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Joint System Prognostics for Increased Efficiency and Risk Mitigation in Advanced Nuclear Reactor Instrumentation and Control

Workshop Meeting on Advanced Control-System Designs

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Introduction

The science of prognostics is analogous to a doctor who, based on a set of symptoms and patient tests, assesses a probable cause, the risk to the patient, and a course of action for recovery. While traditional prognostics research has focused on the aspect of hydraulic and mechanical systems and associated failures, this project will take a joint view in focusing not only on the digital I&C aspect of reliability and risk, but also on the risks associated with the human element. Model development will not only include an approximation of the control system physical degradation but also on human performance degradation. Thus the goal of the prognostic system is to evaluate control room operation; to identify and potentially take action when performance degradation reduces plant efficiency, reliability or safety.

Why is this research a critical step toward advance reactor control systems? Comprehensive joint system control system prognostics research is necessary because:

- The failure of digital I&C systems is shown to have an impact on nuclear power plant performance [Brill 2000]
- An increased reliance on digital systems and automation will be required to support a “100 person” plant;
- Testing and design validation methods are essential, but cannot account for all the complex real-time interaction and potential failure of hardware, software, and human systems within these control systems;
- A defense in depth and diversity [Chapter 7, NUREG0800, BTP-19, 1997] approach is necessary to anticipate and mitigate the effects of potential system failures to optimize plant efficiency, maintain high availability, and ensure system safety margins.

This paper presents the research currently being conducted at the Idaho National Laboratory (INL) to expand the realm of prognostics application to address control system issues including human performance. This research will support the design and implementation of advanced control rooms for NP2010 and Gen IV Plants.

Technical Objectives and Significance.
Control systems and the associated sensor systems are an intricate network of data flow and controls signals orchestrated by an enormously complex software architecture. At the helms of this system are human operators that monitor and direct system operation, coupled with various degrees of automatic system functions. Software reliability and Digital I&C reliability assessment is essential not only in the design process, but during operations. Supervisory control and data acquisition (SCADA) systems utilized in industry are a good example of this complexity and the consequences that can occur in off-normal events.

The Northeast Blackout of August 14, 2003 resulted in major portions of the northeastern United States and the Ontario area of Canada being left without power for over 24 hours in some areas. The blackout spanned 93,000 square miles and affected 60 million people. The initiating event for the blackout resulted from high-voltage lines in Ohio sagging into unkempt trees and “tripping” offline. Compounding the event was the fact that First Energy’s SCADA computerized alarm failed silently and control room operators did not know they were relying on outdated information, trusted their systems, and discounted phone calls warning them about worsening conditions on their grid.

After the grid was restored and an investigation occurred, it took several weeks for engineers to reproduce the Ohio alarm crash in a test laboratory. What they discovered was what is known as a race condition. A spokesman for the SCADA vendor reported; “There were a couple of processes that were in contention for a common data structure, and through a software coding error in one of the application processes, they were both able to get write access to a data structure at the same time, and that corruption lead to the alarm event application getting into an infinite loop and spinning.” [LaPedis 2004].

If an online prognostics system were utilized, could the race condition and subsequent alarm malfunction have been identified or better yet, prevented? Consider also the ramifications if an "advanced" computer control system malfunction resulted in even a minor "event" at a commercial nuclear facility. The likely shutdown of the plant, the time required to isolate the problem, and the time required to recertify the system would cause great economic and political hardship to the facility. Regardless of the above consequences, consider the loss of public confidence in the system.

Brill [2000] conducted an analysis of the impact of instrumentation and control system failure on nuclear plant operations from 1994 to 1999 based on Nuclear Regulatory Commission (NRC) Licensing Event Reports (LER). The goal of the study was to provide insight into the potential vulnerabilities of digital I&C systems as well as to provide a basis for research as the new digital technologies are proposed for introduction into nuclear power plants. The study identified the following for the 6681 LERs submitted during the 1994 – 1998 timeframe:

- 385 involved digital anomalies
- digital anomalies contributed to 60 of the 484 total reactor trips.

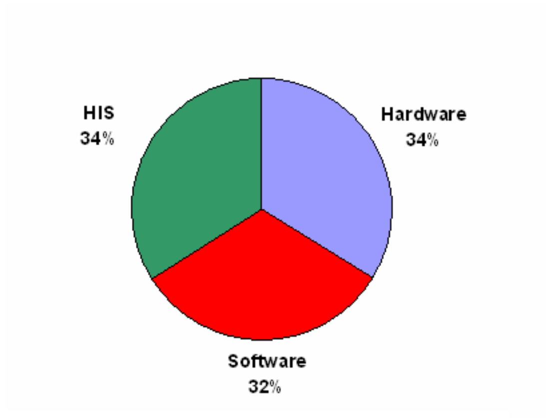


Figure 1. Digital anomaly distribution

Brill further categorized the digital anomalies in terms of hardware, software, and human/systems interface (HIS). Figure 1 shows the distribution of these failures.

Digital instrumentations and controls (I&C) and software reliability represent an enormous challenge in terms of availability and safety validation. Additionally, as new reactor control designs include greater levels of digital I&C, developing a technical baseline for licensing such systems becomes ever the more challenging.

Real-time control systems represent an intricate combination of hardware, software, and human interaction. Conditions that resulted in system anomalies, like the SCADA system failure during the NE Blackout, are rarely accounted for in testing. The program controlling the alarm and indication portion of the SCADA system contained over 1 million lines of code. It is unrealistic to believe that extensive software testing could have even found this condition. It must be realized also that such testing does not assure that flaw or unsafe conditions do not exist, it merely confirms their presence within the confined testing space. Current software debugging techniques may be insufficient for identifying system errors due the specific timing characteristics and the interactions with system components [Lindahl 2005]. Nor can every possible event be explored. Additional anomalies follow system upgrades. Many have realized this same frustration when upgrading software or hardware on their computer, which results in the inoperability of another system component.

Nancy Leveson (2004) of MIT's MIT Aero/Astro Software Engineering Research Laboratory states the following about the development of complex systems:

> We are designing systems with potential interactions among the components that cannot be thoroughly planned, understood, anticipated, or guarded against. The operation of some systems is so complex that it defies the understanding of all but a few experts, and sometimes even they have incomplete information about its potential behavior. Software is an important factor here: it has allowed us to implement more integrated, multi-loop control in systems containing large numbers of dynamically interacting components where tight coupling allows disruptions or dysfunctional interactions in one part of the system to have far-ranging rippling effects. The problem is that we are attempting to build systems that are beyond our ability to intellectually manage: Increased interactive complexity and coupling make it difficult for the designers to consider all the potential system states or for operators to handle all normal and abnormal situations and disturbances safely and effectively.

Thus the complexity of such systems reduces our ability to fully understand and quantify the risks of operation under all circumstances.

Objective:
The objective of this project is to develop an online digital control system prognostics framework and prototype that will assess the joint system performance to include human in the loop operations and initiate appropriate system response to improve reliability, efficiency and safety. To meet this objective, this project will address the following tasks:

- Identify online system measures (either calculated or sensed) that have potential for digital system performance prediction.
- Develop the model of the precursive relationship between measurable elements and component failure / digital system degradation / out-of-norm behavior.
- Identify online measures within the digital control system that have potential for human performance prediction.
- Develop the model of the precursive relationship between measurable elements and degradation in human operator performance (i.e. loss of situation awareness, excessive workload, fatigue, etc…)
- Develop a prototype prognostics system that evaluates overall control system performance that is based on the combined performance of the physical system, the human operator, and the interaction between the two.
- Based on the prognosis, develop a set of possible system responses to mitigate or improve reliability, efficiency, and safety. This may include the automatic shifting between different levels of autonomous system control.

Research Design and Method
At the very basic level, this task addresses three research questions:

1. Can a digital system "health meter" be developed for evaluating control system operation and predicting hardware and software performance?
2. Can a human system "health meter" be developed based on human interaction with the control system to predict sub-optimal and potentially hazardous performance? (e.g. loss of situation awareness, overload, fatigue.....)
3. Can the knowledge and actions initiated based on (1) and (2) be combined to increase overall system reliability, efficiency, and safety?

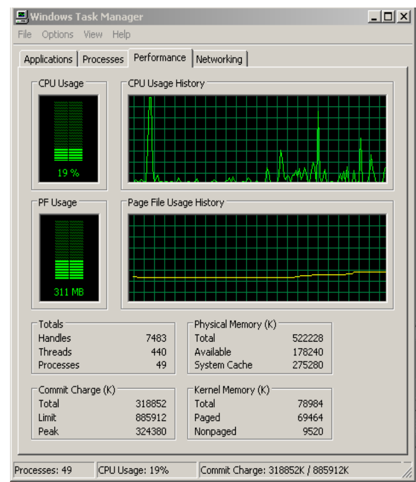


Figure 2. Windows

This research is novel, but it does have a basis in current technology. Current computer system tools allow a user or system administrator to monitor various performance measures. These include utilization rates, system logs, and process information. These systems rarely, however, work in an online capacity to predict system degradation and offer preventative solutions. Consider your desktop computer and Microsoft Office Applications. Pressing "Ctrl + Alt + Del" brings up the Windows Task Manager in which one can monitor the "performance" of the system. Figure 2 illustrates the window showing CPU usage and Page File usage, but really what does this mean in terms of optimal performance, pending system failure, etc… Computer network monitoring is another performance monitoring application. Here communication flow between users is monitored to ensure connectivity, minimize congestion, and to identify potential aberrant user behavior. Systems such as these are rarely prognostic in nature.

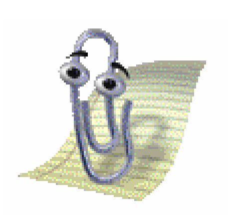


Figure 3. Office Assistant

Online human performance prediction is not entirely new either. Consider the "Office Assistant", figure 3, that is known to many Microsoft Office users. The system, more precisely, the Microsoft Office product, senses user action and infers intent, offering suggestions, when the actions are not recognized.

Real-time control systems.

Real-time control systems differ in many ways from the above desktop computer examples. Real-time control systems may be distributed over large areas, linked to thousands of sensors, in control of thousands of actuator, and divided into multiple levels of subsystems. A common characteristic, however, is the time driven nature of data or information. Philippi (2003) conducted an analysis of fault tolerance and reliability in a distributed real-time system, namely the electro-mechanical brake (EMB) system for an automobile. Electronic control units (ECU) independently control the actuators for the brakes at each wheel. A centralized control unit contains a model of vehicle motion, which in turn communicates with the ECU's for the individual wheels. Human interaction with the system consists of applying pressure to the brake pedal. Within this control and actuation network he proposed the concept of an information horizon to reflect this flow of information.

The operation of each component requires a specific information flow for operations. This represents the information horizon of the component. If this information horizon requirement for each component can be identified and measured online, then it may be possible to calculate system reliability or conversely degradation. Similar to the physical system, what is the information horizon that the driver requires to apply the brake in the appropriate amount of time to avoid collision?

Mathematical Derivation Of The Problem Space

Building upon Philippi's [2003] definition of a real-time control system architectures, Let S= (N, C, Fc, M, U, Fu), with

- N the set of system nodes or processes, i.e. sensors, controllers,
- C the set of communications systems
- Fc: N→ P(C) a function linking nodes to communication systems
- M = {(s,r,c,id)} the set of message types in the system, each characterized by the sender s ∈ N, the receiver r ∈ N, the connection c ∈ C, to use messages of this type and an id to uniquely identify different message types.
- U the set of human operator interactions to the system
- Fu: U→ Q(C) a function liking human interaction to communications systems
- Pn: the set of performance characteristics defined for N
- Pu: the set of performance characteristics defined for U
- Pc: the set of performance characteristics defined for C
-

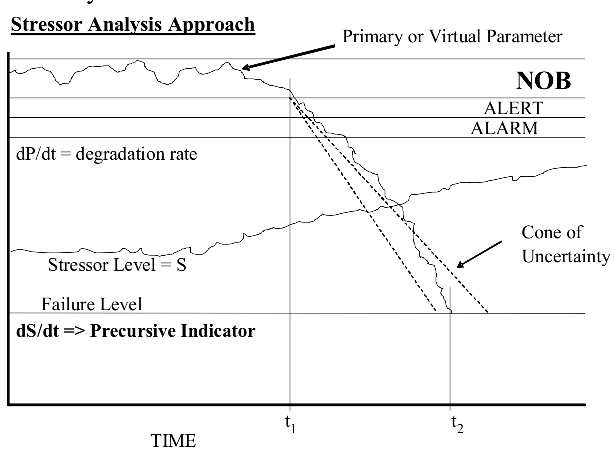


Figure 4. Degradation

With this definition it is now possible to mathematically define the system degradation in terms of a performance level (Pn, Pu, Pc).

This project seeks to identify and quantify system stressors that act as precursors to control system degradation. The hope is to extend the methodology utilized by Bond et. al. [2002]. While their project demonstrated a prototype prognostics system for a physical system, this project will develop a prognostics system to monitor the performance of a digital control system and the associated human system interaction.

As such define

$$dP/dt = \text{performance degradation rate}$$

and the overall control system degradation is a function of individual component degradation.

$$dP/dt = G(S)$$

where S = {Sn, Su, Sc}, the set of stressors for N, U, and C respectively. Then

$$dDR/dt = d^2P/dt^2 = dS/dt, \text{ the stressor trend or slope.}$$

Figure 4, [Bond 2002], illustrates these relationships. Within the scope of control room operations, the idea is to characterize the above behavior for the set of critical performance characteristics and promote the ability to take either human initiated or system initiated action at time t_1 instead of time t_2.

Techniques.
While the application of joint systems prognostics for a control system may be novel, prognostics methods have been developed for a wide range of mechanical and hydraulic applications. These techniques normally apply a pattern matching technique and predictive technique based on a weighted set of measured or calculated parameters. Additionally, software and digital reliability methods will be evaluated for applicability. These techniques may include statistical techniques such as regression or employ artificial intelligence such as neural networks or expert systems. Patra (2003) proposes a neural network approach for determining the mean-time-between failure for software programs. Other example methodologies of potential interest in the area of real-time control systems include Kim (2000), Garrett and Apostolakis (2002), Philippi (2003), and Hassan and Aldemir (1992). While these techniques represent system and software models, they do not address online system evaluation.

Similar to Brill's analysis of digital system failure, this project has a three pronged approach to addressing the problem domain:

- Physical system degradation (hardware);
- Software system degradation/failure; and
- Human performance failure (HMI)

Under the INL's direction, efforts in these areas are being led as follows:

- Dr. Donald Miller, the Ohio State University – analysis of controls system environmental stressors and failure modes;
- Dr. Humberto Garcia, the Idaho National Laboratory, the application of hybrid prognostics techniques for detecting material failure;
- Dr. Wesley Hines, the University of Tennessee, benchmarking and the application of prognostic principles to software performance including cyber intrusion detection; and
- Dr. Tuan Tran, the Idaho National Laboratory, the identification of human performance measures associated with human-machine interaction and the application of prognostics analysis.

While each of these areas constitutes multiple research papers in itself, the remainder of this paper will address the aspect of human performance measures.

Human Performance: Human System Health Meter

Next generation control room will be more complex and automated, thus shifting the operator's role to more of a supervisory control with emphasis on monitoring, and in some cases, under high task-load (e.g., in a multi-modular reactor system, operator may be required to monitor more than one reactor system). High task-load is known to induce stress as well as fatigue, while vigilance is recognized to drop drastically after 30 min of prolong monitoring. Interactively, these factors can severely diminish one's ability to perceive, recognize, and respond to emergency or unanticipated event, thus can place both the operator and system at risk (Ji & Yang, 2002). For this reason, developing a human "health meter" system that can actively monitor and assess an operator's level of workload, stress, and fatigue is essential to reduce plant risk.

Traditional approaches in human-computer interaction (HCI) to alleviate human cognitive limitation have focus primarily in design and training (Pavel, Wang, & Li, 2002). For example, memory ads such as checklists or mnemonic are embedded within the design process and plant procedures to circumvent human memory limitation. Repetitive training and rote-learning are performed to improve performances under stressful conditions. And finally, task analyses are conducted during the design process to determine shared resources among operators to reduce workload. The major limitation to these approaches besides high costs and time is that they are ineffective in generalizing to novel events (Pavel, Wang, & Li, 2002). For instance, during an unanticipated event, automation control may be shift to operator's manual control. This shift in control can abruptly places high workload upon the operator particularly, in highly arousing time pressure or diminish vigilance due to prolong monitoring. Under these situations, it is advantage to have a system (similar to Figure 1) that can monitor, assess, and be sensitive to human limitations.

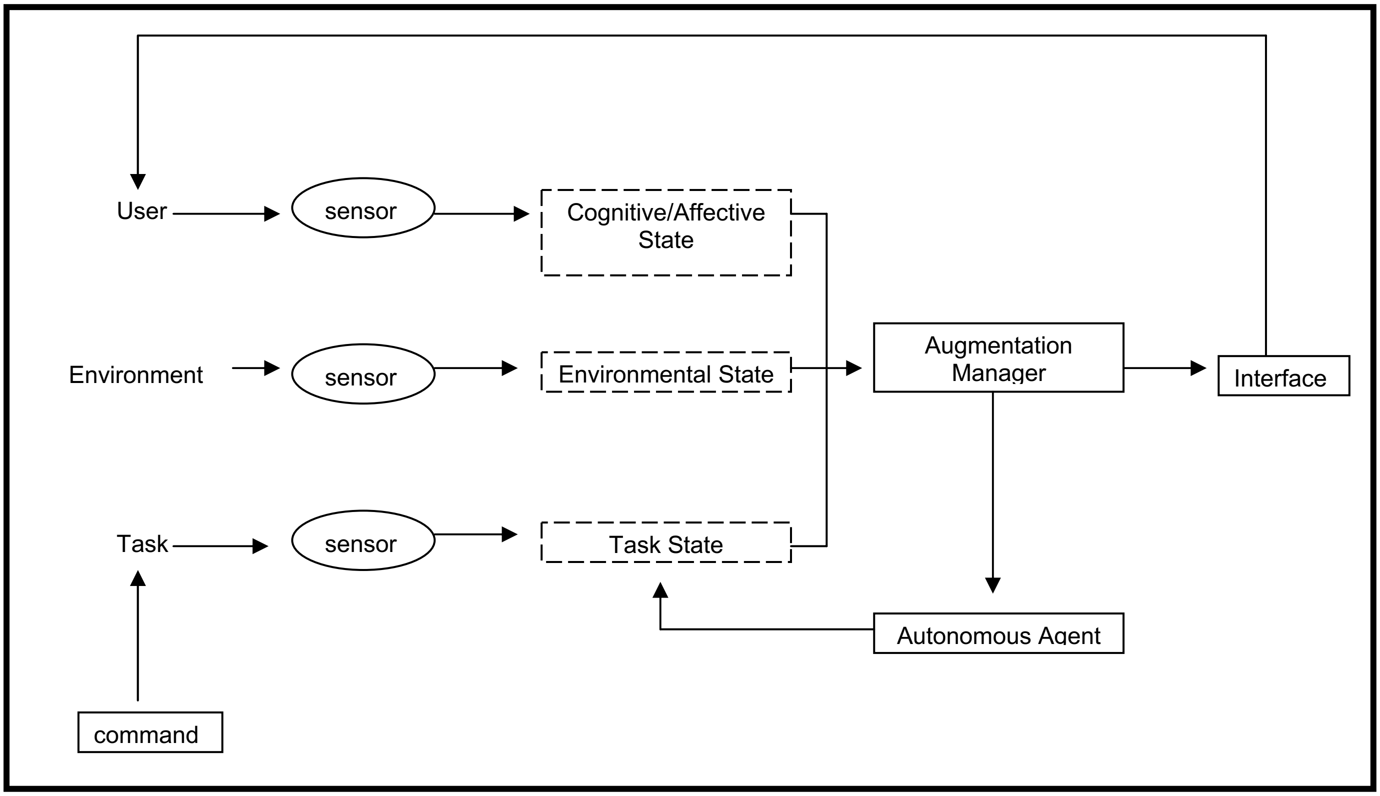


Figure 1. Diagram of an Augmented Cognition System (Marshall & Raley, 2004)

The diagram in Figure 1 begins with a command (e.g., an event induces the control to be switch to manual) influencing the task. The sensors (i.e., gauges) detect activity from the user, environment, and task, and produce models that reflect the current state of the user, environment, and task. The produced models are integrated and interpreted by an augmentation manager that assess and determine an appropriate strategy to mitigate the information system bottle-neck (Marshall & Raley, 2004). Hence, with an augmented cognition system, an operator experiencing heavy task-load, stress, or fatigue, can be asses by the system. The system can then re-configure and decrease the flow-rate of information to heavy-tasked operator, guide the operator's attention to relevant information in the display by highlighting, blinking, or zooming in to the pertinent information (Pavel, 2003), or the system can advise the operator to switch more of the workload activity to automation during highly stressful conditions.

The emerging field of augmented cognition is focus on developing computational methods that address information processing bottlenecks that are inherent in human-computer interaction such as processing limitation, mental fatigue, boredom, and stress (retrieved July 2006 at http://www.augmentedcognition.org). Two questions currently addressed by the field of augmented cognition are: First, how to quantitatively assess the individual's cognitive state in terms of specific measures (gauges)? And secondly, how to use these measures to control the augmented cognitive aids? Thus, the field of augmented cognition has a significant overlapped with our goals of developing a human "health meter" system, a segment within our overall joint system prognostics. Because of this, we have relied on its literature in deriving theoretical frameworks and practical performance gauges to initially support our research program. Our research program in developing a human "health meter" system consists of three phrases: First, we aim to identify on-line performance gauges that are unobtrusive and can be built within the digital control system. Second, we aim to validate these on-line performance gauges in phrase 1 experimentally and within the context of the control room. Finally, we aim to develop a system model (e.g., augmented manager in Figure 1) capable of identifying degradation in human performance as well as determining relevant actions (e.g, reduce information flow after recognizing that the operator is fatigue) to support optimal human performance level. We next discuss each research phrases in depth.

Research Phrase #1: Identified on-line performance gauges that are unobtrusive and can be built within the digital control system.

Currently, the most popular on-line performance gauges in assessing operator's cognitive and affective states are physiological measures (e.g., EEG, fNIR). However, concerns with many popular physiological measures are its obtrusive nature (e.g., interfering or restricting natural body movement), poor comfortability, cannot be worn for a long duration of time, and bodily fluid (e.g., sweats) interfering with the devices (Ikehara& Crosby, 2005). To mitigate these concerns it is ideal to have performance gauges that can be built onto or within the control system. Below is a list of performance gauges we have identified as being suitable for use in control room.

a. *Eye-Tracking and Image-Based Technology.* Eye-tracking research has become a popular tool in many disciplines in generating understanding to cognitive behaviors such as what information people use, where do they look for the information (i.e., scanning patterns), when do they use the information, and how much time is needed to process various pieces of information (Salvucci, 1999). Similarity, image-based technology has also been used to assess individual's cognitive and affective states. Image-based technology rests on the theoretical foundation that a person's states can be "exhibit in certain visual behaviors that are easily observable from changes in facial features such as the eyes, head, and face" (Ji, Zhu, & Lan, 2004). Thus, eye movement behaviors (e.g., eye-blinking frequency, eye-closured speed, pupil dilation, and gaze duration) and visual behaviors (e.g., yawning, sluggish in facial expression, sagging posture, body- and face-movement) can be use collectively to asses a person cognitive and affective states. Applications of such technology have been validated as evidence of its increasingly use in the field of human-computer interactions in exploring the speed and ease of interface usability (Salvucci, 1999) and in the driving industry in exploring driver's state of vigilance and fatigue (Ji & Yang, 2002).

b. *Input Device Behaviors.* Behaviors on input devices (e.g., amount of pressure place on the device) have also been explored to asses a person's cognitive and affective states. For example, mouse behaviors (e.g., clicks, pressure) have been cited as a good gauge in assessing a person's cognitive and affective states (St. John, Kobus, & Morrison, 2003).

c. *Behavioral Activity and Performance.* Behavioral activity assesses the frequency (i.e., patterns) in which the operator interacts with the systems such as repeatedly re-sampling of information regarding a particular system statues or repeatedly cycling through the system (van Orden, 2001). Behavioral performance assesses the operator's deteriorated task performance as an indication of the operator's cognitive states such as slower responses to task, skipping steps in procedures, and spikes in committing task errors. In the driving literature, vehicle behaviors such as speed, lateral position, and turning angle, have been used as indicators of driver's alertness level (Ji, Zhu, & Lan, 2004).

d. *Verbal Activity.* Verbal activity assess the quality of speech (e.g., pitch) as indication of operator's cognitive states (van Orden, 2001). Thus, the difference in a person's pitch, voice segment, and speed of speech can be use as indicators of a person's cognitive and affective states.

As discussed earlier, a successful performance gauge in control room must be unobtrusive. Thus, we have selectively identified performance gauges in the literature that can be easily built onto or within the control system. For example, both eye-tracking and imaged-based technology can easily be embedded onto a computer monitor or display. Thus, such performance gauges can assess human performance without interfering or restricting the operator's natural movements. Input devices, behavioral activity and performance, as well as verbal activity, are performance gauges that can be part of the control system (i.e., part of normal control room activities); thus, relieved our concerns of performance gauges obtrusiveness and comfortability.

Research Phrase #2: Experimentally validating on-line performance gauges in control room setting.

As illustrated in Research Phrase #1, we were successful in identifying several performance gauges in literature. Furthermore, some our selected performance gauges have been successfully validated in the literature. Even so, in the current research phrase, we aim to experimentally validate our selected performance gauges to control room setting. There are many reasons for a need to validate our selected performance gauges; for example, control room activities and tasks are more complex and dynamic than many experimental studies in the performance gauge literature. More importantly, many studies in the psychological literature use students as participants who are unfamiliar to the experimental task(s). Conversely, in the control room, operators are highly experience and skillful in performing task(s) that are highly proceduralized in nature. We next briefly outline our experimental protocol which includes our participants, materials, procedures, and analyses.

Participants

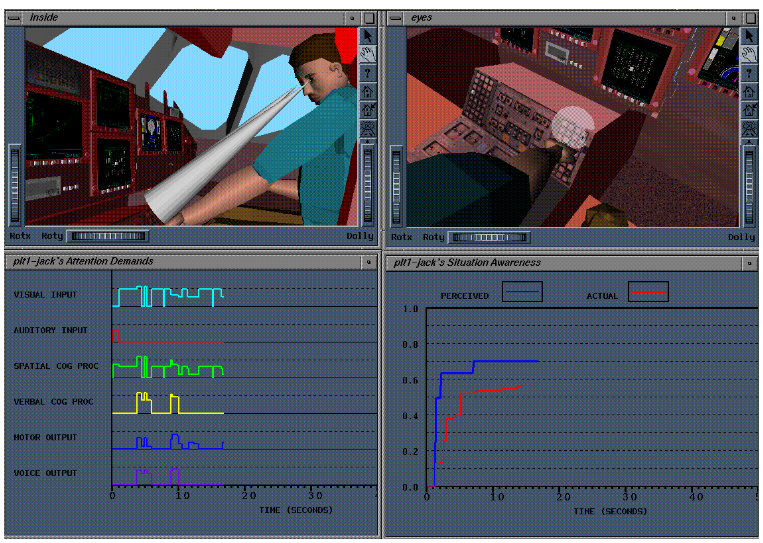
As mention above, control room operators are highly experienced and knowledgeable of their tasks. Therefore, using any other participant pool other than licensed control room operator can seriously hamper the external validity of our performance gauges (i.e., are we confident that what the performance gauges measure is true for the target population?). To maximize our participant pool of licensed operator we have identified two primary sources of recruitment, Idaho National Laboratory (INL) Advance Training Reactor and Halden Reactor Project in Norway. This partnership between INL and Halden will allow us to perform *cross-validation studies* (i.e., did the results in one facility replicate the other facility findings) that will greatly enhance the external validity of our performance gauges.

Materials

To conduct our studies, we will need to generate *control room scenarios* consisting of embedded critical events (e.g., emergency situation, information overload) that we are confident to have an effect on individuals' cognitive and affective states. Using traditional experimental methods, such critical scenarios can be constructed by either 1) taking validated scenarios from the literature or 2) designing new scenarios and then conduct pilot studies to validate it. Unfortunately, published studies on control room are scarce and designing and validating new scenarios will take large amount of time and cost. Thus, in context of the current research, it is not ideal to rely on traditional experimental methods in constructing control room scenarios. An alternative approach is to use current advances in cognitive modeling (that is based upon fundamental models of human performance) as a tool to construct, stimulate, and validate new control room scenarios. In other words, the cognitive modeling tool will output if (and to what degree) our embedded critical events have a significant effect on individual cognitive and affective states based upon hundreds or thousands of stimulated trials. Because each stimulated trials is well-rested upon theories of human performance, we would expect actual human behavioral data (if we were to conduct an experiment) to closely match with the final stimulated data. Thus, this demonstrates a strong advantage of using a cognitive modeling approach. We have identified the Man-machine Integration Design and Analysis (MIDAS) modeling environment to be suitable in achieving our objectives.

MIDAS consists of three integrated modeling systems: 1) **the human operator model (H-M)** – characterizing the operator's perceptual, cognitive, and motor behaviors based upon well-founded psychological principles and theories, 2) **the task/equipment model (IT-M)** – defines the task(s) and equipment(s) that the operator interacts with to fulfill a goal, and 3) **the environment model (E-M)** – replicating the actual element(s) of the environmental context (i.e., terrain) using 3-D computer aided design (CAD) software (Gore and Jarvis, 2005). These three models can be simultaneously or selective manipulated.

MIDAS operates in two major modes with each mode producing a unique output. The first mode is the "Interactive Mode" that examines the anthropometric and visibility characteristics of the simulated human behavior. The interactive mode is shown in real-time within a 3-D animated graphical representation consisting of the task environment and a human operator "Jack," a full-scale body figure with realistic movement. This visualization output of "Jack" behavioral action with in a 3-D graphical environment promotes simple and straightforward analysis of ergonomics and visual attention properties within the virtual environment. The second mode is the "Simulation Mode" that examines behavioral performance given the task properties, environmental context, and human characteristics (i.e., perception, cognition, and motor behavior). Results of the simulation mode are presented on a graph on which the y-axis represents the different individual performance systems (e.g., visual) with its level of workload while the x-axis represents time in seconds (see Figure below)



Sample MIDAS simulation of astronaut work-load during Space Shuttle landing.

MIDAS will make it possible for us to examine and validate our constructed scenarios based upon theories of human performance in a wide variety of configurations and design concepts (e.g., types of staffing models) prior to conducting human experiments; thus saving time and costs compare to traditional experimental methods.

<u>*Experiment procedure*</u>

Participants will be asked to complete several scenarios in a high-fidelity control room simulator. Beside the eye-tracking device (due to calibration procedures), participants will not be informed of the presence of different performance gauges that are embedded (e.g., image-based device) or within (e.g. input devices, behavioral activity) the control system. Scenarios will consist of routine procedures and critical events. The experimental session will be taped. After completing the experiment, participants can be asked to review the taped session and make remarks (e.g., scale questionnaire) regarding to their cognitive and affective states on various critical moments during the session.

Analyses and Expected Results
The reliability and validity of our performance gauges can be asses by examining how consistent our performance gauges revealed a ***difference*** in performance activities when the operators encountered a critical event compare to performance activities when the operator performed routine procedural task. Furthermore, we want to examine the ***relationship*** between changes in our performance gauges activities corresponding to critical events as well as operator's post-experiment self-report of their cognitive and affective states during critical events. Finally, we can use advance multivariate statistics such as discriminate analysis or logistic regression in examining the question, "given our performance gauges results, how accurately can we classified (i.e., high, med, low) this operator's cognitive and affective states?" and structural equation modeling, in assessing how well each performance gauges accounts for our operator's performances.

Research Phrase #3: Develop a system model (e.g., augmented manager in Figure 1) capable of identifying degradation in human performance via the different performance gauges as well as determining relevant actions (e..g, reduce information flow after recognizing that the operator is fatigue) to maintain optimal human performance level.

The focus of this research phrase is on developing a system model that can detect, assess, and classify operator's cognitive and affective states; but more importantly, developing a system model that can choose the best course of actions given the states of the operator. Thus, the current research phrase will be exploring and examining different artificial intelligence systems (e.g., Baysian Network) to fulfill our research objectives.

In summary, our research program in developing a human "health meter" system consists of identifying and validating performance gauges for use in control room setting, and to develop a system model that can identify degradation in human performance as well as determining the best course of action to maintain optimal human performance. This research program will support our over-arching goal of developing a joint system prognostic that integrates human, software, and hardware degradation systems.

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