Utilizing VR and Gaze Tracking to Develop AR Solutions for Industrial Maintenance

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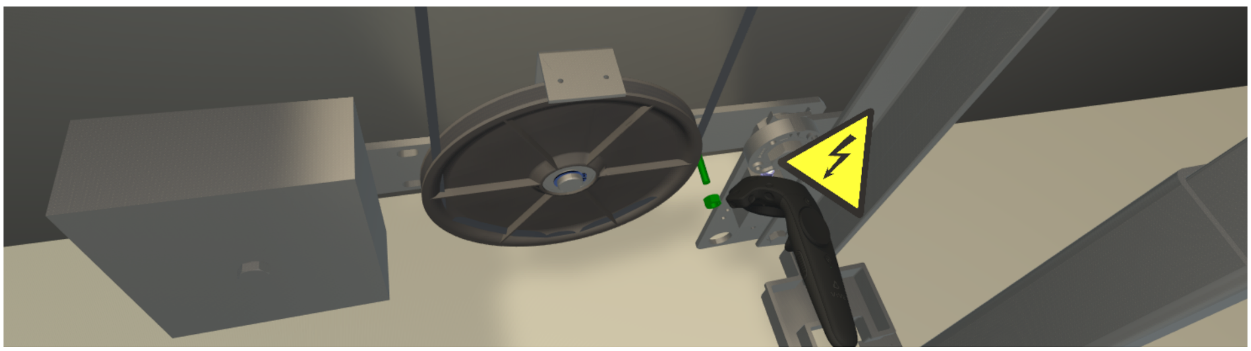

Figure 1. Simulated AR safety warning as seen in the VR training environment.

ABSTRACT
Augmented reality (AR) presents a variety of possibilities for industrial maintenance. However, the development of real-world AR solutions has been limited due to the technological capabilities and uncertainty with respect to safety at deployment. We introduce the approach of using AR simulation in virtual reality (VR) coupled with gaze tracking to enable resource-efficient AR development. We tested in-field AR guidance and safety awareness features in an iterative development-evaluation process with experts from the elevator maintenance industry. We further conducted a survey, utilizing actual gaze data from the evaluation to elicit comments from industry experts on the usefulness of AR simulation and gaze tracking. Our results show the potential of AR within VR approach combined with gaze tracking. With this framework, AR solutions can be iteratively and safely tested without actual implementation, while gaze data provide advanced objective means to evaluate the designed AR content, documentation usage, and safety awareness.

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CSS Concepts
• **Human-centered computing~User Studies; Mixed / augmented reality; Virtual reality**

INTRODUCTION
Industrial maintenance is an area where information technology is taking an increasingly large role. The concept of the Mixed Reality (MR) continuum [23] expands the possibilities of classical practices via exposing the use of computer-mediated multimodal data both in an immersive virtual environment or as augmentations over the real world. On one side, virtual reality (VR), has proved to be a viable environment for learning and training [7] due to the flexibility [4] and realism of experience [12], in addition to the possibility to safely simulate dangerous operations and contexts [33]. On the other side, in-field guidance via augmented reality (AR) can improve speed, quality, and safety of work, resulting in decreased physical and mental workload for the technicians [13]. So far, these concepts have been studied separately despite the potential of uniting AR and VR under one comprehensive platform, including cost savings due to shorter development time, increased efficiency in training, and the possibility to integrate safety-related aspects deeper into organization's culture and processes.

Benefits of AR, especially solutions based on see-through head-mounted displays (HMDs), come from immediate access to information in a context-sensitive manner during work. Moreover, AR can actively support safety by displaying warnings and other critical information when relevant. However, AR can also create safety risks if the information is displayed in an inappropriate manner, thus, distracting the user from noticing real-world hazards. Hence, industrial AR solutions should be reliable, flexible, and efficient since work tasks involve many risks and hazards. The development of industrial AR solutions should be iterative, with systematic testing, to identify the best strategies of information presentation and interaction for accessing the AR content. This includes media types, such as text, video, audio, pictures, and 3D models, and interactions like browsing, acknowledging messages, and searching for information. Errors in design may lead to dramatic consequences.

So far, there has been little focus on defining what kind of technical information should be displayed in AR applications and how [10, 37]. The development of AR solutions is often frozen in the proof-of-concept state and such solutions are rarely implemented in a real context due to hazards of real-life evaluations and technical limitations of see-through HMDs. As technology develops and becomes feasible for industrial maintenance, technical content must be fitted to the needs of the users, context, tasks, and devices. Considering the risks associated with testing in a real industrial context, an easy, resource-efficient, and safe way to test content and interactions is required to boost AR development further.

The flexibility of VR simulations makes them a feasible and efficient approach to address AR development issues [3, 29]. Within VR, potential AR concepts can be evaluated in a realistic simulated context, and aspects like information presentation, interaction techniques, and context-sensitive functionality can be tested in a safe environment. VR solutions can also simulate many of the limitations of AR technologies including field of view, tracking accuracy, and image contrast and color. Furthermore, VR prototyping can provide material, that can be used to elicit comments and opinions from domain experts, which is vital given the special characteristics related to the field of industrial maintenance. Finally, considering the digitalization of industrial design processes, prototyping in virtual environments (VE) can be done in a resource-efficient manner.

Furthermore, HMD-integrated gaze tracking provides extended analysis possibilities for the usage of the augmented content and other user behavior [2, 18]. Gaze tracking has proven itself as a valuable tool to analyze attention span [18] as well as to measure learning [5] and safety awareness [2]. In VR prototyping and training, gaze tracking can provide an understanding of how maintenance technicians perform their tasks, how they notice and utilize AR content, how the AR interface affects their performance with the task, and how it affects work safety.

We have explored the potential of VR technology coupled with gaze tracking for prototyping industrial AR solutions, focusing on how experts involved in the development process perceive the benefits and challenges of the approach in the industrial context. To enable this, we developed the *xR Safety Kit* framework, a multipurpose VR platform with AR simulation and gaze tracking to support AR prototyping and training. We also performed an iterative, industrial development-evaluation process with expert participants to demonstrate how AR features, in our case *in-field guidance* and *safety warnings*, may be evaluated in a resource-efficient manner with a small number of participants. In addition, the resulting materials, e.g., visualized gaze tracking data and recordings of the testing procedure, were utilized in an online survey to gather domain experts' opinions on the framework and the use of AR, VR, and gaze tracking in industrial context.

Our results show the potential of utilizing VR coupled with gaze tracking for efficient industrial AR development. The *xR Safety Kit* is a flexible and safe framework for AR prototyping, which may be easily deployed by utilizing existing materials in industrial contexts. Using gaze tracking while testing provides valuable understanding, which cannot be gathered with traditional evaluation methods. We further framed design suggestions for documentation presentation and safety warnings for an in-field AR tool, which are generalizable for other hazardous industrial contexts of use. Moreover, we found positive attitudes toward, and the desire for, utilizing innovative technologies in the industry. Additionally, our results indicate that integrating industrial working processes into a virtual environment to enable collaboration of different departments would positively affect not only the employees' motivation but also the overall company performance.

RELATED WORK

Three decades of work within the MR continuum in the industrial context have resulted in a set of prototypes, concepts, and evaluations indicating the benefits of utilizing AR and VR as assistive environments, including cognitive support, quality assurance, and training [7]. This chapter presents use cases and opportunities related to the use of AR, VR, and gaze tracking in the industrial context.

AR in Industrial Maintenance

The field of maintenance remains the second most popular application field of AR [6] due to the complex and dangerous nature of the work [21] combined with significant physical and cognitive requirements [13]. AR has been reviewed as a promising supporting technology [6] due to its possibility to enrich the real-world experience with computer-mediated data [23]. Early research [13] in the field demonstrated that effective AR assistance can reduce mental and physical workload by increasing the efficiency of workers and minimizing head and neck movements. Over the years, augmented reality has been applied to industrial maintenance in various prototypes, which provide access to information, guidance in work procedures [13, 16, 27], and ways to record information [11]. Research by Platonov et al. [27] demonstrates a prototype of a monocular wide-angle camera AR setup with markerless tracking that was tested on BMW 7 series engine maintenance and showed robust and stable system behavior and successful task performance. An AR system for guiding technicians in aircraft maintenance, presented by Jo et al. [16], showed a decrease in preparation and repair time in comparison with implementing the task relying on paper-based manuals.

Nevertheless, existing research in maintenance-related AR has contributed to narrow use cases, thus, lacking in the generalization of content creation and adaptation [9]. The same applies to the field of technical communication, which conveys technical or specialized information and uses technology to communicate instructions [40]. Traditionally, technical information has been delivered on paper, as electronic prints, as embedded online help, or, more recently, through online portals or web services. However, very little has been done to create any guidelines for the use of new media and technologies, such as AR glasses, in technical communication [37]. A recent study [34] in an industrial setting demonstrated that existing, traditional technical documentation content does not work when viewed with AR glasses. The amount of text is generally too large, and the user is forced to scroll to find the needed information, which makes it difficult to comprehend the content. Furthermore, an adaptable delivery channel from the documentation system to the guidance application is required, as it is not feasible to tailor the content only for a specific device or task.

Other popular directions for industrial AR are in-field training [12, 39] and tele-assistance [24]. The main benefit of AR training over VR is the possibility to utilize virtual information overlaid on real equipment [12], enhancing the mapping between the training and the task [39]. The study by Gavish et al. [12] demonstrated a significant difference in performance, e.g., a reduced error rate for the participants trained with AR. Further, De Pace et al. [24] introduced two AR designs for collaborative MR tele-assistance where the trainer, being in VR, gives instructions to the trainee (in the form of abstract metaphors or as an avatar) working on real equipment with AR. AR is also seen as a viable tool to address safety in hazardous working environments through situation awareness and hazard identification. The benefits of AR in terms of safety have been shown in the field of construction [1, 19] and driving [31]. Yet, the potential of applying AR in maintenance to address the safety aspects is unexplored [6].

VR as an Environment for AR Prototyping and Training

Despite the benefits that AR technology can bring to industrial maintenance, the technology has not yet been widely applied in real-life contexts [10, 15]. The challenges of AR development have been divided into three areas: *authoring* (augmented content creation), *context awareness* (content adaptation to the environment), and *interaction analysis* (advancement of the interaction between the user and the system) [9]. One approach to address *interaction analysis* is prototyping AR solutions within a VR environment. This provides a safe and controlled way to test techniques and hardware with manipulation of factors such as field of view and image resolution [29]. For example, Alce et al. [3] introduced the Immersive Virtual AR method for prototyping wearable AR interaction and showed its potential in the industrial setting due to fast prototyping of several designs. Moreover, virtual prototyping benefits the existing industrial product development framework by enabling cooperative engineering in open and distributed environments with diverse data formats and content [30]. Considering rapidly increasing digitalization processes in the industry (the development of CAD models and structured technical documentation), establishing realistic VEs and data does not require extensive content production. Thus, integrating VR into the industrial development processes can actually reduce the development time and costs and increase the quality of operations [30] without additional efforts and resource usage. Further, AR prototyping in VR can be integrated into existing VR training environments, while testing could be performed together with the training of target users.

Training via VR brings significant value for the industry due to the extended adaptability and flexibility [4] with the possibility to provide standardized training worldwide for various skill levels within one system. Furthermore, in VR trainees can perform the practice tasks in a realistic manner (e.g., training physical memory or patterns of the task) without visiting the real environment. The use of VR in training ranges from non-immersive training platforms [4] to simulators [33] and HMD-based VR solutions [28]. For instance, Borsci et al. [38] found a significant increase in trainees' acquisition of the procedural skills when training in a VE, meanwhile showing no significant difference between a fully immersive CAVE system and a simpler holographic 3D table. Further, Quevedo et al. [28] suggested a multi-layer scheme for the development of immersive, HMD-based, virtual training environments and demonstrated a comprehensive prototype that allows selecting different working environments and difficulties. In contrast, the study by Gavish et al. [12] showed no significant difference in performance between VR training and traditional training methods. They suggest that VR training may still be advantageous, and note, that the results are based on a small number of participants. All in all, there is still no clear understanding of how fully immersive training environments should be designed to benefit the training process.

Gaze Tracking

In addition to the information gap in terms of knowledge representation [9], there is also a gap regarding the integration of AR with other technologies and analytic tools [10], including gaze tracking. Gaze tracking is a traditional tool in usability engineering and it is increasingly being applied to VR and AR [14, 26], as it is the most accurate method to investigate the allocation of visual attention. 3D gaze visualization has been studied by, for instance, Stellmach et al. [35] and Maurus et al. [22]. In particular, Stellmach et al. developed generalizations of existing 2D visualizations (heatmaps, scan paths, and timeline representations) into 3D space. Another motivation for increased gaze tracker adoption in HMDs is that it can facilitate foveated rendering for increased rendering performance in VR applications [25].

Gaze data have also been used to facilitate and measure learning. In 2002 [8], the gaze data of expert doctors were utilized to increase the performance of novice doctors in assessment strategies, while in 2012 [18] gaze data analysis demonstrated a significant difference in visual attention (gaze overlay) between expert and novice surgeons while watching a laparoscopic operation. This suggests that gaze data recordings are useful to gain insight into the learning of surgeon students. Other studies [5, 17] have utilized gaze data for user modelling, using classification models to predict high vs. low achievement based on gaze data, with a goal of providing online systems that could provide feedback also during the interaction, not only after the fact. Some studies have also used gaze tracking to improve safety, i.e., to measure the impact of safety warnings during driving [2] or to improve process safety while dealing with hazardous materials [32].

XR SAFETY KIT: SYSTEM DESCRIPTION

We designed the *xR Safety Kit* framework, a multipurpose VR system, which allows performing maintenance tasks in virtual environments (wearing an HMD and using hand controllers) for training as well as for AR content development and testing. The system was made with the Unity game engine and the existing 3D CAD model of an elevator shaft. The virtual elevator shaft contains equipment and tools relevant to the current task, as seen in Figure 2, top. The virtual objects detect collisions with tools, animate, and play sounds at appropriate moments to give information on the progress of the task. The system also stores the user's gaze data, object positions, and task progress. User activities can be played back with gaze data visualizations (scan path and heatmap over the virtual environment).

The system assists the user in performing a maintenance task with instructions, extracted from existing XML-based maintenance instructions currently used by the technicians in paper format. As an exemplary task, the users of the system are to perform the *Remove and Replace Tension Weight* maintenance task in VR the same way they would do it in real-world settings: The users read the instructions, select and use the correct tool on the correct spot in the tension weight assembly and repeat these steps until they have completed the disassembly phase. After replacing the tension weight, the users perform the assembly, which consists of the same steps as the disassembly, in reverse order.

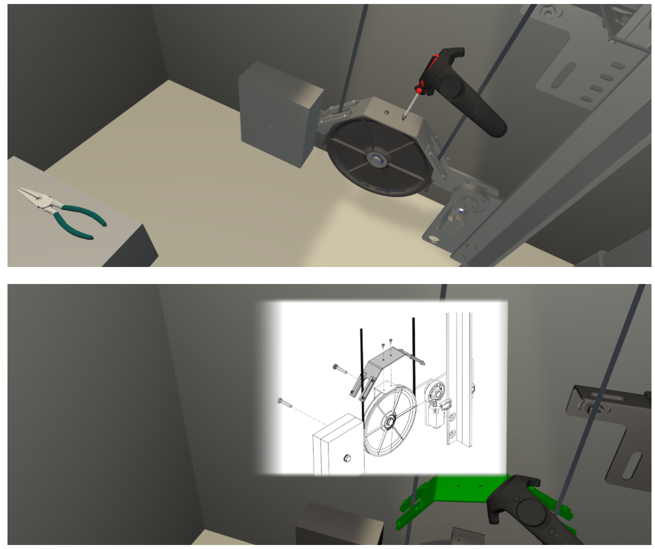

Figure 2. User's view while using a screwdriver (top) and with the DocPanel and guidance highlight (bottom).

The distinctive feature of our VR-based system is the simulated AR mode. Simulating AR within the VR system has two major purposes: Firstly, it allows evaluating AR features, *in-field guidance* and *safety awareness*, in a safe and controlled environment. Second, it allows the testing of different hardware aspects of AR presentation. These include field of view (FoV), image quality, colors and transparency of objects, fonts of the AR display, and AR tracking precision. The system simulates AR glasses' FoV by displaying AR content over a rectangular area. In our evaluations, we used a FoV of 40° horizontally and 27.5° vertically, centered to the user's field of view, as it is in the range of the currently available commercial AR solutions. The edges of the FoV are feathered to avoid visual discomfort. Optical distortions that may be caused by AR glasses were not simulated.

To sum up, the system can be potentially used for several purposes: It enables **1)** maintenance method training for unexperienced technicians in realistic, yet safe settings via step-by-step task guidance, and **2)** risk identification, safety training and certification via gaze tracking, and user activity analysis. The logged data and the system can be further utilized for **3)** maintenance methods development and testing, **4)** documentation development and testing, and **5)** AR content development and evaluation of, e.g., multimodal interaction techniques for in-field technologies and adaptation to the industrial context of use.

In-field Guidance: DocPanel Tool

As a metaphor to classic paper instructions, we created a documentation panel tool, the *DocPanel*, for step-by-step task guidance. The DocPanel visualizes instructions in the form of text, pictures, and animations over a white square (Figure 2, bottom). The user can move the panel in the 3D space and center it to eye-position. The panel position is parented to the user's head location, but its orientation is fixed to the world orientation. This allows the user to find the panel always in the same direction and supports information retrieval with a glance as the DocPanel can be located in a comfortable spot for each working position. In addition, when the user progresses with the maintenance task, the VR system highlights the tools and equipment that are required during the current step, as seen in Figure 2, bottom.

Safety Awareness: Multimodal Safety Warnings

We designed three *multimodal warning types* to inform the user about possible hazards in the elevator shaft context:

1. *Textual Safety Notification* is used to present task-related hazards, e.g., heavy equipment parts. It contains text and a static icon to explain the risk displayed over the relevant object at relevant steps during the task.
2. *Animated Safety Warning* is used to indicate environment-related risks and is shown in the form of an animated icon when the user is at risk to interfere with, e.g., by touching, dangerous elements. The icon remains visible for 1 second over the dangerous area after the user has moved their hand away. In case the area is out of the user's FoV, the system plays an audible beep and displays a red arrow pointing toward the risk area. See Figure 1 for an example.
3. *Audio and Visual Safety Warning* utilizes both voice warning and an icon to warn of an environment-related risk when a visual icon alone is not enough to explain the danger. If the hazard is out of the user's FoV, a red arrow and voice warning are used to communicate the danger.

METHODOLOGY

In order to investigate the feasibility of our system in terms of VR for training and AR within VR, we carried out three development-evaluation iteration rounds in a realistic industrial context with expert participants from an elevator company. Utilizing experts was vital in our industry-focused study, as the needs and challenges of systems designed for industrial maintenance are different from other systems. We also collected attitudes and thoughts from another set of experts with a survey utilizing, e.g., gaze data collected in the user evaluations. Next, we describe our evaluation and development activities.

Iterative User Study

The first iteration was carried out to verify the concept and collect ideas and requirements to proceed further with the system development. At this stage, the virtual environment represented the elevator shaft with equipment and the DocPanel tool; however, it did not support maintenance task guidance. Four expert participants explored the designed VE without defined instructions and afterward answered three interview questions. The collected data provided us with directions for design decisions on, e.g., the DocPanel tool interactions and font size, safety warning locations, and sizes and textures of 3D models.

The 2nd iteration was focused on investigating the usability and efficiency of the in-field AR guidance and warnings in general. Modified after the first iteration, the system now allowed users to proceed with a maintenance task fully, displaying a safety warning of electric shock hazard in the form of a static picture. The outcomes of this stage resulted in fixing minor usability issues, designing the highlight of maintenance tools and equipment parts to increase the effect of guidance, and the deployment of three types of safety warnings. In addition, the need for advanced logging of the 3D objects and gaze tracking was identified.

In the 3rd iteration, the system design corresponded to the description in the previous chapter. The focus of this evaluation iteration was on safety aspects: e.g., the evaluation of the designed safety warnings and further exploration of the DocPanel tool's efficiency with gaze data.

Next, we provide a more detailed description of the second and third iterations' evaluations, which were similar in methods and procedures.

Participants

Five male experts from the elevator company took part in the 2nd iteration evaluation and four male experts in the 3rd iteration. Two of the participants had no experience in elevator maintenance but were specialized in information architecture related to it. The rest had at least 2.5 years of elevator maintenance experience ($M = 15$) and at the time of the evaluation, some were working in the office on different positions (R&D, Reliability, Field Trainer, Method Development, etc.). Six of the participants had tried both AR and VR technologies before the evaluation, two had heard about them while one had no prior experience.

Collected data

We collected both objective and subjective data in the two latter iterations. Subjective data were collected via a digital questionnaire and a semi-structured interview. The questionnaire consisted of six parts: 1) background information, 2) system effectiveness, 3) usability and user satisfaction, 4) AR guidance tool, 5) safety aspects, and 6) VR-related questions. Due to the focus on safety, in the 3rd iteration, we utilized also paper questionnaires for each safety warning type. The interview questions were designed to gain deeper insight into the framework in the industrial context on the same aspects as the digital questionnaire.

Collected objective data consisted of gaze and user behavior data, i.e., the orientations and positions of the HMD, hand controllers, and virtual objects, and the use of buttons. Data on the DocPanel usage was collected during both iterations ($n = 9$), while data on safety warnings were gathered only from the 3rd iteration ($n_3 = 4$). The eye tracker sampling rate was 120 Hz and behavior data were logged once per frame. The gaze vectors from the eye tracker were converted into gaze points by taking the normalized sum of the direction vectors from the left and right eye and performing a ray cast to the closest surface in the virtual world. Only samples marked valid for both eyes by the manufacturer's software were included. The mean percentage of valid samples out of all samples per user was 96.1% (min = 93.2%, max = 98.5%). Invalid samples may happen as a result of blinking or if the HMD moves too far on the user's face, causing one or both eyes to go outside the detection window of the eye tracker. The gaze points were further processed into fixations using a sliding window of 200 ms [20]. By default, a new fixation was created if all the gaze points inside this window were a maximum of 10 cm away from the average for the window. However, if the distance from the potential new fixation to the previous fixation was under 5 cm, a fixation was not created. We consider it acceptable to use the fixed thresholds of 10cm and 5cm because the distance from the fixation points to the user is limited inside our elevator shaft model. These criteria for defining a fixation were also used for creating the scan path gaze visualizations for our domain expert survey.

Procedure

The evaluation sessions in both iterations took place in a spacious meeting room, in the premises of the company where the experts worked. We used HTC Vive HMD with an integrated Tobii 120Hz eye tracker and Vive controllers for the study. The view the participants saw via the HMD was mirrored on a screen, so the moderators could see the process and assist if needed. First, the moderator presented the study objectives and described the study shortly. Next, the participant practiced using the controllers and learned the functionalities in a training session. After that, the scenario was presented, gaze-tracking calibration was performed, and the participant started to perform the maintenance task following the guidance provided by the system. After completing the task, the participant filled in the online questionnaire about their experiences and answered the interview questions. The procedure was audio-recorded with the participant's written consent.

Survey on AR, VR, and Gaze Tracking Feasibility

The main goal of the survey was to gather expert opinions on the usefulness of the AR within VR approach and gaze tracking in the context of industrial maintenance. The digital survey was created with an in-house tool; the link was shared with the experts in different departments of the elevator company. The survey consisted of three parts and included videos, open-ended questions, and altogether 29 statements answered on a 5-point Likert scale with extremes of Totally disagree (1) and Totally agree (5). An electronic consent to participate was collected at the beginning of the survey.

The survey firstly introduced the designed system's functionality with a demo video and textual description as well as defined the terminology used in the statements. The first part of the survey collected data related to the AR simulation, training, in-field guidance, safety aspects, and technical documentation development. Prior to the questions, a video demonstrating the maintenance task in VR from the user's point of view was shown. The second part of the survey collected data related to the potential of gaze tracking for the industry; a video with gaze tracking data visualizations was shown before the questions. The video used the scan path visualization of gaze data we implemented (similar to [36]) with arrows indicating the order of fixations. The final part of the survey gathered respondents' background information including age, gender, areas of expertise, and previous experience with VR and AR technologies.

Respondents

Twelve experts (10 male, 2 female), aged from 37 to 59 (M = 49.5) filled in the survey. The respondents were proficient on at least, but not limited to, one of the following areas of expertise: 50% of the experts were proficient in Safety and/or Training, 41% in Maintenance and/or Technical Documentation, and 33% were proficient in XR use cases. Most of the respondents (83%) had used VR technology a couple of times at most before filling in the survey, one respondent had used it a lot, and one had only heard/read about it. Similarly, 75% of the participants had used AR technologies a couple of times at most; two participants (17%) had used them many times and one had heard/read about it. Ten participants (83%) reported that they were glad to use digital devices as a part of their daily life, while two (17%) considered themselves to be even among the first ones to try out new digital devices or services.

RESULTS

This chapter presents the results of our three-round iterative study, including participants' performance and behavior metrics, and user experiences, followed by combined objective and subjective results on the DocPanel usage and safety warnings. Finally, we present the results from the expert survey on AR, VR, and gaze tracking feasibility.

Iterative User Study Results

The *xR Safety Kit* framework was perceived as a viable and promising innovation for the industrial context. The participants showed eagerness about the possibilities of working with both AR and VR technologies in their daily routines and further ideated on how such technologies could be integrated into the company's processes. The participants pointed out that the VR environment coupled with gaze data "*would be useful for testing new maintenance methods"* (P1), *"would be a good way to test out documentation"* (P2), and *"can be used for risk assessing"* (P3).

All the participants in both iterations successfully finished the maintenance task. On average, the session (the overall time the participants were wearing HMD excluding training) took 13.1 minutes (min = 5.5; max = 20.8) during the 2nd iteration and 11.1 minutes (min = 7.5, max = 14.7) during the 3rd iteration. The participants spent 35.4% of the session reading instructions (min = 14.6%, max = 63.8%); the large variation is explained by the participants' different backgrounds and different requirements for system assistance. As the logged data from the 3rd iteration were more detailed, we separately analyzed the time spent for disassembly and reassembly, excluding the equivalent first and last subtasks (3.6 minutes and 0.3 minutes on average, respectively), as some of the participants spent extra time observing the environment at the beginning of the session. The disassembly took on average 3.0 minutes (min = 1.7, max = 5.8), from which 27% of the time participants were reading instructions, while reassembly took on average 2.2 minutes (min = 1.5, max = 2.8), from which 19.3% of the time was reading instructions. The participants in the 3rd iteration navigated backward in the DocPanel 8 times on average (min = 3, max = 15); the maximum number comes from a participant who browsed through all the steps in the DocPanel before starting the task.

Figure 3 represents the combined questionnaire results from the second and third iteration rounds. It illustrates the participants' more positive experiences in the third iteration due to the usability improvements and system modifications made after the second iteration. All the participants ($n_2 = 5$, $n_3 = 4$) found the system to be easy to use ($Mdn_2 = 6$; $Mdn_3 = 5.5$ out of 7). Eight participants (89%) would like to use this system frequently in the work context ($Mdn_2 = 5$; $Mdn_3 = 6$) and felt confident while using it ($Mdn_2 = 5$; $Mdn_3 = 6$). Further, eight participants (89%) agreed that VR motivated them to perform the task ($Mdn_2 = 5$; $Mdn_3 = 6$) and, similarly, eight participants (89%) found it easy to map the VR objects to objects in the real world ($Mdn_2 = Mdn_3 = 6$). Besides, all of the participants showed a positive attitude toward the idea of utilizing VR for training purposes, saying, "*It's much more powerful way to make people really remember*" (P4) and "*the huge benefit is it is a safe environment to practice instead of going at the field area"* (P1). In both iterations, the participants agreed that using a VE is a practical way to simulate elevator maintenance tasks ($Mdn_2 = 5$; $Mdn_3 = 6.5$) and this VE would be useful for inexperienced maintenance technicians ($Mdn_2 = 6$; $Mdn_3 = 6.5$).

In-field Guidance and DocPanel tool

The majority of the participants showed enthusiasm toward the idea of utilizing a head-mounted AR display for in-field assistance. One of them said, "*The direction is very good. I support it 100%*" (P5). The main advantage of this was seen in easier access to information (P3): "*The system would affect the working process in a positive way, because the maintenance workers can have the instructions right away.*" Also, the information presentation was appreciated (P6): "*I liked these animations, it's much better compared to paper instructions what we have today.*" The DocPanel tool was found to be useful for the maintenance context ($Mdn_2 = Mdn_3 = 6$) and easy to use ($Mdn_2 = 5$; $Mdn_3 = 6$). The participants liked the functionality to move and place the panel anywhere in the 3D space ($Mdn_2 = 6$; $Mdn_3 = 7$) and center it to eye position ($Mdn_2 = 5$; $Mdn_3 = 6$). However, some of the participants demonstrated mistrust of the current state of the technology and fear of wearing an AR headset, which limits the visibility, in the context of an elevator shaft. Two participants (22%) disagreed that AR headsets are safe to use in maintenance task contexts.

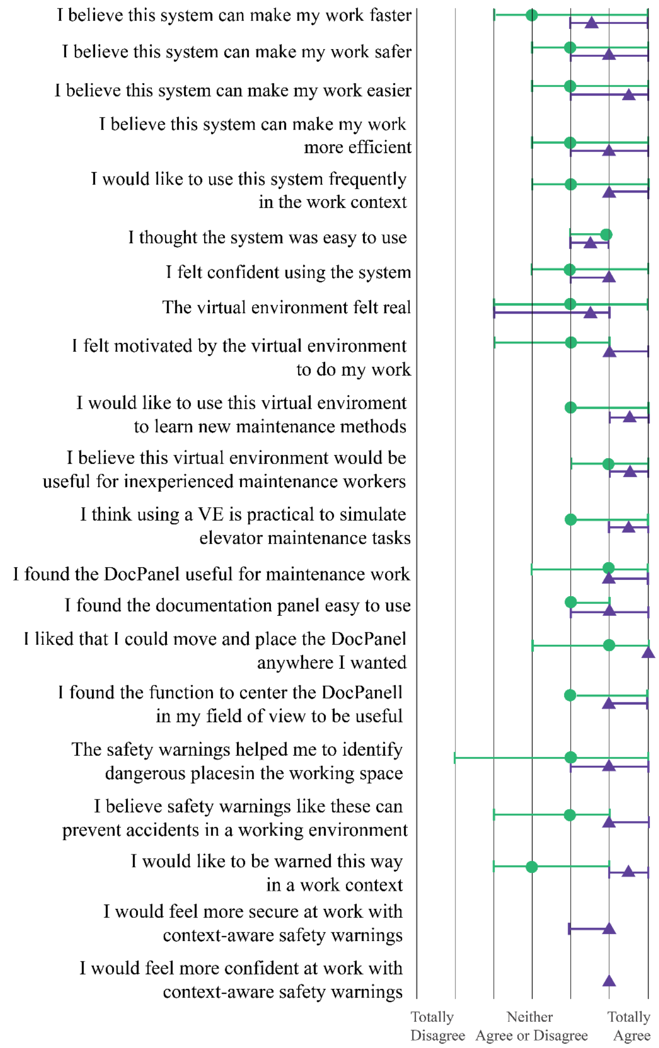

Figure 3. Questionnaire results as line-and-symbol combinations (minimum, median (ball/triangle), and maximum). For each item, the upper, green values are from the 2nd iteration ($n_2 = 5$) and the lower, purple values from the 3rd iteration ($n_3 = 4$).

The participants were able to read the instructions from the DocPanel without directly facing it: On average, the gaze vector angle relative to the HMD was over 7 degrees (M = 7.45°, Q1 = 4.14°, Q3 = 8.87°), while the interquartile range (Q3–Q1 = 4.73°) demonstrates the variability in gaze angle to HMD when reading the panel. Figure 4 illustrates how the participants chose to position the DocPanel relative to their head. The participants preferred to place the DocPanel in front or to the left of the work area, below their head position so the instructions could be seen without turning one's head. A possible contributing factor is that the default position of the DocPanel was in the negative z-direction. We sampled 10,000 DocPanel positions from each participant (training phase excluded) for the histogram, spread evenly over the session. The color of each cell indicates how commonly the position was chosen for DocPanel placement.

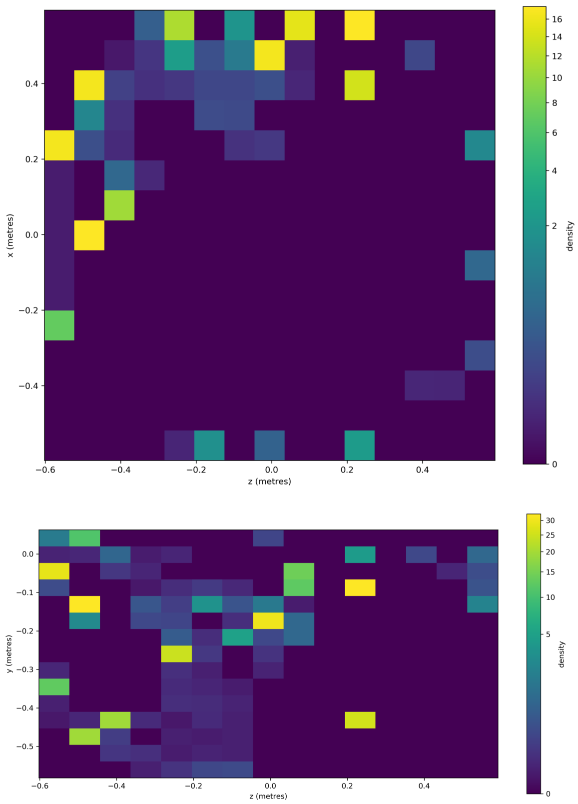

Figure 4. The positioning of the DocPanel, top-down perspective with the working area in positive x-direction (top) and back-to-front perspective with up in positive y-direction (bottom). (The lighter the color, the more common the position.)

Safety Warnings

Since the three warnings were added after the 2nd iteration, these results concern only the 3rd iteration round with four participants. All participants verified the need for in-field safety warnings. Two participants noticed all three warning types and two participants noticed two warnings*: textual safety notification* and *audio and visual safety warning*. All participants found the warnings to be self-explanatory, easy to understand ($Mdn_3 = 6$), and helpful to identify dangerous places in the working space ($Mdn_3 = 6$). One of the participants commented: *"I liked it in a way that it really wakes you up. If I don't immediately see or recognize it, then the voice … it's like a waking up call"* (P4). Further, participants agreed that similar warnings can prevent accidents in a working environment ($Mdn_3 = 6$) and would like to be warned this way in a work context ($Mdn_3 = 6.5$). None of the participants found the warnings to be annoying or destructive, commenting: "*It was not annoying because it was there exactly where it should be"* (P7).

Nevertheless, the preferences in visualization methods and modalities were diverse. For every designed warning the participants preferred different visualization approaches or modalities, e.g., one participant commented that only visual warning in the form of a static picture would be enough to inform about the dangerous area, while another suggested using text, voice, and blinking to attract attention.

We also calculated the number of fixations for *textual safety notification* (e.g., heavy object warning) and *animated safety warning* (electric shock warning). Visual attention patterns were not considered in the case of *Audio and Visual Safety Warning*, because the voice warning component alone was descriptive enough for the participants to understand its meaning. We consider the participants to have observed the warning if there was at least one fixation on the warning while it was shown to them.

The electric shock warning was observed 4 (min = 0, max = 3 per session) out of the 22 times it was shown in total (min = 1, max = 9 per session). 2 out of 4 participants did not observe the electric shock warnings at all, although it should be noted that the warning also got less frequently activated in the first place as a result of these participants' behavior. This indicates that the electric shock warning was unsuccessful in deterring the participants from touching the area. This may be because the warning often appeared outside the simulated AR field of view as it was statically positioned to indicate the location of the dangerous area. To guide the user's attention to warning icons placed outside the AR FoV, the system played a warning sound and displayed a small red arrow pointing in the direction of the warning icon whenever it was outside the simulated AR field of view. This sound, however, may have had the opposite effect of encouraging the participants to interact with the dangerous area, and the arrow may have been too small to strongly guide the user's attention.

The heavy object warning was observed 7 times out of the 8 times it was shown in total (2 times per session). Based on the gaze data, it can, therefore, be argued that the larger heavy object warning with static icon and text was mostly successful in alerting the participants, while the smaller electric shock warning with an animated icon and sound was mostly unsuccessful.

Survey on AR, VR, and Gaze Tracking Feasibility

The survey filled by the 12 experts from the elevator industry verified the usefulness of gaze tracking, VR, and AR simulation within VR and pointed to related challenges. More than half of the respondents (67%) found the opportunity to analyze where the user pays attention in the VR environment to be important (Mdn = 4 out of 5). In addition, 75% of the respondents agreed that the visualizations produced from the users' visual attention are useful in training (Mdn = 4) while analyzing gaze data visualizations by expert maintenance trainers could be utilized to improve also the traditional training methods (Mdn = 4). Tracking users' movements and visual attention was found to be efficient to determine the best suitable multimodal combinations and designs for safety warnings (Mdn = 4; 67% totally or somewhat agreed) and the best locations and visualization techniques for visual safety warnings (Mdn = 4; 75% totally or somewhat agreed). One of the respondents commented, that gaze tracking is useful to *"check the optimal locations where to display information"* (R1). Most of the respondents (83%) agreed that the possibility of gaze tracking to investigate how much the documentation is utilized during work and which parts of it draw the users' attention is important, while 17% somewhat disagreed. The respondents also verified that testing existing technical documentation in VR simulation would help to improve the documentation (Mdn = 4, 83% agreed); one of them commented that gaze tracking should also be used *"to ensure that user does not skip any content when following instructions"* (R2). However, 42% of the respondents somewhat or totally agreed, while 17% somewhat disagreed, that real-time gaze tracking and gaze visualizations would be beneficial for guiding maintenance technician trainees. One of the respondents shared their concern, saying *"the person who is analyzing the gaze tracking must be extremely well trained so that he/she can understand which eye movement is unnecessary"* (R3).

All the respondents perceived VR with AR simulation as a practical (Mdn = 5, n = 11) and safe (Mdn = 5) environment to design and test AR solutions, that may boost the development of AR solutions in industrial settings (Mdn = 4, n = 11). The respondents commented that AR simulations' *"role and importance will increase in the future"* (R4) as this environment *"can be used to test radically different ideas without, for example, safety concerns or limitations by the real environment"* (R1). Further, 55% totally agreed, and 36% somewhat agreed, that utilizing both AR and VR technologies in training would increase the overall quality of training (Mdn = 5, n = 11). All respondents totally or somewhat agreed that complementing traditional training methods with AR would make the training more efficient overall (Mdn = 4, n = 11). Meanwhile, 82% of the respondents totally or somewhat agreed that trainees would learn the maintenance tasks faster with VR simulation compared to the traditional training methods (Mdn = 4, n = 11) and 91% totally or somewhat agreed that trainees would be more ready to perceive the traditional training if familiarized with VR simulations first (Mdn = 4, n = 11). The respondents found VR with AR simulation to be a suitable environment to *test* various designs and multimodal combinations for in-field safety warnings (Mdn = 4, 92% agreed somewhat or totally). Moreover, they also found the environment to be suitable to *determine* the best safety warnings (Mdn = 4, 75% totally or somewhat agreed) and the best locations and visualization techniques for visual safety warnings (Mdn = 4, 83% totally or somewhat agreed).

Summary of the results

In summary, the results of both iterative studies and the survey showed a positive perception of, and eagerness in, utilizing AR/VR technologies and gaze tracking by the domain experts for multiple purposes. The AR within VR was found to be efficient and, most importantly, a safe approach for industrial AR prototyping, while HMD-integrated gaze tracking is seen as a viable analytic tool for AR content testing. Gaze data analysis also illustrates the strategies for identifying the value of the designed solution, e.g., the success of the DocPanel tool and the failure of the animated safety warning. Further, gaze tracking was found to be useful in the development of training procedures and technical documentation.

Finally, our results indicate the potential of utilizing a virtual environment for other companies' processes to accommodate efficient collaboration and resource sharing between different departments.

DISCUSSION

In this study, we explored the capabilities of VR coupled with gaze data to address AR content development and testing. We deployed the *xR Safety Kit* framework and tested AR features (*in-field guidance* and *safety warnings*) in a realistic industrial evaluation process with experts from the elevator industry. In addition, we utilized resulting materials to elicit feedback from another group of domain experts on the use of such technologies in the industry.

Based on the collected expert opinions, we identified the need, desire, and benefits in utilizing AR, VR, and gaze data in the context of industrial maintenance. The industry requires well-designed assistive AR solutions, which reduce risks by providing guidance to technicians and increase safety awareness in hazardous working environments. All expert participants confirmed the necessity to replace the existing paper-based manuals with an AR-based solution that would not require any hand manipulations while performing the tasks. What is more, the industry requires flexible and safe ways to develop such solutions. While AR technology is currently unsuitable for the context, as wearing heavy head-mounted displays that limit the user's view is unsafe, e.g., the *authoring* and *interaction analysis* of assistive AR tools for the industry can, and should, be done already now.

Our study demonstrates the relevance and success of utilizing VR with gaze tracking to prototype and evaluate AR content. The conducted iterative study shows an example of how the *xR Safety Kit* framework can be applied for safe, efficient, and fast industrial AR development with a small number of users. Integrated gaze tracking brings an advantage to gathering detailed and objective data for further analysis, which could not be gathered via traditional user study methods, such as interviews or questionnaires. For instance, gaze data helped us to identify that the designed animated safety warnings were unnoticeable by most of the participants. While subjective results indicated that animated safety warning was noticed by 50% of participants due to wrongly selected visualization technique (e.g., too small animation and arrow, improper placing), gaze data analysis exposed that the participants fixated their gaze at the warning in only 18% of cases, clearly demonstrating the failure in the design of the warning.

Similarly, gaze data were useful to evaluate the technical documentation presentation by providing information on reading behavior and positioning in 3D space. We identified that the DocPanel tool is a good maintenance solution with comprehensive functionality. The participants utilized the option to place the information in the position they preferred, and analysis showed that this place is mostly to the left or in front of the working area and below head level. This enabled participants to glance at the instructions without much effort. Subjective feedback indicates that the participants found the design efficient and valuable. However, we identified the need to redesign the existing XML instructions to fit the AR visualization capabilities, e.g., emphasize the use of 2D and 3D schemas, pictures and animated instructions with appropriate color-coding to decrease reading time and minimize eye strain. To increase the assistive effectiveness, the DocPanel should also visualize the tools required for the task and related to the task dangers.

In addition, we have formulated suggestions related to the design for safety in the industrial context, which may be generalized for other use cases. We found that novice technicians require more attention grabbers and interaction with the warnings, while experienced technicians found the extensive notifications irrelevant, focusing on task performance and productivity. Hence, multiple levels of awareness are recommended to support technicians of different expertise, e.g., variations of modalities, visualization techniques, levels of instructiveness, times of displaying, and sizes of the warnings. Different levels of awareness may be also considered for communicating repeating risk. Further, the safety indicator (e.g., visualization of the level of associated risk) is another way to inform the users about possible dangers, related to the task or environment. It can either be visualized on the DocPanel or constantly displayed in the user's field of view. Lastly, AR solutions for an industrial context should support cooperative work, e.g., by tracking the progress of two technicians working in separate spaces as well as integrated guidance in case of an emergency.

Our study demonstrates the usefulness and efficiency of AR development and testing within VR while utilizing gaze tracking. Such an approach was found to be suitable in the industrial context due to three main aspects: **flexibility**, **safety**, and **advanced analytics**. It allows quick and resource-efficient iterative development processes with both the target users (maintenance technicians) and other specialists involved in the decision-making and development process. In addition, our study uncovered the potential of utilizing the MR continuum to address other industrial processes and enable collaboration between different departments, which should be further explored.

Limitations and Future Work

A limitation of this study is the focus on elevator maintenance. The expert participants were sharing their opinions on the usefulness of the MR continuum based on experience in this field and the existence of CAD models and structure of technical documentation in their company. Although our findings are applicable for similar industrial contexts, future work can explore how the technologies are perceived on, and what benefits they bring, to other fields to determine common patterns. Utilizing both AR and VR in the industrial context is promising. However, identifying the requirements for such platforms that provide smooth collaboration and content creation within the VE requires further research.

The gaze data analysis requires adaptation and further development. Fixations can demonstrate only gaze landing at objects, and thus, may cause misinterpretation of results in terms of safety awareness. Considering the complexity of human vision, objects can be noticed without a direct focus. Thus, future work may concentrate on exploring in what circumstances (e.g., direction of the gaze path, design of the content itself, duration, and sizing) the augmented content is noticed and how the system can record this without a direct fixation. On a larger scale, in order to utilize gaze data efficiently in terms of time and resources, automated analysis methods should be developed. With the growth of machine learning, a viable direction for research, and practice, would be to automate the analysis process for both training and AR prototyping.

CONCLUSIONS

In conclusion, our industry-focused study demonstrates the potential of adopting virtual environments coupled with gaze tracking for AR prototyping. Assistive AR solutions are highly demanded in the industry, as they can support workers in their tasks and, hence, increase the safety and efficiency of work processes. Further, there is a need for flexible and resource-efficient ways to test AR solutions in a safe environment before deploying them in a hazardous, real-world industrial context. This study showed that VR and gaze tracking are a valuable combination to address safe and efficient AR development. Gaze tracking provides advanced metrics for detailed analysis of AR element usage, while VR is a safe and flexible testing environment, which enables fast iteration of AR solutions as well as the simulation of various aspects of see-through HMDs (e.g., FoV, tracking quality, image quality, and other related aspects). What is more, the deployment of such VR platforms is becoming easier due to the growth of digitalization and the availability of relevant materials (e.g., design models, documentation, and enterprise information system data) in digital format.

Finally, our paper indicates that the utilization of the MR continuum in industrial processes, especially blending various tasks under one comprehensive system, may be advantageous and should be further explored in terms of cooperation, training, and documentation and methods development.

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