Human-In-The-Loop Evaluation of Human-Machine Interface for Power Plant Operators

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***Abstract*—This paper describes a human-in-the-loop evaluation of a power plant Human-Machine Interface (HMI), that was designed using a User-Centered Design approach. General Electric (GE) developed ActivePoint* HMI (AP HMI) to increase plant operator efficiency and awareness. UCD was applied as a design process along with existing industry design guidelines and other design approaches. The goal of the evaluation study was to provide GE Power quantitative data on proposed benefits from the new HMI based on systematic design approaches compared to the legacy HMI product, developed by engineers with an *ad hoc* process. Compared to this Legacy HMI, the new AP HMI provides enhanced information architecture, simplified graphics and navigation, as well as improved alarm management allowing operators and plant maintenance personnel to focus on what is important. Nine operations staff from a power plant in France performed simulated tasks using both Legacy HMI as a baseline and AP HMI. We measured their performance and satisfaction on the use of HMI to quantify the enhanced effectiveness of AP HMI. AP HMI resulted in 33% higher success rate, 79% lower navigation time, 42% lower total time on task compared to Legacy HMI. Also, the user satisfaction for AP HMI was rated significantly higher than Legacy HMI.**

Keywords—Human factors; human-machine interface; user interface design;

I. Introduction

Continued advancements in computer technologies have enabled software engineers to collect more data, to use more sophisticated visual graphics and to automate more tasks / functions, resulting in increased complexity for plant operators. The HMI is the operator's interface for managing the plant and its safety-critical systems (such as turbines, aircraft, etc. [2, 3]). HMI plays a critical role for safe operations of these kinds of systems. For example, the case of the Three Mile Island accident showed how a failure in providing clear situational information through the HMI contributed to one of the worst incidents in the industry. Therefore, appropriate design guideline for developing HMI for safety-critical systems is an important aspect of building these systems, and should be executed through a rigorous and thorough process.

II. Background

A significant amount of work has been done on process control HMI design using ecological interface design [11, 12, 13, 14, 15, 16, 17, 18] and the operator-centered interface [19]. These approaches focus on providing not only the physical view of the data but also the functional view of the data, and some also include a task view of the data [18]. These design approaches are often implemented in a hypothetical "microworld [12]" simulations and tested with human subjects and commonly show better operator performance [12, 13, 20, 14, 15, 16, 17, 18, 21, 22] compared to a "traditional" HMI design approach, heavily based on Piping and Instrumentation Diagrams (P&IDs). However, more recent research suggests that these approaches do not provide a complete solution with recommendations including the incorporation of yet more design approaches, such as Task-based design [23] or Interaction-centered design [24].

Functional design approaches focus on the functional relationships in the critical data for a process (such as power generation) as compared to the more conventional, schematic overview, which is based on P&IDs. Notable work by Tharanathan, et al. [21] compared functional and schematic overview displays and found that situational awareness was significantly higher when the participants used the functional overview display rather than the schematic overview display.

Also, as a more comprehensive design approach, function-behavior-state (FBS) framework has been developed [25]. The underpinning principle for this framework is that the design of operator interfaces of an industrial system (e.g., power plant) needs also to be based on the design/manufacture of that system.

A. Legacy HMI

he most apparent characteristics for currently-deployed HMI designs (i.e., traditional HMI design approach) are that the designs are heavily based on P&IDs, and the goal of the designs is to place as much data as possible in one screen without too many usability concerns. As a result, these HMIs show not only the basic usability issues (e.g., excessive use of saturated color, illegible texts, etc.), but also basic human factors issue as pointed out by Nachreiner et al. [17]. Also, our preliminary findings from initial interviews with Subject Matter Experts (SMEs) and heuristic evaluations suggest that the advancements of HMI designs are heavily focused on developing features and functionalities without proper user context and usability considerations, while incorporating those in operator HMIs. Also, there is little to no adoption of progressive and leading-edge design qualities or inspiration from the successes of consumer electronics User eXperience (UX) designs.

B. Design of AP HMI

In collaboration with global power plant operators, GE developed the ActivePoint (AP) HMI to increase plant operator efficiency and awareness [28] as shown in Fig. 1. AP HMI's

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Fig. 1 An example of AP HMI plant overview screen for a combined-cycle power plant. (UX Design: 1997 – 2017 © General Electric Company. All rights reserved.)

proposed benefits include enhanced information architecture, simplified graphics and navigation, as well as improved alarm management, allowing operators and plant maintenance personnel to focus on what is important in.

The AP HMI was designed based on generic UCD processes along with many of the HMI-specific design approaches described above (including representation aiding [29] as an information visualization principle, level-based screen hierarchy using Cognitive Work Analysis [30] and task-based design, etc). Furthermore, the available industry guidelines [4, 5, 6, 7, 8, 9, 10] were analyzed and incorporated into design principles and guidelines, based on user research results from a number of iterative studies. A total of 10 user research studies were conducted, encompassing a total of 61 interview sessions with 43 participants in 19 power plants in multiple countries and continents. Across the 10 studies we used a combination of user research methods, including contextual inquiry, design concept walk-through, participatory design, observation, and prototype testing, based on the level of refinement of our design ideas at that time. The initial user research identified broad general directions to follow, and then the design philosophy and corresponding design principles were established in later research. The later studies explored, evaluated and refined our design proposals.

III. Research Methods

The goal of the study was to evaluate AP HMI on its proposed benefits on the overall power plant operational performance. The study compared the two designs of HMI, the existing legacy GE HMI as the baseline and the AP HMI, (shown in Fig. 2 and Fig. 3, respectively) using metrics such as effectiveness, efficiency, and user satisfaction. The site chosen for the evaluation was the first plant to have the AP HMI installed.

A. Participants

A total number of nine participants (one instrumentation & control engineer and eight control room operators) from a natural gas combined-cycle plant in Europe, participated in the study. All participants were male and their ages were between 25–34 years (n=4) and 35–54 years (n=5) old. Their years of experience in the power industry ranged from 2.5 years to 33 years with a mean of 9.6± 9.60. Participants self-reported their level of expertise on gas turbine (GT) operational knowledge with a mean of 4.8 ±2.86 (using a scale of 0-10, where 0 =

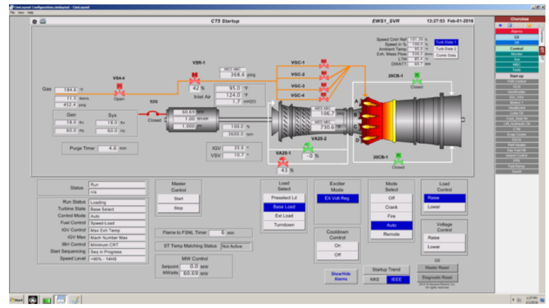
Fig. 2 Simulated GE Legacy HMI system used in the study as a baseline.


Fig. 3 Simulated GE AP HMI system used in the study. (UX Design: 1997 – 2017 © General Electric Company. All rights reserved.)

someone who understands the world of industrial plants, but has never operated a GT, and 10 = someone who is experienced in operating a GT and comes and troubleshoots on site at the plant to get units back online when needed). None had any prior experience with either of the two HMIs.

All were native French speakers with varying levels of English conversation skills, so the study was conducted in French, using a translator who had significant technical understanding.

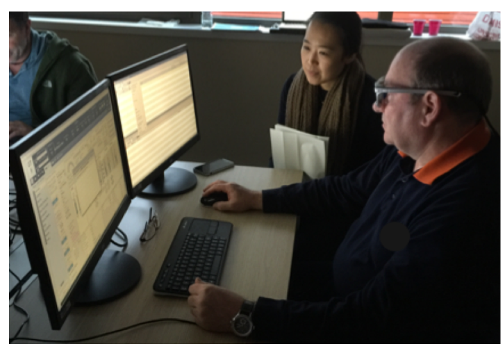
Fig. 4 Experiment Setup

B. Experiment Setup

The experiment took place in a private room in their control room building. A Windows laptop running a simulated HMI system (using a GE-developed simulation framework, *Artemis*) was connected to two 23-inch monitors, one for the HMI screen and one for the alarm viewer. There was also a wireless mouse and a wireless keyboard. Finally, the participant wore SMI eye tracking glasses as shown in Fig. 4, but the data from the eye tracking glasses are not reported in this paper. During each session, we recorded participants' interactions with the interface and their feedback (captured by the screen recording software, *Camtasia*).

C. Simulated Operator Tasks

During this experiment, participants were asked to act as a control room operator, responsible for operating a power generation process and managing overall power plant operation. The participants worked with the HMI and they could also ask questions and assign tasks to an imaginary field operator (played by a GE employee) who followed the scenario's script in answering their requests. The primary objective was to start up the gas turbine and reach a pre-defined target power output, while handling multiple alarms. The goals for each alarm were to detect it, identify it, and resolve it. To minimize the learning effect on the task, two scenarios were created for each condition: AP HMI and Legacy HMI. The task included three types of activities that emulate the actual operator activities during day-to-day operations and test operator comprehension of the situation through the HMI.

1) *Alarm management tasks:* The participant responded to multiple alarms through the simulated and works with a federated field operator (FO) to resolve the issues.
2) *Operation tasks:* The participant started up the GT and synchronized.
3) *Visual search (VS) and situational awareness (SA) response tasks:* The participant responded to the pre-determined queries from the moderator verbally based on the data/information in the HMI.

Following example questions included for VS questions:

- What is the turbine status?
- What is the ambient temperature?
- What is the current VSV angle?
- What is the fuel control mode?

Following example questions included for SA level 1-3 questions:

- What is the turbine speed in %?
- Is the speed increasing or decreasing?
- Is the breaker closed?
- Is the speed increasing or decreasing?
- What is the current speed reference?
- Is the turbine generating the power to the grid?
- Approximately, how much more % speed do you need to get to the reference speed?

All visual search and SA questions prompted in different phases of the oepration (e.g., craking, accelerating, loading) during the task.

D. Procedure

After signing the consent form approved by GE Global Research, we conducted a short interview consisting of demographic information and the level of expertise on GT operational knowledge. Then, the moderator demonstrated a set of simplified tasks, and the participants performed a practice run. With a given HMI, participants were asked to complete the tasks executing a startup of the turbine including detecting any issues and identifying likely causes. After completion of the first session, they were asked to rate their experience using the system usability scale (SUS), and the net promotor score (NPS). After a short break (10min), participants then repeated the same process with the other HMI. The overall study time took approximately 2 hours. After completion of the study, all participants were compensated with a $25 Amazon gift card for their time. The presentation order of the HMI and task set was randomized.

E. Data Collection and Analysis

1) Effectiveness: Effectiveness was measured by task success rate. We measured alarm management task success rate (Fail, Success), alarm management task completion rate by counting the number of desired steps completed, visual search task success (Correct, Incorrect), and situational awareness task success (Correct, Incorrect). Of note, the desired steps were defined in collaboration with in-house operations expert who trains operators gas turbine operation. The desired steps are defined as: a) *Detect an alarm, b) Open the right screen, c) Find the related information/data on the screen, d) Ask the federate field operator to resolve the issues, and e) Acknowledge an alarm*

2) Efficiency: Efficiency was measured by duration and frequency. Of note, the total time on task and the response time included the time for reading alarm and its details as well as certain duration not related to the user performance such as screen refresh time (~4.5 sec), and communication time with the field operator, etc.

a) Activity Duration: Reading alarm time, navigation time, data searching time, and total time on task. The total time on task is an average of total duration when the participant detected an alarm and addressed an issue they found by instructing the field operator. We also included the duration of those who failed on tasks in that either they addressed incorrect issues or could not find an issue, requiring a moderator intervention.

b) Response Time: Time to the right screen, time to the right answer. Both measure are recorded from when the participants detected an alarm to when they reached either the right screen or the right answer. The particular interests to the right screen is due to the fact that normally the power plant operators deal with ~150 to 200 screen in a combined-cycle power plant, and finding the right screen is one of the critical activity that they need to perform efficiently.

c) Frequency: Number of navigation steps to get to the right screens and number of moderator interventions required were recorded. Similar to time to right screen, it is critical to minimize the navigation steps to perform a task. In addition, we counted the number of moderator interventions. We provided the interventions when the participants were stuck for more than three minutes. Therefore, the number of moderator interventions required could imply the level of operator comprehension of the task and the situation as well as the leading indicator to a better or worse performance.

3) Satisfaction: Satisfaction was measured by SUS and NPS. Also, participants also self-reported their level of comfort with the HMI on a scale of 1-10 (where 1 = extremely uncomfortable, and 10 = extremely comfortable). Although similar to SUS, we gathered the level of comfort with the HMI because this could indicate the perceived learning curve on the HMI system. The learning curve is an important aspect to introducing a new HMI system because the AP HMI is designed by a novel approach, resulting in an very unfamiliar design compared other available HMI systems beyond GE Legacy system.

4) Analysis: Because we did not see a normal distribution in our data sets, we used Wilcoxon Matched Pairs Test (a non-parametric equivalent of the paired t-test to test for a difference in repeated measurements). In addition, the percent improvement was calculated by subtracting the Legacy condition data from the AP condition data divided by the Legacy condition data.

IV. RESULTS

Effectiveness and efficiency measures both indicate that AP HMI performed better than Legacy HMI in supporting user performance in operating and monitoring a gas turbine operation. Also, the user satisfaction measures indicate that perceived usability and user satisfaction both scored higher in AP HMI compared to Legacy HMI.

A. Effectivenes

AP HMI led to substantial improvements in alarm management task success, task completion, and visual search tasks success. As shown in Fig. 5, a Wilcoxon Matched Pairs Test shows a statistically significant difference (<.05) in alarm management task success, alarm management task completion rate, and visual search task success between Legacy HMI and AP HMI. However, the situational awareness task success rate showed no difference for both HMI. This could be due to the fact that the questions for situation awareness were relatively simple and straightforward and did not differ by scenario.

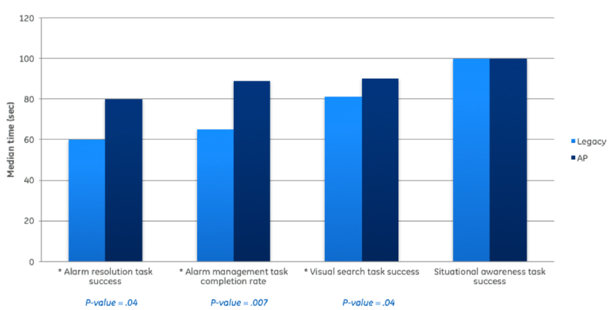

Fig. 5 Effectiveness Results

B. Efficiency

AP HMI led to substantial improvements in reducing reading alarm time, navigation time, data searching time, and total time on task in alarm management tasks.

a) Activity Duration: As shown in Fig. 6, a Wilcoxon Matched Pairs Test shows statistically significant differences in time to read alarms, navigate and search data. This indicates that using AP HMI, the partcipants were more efficient in understanding alarms, navigating screens to find the right one, and also locating critical data to resolve the issues. However, total time on task did not differ significantly. This could be due

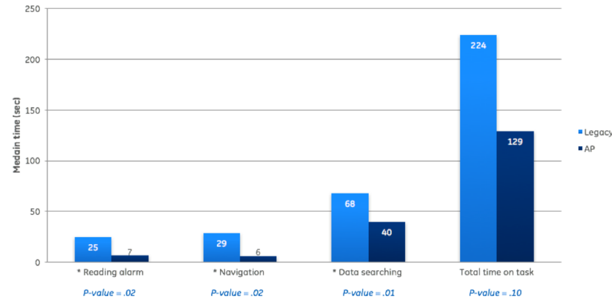

Fig. 6 Activity Duration Results

to significant noise in the data such as technical issues on AP HMI system (e.g., slower refresh rate) and interpretation duration for some participants.

b) Response Time: A Wilcoxon Matched Pairs Test shows no significant difference in time to the right screen and time to the right answer between Legacy HMI and AP HMI. This also could be due to significant noise in the data such as technical issues on AP HMI system (e.g., slower refresh rate) and interpretation duration for some participants.

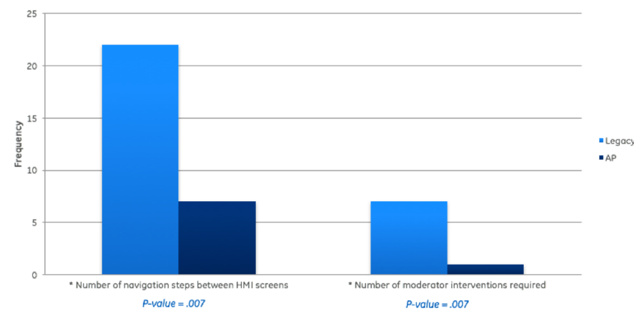

Fig. 7 Frequency Results

c) Frequency: As shown in Fig. 7, A Wilcoxon Matched Pairs Test shows a statistically significant difference (<.05) in number of navigation steps between HMI screens and number of moderator interventions required between Legacy HMI and AP HMI.

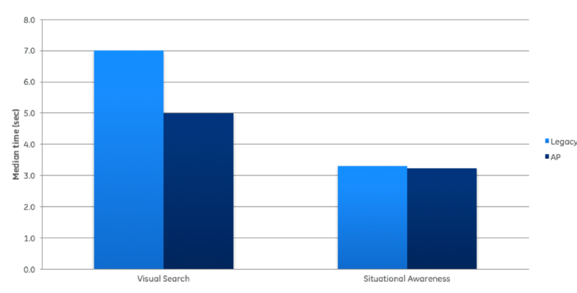

Fig. 8 Response Time for VS and SA

d) Response Time for VS and SA: As shown in Fig. 8, A Wilcoxon Matched Pairs Test shows no significant difference in time during visual search and situational awareness tasks between Legacy HMI and AP HMI.

C. Satisfaction

As shown in Table I, the results of the SUS showed that participants rated AP HMI significantly ($p<0.5$) higher than Legacy HMI. The results of the NPS showed that participants were more likely to recommend AP HMI (-11, 33% promoters) than Legacy HMI (-89, 0% promoter). A Wilcoxon Matched Pairs Test showed a significant difference (<.05) between Legacy HMI and AP HMI in Comfort Level with HMI.

TABLE I. USER SATSFACTION ON HMI

Measures	***Legacy HMI (as baseline)***	***AP HMI***	***P-value***
SUS	38	60	.01
NPS	-89	-11	
Comfort level with HMI	5	8	*< .05*

a) User feedback on HMI: Participants provided their feedback on what worked well and what needed to be improved for AP HMI. They pointed out that the overall experience about AP HMI was simple and easy to navigate essential data and to understand due to an effective informative visualizations such as bar charts and using the right amount of color. They also commented on improvement points for AP HMI. Interestingly, participants pointed out that they felt that it was too easy to start the unit and that the clicking actions are not secure enough. Further comments from the participants showed that, to make sure important user actions such as "Start the unit" and "Stop the unit," the HMI should provide further confirmation steps with serious messages so users ensure their actions with conscious awareness.

V. DISCUSSION

AP HMI showed substantial improvements in performance and user satisfaction compared to Legacy HMI, as shown in Table II. AP HMI resulted in 33% higher success rate, 79% lower navigation time, 42% lower total time on task compared to Legacy HMI. Also, the user satisfaction for AP HMI was rated significantly higher than Legacy HMI.

TABLE II. PERCENT IMPROVEMENT ON PERFORMANCE AND SATISFACTION

Measures	***Legacy HMI (as baseline)***	***AP HMI***	***Percent Improvement (p-level)***
Alarm management task success rate	60%	80%	33% *(P < .05)*
Alarm management task completion rate	65%	89%	37% *(p < .01)*
Reading alarm time	25s	7s	72% *(P < .05)*
Navigation time	29s	6s	79% *(P < .05)*
Data searching time	68s	40s	41% *(P < .05)*
Total time on task	224s	129s	42% *(p > .05)*
Number of navigation steps between HMI screens	22	7	68% *(p < .01)*
SUS (0-100)	38	60	58% *(p < .05)*

The effectiveness metrics are considered as the most important measurement because operators should be able to perform the tasks successfully. The AP HMI showed substantial improvements in operators' success rate (e.g., 33% higher alarm management task success rate, 37% higher alarm management task completion rate, and 11% visual search task success rate). This data demonstrates that operators may have had the challenge to detect and understand the source of alarms from too much information with many colors presented on the screen using the Legacy HMI. In contrast, AP HMI provides a simplified design language with thought-out use of colors to grab the user's attention appropriately. The efficiency metrics were another critical measurements because the control room operators' attentions are required in performing multiple different tasks (beyond monitoring HMIs) inside the control room. AP HMI led to substantial improvement in efficiency, measured by reading alarm time, navigation time, data searching time and the total time on task in alarm management tasks, response time, number of navigation steps, and the number of moderator interventions required. Consistent with the performance measures, the user satisfaction data also show that participants were more satisfied with using the AP HMI as compared to using the Legacy HMI. They emphasized the simple and easy navigation, informative data visualizations, and simple but meaningful color-coding.

VI. CONCLUSION

The study compared the effectiveness of two HMIs with control room operators as participants. As we hypothesized, AP HMI showed improvements in user performance and satisfaction as compared to Legacy HMI. AP HMI showed substantial improvements in operators' performance (e.g., 33% higher success rate, 79% lower navigation time, 42% lower total time on task) compared to Legacy HMI. The user satisfaction for AP HMI was rated significantly higher than Legacy HMI.

Whilst our participants in this final study were using a simulation of their actual plant configuration (unlike those in our earlier design-oriented studies), we still do not have data on their efficiency and effectiveness in operating the actual plant. It is surely possible to infer that our improved metrics will have an impact on their actual day-to-day performance, but there is no basis for estimating the scale, or time-scale of the effect.

The data presented here show that significant improvements in HMI usage are clearly achievable, but we would love to see more detailed, longitudinal studies of actual plant performance that enables judgements about the long-term economic benefits of such improvements, as well as, for example, an understanding of whether the effects are more related to learning (and fade over time) or are they related to skills, thereby increasing over time.

This study can be considered as a case study in which proves the practicality and applicability of the theoretical design approaches in an actual product. Due to the page limit, we did not discuss the details of how they were applied. We plan to share those with the community as an example of connecting academic research to industry use in the future.

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