Re-Introducing Physical User Interfaces into Industrial Control Rooms

Veronika Domova, Maria Ralph, Elina Vartiainen, Alvaro Aranda Muñoz, Adam Henriksson, and Susanne Timsjö

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Veronika Domova
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
veronika.domova@se.abb.com

Maria Ralph
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
mralph.contact@gmail.com

Elina Vartiainen
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
elina.vartiainen@sics.se

Alvaro Aranda Muñoz
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
alvaro.aranda.munoz@sics.se

Adam Henriksson
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
adam.henriksson@gmail.com

Susanne Timsjö
ABB Corporate Research
Forskargränd 7
Västerås
Sweden, 721 78
susanne.timsjo@sics.se

ABSTRACT
Within industrial control rooms the trend has been to move away from physical towards digital interfaces. However, operators working in these control rooms have expressed feeling a loss of connection to the production process and machinery they are controlling. As such we present two prototypes Haptic Mouse and Shift Report Tool which were used to explore the re-introduction of physical user interfaces into industrial control rooms.

CCS CONCEPTS
• Human-centered computing → Human computer interaction (HCI); • Interaction devices → Haptic devices

KEYWORDS
Industrial control rooms, interface design, prototyping, haptics

ACM Reference format:

1 INTRODUCTION

Industrial control rooms are offices serving as a central space to monitor and maintain industrial processes of a large industrial facility. They can be found in various industries such as power plants, oil, gas, traffic control, or production plants. Process maintenance covers monitoring of ongoing processes, tracking alarms, diagnosis of problems, and interventions into the processes. The latter is done by altering physical variables (e.g. temperature, pressure, flow rate) and sending supervisory commands to the process devices controlling the operations on site, e.g. opening and closing valves. Earlier control rooms (see Fig. 1 (a)) were located in close proximity to actual industrial production. Control panels were analogous and consisted of large walls or desks comprised of knobs, buttons, switches and gauges. This required operators to access process variables by physical interactions such as holding, rotating, scrolling, switching and pushing physical actuators on the control panel. As such, process variables were to a large extent perceived through motor, haptic, and acoustic feedback that accompanied the control interactions.

Today, control rooms for the most part have been transformed into purely digital representations, where equipment and machinery are presented in digital displays (see Fig. 1 (b)), in turn losing the physical aspect of the previous control room design. Operators are finding this transition a challenge, since they feel that digital information alone is lacking the support they need for understanding what is happening in the control process [2]. In the interviews conducted by Salo and Savioja at multiple power-plants [20], some operators expressed that they would prefer the old analogous wall panels to modern computer-based tools because of getting a better overview of the processes.

The skills in industry are learned in situ [14] (i.e. situated learning), acquired by actually engaging in physical interactions in a real-world context. As such, operators are familiar with the physical properties of the equipment they are in control of, which is not captured in the input and output devices used in control rooms today. Graphical User Interfaces (GUIs) used in control rooms today act to further separate operators from their physical
As an outcome, when interacting with a Graphical User Interface, operators cannot take advantage of their proficiency or utilize their skills for manipulating physical objects, thus increasing the divide between physical and digital environments [10].

Figure 1: Evolution of control rooms.

Physical interfaces aim to take advantage of how humans naturally interact with objects in their everyday environment e.g. grasping and manipulating physical objects [11]. Presenting digital information through a physical medium enables direct manipulation and instant sensory feedback for users. Therefore, physical interfaces enable operators to interact naturally with the processes they are monitoring, which current screen-based solutions alone cannot fully support. Lundh et al. [15] discuss a qualitative study they conducted of an engine control room on board a Swedish merchant ship whereby analogous equipment had been replaced by digital interfaces. The authors found that "analogous equipment also provided instant feedback on every executed command by means of a sound when turning a switch, a lit lamp or a position of a knob." [15]

This paper presents a preliminary user study that aims to reintroduce physical interaction and sensory perception to operators in industrial control room settings. Two prototypes are presented which focus on supporting operators’ daily routines. In addition, we present observations from a preliminary feedback session with two control room operators who interacted with the prototypes and generally welcomed them to further enhance their daily activities.

The remainder of this paper is organized as follows. Section 2 gives an overview of the related work in the field. Section 3 describes the two areas in industrial context where the transformation from analogue to digital systems and interfaces introduced certain challenges for operators working in control rooms. We then introduce the developed prototypes including the development details and evaluation sessions in Section 4. It is followed by Section 5 with a discussion over findings and implications for future work.

2 BACKGROUND

A number of studies have investigated how computerization of industrial settings changes fundamentally the nature of the workflows taking place by abstracting them from a concrete work context [12]. Zuboff [22] describes the process of computerization of large paper mills, giving details on how work was previously done by sensory perception (such as touch, feel, and sight) and how the work processes were transformed when the factory became automated, turning into an infrastructure manageable via computerized control systems. Zuboff cites young papermakers brought in under the era of computerization who still tend to use their sensory input to differentiate about the consistency of the pulp. One such papermaker refers to this process as "artistic aspects of making pulp that the computer doesn’t know about".

From the multiple interviews conducted at power-plants [20], Salo and Savioja conclude that modernization of control room technology poses several challenges to safe and effective process control including maintaining process knowledge, gaining process overview, and trusting the control system.

German sociologist Fritz Böhle has also researched how computerized control in industrial control rooms and factories influences the role of the experience-based knowledge gained through on-the job multisensory perception by keeping workers out of the actual production processes [2,3]. Böhle and Milkau [2]
describe that during a work process, characteristics and qualities of machinery and processes are not perceived in the same way as through a measuring device, but are rather 'experienced'. The researchers conclude that sensory perception and experience inform an individual’s practical work in a different way than when information is collected and processed through technical means. As such, the authors emphasize the importance of a worker’s action-centered knowledge, developed and enhanced through their physical interactions with objects in their real environment. The authors outline that in the era of automated machines there is the necessity to provide and maintain materials, work processes and sensory perception.

However, the question of how to establish and maintain a sensory connection between workers and their respective machinery while working remotely from a control room is still an under-explored area, with great potential for new forms of interaction capabilities to be developed. Research into human-computer interaction (HCI) including the tools to interact with visual representations of digital information has a long history [18]. There are a number of studies that have questioned the efficiency of modern graphical user interfaces and interaction with them through keyboards and pointers [4,9] mainly because the interaction with a GUI differs from the way interaction takes place in the physical world.

Up to now, a number of studies discussed over different interface styles and investigated how traditional interfaces can be integrated with tangible/haptics and improved this way. Donahue et al. [7] compared three interfaces, mouse, touchscreen, and tangible, and concluded that "closer" interfaces, i.e. tangible and touch, provide a noticeable benefit over the standard mouse interface on tasks centered on deductive reasoning and hypothesis generation. In [5], Chang et al. present a set of interface designs where appropriate haptic sensations are used for feedback instead of standard audio/visual feedback typically used in similar cases. In [8], Gohlke et al. introduce a FlexiKnob - a mouse-like device enhanced with a physical rotary encoder knob aiming at integrating mouse interaction with the benefits of physical video/audio controllers. Several authors [1,5] outline that by providing physical cues, tangible/tactile interaction has the potential to free up visual attention and reduce cognitive load in visually demanding tasks.

With the respect to the work discovered, there is limited research towards the usage of Tangible User Interfaces (TUIs) in industrial contexts. In [4] the authors propose to go away from simplistic tangible interactions towards more complicated skilled actions. They developed two design methods that could potentially boost the focus on skilled actions in the design of tangible user interaction. In [19], the authors developed a concept of a "mirror world" for industrial applications where haptic devices can be used both for control and for getting feedback. As such, the actions in the virtual world are mimicked in the real world and vice versa. Jensen et al. [13] present a design experiment where a group of design students remodeled the interface of a widely used industrial motor controller to incorporate new movement-based interactions. Their workflow was based on an approach of tangible interactive sculptures which provides designers with richer insights concerning interaction properties from a physical perspective. In [21], Sitorus et al. investigate how to support technicians in configuring complex systems by using physical aspects of the systems’ configuration in their interface, taking into account the skills and experiences of the technicians.

One particularly relevant to this paper work is presented by J. Müller et al. in [17]. Similarly to the current work, the authors outlined that a standard desktop interface widely used in industrial control rooms lacks process-related interactivity such as haptic feedback, physical constraints, and the involvement of motor skills. To address this issue, the authors presented a direct-touch and a tangible-object concept for both a slider element and a rotatory control element. Even though this work provides a valuable input, it aims to support manipulation of process variables which is just one of many daily routines of industrial control room operators. The tangible interfaces presented in the current paper are intended to assist the operators in a different set of daily routines which makes the conducted study a valuable contribution to the research field.

To summarize, although there has been extensive research within TUIs and some work towards the use of TUIs in industry, we see the question of how to establish and maintain a sensory connection between workers and their respective machinery while working remotely from a control room as a still under-explored area, with great potential for new forms of interaction capabilities to be developed. Therefore, this study makes a contribution to research on industrial TUIs by describing two cases of tangible prototypes, which were evaluated in industrial control rooms with real users. The prototypes presented focus on supporting operators’ daily routines. In addition, we present observations from a preliminary feedback session where control room operators interacted with the prototypes presented. Our preliminary findings show that operators welcomed physical interfaces to further enhance their daily activities, however, more research is needed in order to improve these prototypes.

3 FIELD STUDIES IN INDUSTRIAL CONTROL ROOMS

To understand operators’ work-practices, we conducted contextual interviews in control rooms at different industrial settings including process plants for a mine, a power plant, and a pulp and paper factory. During the interviews, we asked the participants to show what type of tools they are using today in their work tasks and to describe their typical work practices. These interviews were conducted over 1-2 days per location with 2-3 operators.

Regardless of the nature of the industry, the control rooms generally looked alike. Operators engage with the control processes by looking at computer screens of the operator workstation displaying the process information. They interact with the system by using keyboards and mice. A typical operator workstation consists of multiple screens of different sizes. Bigger displays provide overviews, whereas smaller ones give more detailed information. Even though the operator workstations
might look monolith, they often consist of several computers supplied with several input devices, i.e. a mouse and a keyboard per computer.

According to the operators, a typical work shift consists of monitoring control processes they are responsible for, attending to alarms which indicate problems, diagnosing and troubleshooting the encountered problems. Monitoring and control are performed through the use of computer screens, keyboards and mice. The observed user interfaces of operator workspaces were highly cluttered with information, i.e. process graphics, physical values characterizing the running processes, configurable thresholds, performance variables, estimations, etc. According to the operators, knowing real values is important for them, but they are only interested in a set of parameters whereas today there are too many details on the displays. Introducing tactile representations of process variables potentially might free up visual attention of operators and reduce their cognitive load in visually demanding monitoring tasks.

In all the observed industries, operators also took part in a timed handover meeting between shifts called a shift handover to go through problems which came up during the previous shift. The shift handover meeting is strictly timed (usually 15-20 minutes) and takes place between an operator going off-duty and an operator coming on-duty. Problems found during the shift are captured in a shift logbook, which is typically pen and paper based, and contains details of the types of issues encountered during the shift. Today, during a shift handover operators refer to the shift logbook and discuss around their computer screens, navigating to different displays to show where problems occurred. This requires the current operator to remember which screens and in which order to show to the incoming operator. The challenge during this activity, however, is how to capture and transfer this information between operators in a timely and effective manner.

4 PROPOSED SOLUTION

We started with a set of brainstorming sessions to match the identified problems with possible solutions. During these sessions two major concepts were designed: Haptic Mouse and Shift Report Tool. Haptic Mouse was intended to give operators haptic feedback that is mapped to the machinery they are controlling, while Shift Report Tool aimed to make a digital version of the shift logbook that would be more accessible while still in a physical form. To evaluate the ideas, we have organized a brainstorming workshop with a group of operators (6 engineers of different age, roles and experience levels) from a pulp and paper factory located in Sweden. The participants expressed their opinions and expectations about each of the presented ideas. Their feedback was positive and they were curious to test the prototypes when implemented. Furthermore, they proposed to have the video recording feature for the Shift Report Tool which initially was not planned. The prototypes, their implementation and feedback gathered from the preliminary evaluation session are discussed in the following sections.

4.1 Haptic Mouse

The initial concept of Haptic Mouse took inspiration from the gaming industry, where multiple variations of gaming controls exist giving the players haptic feedback through the use of light or vibration when interacting with game objects. Similarly, the developed mouse interface gives the user haptic sensations corresponding to the physical properties of the object they are interacting with, for instance speed or temperature.

Several generic (i.e. common for machinery in different industries) physical properties were identified such as temperature, vibration, speed, volume, sound, pressure, flow on/off, and weight/amount. Temperature for instance can characterize the temperature of a liquid in a boiler or the heat of a running engine. A set of tactile sensations were defined which could convey the identified physical properties. Based on this mapping, we created the Haptic Mouse concept shown in Fig. 2. The concept consists of a PC mouse which is extended with several actuators: a heating element for conveying temperature sensations, a vibromotor recreating speed and vibrations, a fan producing air flows to simulate on/off states of liquid or gas flows, and a set of LED lamps changing their color in correspondence with the alarming status of the hovered object or current view of the control system.

![Figure 2: The initial concept of the haptic mouse.](image)

4.1.1 Implementation. For the prototype implementation, we kept in mind that the mouse should retain its functionality as a pointing device. As such, we took an ordinary PC mouse (Deltaco MS-737) and embedded a set of available on the market actuators into its case: a vibromotor ($\Omega$10mm x 3.4mm, weighing 1 g, operating voltage 2.5-3.8V DC, maximum speed 12000 rpm) for vibration sensations, chipset axial fan for the airflow ($\Omega$30mm x 6mm, 5V DC, efficiency 6.29 m$^3$/h), a Peltier element for temperature (30mm x 30mm x 3.3mm, 11.43 g, 5-7V DC), an RGB LED light ($\Omega$5mm 25mA) for depicting the alarming status. The actuators behavior is controlled via an Arduino platform. Due to the time limitations of the project, the temperature feature remained unimplemented. The final prototype is shown in Fig. 3.

A GUI was created in order to complement the haptic mouse. The GUI simulates the operator’s view of multiple industrial processes. The processes are composed of four types of industrial objects: tanks, boilers, valves, motors. All the objects have runtime parameters changing in time, i.e. a tank has a volume parameter, a boiler has temperature and volume parameters, a valve can be on or off, a motor rotates with certain rotations per minute speed. The back-end logic of the program monitors mouse movements tracking when the mouse selects/hovers an object. Whenever such an event is detected, the software defines the
appropriate haptic feedback based on the selected/hovered object type and properties and notifies the mouse which haptic feedback it should trigger.

Figure 3: The Haptic Mouse prototype.

4.1.2 Preliminary User Study: Setup. A preliminary study was done to gather initial feedback for the Haptic Mouse prototype, which was arranged at a power plant in Sweden, where we earlier conducted our contextual interviews. Two control room operators participated in the study, both males, aged 40 and 56, each with more than 20 years of professional experience. The aim of the study was to explore how operators would interact with the prototype and to gather their comments regarding both the overall idea of having such a mouse and the developed prototype.

For the "blind" test a Wizard-Of-Oz approach was used [6] whereby participants had their eyes covered and experienced feedback from the haptic mouse (initiated by a moderator behind the scenes) without access to a GUI. Operators were then asked to give their feedback for what industrial object’s physical property they thought was being conveyed. This was done to observe whether operators could couple the haptic feedback experienced with the appropriate type of equipment. Vibrations and airflow were tested and the intensity of the haptic sensations was varied to find appropriate comfort levels for the operators. For the "non-blind" test, participants were then introduced to the GUI and used this GUI and the mouse together. Operators experienced the same sensory feedback from the mouse as was used in the "blind" test except they could now see visual UI elements and associate those elements with the haptic sensations being experienced. Operators were then asked to give their feedback.

4.1.3 Preliminary User Study: Feedback. During the "blind" session, we saw a positive indication between the vibrations and the associations they caused, as the users experienced a clear coupling with motors, working pumps or machines with built-in rotation components. The vibration sensation in its current state was considered as being too strong. According to the users, 141 rotations per minute was acceptable but everything above this value felt uncomfortable. Longer-term user studies of the vibration feedback are needed to establish appropriate use and comfort levels for operators. The participants were unanimous in the opinion that it is better to reproduce the vibration only for a short amount of time, e.g. for one or two seconds, after which it should fade away. They found themselves predisposed to feeling vibrations only in cases where an abnormal situation was taking place, e.g. a machine is broken/misbehaving. They agreed that in this case the vibrations should be more intermittent to attract their attention.

The dependency between the vibration intensity and the speed of the hovered motor was not considered as highly useful by the operators. They explained that they would prefer to retrieve the corresponding numeric value from the visual UI instead of guessing an approximation of this based on their assessment of the vibration intensity alone.

During discussions about the perceived airflow sensation, feedback from operators was that the airflow was generally a pleasant sensation but the intensity needed to be increased so that it would be more obvious (in the prototype we used the maximum possible fan power). Also, the operators did not see an association between the airflow and their personal industrial experiences or the displays of their operator workstations.

During the second part of the evaluation (i.e. "non-blind" test), when users could use the mouse together with the GUI, their attitude positively changed. For example, when testing the vibrations, they were now more open to higher frequency levels of the vibromotor than during the blind evaluation session. Also, the airflow sensation was perceived to be more appropriate. For example, one operator concluded that he could see a connection between feeling the airflow as a feedback for equipment opening/closing actions.

Furthermore, he outlined a clear association with the ventilation system of a plant. For instance, he proposed getting the airflow feedback when switching on or off the plant’s ventilation system.

The LED light, intended to depict the status of the hovered object, given the current design had certain limitations as it did not give enough of a visual cue to the operators due to its placement.

There were a few comments about the overall design of Haptic Mouse. The participants believed that the shape of the mouse is important and should be personalized. One of the operators mentioned that he had significantly bigger hands than others in his team. Consequently, if the mouse is too small, his hand would not completely rest on its surface, which would prevent the user from getting the intended haptic feedback. In general, the operators were not completely satisfied with the mouse solution they have today in the control room and welcomed the new mouse concept presented a first step towards improving their interaction and experience with the control process.

4.2 Shift Report Tool

The aim of the second prototype was to explore how to more effectively support capturing abnormal situations in the control system and facilitate shift handover processes. The goal of the developed prototype was to provide operators with a tool that is as simplistic as the current pen and paper based approach, but is faster and more efficient in the collection and retrieval of important information found in different screens within the control system.
The major inspiration for the prototype design was taken from emergency push buttons often presented in various industrial environments: whenever an abnormal situation occurs in the production, a field worker can push the button to immediately react to the situation, e.g. stop or slow down the process. The design of the Shift Report Tool concept was based on creating a physical device (similar to the emergency push buttons) which when being pushed captures screenshots of the operator’s workstation UI. The concept also includes the knowledge sharing aspect of the logbook used during shift hand-over meetings: operators can type a comment to each taken screenshot and can discuss around the captured information. The final design introduces a button which can be pressed to take a screenshot of the operator workstation UI or rotated to see previously taken screenshots.

4.2.1 Implementation. The developed solution for Shift Report Tool (see Fig. 5) includes a stand-alone physical device and a software application running on the operator workstation as a background service responsible for taking the screenshots. The device consists of a 3D-printed case (60mm x 60mm x 25mm) with a button that can be pressed, but also rotated and a LED ring (⌀44.5mm Adafruit NeoPixel Ring equipped with 16 RGB LEDs) mounted under the top casing. A rubber pad attached to the bottom prevents sliding. The device is controlled by an Arduino Pro Micro board placed inside the casing. The operator pushes the button of the shift report tool to (at once) capture snapshots of each screen of the operator workstation. By holding the button pushed, video recordings of each screen can be recorded. In both cases a LED light is lit, indicating that a new screenshot has been taken. By pushing and rotating the button, the operator browses through all of the stored screenshots. Whenever a screenshot is shown on the UI, the corresponding LED light is highlighted with a brighter color. For the last two interactions, the "dead man’s grip" approach is utilized, meaning that every time the operator removes his/her hand from the button, all recording or browsing activities are stopped and the operator workstation immediately goes back to its runtime view. This interaction was favored in order to minimize mode errors [16] ensuring that an operator is always aware whether he/she is working with a realtime view of the operator workstation, looking at a screenshot or taking a screenshot. In addition, each screenshot has an embedded timestamp shown directly on the screenshot (see Fig. 6). The screenshots from the active screen, i.e. the screen where the operator’s mouse pointer was located at the time, are marked with a bright green border and the position of the mouse pointer is also highlighted. The snapshots of the system (both images and video) are taken using standard graphics API of the operating system.

In order to test the prototype in action we extended the operator workstation simulator developed for the haptic mouse prototype. The extended simulator shows various industrial views on different screens of a computer with simulated runtime data and alarms in order to mimic abnormal situations.

4.2.2 Preliminary User Study: Setup. To evaluate Shift Report Tool, the same two operators were involved as during the haptic mouse evaluation session. We started the session by introducing the desktop program, explaining the idea of the prototype and demonstrating it in action. Participants were then invited to try the technology themselves and to provide their feedback.

4.2.3 Preliminary User Study: Feedback. The overall received feedback was positive. The participants liked the tool because of its simplicity. They stated that the device will make the shift report handover much easier due to its ability to make simultaneous snapshots of the workstation and record videos.

However, we observed operators’ confusion in understanding how the interaction with the device worked. Operators needed
time to make themselves comfortable with holding and rotating the button simultaneously. Furthermore, this interaction occupies one hand while the user is recording a video or browsing through the taken screenshots. We concluded that the “dead man’s grip” concept in its current form was not the best option for this type of interaction.

The operators expressed that having the prototype in its current form, they would still prefer to write down the notes by hand. They explained that in their opinion it would not be as comfortable to take a snapshot using the prototype and then reach out to the keyboard to start typing a comment. As such, additional research around the capabilities within the prototype are needed to support writing/note taking activities.

5 DISCUSSION AND FUTURE WORK

In scope of the current project we hypothesized that additional physicality in digital interfaces will help to establish a better sense of connection with the machinery being operated. We have developed two prototypes aiming towards introducing tactile feedback to the operators and re-introducing physical interfaces to control rooms. During the evaluation sessions, it was found that operators welcomed physical interactions and tactile sensations in the control room. Both prototypes presented were appealing to them even though the current design of the prototypes did not fully match the operators’ expectations.

Feedback from the preliminary evaluation sessions revealed that conveying the physical properties of machinery only via tactile sensations is not effective. Instead, combining haptic feedback with a GUI should be employed. As such, one should use GUIs for showing numeric values and investigate ways to complement this data with tactile cues. Further research is also needed in order to define the proper levels of the given tactile feedback.

Preliminary feedback indicates that the Shift Report Tool concept in its current state was not ready to completely replace manual logbook entries in the shift logbook done today. The fact that participants still preferred using written notes in addition to the prototype indicates that the current concept is seen more as a supplementary solution to their existing routine. A natural progression of this work is to extend the Shift Report Tool to include different alternatives for note-taking and experiment with alternative interaction means to the used “dead man’s grip” approach.

As a next step, we plan to validate the prototypes in real industrial plants, installing the prototypes on site to enable operators to use them for their daily routines over a longer period of time. This will provide us with more insights regarding whether operators would use these types of devices in their everyday work on a regular basis, and how we can improve the design of the prototypes.

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