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Applying the Control Adaptation Method to a Real-World System: Hydropower System Example

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ABSTRACT

This paper presents part of a project aimed at evaluating ecological interfaces in a real world complex system –a hydropower system. We investigate whether an advanced measurement method—here called the control adaptation method (CAM)—can be extended to evaluate how effectively a human operator is coupled to a complex process control environment. So far the CAM has been successfully applied to the simple, DURESS II microworld. In this paper we attempt to extend the CAM to a real-world complex control environment—a hydropower system operating in a deregulated electricity market. We encounter challenges in transferring the CAM to this more complex work domain. Nonetheless, we provide an approximation to the original methodology that should let us measure the effectiveness of ecological displays for hydropower systems. Our findings may generalise to the evaluation of ecological interfaces in other real-world systems.

Keywords

Control adaptation method (CAM), Abstraction Hierarchy, Hydropower system (HPS) control, evaluation, Ecological Interface Design (EID).

INTRODUCTION

With the deregulation of the electricity market, the role of the hydropower system (HPS) controller has changed from traditional supervisory control to a more complex form of control that requires a HPS company to interact with a market optimization process before generation can proceed. HPS companies wish to serve peak electricity demand that is strongly driven by dynamic market forces. A single HPS controller must monitor and analyse a vast amount of data from diverse areas to control an energy source, to generate electricity, to dispatch electricity in real time, and simultaneously to participate productively in the electricity market. HPS controllers must configure the plant so that opportunities can be seized, but also so that the ability to handle disturbances is preserved. However, current displays in HPS control rooms often do not meet such demand (Sanderson, Wong, Choudhury, & Memisevic, 2003; Sanderson, Wong, & Memisevic, 2004).

Our research is concerned with whether it is possible to apply Ecological Interface Design (EID) to help HPS controllers maintain better situation awareness, trust, team coordination, adaptation to the new market environment, and ability to handle disturbances. EID is an approach to display design based in the idea that displays should reveal the first principles of operation of a work domain to a controller, while supporting the controller's activity at the skill-, rule- and knowledge-based levels of behavior (Vicente & Rasmussen, 1992). EID displays should support better controller adaptation to unexpected events or system disturbances.

In our research, the proposed EID interfaces ("functional" displays) are intended to supplement the conventional installed base of displays in the current HPS control room ("current" displays). To demonstrate their effectiveness, the functional displays will be tested against the current displays on a high fidelity simulator with professional hydropower controllers. We will evaluate whether there are better outcomes in performance, situation awareness, trust, and—the topic of the present paper—better control adaptation with the functional displays.

In this paper we present part of the conceptual work towards that evaluation. We discuss how to measure the effectiveness of the functional vs. current displays for supporting the HPS controller's ability to handle disturbances of various kinds. First, we explain the control adaptation method (Yu, Elfreda, Vicente, & Carter, 2002) and identify challenges in applying it to control in a deregulated electricity market. Second, using an abstraction hierarchy model (AH: Rasmussen, 1985) we distinguish high vs. low levels of functional structure in the HPS domain and indicate how our interface design methods focus on revealing high-level functional structure. Finally we suggest how to measure performance in ways that operationalise the control adaptation method most effectively.

CONTROL ADAPTATION METHOD

The control adaptation method (CAM) is a dynamical systems-theory inspired set of methods for data analysis based in an understanding of how controllers might use the functional structure of a work domain when handling disturbances (Hajdukiewicz & Vicente, 2002; 2004; Yu et al., 2002). The functional structure of a work domain is revealed by describing the work domain at five levels of abstraction, ranging from levels describing the purpose of the work domain to levels describing the physical processes and configurations of the work domain. In the resulting "abstraction hierarchy", the high-level functional purpose and abstract function levels reveal the overall rationale and the first principles of operation of the work domain, the physical function and physical form levels show the physical substrate of the work domain and its processes, and the generalised function level in the middle shows how the physical processes are assembled in order to satisfy the first principles of the work domain. We refer to variables at the functional purpose and abstract function levels as "high-level" or functional variables, and those at the physical function and physical form levels as "low-level" or physical variables (see Table 1.)

First, according to the CAM an ecological interface should reveal the functional structure of a work domain so that options available for achieving high-level functions are evident (Hajdukiewicz & Vicente, 2004). People using an ecological interface should be better able to preserve high-level properties of a system despite disturbances, so system performance will be better. These people will use control strategies that reveal knowledge of the functional structure of the work domain and that achieve high-level properties more consistently across similar situations. In subjective reports of their control strategies they will refer to higher-order properties more often and their strategies are more likely to reflect system context.

	Non-EID (non-functional) Display	**EID (functional) Display**
F	Large s^2 (worse performance)	Small s^2 (better performance)
P	Small s^2 (control recipes, fast, fewer steps)	Large s^2 (faster, more steps or more control options)

F = high-level functional properties; P = low-level physical properties; s^2 = variability in a participant's performance; () = other properties of control.

Table 1 Control adaptation measures.

Second, a multidimensional variance in a particular level of the abstraction hierarchy—calculated by taking multiple observations of an individual performing similar control problems—can quantify the consistency of control at that level. The variability over multiple observations in data trajectories over time becomes the CAM measure. As shown at right in Table 1, the benefit of an EID interface is evident when there is small variability in a participant's ability to preserve high-level properties, but large variability in a participant's use of low-level processes (Hajdukiewicz & Vicente, 2002). In contrast, displays without the properties of ecological interfaces support the opposite pattern—large variability in a participant's ability to preserve high-level properties but small variability in a participant's use of low-level processes.

In related CAM work, researchers have sought similar patterns of variability *between different participants* performing the same control problem, rather than within individual participants performing the same control problem over and over. For example, Reising and Sanderson (2000) found greater similarity between participants using an ecological interface in the control of high-level variables and less similarity between participants in the management of low-level variables. The pattern was reversed for participants not using an ecological interface. This suggests that the ability of an ecological interface to produce more stable high-level performance within an individual may also operate across individuals. Ecological interfaces appear to control people's behavior so that they become more like each other in the way they capture high-level goals.

ANALYSING HYDROPOWER SYSTEM CONTROL

The present paper describes our attempt to extend the CAM from a manual control-based microworld into a largely automated real-world HPS environment. We describe the HPS environment, outline a work domain analysis performed for a HPS company, and briefly describe our display design effort.

The primary concern for a HPS company is maximize revenue by selling power and services into the market. The company sends a bid to an independent market operator—the National Electricity Market Management Company, or NEMMCO—that indicates how much electricity the HPS company wants to sell and for what prices. The independent market operator receives bids from all sellers, submits the bids to an optimization routine that determines how much electricity each seller will be asked to produce (the "dispatch target"), and informs each seller of their dispatch target. The HPS controller has to generate power in real time to match the dispatch target commanded by the independent market operator. The HPS company will also respond to contingencies by rebidding into the electricity market. Automatic Generation Control and automated Supervisory Control and Data Acquisition systems control real-time operation of the HPS and so increase the internal complexity of the system. For example, the simulator in our study, which reproduces the major functions of the hydropower plants, has over 7000 state and control variables (Memisevic, Choudhury, Sanderson, & Wong, 2004; Memisevic, Sanderson, Choudhury, & Wong, 2004).

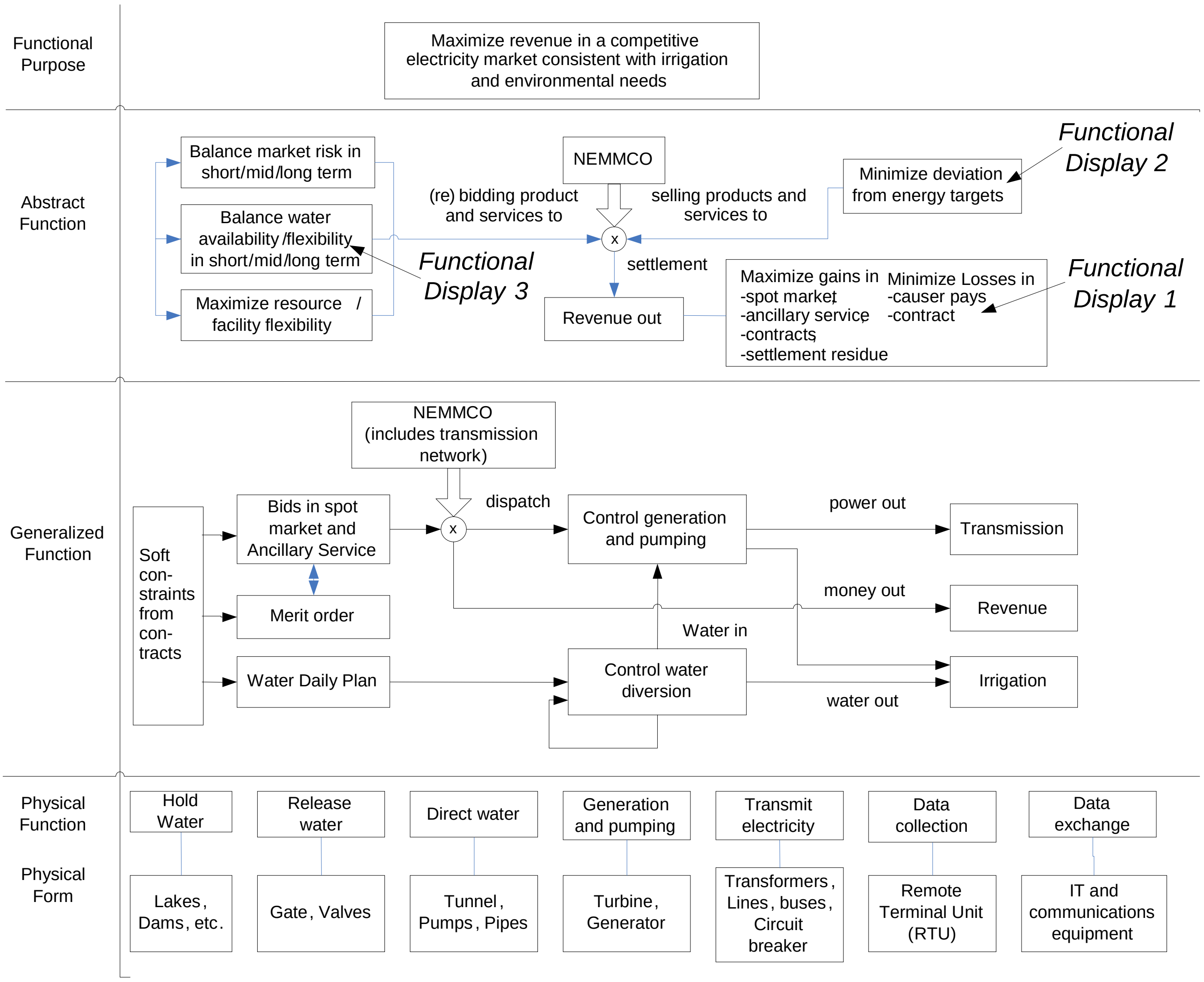

Figure 1. Work domain analysis of HPS control (simplified version)

Figure 1 shows an analysis of the work domain of HPS control in the form of an abstraction hierarchy. It is a simplified version—links between levels are not shown here and the breakdown into levels of aggregation has not been detailed. The figure shows properties of the HPS work domain at different levels of abstraction and takes into account the complex nature of control under the deregulated electricity market.

At the *functional purpose* level, the overall rationale of the HPS is maximizing corporate profit in a deregulated electricity market, consistent with the irrigation and environmental needs.

At the *abstract function* level, priorities are the relationship between market risks and operational constraints of the HPS, including the availability and flexibility of water. The bid to NEMMCO represents the best balance amongst these concerns. The controller must also minimize deviation of real time generation from the dispatch target to avoid financial losses.

At the *generalized function* level, there are separate outputs of transmission, revenue, and irrigation (see right side). Contracts (see left) are long-term strategies to manage market risks that provide a backdrop to shorter-term market activities. Bids include the amount of power the company wants to sell through the day, and at what price. The merit order and daily water plan are internal guidance for how to bring resources into use. Finally, generation, pumping and water diversion are the means by which plans are put into play, once processed by the market operator, NEMMCO.

At the *physical function* and *physical form* levels, the physical plant of the HPS scheme, such as dams, tunnels, turbines, and the (re)bidding facilities in communication with NEMMCO can be controlled by the automated systems or the HPS controller. Much of the data of the HPS is contained at these two levels.

The abstraction hierarchy in Figure 1 does not show the vast number of variables that exist, especially for low-level variables at the component and unit levels of aggregation of the work domain. If we are to use the CAM to evaluate HPS control we need to manage the size of the problem in a way that is not needed for simpler microworlds. How this is achieved will be described in a later section.

Functional displays in HPS control room

In Figure 1 there are annotations at the abstract function level indicating where the high-level properties of the HPS have been captured in three new functional displays. Functional Display 1 provides information about sources of revenue and losses. Functional Display 2 provides information about how well energy targets are being achieved. Functional Display 3 provides information about how water is being used, allowing the HPS controller to project into the future. (The details of the new displays are less important for this paper than our method of evaluating them, and will be the subject of a future report.)

Figure 2 shows how our development of functional displays has proceeded. We have developed a HPS simulator based on an existing HPS where there is already an installed base of displays. Our simulator includes 36 interfaces (windows or screens) that support a human controller's monitoring and control. In recent years, the HPS company has developed monitoring displays in-house, some of which integrate information at the lower levels of the abstraction hierarchy to achieve aggregation rather than providing information about properties at the higher levels of the abstraction hierarchy. In the current displays, information about market risk and resulting output is not displayed. Information about constraints on real time control is merely distributed among several displays or is not explicitly provided. Our goal for the new functional displays is to show properties at the higher level so as to guide the use of physical aspects of the system. Figure 2 provides a framework for understanding how the new functional displays will supplement rather than replace the current physical (and sometimes integrated) displays.

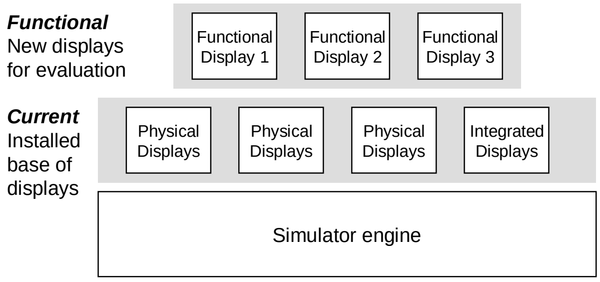

Figure 2 Novel functional displays that supplement existing physical and integrated displays will be tested using our HPS simular.

Functional displays built according to EID principles should act as a feedback channel between the hydropower scheme and the HPS controller, showing the controller the impact of control actions and disturbances on high-level work domain functions and making it easier to consider and select among alternative courses of action. Specifically, the functional display reveals the current state of the system and any deviation from the desired state. The functional display should make it easy for the HPS controller to see what means exist to achieving the desired state. If the HPS has been subject to a disturbance, making some means impossible or impractical to apply, then the functional display should make optional alternative evident for achieving the desired state. The HPS controller then selects a course of action and executes it, monitoring progress in the functional displays.

CHALLENGES TO OPERATIONALISING CAM

A key challenge to operationalizing the CAM for the HPS domain is the complexity of the domain. To determine the best CAM measures to use in our experiment, we must consider the context of previous CAM studies and compare them with the challenges we face in mounting our study.

To date, studies exploring the CAM have focused on simple manual control microworlds, such as DURESS (Hajdukiewicz & Vicente, 2002, 2004; Yu et al., 2002) and Pasteurizer II (Reising & Sanderson, 2000). Such systems are normally represented in a single ecological interface that includes ten or twenty variables. The simplicity of the domain makes it easy to use a few configural displays to demonstrate relationships between low-level processes and high-level properties. Because of the simplicity of microworld domains, strategies can usually be enumerated without too much trouble. Participants typically acquire a fixed control target, such as keeping a stable outflow rate. Comparisons are made between situations with and without a single local disturbance such as a valve failure. Both high-level properties and low-level processes can be easily quantified so that variability in the coupling of the operator to system dynamics can be tracked in some detail.

In contrast, HPS control is a highly automated control environment. In the so called normal situation, the automated generation control system completely takes control of the plant from receiving the dispatch target to allocating generation to each physical generating unit. After starting generating units and making them available to automated generation control, the HPS controller intervenes only when the situation is abnormal or unexpected, such as if a generating unit fails. Thus it is not possible to measure human control behavior in the way that direct manual control makes possible.

Previous studies applying the CAM to DURESS (Hajdukiewicz & Vicente, 2002, 2004) suggest that low variability in low-level control activities is caused by repeatedly using low-level components in the same way ("control recipes"). However, our HPS simulator contains thousands of state and control variables, mostly for the automated control system, and it is impossible to distinguish whether changes in these variables result from human or automated control. Moreover, the market income is updated regularly from the market every 5 minutes, whereas most low-level variables, such as frequency and active power, change in milliseconds. All these factors make it impractical to use quantitative measurement for low-level information in exactly the same way that was done for DURESS. We must develop a different way to measure variability of performance involving low-level components.

In addition, we have to measure how the HPS controller interacts with the external environment as well as how he or she supervises the internal generation process. Unlike a controller of DURESS or Pasteurizer II, a HPS controller is not necessarily aware of all market risks and all physical constraints operating on real-time power generation. Moreover, the HPS controller must participate in creating a bid to the market, although the dispatch target finally handed to the HPS company from the market operator is influenced by factors outside the controller's control, such as the bids of other market participants and the state of the electricity network.

Given the above, a thorough evaluation of an EID interface with the CAM would have to cover many more situations than are produced within a microworld. Test scenarios would have to show how effective the EID interface is in helping the HPS controller handle representative operational and financial risks as well as representative external and internal disturbances that a HPS company might experience. This leads to a very broad variety of test scenarios to cover in an evaluation.

For example, in scenarios for representing *operational risks* such as a sudden failure of the internal equipment, the system is required to recover from the disturbance into a stable status as soon as possible. In contrast, in scenarios for representing *financial risks* such as a sudden change of forecast, the system is required to move from one stable working point to another in order to meet the demands of the electricity market. Uncovering control strategies for all these contingencies is a daunting task, and testing with enough repetition to subject performance data to tests of variability, as shown in Table 1, is equally daunting.

Even if an evaluation is confined to a more limited set of representative test scenarios, capturing and classifying strategies in a full simulator remains daunting. Within an abstraction hierarchy, high-level functions provide reasons why low-level processes exist. For instance, "revenue" is why the HPS is operated as it is and revenue can be measured. Hence high-level functions can be measured by figures of merit associated with them. Low-level processes that achieve such outcomes are harder to measure. We must consider all possible ways that a high-level outcome might be realised through actions of the (automated and human) agent in the state space of the HPS work domain. Therefore, the structure of all possible control options and the coordination among them is the meaningful "variability" of the low-level information as shown in Table 1.

AN OPERATIONAL SOLUTION

Based on the above principles, and in face of the problems noted, we have developed an approximation to CAM measures that may help us evaluate the effectiveness of HPS controllers' adaptation to the demands and disturbances of the deregulated electricity environment. In the following section our focus is on which specific measurements could be used to represent control behavior in different levels of the work domain.

CAM at high level

As shown in Figure 1, maximizing profit is the ultimate goal for every generating company. However, there are diverse ways of making money in electricity market, such as financial contracts, the spot market, frequency control services, and others. Although traders working separately from control room personnel decide strategy, consulting with controllers on availability of resources and plant safety, strategy is put into action in the control room. Therefore income from the market is influenced by how well the HPS controller manages the plant.

For example, if a dispatch target is not met within tolerance, then the HPS company will suffer a penalty from the independent market operator. A dispatch target not being met will be the direct result of some shortcoming in the HPS controller's activity.

Minimizing water consumption cost is another important metric because water is the energy resource. Ideally, the operator is expected to generate to the market target while minimizing wastage of water. Water efficiency shows how well this energy resource is used.

Therefore three key variables are proposed to represent the high-level properties of the HPS work domain: (1) maximizing market income, (2) maximizing water efficiency, and (3) minimizing deviation of generation from targets. These properties are conveyed in the functional displays indicated in Figure 1.

The status of each variable in a test scenario can be recorded in our HPS simulator data capture programme and then can be plotted as a sample trajectory over time as shown in Figure 3. In the imaginary example shown in Figure 3, participants are asked to take over HPS control at around 2 pm (see vertical lines in centre of the figure). They will be asked to perform planning for the rest of the day and to respond to any contingencies. Half the participants will use the current displays whereas half will use the current displays supplemented by the functional displays. Participants provided with the functional displays are expected to have a higher market income, better water efficiency and a lower variability in capturing high-level goals than is the case for the current interface.

Figure 3 presents imaginary results for market income only, showing that the participants are able to handle opportunities and contingencies presented to them in a way that leads to greater market income than for the group using the current interface alone. Our ability to use the variability measure of the CAM on market income will depend on the availability of trained HPS controllers. There is a tradeoff between the number of representative scenarios we wish to test and the desire for repeated observations to observe variability within individual HPS controllers. At the very least we should see less variability between HPS controllers using functional displays in the amount of market income produced, in comparison to HPS controllers using current displays.

Finally, we will collect information about control strategies from HPS controllers using the simulator. When controllers have the functional display available we expect their control strategies to make greater reference to the high-order properties embodied in the three functional displays.

CAM at low level

Video data capture and keystroke logging can provide the data to explore search patterns. Patterns of participants' control activity on the current interfaces will represent low-level processes in the work domain. Participants' search patterns through the displays may also suggest the strategy used.

For example, more frequent viewing, or a shorter viewing time, or faster detection time is expected for functional displays compared with current displays. Frequency of viewing may indicate participants' dependence on a particular display, whereas viewing time may indicate the participant's understanding of that display.

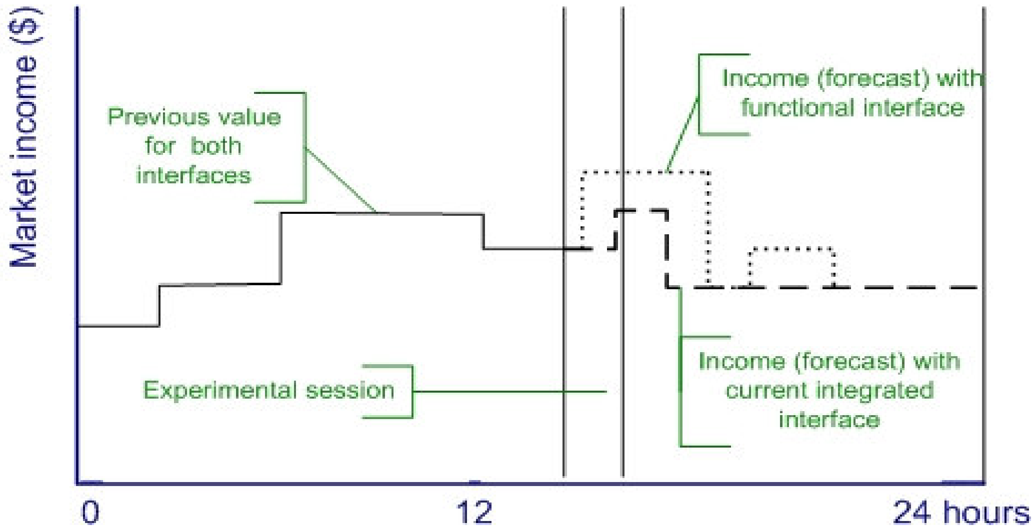

Figure 3 Example of hypothesised result for a high-level property in the HPS work domain

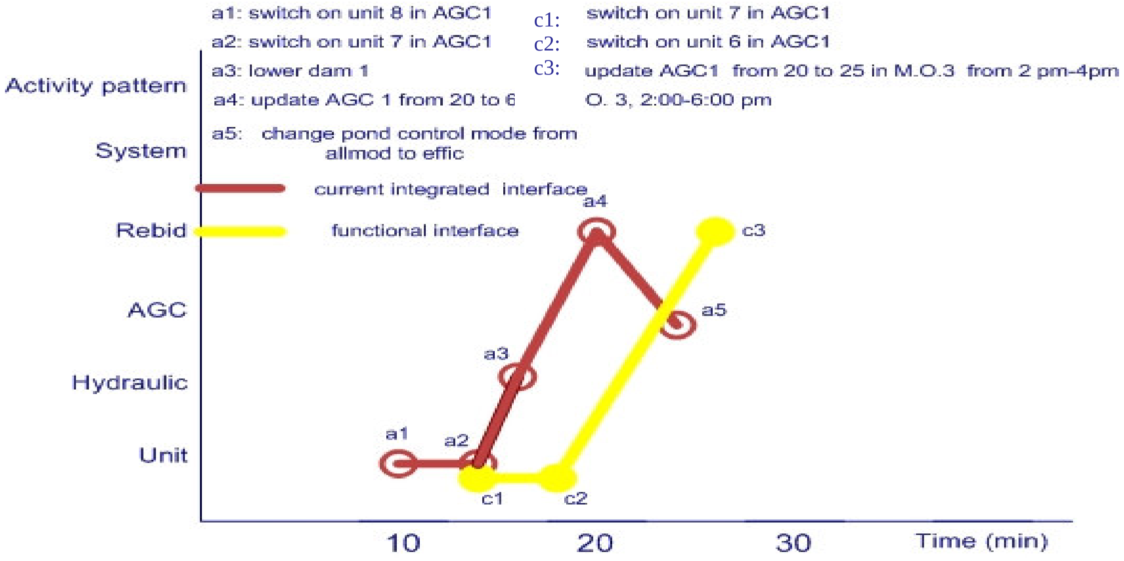

Figure 4 Example of hypothesised result for activation of low-level processes in the HPS work domain

As noted, because of the complexity of the HPS environment we are simulating, there are hundreds of potential control actions in our HPS simulator. A challenge is being able to compare sequences of control actions in a way that allows variability between sequences to be measured. One method is to look for sequences of activities across groups of displays that have a common function. The current displays can be grouped as shown in the following list. Taken together, the items in the list cover processes associated with all physical objects in the physical form level of the HPS work domain (Figure 1).

- *Generating Unit Control Displays.* These displays allow direct control of the physical generation unit, such as switch on/off. Any operations there will have an immediate impact on actual energy output.
- *AGC Control Displays.* These displays allow controllers to adjust the fit between the control system and the surrounding environment, such as communication with NEMMCO's Supervisory Control and Data Acquisition system, the allocation of generation among units within a power station or group of power stations and so on. This type of control can also be part of a longer-term control strategy, which may not have an immediate impact on real time energy output, but may result in a different output for water efficiency and for the deviation or otherwise of the energy target.
- *Hydraulic Control Displays.* These displays include the control display pages for all the gates and dams. Actions on hydraulic facilities have a direct impact on water efficiency.
- *System Characteristics Displays.* These displays are responsible for setting the constraints, like regulating limits and rough running ranges of generating units. Any changes here are based in a concern for system safety and utility.
- *Rebidding Displays.* These displays relate to the coupling of the HPS to the electricity market. Any changes will send a new bid into the electricity market and the effect on revenue will be seen.

In this way, the space of possible actions for the human operator is categorized into several qualitatively different subspaces. Each subspace is concerned with part of the means for achieving high-level control. As illustrated in Figure 4, the participant's use of different displays in each test scenario can be plotted as a trajectory over time. Sequential data analysis methods can be used to determine the similarity of sequences in terms of the ordering of displays or of display groups and in terms of the timing of actions.

Participants using the functional interface are expected to be more active than participants using the current interface. They will take more actions, use a wider variety of strategies, and will have a quicker response time.

Moreover, the linkage between the dynamics of the high-level output (as shown in Figure 3) and the structured space of state variables at the low level (as shown in Figure 4) for each test scenario provides an opportunity to describe quantitatively how human controller use of low-level processes cause the change in high-level system properties. This will help to define patterns of activity that relate high-level and low-level output.

CONCLUSION AND FUTURE WORK

In this paper we have examined how the CAM might be applied to the evaluation of functional displays built according to EID principles. If functional displays are intended to provide greater coupling between the human controller and the system they are controlling, especially under disturbances, then we need figures of merit that reflect the quality of coupling, rather than measures that simply show that the functional display led to "better" or "worse" performance.

According to the CAM, finding low variability in high-level functions indicates that high-level functions are being maintained at relatively stable levels across different situations. Finding high variability in low-level functions at the same time indicates that controllers are using the degrees of freedom provided in order to achieve greater stability of the high-level functions. If controllers use only a small amount of the variability that is offered to them it is likely they will not be able to respond to all contingencies. Therefore a functional display should pave the way for higher variability in low-level control activities by providing more control options when people are performing the same task—especially when there are disturbances to the system.

As is evident, there are some substantial challenges in the task of operationalizing such a strong version of the CAM for a complex real-world system that works through the operation of an independent market operator. Specifically, in the distributed supervisory control context of a deregulated electricity market, the direct connections between output targets and actions that are seen in simpler microworlds are no longer seen. Nonetheless, if functional displays are any help in complex systems, then they should help by stabilizing control at high levels, while making the relationship between high-level output and a broader range of possible actions lower levels evident to controllers. The opposite tendency may be evident for conventional displays.

The constraints associated with evaluating functional displays with real HPS controllers, whose availability is limited, compound the above difficulty. As a result, we need to capture the essence of the CAM in the measures we take. We should seek the pattern of results shown in Table 1, even if we cannot perform the detailed kind of analysis seen in Hajdukiewicz & Vicente (2002) and even if we must make our case on the basis of multiple figures of merit rather than one all-encompassing one.

We believe that the approach we have proposed offers a reasonable operationalization of the CAM for a complex control environment. Three experiments based on the proposed methodology to test the effectiveness of the advanced displays are planned for 2005. In addition, the proposed methodology will be verified in the experiment.

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