background for our work, provide illustrations of the “lattice” displays, and discuss the exact sense in which the interface is and is not an instance of “Ecological Interface Design.”

ECOLOGICAL INTERFACE DESIGN

Ecological interface design (EID) is a principled approach to the design of interfaces that is intended to help operators deal as effectively with abnormal, unanticipated situations as with normal, anticipated situations (Vicente & Rasmussen, 1990, 1992; Rasmussen et al., 1994). EID is concerned with support adaptive operator behavior while allowing the operator continual awareness of how near or far the system is to its
boundaries of operations. The three characteristics of an ecological display are (1) that it should reveal functional relationships within and between levels of abstraction of a system, as determined in a work domain analysis; (2) that it should support skill-, rule-, and knowledge-based behavior as identified in an activity analysis; and (3) that it should provide perceptually-based solutions to representing system state and possibilities for operator action.

The displays proposed herein have been developed under the philosophical guidance of EID. However, as will be seen, for the most part they support rule-based behavior for a distinct subset of plant conditions, making them at best just a subset of a full ecological interface. This issue will be discussed in the conclusion.

NUCLEAR POWER PLANT START-UP PROCEDURES

The startup procedure in a NPP is currently supported by written Standard Operating Procedures (SOPs) that are presented in the text-based form shown in Figure 1, or in an electronic version of the same. The startup procedure for a pressurized water reactor (PWR) that we observed works through mode transitions that are characterized by conditions that should be reached before passing to the next mode, from Mode 5 (0% turbine power) to Mode 1 (100% turbine power). Each step is numbered and may involve multiple substeps for its satisfactory completion. Figure 1 shows the start of the written SOP for step 39 of the third SOP manual, which can be seen on Figure 3 as well. In addition to the text-based representation of the SOPs, the steps involved are sometimes summarized by flowchart diagrams where each node is labeled with the step number. Not unexpectedly, the written SOPs are difficult to use for several reasons:

- They run to several hundred pages so that following pathways can become very cumbersome.
- They do not provide a checklist facility.
- They do not inform operators about steps omitted or steps performed in the wrong order or at the wrong time.
- They do not indicate if the wrong steps have been made or correct actions taken.

Roth and Woods (1988) and Woods and Roth (1988) discussed the level of coordination required between operators in bringing systems up to operating conditions and aligning them during NPP startup. They examined the cognitive and social challenges of bringing the feedwater, steam, and turbine systems on-line in alignment with each other, and proposed an integrated display that could help with this task. The work described herein carries this philosophy forward.

APPLYING EID TO PWR NPP START-UP

The process of start-up can be represented in abstract terms by the diagram shown in Figure 2. Although this representation is technically not a lattice, for the sake of brevity we will use the term lattice to describe it. At the bottom of the lattice is a row of inverted branches, each of which corresponds to a simple, single component of the plant (“Parts”). During plant start-up these parts are aggregated into subsystems by being activated and connected, either physically or functionally. In the lattice representation, then, each junction of lines represents the fact that a subsystem has been configured and is beginning to run up towards its set point(s) as a result of the start-up procedure (“Processes”). When several such processes are running, and when required checks have been made to ensure that all is normal, they must be "aligned" with each other to ensure synchronization, to ensure a mass or energy balance, and so on (“Functions”). The operator can now think in terms of connecting that functional unit to other completed units to create further “Functions” and some of the previous details can be ignored. The process proceeds up and to the right in Figure 2 towards a fully synthesized plant and full normal operating conditions.

ILLUSTRATIONS OF PROPOSED DISPLAYS

Our goal in this project was to instantiate the above ideas for the start-up sequence of a PWR NPP. We found that the flowchart representations of the SOPs could be transformed and represented in terms of the abstraction hierarchy framework. For example, the successful acquisition of each mode of startup operation (Modes 5 through 0) represented the “construction” of a significant level of plant functionality at the generalized or abstract functional level of Rasmussen et al.’s (1994) abstraction hierarchy. At each level there were system parameters that had been brought up to a certain level of functioning or that were operating within certain bounds. Summary displays—often with configural or “direct perception” characteristics—were developed to provide a view into the system state and level of functioning achieved to the present point in the start-up procedure (Bennett & Flach, 1992; Vicente, Moray, Lee, Rasmussen, Jones, Brock, & Djemil, 1996).

Figure 3 shows just one of the numerous junctions in the lattice display with its accompanying displays. The example focuses on feedwater system start-up. At the top of the figure several configural state-space displays and a mimic display (second from left) are
F. 39. Placing Feedwater Control in Automatic:
   a. ENSURE that the Turbine Generator is at approximately 20% power (235 MW).
   b. VERIFY/MAINTAIN Steam Generator levels at or slightly above program level, by ADJUSTING the
      FW Reg Bypass Valve(s), as necessary.
   c. VERIFY/CLOSE 1FW510, 520, 530, and 540, FW Reg Valves.
   d. VERIFY/OPEN 1FW006A,B,C, and D, FW Reg Isol Valves.
   e. With each Steam Generator’s level at or slightly above the program level, PLACE the
      associated FW Reg Isol Valve in AUTO.
   f. PLACE the FW Reg Bypass Valve controllers in MANUAL, and SLOWLY THROTTLE the Bypass Valves
      CLOSED.
   g. ENSURE that the FW Reg Valves begin to open as the Bypass Valves are throttled closed.

Figure 1: A illustration of a PWR’s written start-up procedures for one step in bringing the FW system on-line.

Figure 2: The “lattice” that represents plant start up as aligning and connecting plant components and sub-systems. Types of
displays that could be used to support the start-up procedure at the appropriate level of abstraction are indicated by the
gray background.

presented to provide an overview of the system state. At
the bottom of the display is the currently salient part
of the start-up lattice. Start-up tasks are executed by
clicking the mouse on the nodes in the display, from left
to right. The clear nodes with dotted lines indicate that
the first two tasks—FW system realignment and 40% steam dump for synchronization—have been completed
(in the color version of the display the nodes change
from gray to green when the functions they represent have been completed). This means that the next task is to place the feedwater control in automatic (FW control in AUTO). The operator clicks on the black node and is presented with a sub-lattice that provides guidance through the steps that need to be completed (see Figure 4). In fact, Figure 4 corresponds to the portion of the written SOP presented in Figure 1. In our lattice interface there is a further level that lies below the nodes in Figure 4, and that level shows how the individual components are to be manipulated (see Figure 5). This is the level at which direct control is exercised.

Figure 3: Lattice display for feedwater system startup, presenting steps to be executed in order from left-to-right, as well as state-space and system displays at the top.

Figure 4: The display for the “Place FW control in AUTO” node in Figure 3.

Figure 5: The display for the “VERIFY/OPEN 1FW006A, B, C, D FW Reg Isol Valves” node in Figure 4.
LIMITATIONS OF PROPOSED DISPLAYS AND FURTHER EXTENSIONS NEEDED

The displays shown here are just a sketch of what is needed to support NPP operators during startup. The concepts will need some refinement and further development before further prototyping is warranted. Further research should identify the precise information needed to ensure that each “junction” in the lattice has been successfully reached, and how that information should be displayed. Further issues involve handling display “real estate” and visual (and cognitive) momentum (Woods, 1984). The overall lattice is so large—particularly when supplemented by configural displays—that the operator could easily get lost. To aid navigation and preserve visual momentum between adjacent parts of the interface, either multiple computer monitors, multi-windowing display management, or distortion-based display techniques are needed (Leung & Apperley, 1994). We will discuss our progress towards solving these problems. A final issue is how a lattice representation of startup—plus its accompanying configural displays—will affect existing work practices and communication between operators during startup procedures. Field studies are needed to model how operators work together during start-up and to predict the impact on work practices of the kinds of displays we have proposed.

CONCLUSIONS

Although the lattice diagrams have been stimulated by EID, they are not full ecological interfaces in the sense normally advanced by EID. Start-up is a special mode of operation and start-up SOPs are usually designed to constrain activity to rule-based procedures rather than extending to support for skill-based or knowledge-based behavior, as EID proposes. However, our displays belong to the EID approach for the following reasons. First, the lattice is rooted in an abstraction hierarchy-based analysis of startup. The operator is guided in how to “construct” the plant, and receives feedback on the success of these activities in a general movement rightwards and upwards in the abstraction/aggregation space (see Figure 2). Important functional relations within and between levels of abstraction are revealed as the operator invokes those relations during startup. Second, the lattice shapes behavior to a rule-based procedure because the trajectory to full power is itself narrow. Small perturbations can mean an expensive and time-consuming return to the beginning (Roth & Woods, 1988; Woods & Roth, 1988). Rule-based support here is a special kind of guidance based on the unique requirements of start-up, rather than a commitment to rule-based operations for their own sake. Third, the functional significance of rule-based activities should be made evident to the operator through displays showing the status of critical plant parameters at different levels of abstraction. This is critical for dealing with unexpected variability in system state during startup (Tanabe & Rasmussen, 1997). Activity is thus supported by perceptual feedback about its consequences, thereby giving the operators not only a perceptual appreciation of their place in the startup trajectory, but also a sense of the degrees of freedom remaining. For these reasons we might think of the lattice display as an ecological interface customized for a difficult mode of operation by dynamically prioritizing the presentation of certain affordances and relations as startup proceeds.

In summary, our approach is not to get rid of written SOPs, but instead to make SOPs available to the operators in a form which more effectively couples them to the challenges of startup. We argue that the lattice interface and its accompanying configural displays would not only be just as effective as written SOPs, but would also provide a broader envelope for the success of the SOPs. The interface goes beyond the written procedures not only by preserving the integrity of the sequence of actions but also by showing the significance of those actions in relation to the structure, functioning, and purpose of the system. The lattice displays described herein have potential applications to domains and contexts outside NPP startup.

REFERENCES


