Challenges in multimodal notifications for monitoring cyberphysical systems

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***Abstract*—In this paper, we discuss the main challenges for human monitoring of complex cyberphysical systems, with the use of mobile technology such as smartphones, tablets and head-mounted augmented (or virtual) reality headsets. We discuss the limitations of human cognition in terms of attention management, and provide an overview of the state of the art in mobile notification systems. Concluding, we describe the role of machine learning and artificial intelligence in the assistance of mobile CPS monitoring engineers.**

***Index Terms*—Cyberphysical systems, Human-Computer Interaction, Context Awareness, Artificial Intelligence, Attention Management**

I. Introduction

Modern Cyberphysical systems (CPS) involve the operation of hundreds, if not thousands of component subsystems. The requirement for supporting heterogeneity, scalability and robustness in these systems dictates the implementation of decentralised and multi-tier complex architectures, such as cloud, edge, fog and mist computing paradigms (e.g. see [1]). Monitoring the operation of these systems is critical to reliable and secure operation. Complex CPS monitoring is enabled by automated processes (e.g. algorithms) that attempt to detect abnormal events and circumstances [2]. Some autonomy is possible in such systems (e.g. taking automatic recovery and corrective actions). However in many cases a solution requires the intervention of a human operator, and even if not, human operators might need or want to be kept informed of events and the autonomic action that the system took.

Monitoring complex CPS is traditionally done in control centers, but as systems are dynamically reconfigured, or spatially distributed, more fine-grained and in-situ monitoring (at a local level) might be required. This may extend to monitoring multiple cooperating sub-systems, or the monitoring of a single but complex subsystem. To support mobility and flexibility requirements, monitoring engineers can be assisted through the use of mobile and wearable devices. Tablet and smartphone type devices, or augmented reality headsets, can help engineers attain higher levels of local system context awareness. However, engineers tasked with the supervision of a system are typically engaged in multiple simultaneous activities – either monitoring multiple system components, or, when working towards solving an emergent problem, monitoring of components while fixing the ongoing issue. At the same time, engineers must use these devices for related activities, such as talking to other engineers, obtaining service and operational manuals etc.

In this potentially chaotic and high-stress environment which can emerge, it is important to consider the issue of attention management and support for engineers through the design of appropriate human-machine interfaces. In this paper, we examine the challenges for the human monitoring of CPS, with particular reference to the use of mobile and wearable systems that support this task.

II. Attention in safety-critical environments

The field of attention management in high stress safety-critical environments is not new. Perhaps some of the most significant advances in this domain have been made over several decades, in the aviation industry [3]. The modern aircraft environment fits the concept of a CPS system very well, since they are complex systems operated as much by computers as they are by humans. In civilian passenger aircraft, where safety is most critical, a pilot is in constant communication with co-pilots and other crew members, as well as remote operators in control towers or airline ground engineers. At the same time, a series of inputs compete for the pilot's attention, who must keep aware of situational changes in a large number of flight parameters and the status of the various mechanical, electrical and electronic subsystems of the aircraft. This work can be stressful even when no incident is taking place, but the level of stress becomes a debilitating factor when an unforeseen event takes place, such as sudden loss of altitude, or an engine.

To be able to respond to emergent events, but also to ensure that planned operations take place without the omission of steps and actions, humans interacting with CPSs must be kept aware of the system state and events as they emerge. Therefore, to maintain this level of context awareness, an operator must be able to perceive input (information about system events, e.g. via multimodal notifications), interpret the input and its

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significance to the current situation, and balance their focus between ongoing events and maintaining the input stream without missing any important events. In the next sections, we examine the physiological and cognitive barriers that set the limits of performance in human attention management, with an aim to explore where technology can provide solutions for the design-operation continuum of CPSs.

III. Attention management

Human attention fundamentals are extensively discussed in the context of digital systems in [4]. This background on human cognition and attention to ongoing tasks, is especially relevant to the monitoring of CPSs, if we consider that everyday operations of a cyberphysical system require engineers to perform a series of tasks. Many of these tasks are prescribed in standard operational routines (for which we assume an engineer receives thorough training), however, a large number of tasks emerges ad-hoc, as the context of operating a CPS changes. In [3], tasks are classified according to the need of an operator to recall information from memory in order to perform a task in the future (prospective memory). In this classification, tasks are labelled as *episodic* (i.e. ad-hoc tasks that are generated by some external authority or factor, and which need to be performed at a specified time in the future), *habitual* (tasks which take place frequently and in a pre-determined, known procedure), *atypical actions* (which substitute for habitual actions, such as a deviation from standard practice due to a specific transient factor), *interrupted* (switching from a current ongoing task to another task), and finally *interleaving* (processing multiple tasks simultaneously, or "multitasking").

The variety and sheer number of tasks potentially requiring accurate recall from memory at the appropriate time to act, leaves open a wide margin for human error (which has, regrettably, often led to catastrophe). Further exacerbating the problem, interruptions and distractions during task performance have a significant detrimental effect on the ability to perform tasks [5]. These effects are caused by well-known phenomena, such as the lag that follows an interruption and further lag that precedes the resumption of a task, as the brain pays an "overhead" to assess the incoming interruption, and to retrieve from memory all the necessary information that is required to prepare the resumption of a task [6] (Fig. 1). Interestingly, self-interruptions lead to slower task execution compared to external interruptions (e.g. by some system), and this effect is caused by the post-interruption lag rather than the resumption lag [7].

To perform monitoring tasks in a complex CPS, requires the engineer's diversion of attention to the information flows from various subcomponents, a process heavily influenced by the limits of human attention allocation. According to [8], human attention has three varieties. *Selective* attention refers to human ability to ignore certain input in order to process other, a trait which allows us to focus on the task at hand. *Divided* attention is the ability to perform more than one concurrent tasks by flexibly allocating attention to each task and switching

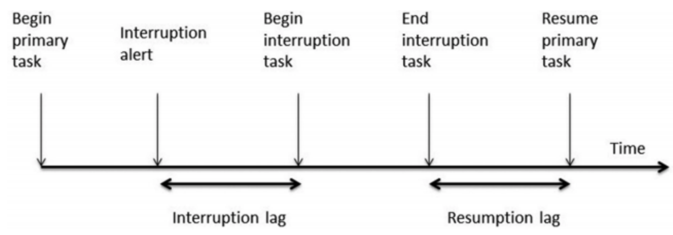

Fig. 1. Mental process during task interruption [6]

between them (often, at a significant efficiency cost). Finally, *Sustained* attention relates on our ability to avoid distractions and focus on a specific task for prolonged periods. Arguably, monitoring a CPS is a task that requires sustained attention and the division of attention across the CPS components.

To monitor a CPS, engineers need a real-time flow of information. This information can be visualised as a flow of raw data values, or coded system states (e.g. colour-coded status indicators), which may be also accompanied by notifications about events relating to these values (e.g. exceeding some threshold) (Fig. 2). Obviously, in the context of a mobile engineer using a portable device to assist monitoring (e.g. AR headset, tablet or smartphone), the volume of displayed information is limited by the need to prevent excessive occlusion of the engineer's field of view (in case of AR [9]) and the physical size of the display device. High-resolution information (e.g. historical data charts) can only be displayed simultaneously for a small number of operational parameters. Therefore the engineer is forced towards selective attention on a particular subcomponent, minimizing their ability to obtain a system-wide context awareness. In fact, this selective attention and the empirically understood cognitive costs of switching, leads to a form of inertia that compels operators to persist with the current task rather than divert their attention to others [10].

Fig. 2. Example of an IoT-based CPS monitoring dashboard.

Challenges emerge from our selective attention, which means that a monitoring engineer's focus on monitoring a particular subsystem, might make them blind to emergent information from other components. Even if we supposed that under given contexts, selective attention is not a limiting factor, the very flow of information, which for IoT-based CPSs is very high, means that achieving system-wide context awareness will result in a large volume of notifications, which can be distractive and lead towards increased demands for divided attention and limiting the engineer's ability to apply sustained attention to a particular component. Without some form of intelligent and autonomic notification management, the engineer can easily become overwhelmed, resulting in issues with task completion [11], performance [12] and stress [13]. Task performance is optimised even under interruptions, when the decision to interrupt is removed from the subject [7].

Therefore, an assistive artificial intelligence can be quite helpful to CPS operators, reminding them that they need to perform a certain action, or that a certain event has taken place, which must lead to some action, acting as a system-wide context-aware monitoring assistant. To support monitoring of CPSs, such an AI should be able to a) understand the main task an engineer is currently committed to (i.e. what information does the engineer need to complete the task, where to obtain this information and when to deliver it), b) understand the context under which it is being performed (e.g. is it routine monitoring or maintenance, or is the engineer focusing on some incident), and, c) understand and balance the priority of the current task over other interrupting tasks or tasks that are taking place simultaneously. Such a system should be able to make autonomic decisions on which events to notify the engineer about, the timing of the notification at opportune moments, and the modality which to use, in order to attract (or not) the engineer's attention, and, as stated in [11], "balancing the user's need for minimal disruption and the application's need to efficiently deliver information". In result, the challenge is to develop assistive AI that mediates notifications (e.g. defer to an appropriate time depending on activity [14] or mental workload [15]), mitigates notifications by choosing alternative output devices [16] or notification modalities [17]), and understands the interruptibility of a user [18].

IV. Perception of input

Assuming that the assistive AI described in the previous section can be built, and that it can identify pertinent events to inform the engineer about (and the right time to do so), the question remains, how to deliver this information. As discussed, apart from selectively focusing on the real-time flow of information about the operational parameters of a specific component, engineers need to maintain a system-wide context awareness. On limited displays such as AR headsets and mobile devices, this is best achieved through multimodal notifications. Human cognitive ability relies on the ability to perceive stimuli through the various senses (vision, hearing, tactile etc.). According to Wickens' Multiple Resource Theory [19], [20], a human operator has several pools of resources that can be simultaneously tapped by the same, or multiple concurring tasks (Fig. 3). These resources include the user's sensory organs and the cognitive processing of stimuli (perception, processing, action, and reasoning). When multiple tasks occur, a competition for these resources emerges, whereas when a single task is taking place, these resources can be tapped in parallel, enhancing user performance (e.g. if a user misses a notification sound, they can still perceive it through visual feedback, hence successfuly perceiving it). Thus, for a high notification volume system, in which the user's attention is simultaneously divided or applied sustainedly, the ability to notify via multiple modalities is critical to ensure that important information is not missed due to selective attention.

Another issue related to perception is the semantic encoding of information. Both in visual as well as in haptic and audio modalities, information can be encoded in order to help the user obtain more information about an event [21]. For example, to signify event criticality, visual displays can make use of colour and iconography, haptic feedback can vary the frequency and intensity of repeating haptic signals, and audio feedback can use speech or structured audio messages (earcons) with varying pitch, tone and frequency. Interpretation of these encodings is sometimes intuitive, based on previous user experiences and cultural backgrounds (e.g. red typically signals danger). However, for other types of signal, these encodings must be learned and there are limits to the number of levels (or classes) of information that can be distinguished successfully.

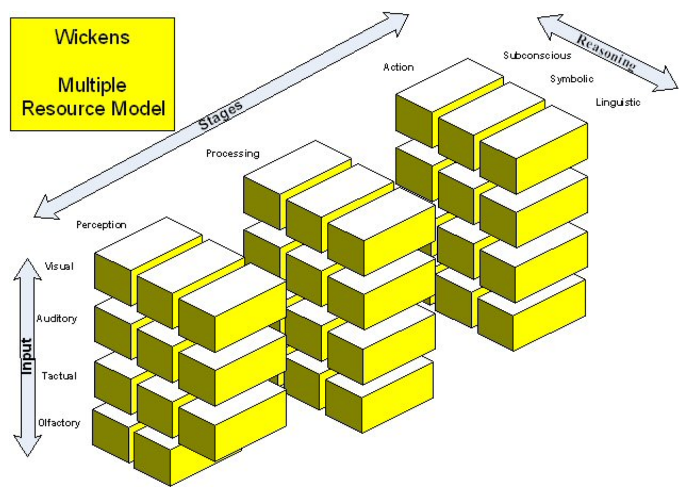

Fig. 3. Wicken's MRT perception model

Research in smartphone and AR notification modality efficacy is somewhat limited. Concerning the use of smartphones, studies report conflicting results on the efficacy of sound and vibration to attract a user's attention, due to the fact that this research reports on findings from in-the-wild studies and has several internal validity issues [22]. In [23] a controlled laboratory environment study compared the efficacy of notification modalities for attracting user attention, examining both smartphones and ambient lighting, showing that vibration does not strongly affect users' perceptibility of notifications under heavy mental workloads, and that both sound and ambient lighting can be better attractors for attention. The delivery of visual smartphone notifications on a wearable AR display during a typing task was investigated in [24], and compared against traditional delivery methods (e.g. the smartphone status bar, lock screen), and a second peripheral display. Although

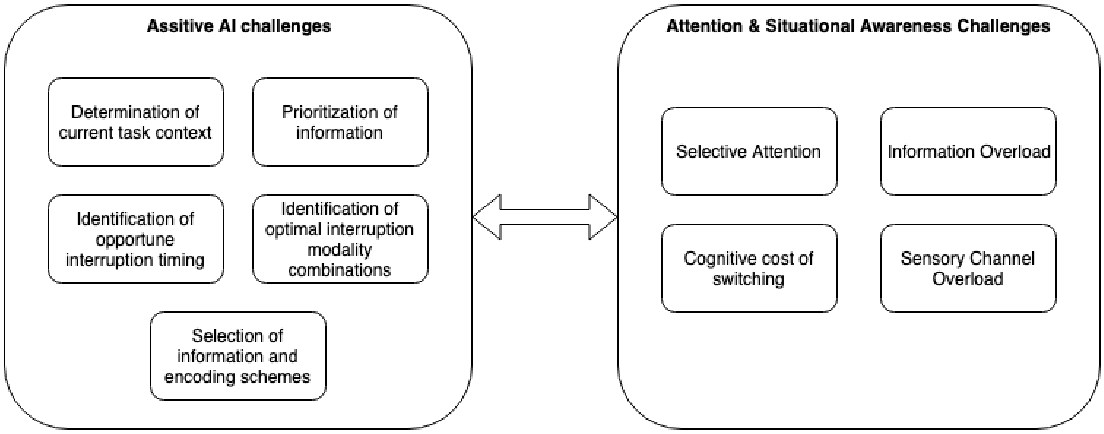

Fig. 4. Overview of challenges in notification delivery for CPS-monitoring systems

it didn't compare favourably in ease of use and frustration, notifications in AR were found to exhibit several desirable properties, such as privacy, ability to use without requiring hands (e.g. while wearing gloves) and the ubiquity of the method, which does not rely on having situated computing equipment.

A more complete investigation on notification modalities on head-mounted displays is presented by [25], where the perceptibility of notifications in VR headsets were examined. In this study, visual notifications during an on-going task were found to be the least perceptible, and that adding audio to visual notifications helps their perceptibility more than adding a vibration. These findings are completely in line with [23]. In a study on collaborative task solving via AR, users were found though to prefer visual over audio notifications for instructions pertinent to the task, for the reason that users' attention was already devoted to a task requiring visual input, thus audio notification was found to be distracting to task completion [26]. As highlighted in [27], audio notifications also suffer from the issue of permanence. While visual notifications can persist on the user's display, audio notifications have to be repeated in case they are missed. On the other hand, persistent visual notifications add to the "clutter" and demand more of the user's limited display area. To address the problem, pseudo-ambient notifications are proposed, which are triggered at regular intervals [28]. In this case, the authors investigate tactile notifications, however their findings can be applicable to other modalities.

V. Illustrations of use cases in an IIoT context

As discussed in the previous sections, a range of challenges in the notification delivery for CPS monitoring systems arises from the very nature of humans and the cognitive processes that are involved in situational awareness. Although we argue that AI can assist in mitigating these challenges, at least to some extent, it is clear that such AI systems need to also solve a range of challenges that relate to their ability to operate in a context-aware manner. These are summarised in Fig. 4. In the next sections, we will attempt a design discussion around the application of the aforementioned theory, in the context of monitoring a CPS, composed of Industrial Internet of Things (IIoT) architecture. We present three use cases employing different interactive monitoring systems that demonstrate how the use of AI can assist the balancing of minimal distraction, while ensuring the efficient delivery of information. These examples also illustrate how some of the challenges discussed previously, can be addressed through notification design.

A. *Intelligent notification display on dashboards*

One common approach to monitoring large installations is the extension of the visual display area to large displays. To achieve this, a series of large panel monitors can be physically arranged together to form a larger, wall-sized display. Monitoring engineers are placed in the control room, where the wall-sized display shows an overview of the whole system state, while individual engineers have personalised monitoring stations, often with multiple displays, which allow them to focus on specific target areas.

This setup presents several problems. Firstly, due to selective focus and also the occlusion of parts of the wall-sized display by the personal workstations, it is difficult for an engineer to obtain a simultaneous awareness of their local and global environment. As seen in Fig. 5, even local awareness can be difficult, as the engineer's display area exceeds the normal field of vision (FoV), e.g. see the laptop screen on the bottom right of the figure. To draw attention to ongoing events outside the engineer's FoV, multimodal notifications can be used (e.g. sound), however the engineer must scan all the available display area to identify the relevant section that requires attention. In this case, a smarter display system could track the user's head position relative to the display area, and chose to display the notification on a surface which is likely in the current view of the engineer. The choice of notification size, colour, accompaniment by sound and amount of information displayed in the notification, can be handled by the assistive AI, depending on the criticality of the event, and the user's current task and interruptibility. A pertinent challenge here is for the AI to determine how much information is pertinent to display - it should be enough to assist the user in determining the nature and severity of the issue, thereby supporting the decision to switch task contexts, but not too much so that it floods the user with unnecessary detail.

Fig. 5. Typical control center setup

B. Virtual dashboards

In a system such as discussed in the previous section, engineers are stationary and this prevents them from obtaining awareness while on-site. Another issue is that if the engineer needs to monitor another subsystem which is not typically under their responsibility, as part of an ongoing task, they need to switch their attention across multiple displays, some of which might be occluded by other hardware or engineers.

A mobile engineer could make use of a virtual reality headset, which can extend the display space to 360 degrees around the user, as well as above and below the user line of sight (e.g. Fig. 6), therefore completely eradicating the display area problems of mobile devices, and occlusion problems of a traditional control center. This solution allows for flexible configuration of the display area, hence the user can obtain an overview of the entire system state, while manually arranging the individual display widgets (or widget groups) in proximal configuration, to better suit the current task needs.

In the event of a subcomponent raising an alert, the user can be informed in multiple ways, depending on the assumed interruptibility of the user, and the criticality of the alert. As mentioned in the previous section, this choice can be mediated through an assistive AI. A subtle notification modality, since they are wearing a headset, is the use of 3D sound to issue directional audio cues to the display area outside a user's FoV, which has raised the alert. Additionally, a small visual notification can emerge in the current user's FoV. Finally, in the case that an event is critical, part of the user's current display can be dynamically replaced by the widget which has caused the alert, bringing that display segment to the fore.

C. Augmented reality monitoring

On-site engineers can use augmented or mixed reality headsets to examine the state of individual IIoT components

Fig. 6. Virtual desktop environment. A 3D audio signal alerts the user to the display area which is currently exhibiting an alert.

in real time. Although the idea and use cases for AR (in the context of the shipbuilding industry [29]) have been proposed in the past, only very recently have such concepts began to be implemented and investigated. In [30], the authors propose an augmented reality interface for visualising the state of IoT devices and the workflows that interconnect these, in order to achieve a specific task or goal. Another similar work [31] discusses the visualisation of energy consumption of individual subsystems in an assembly line through AR. These concepts have not yet been formally evaluated, and more specifically, there is no discussion as yet regarding how off-FoV events could be brought to the user's immediate attention.

In AR applications, one significant issue is visual occlusion - it's not always possible that IoT enabled devices related to a specific task are visible, for example, components might be deeply embedded and positioned in close proximity within enclosed containers, or remotely placed behind walls or other furniture and equipment. Close proximity of IoT devices also may cause occlusion of the AR information related to it. This problem stems from the tight coupling of AR elements to the real world, since, in contrast with our previous VR example, the AR elements need to visually correspond to the position of physical objects, in order to maintain situational consistency.

As an example, we illustrate these issues in Fig. 7. In this example, a simple assembly line is demonstrated. The engineer is able to see IoT device states and the workflow rules connecting their operation, using an AR headset. Items move on the conveyor belt CB2. They pass through the label printer LP2. As they arrive at the end of CB2, a sensor EOLS2 detects their presence and instructs the robot arm PA2 to rotate to pick them up. The sensor EOLS2 is connected with a workflow rule to CB2 (Workflow92), stating the sensor should be enabled when the conveyor belt is also switched on. Another relationship (Workflow93) links the sensor EOLS2 to PA2, stating that when the sensor detects an item, the arm should rotate to pick it up. In the example, EOLS2 malfunctions because an item is already in position, but the sensor has not detected it. The item is about to fall off but the engineer can't see this happening as the events unfold outside their FoV (grey area). Also, the engineer is not able to see

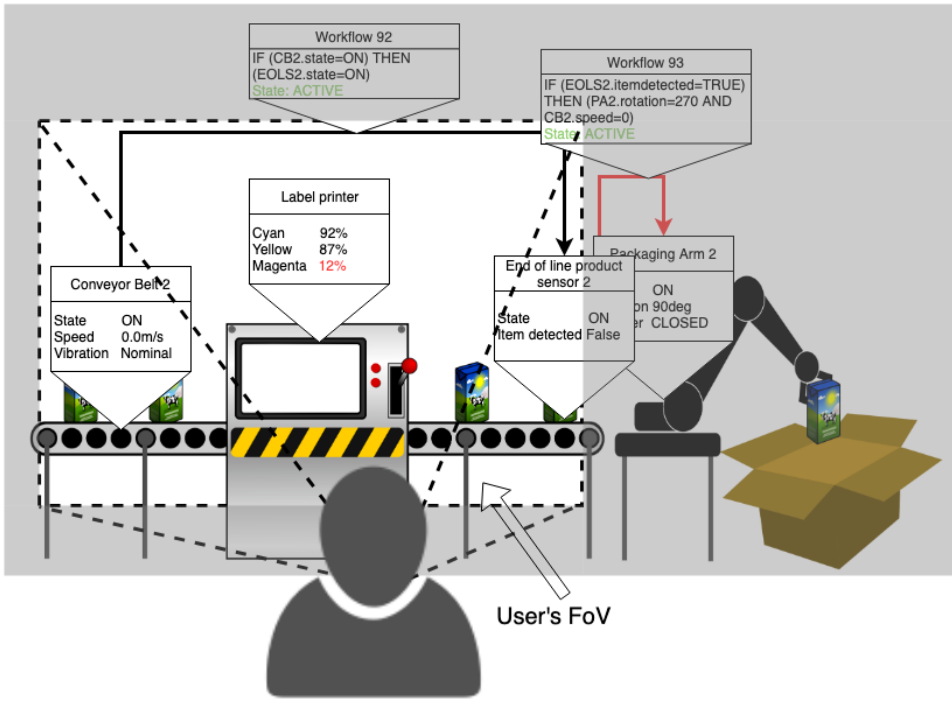

Fig. 7. AR monitoring of an assembly line section.

the incorrect state of EOLS2 since the AR label is partly outside their FoV. Instead, they are focusing on the printer supply levels which is indicated as low. Since an item is being printed, CB2 has stopped, and Workflow93 becomes red, since it expects the robot arm to be in position to pick up an item when CB2 stops. This should be enough to warn the engineer that something is wrong, but again, the colorisation event of the workflow is outside their FoV, hence it can't be noticed.

In this example, we note several issues. Firstly, AR labels occlude one another when IIoT devices are in close proximity. Next, as the user's selective attention is focused on a particular problem (which is not critical), another more important event takes place outside their FoV. To mitigate these problems, assistive AI can alter the depth hierarchy of AR labels and rearrange items automatically, to identify all those items involved in a malfunction issue, and then present their AR labels at the top of the hierarchy (i.e. in front of others). Popping up a small notification in the user's display area is possible, but this does not provide situational (location) context. A better solution would be to display directional cues (e.g. arrows), directing the user to shift their attention to the appropriate area of the assembly line.

To illustrate this concept, in Fig. 8 we demonstrate the engineer's view of two properly functioning welding robots. At the same time, another robot outside the engineer's FoV is running out of wire (Welder 4). The event is not critical hence a yellow colour code is used to display the event information in a notification box at the bottom of the engineer's FoV. At the same time, a directional arrow shows the approximate direction of the robot from the engineer's current position. Next, a further robot (Welder 3) suffers a catastrophic failure and ceases to operate. The event is of higher priority and therefore its notification box is coded red, and it is positioned on top of any other ongoing notifications. An arrow also shows its direction, but the shorter length of the arrow shows that it is closer to the engineer than the other robot.

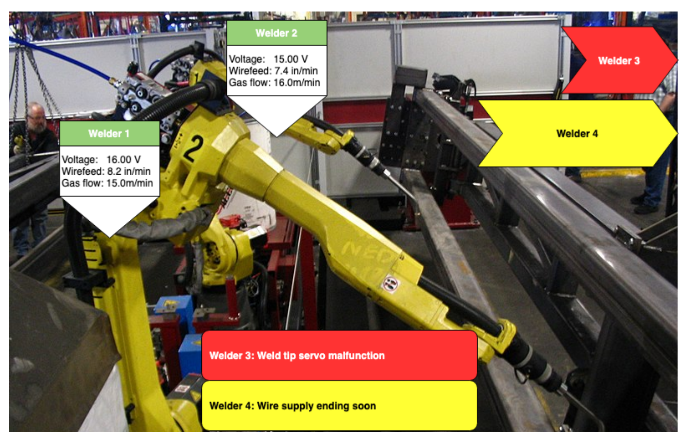

Fig. 8. Mockup of an AR notification system.

VI. Conclusions

In this paper, we have outlined the main challenges in human monitoring of CPSs. The fundamental functional properties of human cognition (working memory, long-term memory, perception and interruption management) place stringent requirements on the design of complex CPS monitoring systems.

To an extent, the goal of affording a single engineer a holistic, system-wide context awareness seems unattainable. At the very least, it seems unfeasible to merge the utility of large (even wall-sized) monitoring interfaces with the requirements of mobility, and even if that were possible, the limits of human cognition are such that selective attention to specific tasks and system components practically prevent the possibility of full context awareness. In the coming years, advances in AI might help towards attaining that awareness, first at a system level, and then at the level of being able to efficiently communicate this awareness to human operators. Without assistive AI to mediate, mitigate and select the modality of system-human communication, human operators will be excluded from the monitoring loop, possibly with disastrous results.

Future research should focus not just on AI, but also strongly on the modality perceptibility and notification design spaces. Currently, information visualisation via notifications is surprisingly understudied, both in terms of smartphone notifications, but even more so for head-mounted displays. This research is necessary, so that its findings can be best exploited by the assistive AI that is so central to monitoring future complex CPSs.

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