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A Prototyping Environment for Research on Human-Machine Interfaces in Process Control

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Use of Microsoft WPF for Microworld and Distributed Control System Development

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Abstract—**Operators of critical processes, such as nuclear power production, must contend with highly complex systems, procedures, and regulations. Developing human-machine interfaces (HMIs) that better support operators is a high priority for ensuring the safe and reliable operation of critical processes. Human factors engineering (HFE) provides a rich and mature set of tools for evaluating the performance of HMIs, but the set of tools for developing and designing HMIs is still in its infancy. Here we propose that Microsoft Windows Presentation Foundation (WPF) is well suited for many roles in the research and development of HMIs for process control.**

Keywords—human-machine interface (HMI), distributed control system (DCS), prototype, microworld

I. INTRODUCTION

Monitoring and controlling industrial processes, such as nuclear power production, is complex, and human performance represents the single largest contributing factor to the overall reliability of a system [1]. The dynamics of such processes are often high-order with cross-coupled key process variables. Further complexity is added through the incorporation of setpoint controllers, safety interlock systems, and other forms of automation. Consequently, operators must understand how to anticipate, monitor, and occasionally override automation in addition to understanding the processes being controlled by automation. Often system processes cannot be directly observed. Operators must rely on "keyhole" views of processes provided by electro-mechanical sensors and digital human-machine interfaces (HMI) [2]. The proliferation of digital systems offers many new capabilities. Estimates can be made more reliable by incorporating redundant sensors, redundant analog-to-digital converters (ADC), and applying digital signal filtering. Signals can be recorded to historical databases and potentially displayed at a moment's notice. In many instances indications do not directly convey the information that may be of interest to an operator. For example, in a two state thermal hydraulic system (i.e., liquid and vapor) operators may need to know the mass in a particular location. Indicators might tell the operator the pressure and temperature at a location, but do not directly convey mass. Systems that perform real-time thermo-hydraulic balancing can approximate and represent such information to operators and may aid in the reliability, safety, and efficiency of industrial processes.

However, despite these advances, having more data is not always beneficial. Distributed control systems (DCSs) and supervisory control and data acquisition systems (SCADAs) have greatly increased access to available data and potential alarms, but the information processing capabilities of operators has remained unchanged. Consider configured alarms, which have increased exponentially from the 1960s to 2000s. The result is that even when processes are in steady-state alarms will sound, providing little to no informative value to operators and potentially hindering their ability to attend to the process [3]. Interfaces need to capitalize on advances in digital control by providing operators with data in context. Rasmussen and Vincente [4] describe data in context as "the goal to make the invisible, abstract properties of the process (those that should be taken into account for deep control of the process) visible to the operator."

Knowing how to effectively present information to operators is part art and part science. Current Human factors engineering (HFE) is often more diagnostic than prescriptive. It offers normative approaches to evaluating interfaces (e.g., NUREG-0700 [5]) and guidelines specifying what interfaces should do (e.g., they should support operator's mental model of physical system or they should provide information relevant to users), but falls short when it comes to explaining *how* such feats can be accomplished. There may be many contributors to this problem. Real-world industrial processes are often one-of-a-kind and require extensive training to understand and operate. Cognitive systems engineering (CSE, [6]) proposes a framework for understanding and evaluating the rules, skills, and knowledge operators use to process information. In conjunction with Ecological Interface Design (EID, [4, 7, 8]) a "triadic" approach to interface design can be established as one that is tailored to specific work demands (domain/ecology), leverages perception-action skills of the human (human/awareness), and uses interface technologies wisely (interface representation, [9]). All three of these components are necessary conditions for the success of an interface. Unlike traditional user-centered design, EID focuses on making the constraints of the physical system being presented. Pragmatic approaches to design such as Tufte's [10] aesthetic approach or Hollifield, Oliver, Nimmo, and Habibi's [11] experience driven "High Performance HMI" handbook approach, or Halden's perceptually oriented Information Rich Design [12] approach also offer significant value to perspective practitioners, although they may forgo much of the theoretic and empirical rigor of approaches like CSE and EID. Guidelines likely lead to resilient interfaces when applied in well-defined contexts. However, when context changes, pragmatic approaches may fall short as they provide knowledge on *how* and not necessarily *why* a solution works. The primary downside to CSE and EID is that it is viewed as academic and overly theoretical. A potential interface designer might think they need to first obtain a PhD in Cognitive Psychology and then ponder the meaning of "meaning" before venturing into actual design work.

The goal here is not to present a treatise between basic and applied perspectives. Bennett & Flach [9] have already provided some poignant analysis on these issues. They also believe the situation to not be completely disparaging. For HMIs to progress a theoretical understanding of how operators perceive, understand, and act on information is needed. This understanding must capture the full complexity provided by real-world work-domains. Unfortunately, conducting field studies is not always possible or practical: system and organizational complexities hinder experimental control, using a full-scope simulator with fully qualified operators provides external validity but at a significant financial expense, and lastly the entire population of qualified operators for a real-world process may be insufficient to draw statistically reliable conclusions. The alternative is to use *microworld* simulation environments to capture the essential characteristics of the real-world problems. By examining *in vitro*, confounding variables can be eliminated and underlying scientific principles can be discovered [13-15]. Then findings can be applied and tested with full-scope simulators, and eventually validated with real-world systems.

Here we suggest that Microsoft Windows Presentation Foundation (WPF) is perhaps an overlooked or at least underutilized tool for HMI research. WPF provides a tremendous amount of value, reliability, graphical sophistication, and scalability to the implementation of HMIs for process control. Implementing novel displays and controls in vendor DCS solutions is not always possible or may entail specialized knowledge of and skills with proprietary software. Obtaining the requisite skills and knowledge may even pose difficulty or significant expensive. In contrast, WPF is Microsoft's de facto development environment for building native Windows applications. Development pertinent information is readily available as is a cadre of skilled individuals. In practice, this translates to a common tool set for developing microworlds, EIDs, and full-scope prototypes. Elements developed and tested in microworlds can be up-cycled into full-scale process control prototypes.

II. WINDOWS PRESENTATION FOUNDATION

WPF is built on Microsoft's .NET framework and utilizes their Visual Studio integrated development environment. The large user base has allowed Microsoft to devote a tremendous amount of resources to developing an extensive and reliable suite of controls and programming libraries. WPF inherently separates the presentation or *view* of an application from the underlying model. This analogy is easily adopted by both microworlds and full-scope prototypes. Microworld models can be implemented in any .NET language (C++, C#, Visual Basic, Python, F#). WPF applications can communicate with full-scope simulation models using standard protocols such as TCP/IP sockets, Object Linking and Embedding for Process Control (OPC), or through vendor provided .NET interfaces.

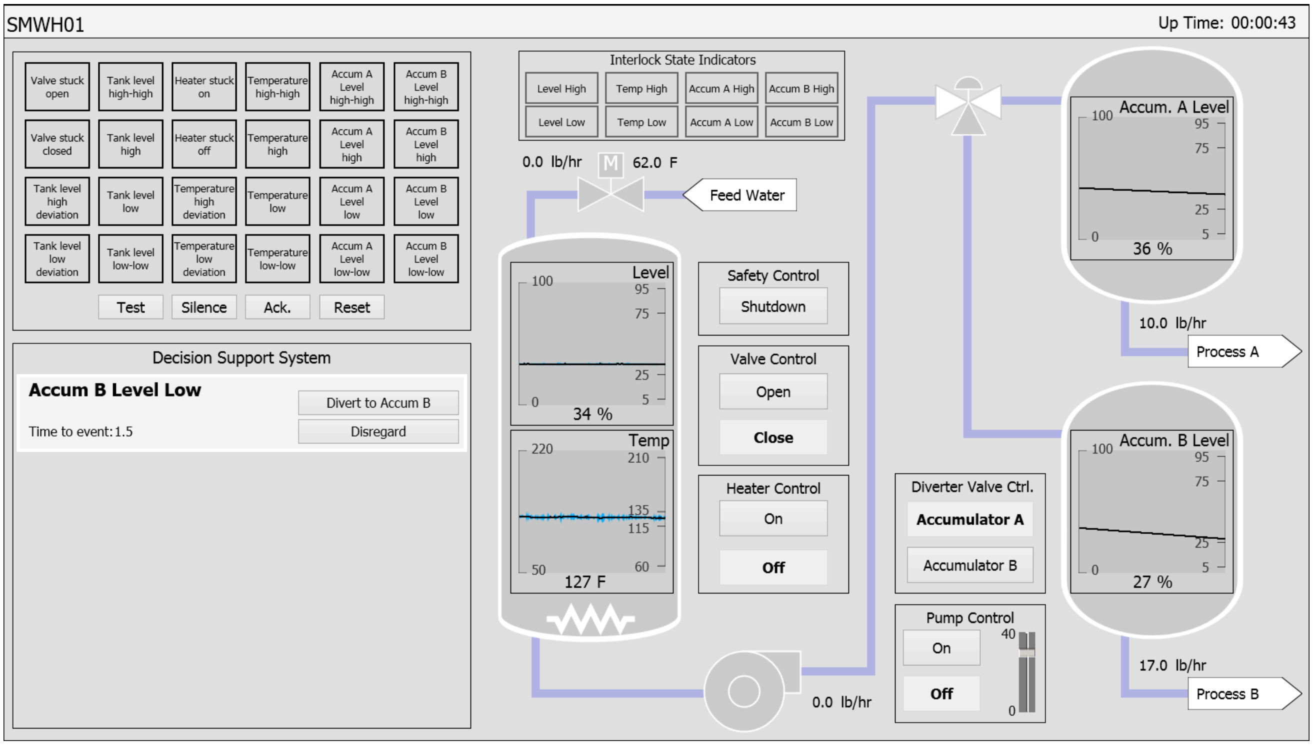
With the WPF architecture the visuals can be defined by extensible application markup language (XAML). The markup is XML compliant (like HTML) and can be coded or produced using graphical design tools like Microsoft Blend or Visual Studio. Custom user controls and objects can be developed and reused across applications. This inherent flexibility allows for non-programmers to design and mockup interfaces that can be developed into real applications. Custom user controls can also be developed and tested independent of larger applications. This would allow less experienced software developers, junior engineers, or students to work on components independent of the complexities involved with communicating with full-scope process simulators.

The use of the graphical HMI front-end of WPF also translates into reconfigurability of objects and controls. As such, the look and feel of one proprietary environment (e.g., Emerson/Westinghouse Ovation) can be exchanged with another (e.g., Honeywell Experion) simply by changing the style properties of the objects. This allows easy prototyping flexibility for different needs and applications. Changing the look and feel of the objects and controls also facilitates HMI research, as aspects of the design can be readily and easily modified to validate and optimize visual elements.

WPF essentially becomes a library of objects and controls that can be readily reused or adapted for rapid prototyping purposes. It is important to note that the objects defined as part of WPF include not only graphical properties but also behaviors. Simple logic can be built into each object as parameters. For example, a valve may be defined as having an open or closed position. The valve position may be driven by external data sources such as the OPC database used by most full-scale simulator vendors. This relationship may be bidirectional—a change in the valve object in the HMI may change the value in the plant model via OPC, or change in the environment (e.g., automatic valve closing in response to abnormal conditions) may change the status of the object. As our library of objects and controls has grown with use, we have successfully created a standardized set of HMI elements that can interface with internal simplified prototype simulations to full-scope nuclear power plant models.

III. CASE EXAMPLE 1 - MICROWORLD SMALL MODULAR WATER HEATER

Figure 1 depicts a microworld process control application intended for academic research. The process simulates a resistive electric water heater feeding a pump. In series with a pump is a diverter valve leading to separate accumulators and process supplies. To the top left is an alarm



Decision Support System

Accum B Level Low

Time to event: 1.5

Figure 1. Small Modular Water Heater microworld with Decision Support System. The SMWH is available under the GNU General Public License from the primary author.

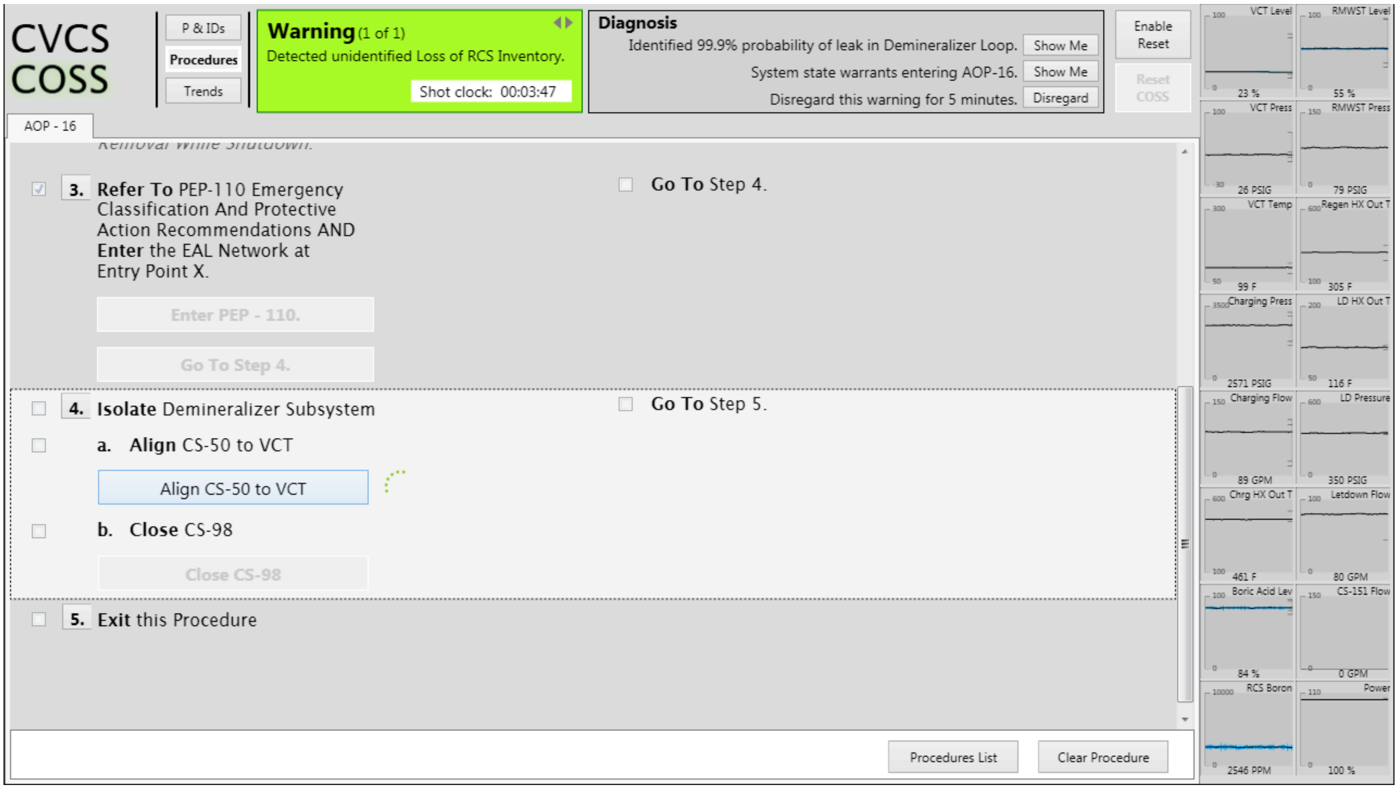
annunciator panel. The alarm setpoints correspond to the ticks on the right axes of the trend indicator displays. When a setpoint is reached the corresponding alarm tile flashes and an auditory alert is sounded.

As technology improves, automation is able to perform many tasks once assigned to human operators. Instead of actively engaging in control actions, operators take on a passive supervisory role where they intervene only when necessary. A consequence of automation is the potential for reduced situational awareness. The microworld can run with three levels of automation [16]. At the lowest level of automation the operator must monitor the process variables and control the feedwater valve, pump, and diverter valve to maintain the system within operating parameters. At the highest level of automation the system controls the valve and pump states. The operator is tasked with ensuring the system stays within bounds and shutting down the system if any of the low-low or high-high thresholds are reached. An intermediate level of automation monitors the value and derivative of each process variable. When it detects a variable is about to fall out of bounds it will prompt the operator with a decision support dialog and a soft control to initiate the appropriate action. All levels of automation also have a safety interlock system that intervenes at the low-low and high-high alarm thresholds to ensure the operator (participant) completes the trial. In addition to cognitive research related to the implications of automation, the microworld can serve as a testbed for examining and characterizing the perceptual properties of various presentations of information. Future versions envision requiring a single operator to simultaneously monitor and control several water heater displays, a feature that lends itself to research related to the multi-unit small modular reactors (SMRs) currently under development.

IV. CASE EXAMPLE 2 – COMPUTERIZED OPERTATOR SUPPORT SYSTEM PROTOTYPE

A Computerized Operator Support System (COSS) is a collection of technologies to assist operators in monitoring overall plant performance and making timely, informed decisions on appropriate control actions for the projected plant condition. A prototype COSS for monitoring and controlling the Chemical and Volume Control System (CVCS) of the 3-loop Generic Pressurized Water Reactor (gPWR) was constructed in support of DOE Nuclear Energy Enabling Technologies (NEET) program [17]. The gPWR full-scope nuclear plant simulator was licensed from GSE Systems, and the control displays have been tailored to fit the bays using GSE's JADE (Java Application Development Environment) software toolkit.

The prototype incorporates four underlying elements consisting of a: digital alarm system, computer-based procedures, piping and instrumentation diagram system representations, and a recommender module for mitigation actions (see Figure 2). Unlike a purely language based description, the WPF prototype conveys concepts in a fully interactive and graphical manner. They say that "a picture is worth a thousand words;" it turns out a five minute interactive COSS prototype is worth quite literally 17,420 [17]. Concepts in the COSS could apply not only to control room modernization of existing light water reactors, but also to Next Generation Nuclear Plants (NGNP) like SMRs.



Warning (1 of 1)
Detected unidentified Loss of RCS Inventory.
Shot clock: 00:03:47

Diagnosis
Identified 99.9% probability of leak in Demineralizer Loop.
System state warrants entering AOP-16.
Disregard this warning for 5 minutes.

AOP - 16

Removal While Shutdown.

☑ **3.** **Refer To** PEP-110 Emergency Classification And Protective Action Recommendations AND **Enter** the EAL Network at Entry Point X. ☐ **Go To** Step 4.

☐ **4.** **Isolate** Demineralizer Subsystem ☐ **Go To** Step 5.

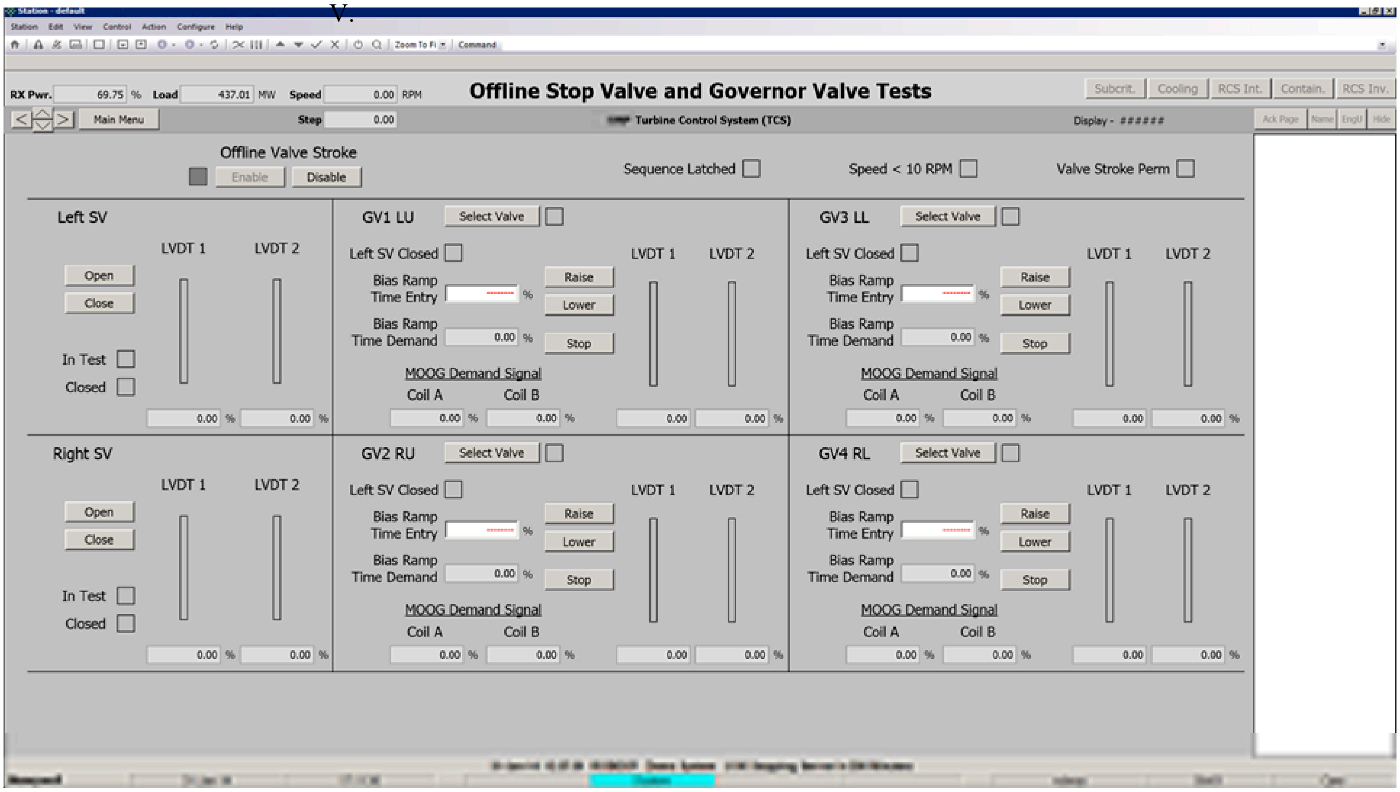
☐ a. **Align** CS-50 to VCT

☐ b. **Close** CS-98

☐ **5.** **Exit** this Procedure

Figure 2. Computerized Operator Support System (COSS) with Computer Based Procedure (CBP) prototype implemented in WPF.

V.



RX Pwr. 69.75 % Load 437.01 MW Speed 0.00 RPM

Offline Stop Valve and Governor Valve Tests

Step 0.00

Turbine Control System (TCS)

Display - ######

Figure 3. WPF emulating the “look and feel” of a Honeywell Experion system.

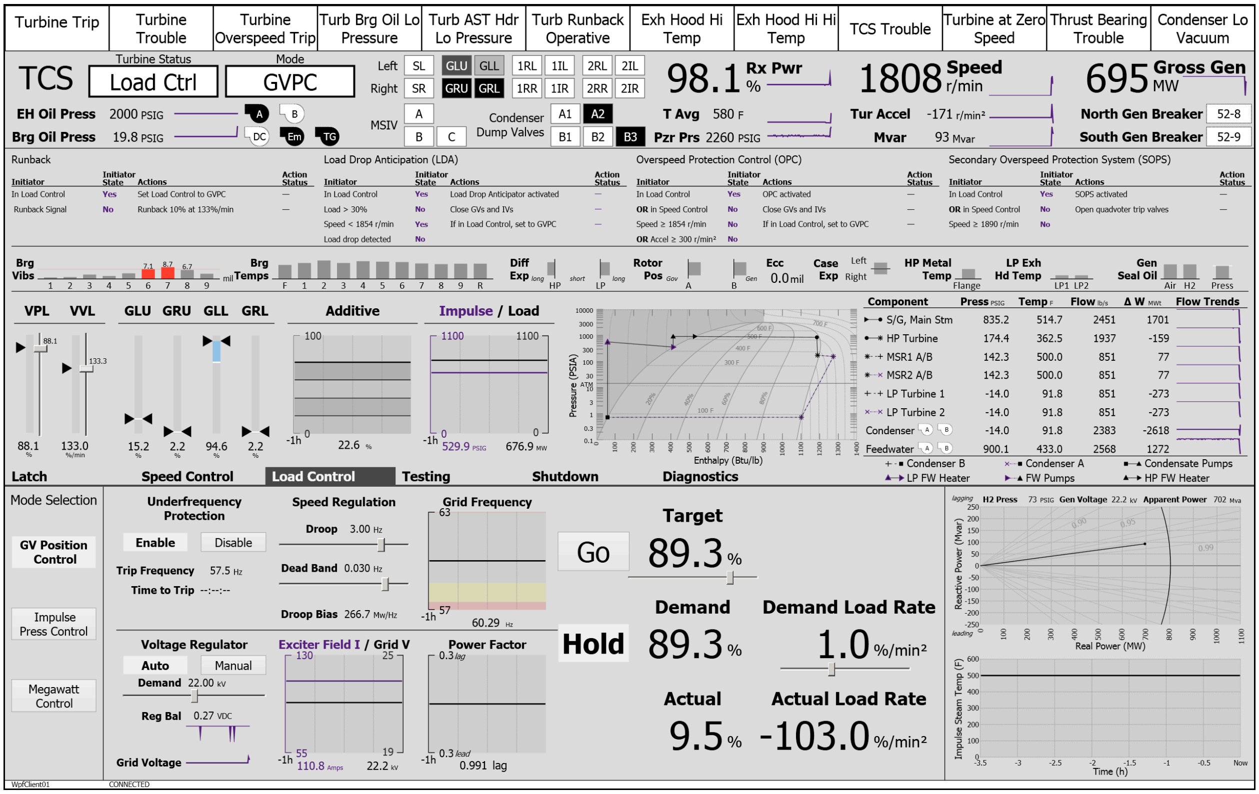


Figure 4. Turbine Control System Prototype with full-scope NPP backend.

VI. CASE EXAMPLE 3 – EMULATING HONEYWELL EXPERION FOR FORMATIVE USER EVALUATION

WPF may also have a niche in formative evaluation of HMI prototypes intended for real-world settings. The flexibility and extensibility allows WPF to emulate existing vendor DCS solutions for early stage prototyping and user testing. Real DCS solutions are designed to operate with physical systems and additional layers of complexity may be required to integrate them into simulated environments. Implementing early stage prototypes in WPF enables formative expert evaluation and user testing well in advance of when logistics might allow a DCS system to interface with a virtual PLC (Programmable Logic Controller), plant model, and full-scope simulator. Secondly, WPF is divorced from vendor and controller constraints. When potential issues arise, alternatives can be evaluated before proceeding with change orders. Under contract with a major US utility, the INL's Human System Simulation Laboratory (HSSL) has developed a WPF prototype emulating the look-and-feel of Honeywell Experion [18]. The prototype (see Figure 3) has two-way communication with the simulator and integrates into a full-scale, full-scope glasstop control room simulator.

VII. CASE EXAMPLE 4 – "ADVANCED" TURBINE CONTROL SYSTEM INTERFACE PROTOTYPE

In support of the DOE Nuclear Energy Light Water Reactor Sustainability (LWRS) Program a prototype turbine control system (TCS) for a multistage turbine and 3-loop pressurized water reactor (PWR) is currently in development (see Figure 4). The turbine control system is implemented in WPF and communicates with a full-scope simulator of a nuclear power plant (NPP) developed by Western Services Corporation (WSC) using a DLL interface provided by WSC. The prototype serves as a test-platform for evaluating "advanced" display formats against typically available presentation schemes. The Advanced TCS prototype presents, features, and displays that go beyond what would be considered current practice in DCS control and visualization. WPF has enabled such features to the extent we have felt limited only by our imaginations. With sufficient time and diligence nearly anything one would reasonably expect to accomplish can be implemented or at least contrived.

The TCS prototype is envisioned as a retrofit to an existing PWR. The monitor would be mounted at the board and is intended for a high resolution monitor with a 16:10 aspect ratio. Because the DCS would potentially be at the Main Control Board (MCR), critical values (such as reactor power, turbine speed, and load control variables) are intended to be visible at a distance of 20 feet. The top row of the display contains an alarm annunciator panel. Centrally located is a Level One overview. This overview presents the operator with the most critical information pertaining to the current state of the turbine/turbine protection system/turbine control system, the primary system supplying the turbine, and the electrical grid. The bottom third of the display contains a tab controlled interface to allow the operator to select information appropriate to particular operational modes such as "Load Control" as depicted in Figure 4.

The design encapsulates a variety of influences. The overview layout of the display is intended to provide a graphical Information Rich Design overview of the most pertinent operating parameters, allowing operator at-a-glance diagnosis and maintenance of overall situation awareness [12]. Hollifield et al. [11] emphasize how HMIs should not look like P&IDs. A review of TCS interfaces suggests that vast majority fall into this trap. The arrangement of valves in relation to the high and low pressure turbines is well engrained in any licensed turbine operator and does not need to be explicitly displayed. What would normally be an entire display can be condensed into the digital "light box" below the annunciators. Tufte [10] evangelizes on the benefits of high density information graphics and sparklines as "intense, simple, word-sized, graphics." Tufte's influence is revealed in the information dense row of supervisory bar graphs, and the auto-scaling mini trend lines. CSE provides insights to human cognitive processing and decision making, and EID presents rationale for why displays should present the engineering constraints rather than the task constraints. Essentially, a good interface should be akin to directly observing the movement of a tourbillon watch through the eyes of a master watchmaker. No essential truths pertinent to the operation of the timepiece are concealed. Several EID displays are implemented throughout the interface, including a dynamic pressure enthalpy display of the entire Rankine heat cycle of the turbine system, and the dynamic generator capability curve located in the load control tab.

VIII. SUMMARY AND CONCLUSIONS

Here we have presented four examples of how WPF can be used for process control in the hope that it will give the readers an impression of what is possible. Note that our purpose is not to endorse a particular software development platform (e.g., WPF), and we believe other development environments will likely prove equally adept for HMI prototyping. In the introduction the claim was made that HMI design is both art and science. One does not become an artist by reading about art; one becomes an artist by creating art. The value is in finding a tool that will allow ideas to be put into pixels. The process of developing HMIs for process control has helped us broaden from mere Ivory Tower HFE theoreticians to something resembling a team of prescriptive HMI designers.

We are admittedly newcomers to process control HMI research, and WPF, having just shy of a calendar year's worth of experience, yet gauchely suggest this is a testament to the value of WPF for process control. WPF is a tool that has allowed us to make mistakes faster. Design is inherently iterative. Many ideas that seemed good on paper have turned out to be less than stellar once implemented. Being able to see displays change in real-time to transient events is subjectively a much more powerful tool than having to rely on one's imagination of the dynamic characteristics and utility of a display.

The ability to demonstrate functional prototype designs for control room modernization has proven particularly useful as industry works to update analog control rooms to digital or analog-digital hybrid replacements. Evaluating DCS systems prior to implementation is a powerful way to reduce the need for do-overs and to ensure that replacement HMIs are optimized to ensure the continued safe operation of plants.

We have found the WPF environment a powerful tool for design and development of digital HMIs and are actively using it in conjunction with operator-in-the-loop studies to validate design concepts and verify operator performance when using new HMIs [18].

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