Virtual Reality Training Applications in Industry

Towards a User-friendly Application Design

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The purpose of this research is to aggregate and discuss the validity of challenges and design guidelines regarding industrial Virtual Reality (VR) training applications. Although VR has seen significant advancements in the last 20 years, the technology still faces multiple research challenges. The challenges towards industrial VR applications are imposed by a limited technological maturity and the need to achieve industrial stakeholders' technology acceptance. Technology acceptance is closely connected with the consideration of individual user requirements for user interfaces in virtual environments. This paper analyses the current state-of-the-art in industrial VR applications and provides a structured overview of the existing challenges and applicable guidelines for user interface design, such as ISO 9241-110 or Shneiderman's eight "golden rules" for user interface design. The validity of the identified challenges and guidelines is discussed against an industrial training scenario on electrical safety during maintenance tasks.

1 Introduction

Virtual Reality (VR) can be defined as a human-machine interface (HMI) technology that conveys an immersive, interactive, computer-generated experience in which a person perceives a simulated environment in real-time (Mandal 2013). The immersion distinguishes VR from traditional media by substituting the primary sensory input with data received produced by a computer (Heim 1998).

Industrial VR applications are emerging in multiple areas such as education (Salah et al. 2019), telerobotics (Lipton et al. 2017), and production planning (Zhang et al. 2019). Although VR has seen great advancements in the last 20 years, the technology still faces multiple research challenges and holds significant potential (Berg & Vance 2017). The challenges towards industrial VR applications are imposed by a limited maturity of the technology and the need to achieve industrial stakeholders' technology acceptance.

This paper analyses the current state-of-the-art challenges and design guidelines regarding industrial VR applications and discusses the validity of these findings against a VR application on electrical safety training for maintenance tasks. According to the considered VR application, the paper focuses on industrial training applications in VR. With regard to the state of the art of VR technology,

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this paper considers the implementation of the VR application for VR headsets. This head-mounted display (HMD) and the associated controllers for user interaction are tracked with the help of base stations, and the training environment is displayed in the field of view. The user's interaction with virtual objects and the movement through the virtual environment are done by the controllers (see Figure 1).

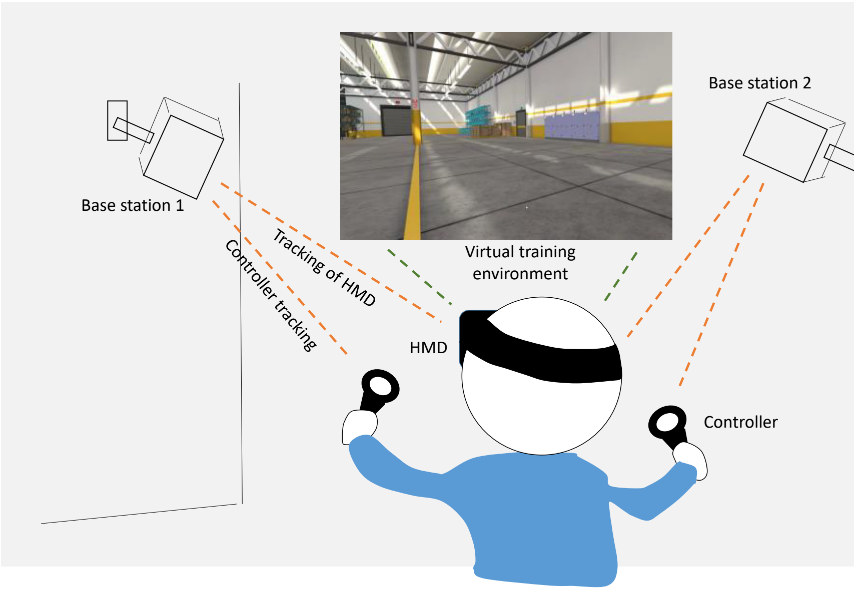

Figure 1: VR training environment

2 Related Work

This section describes related review papers on industrial Virtual Reality (VR) applications focusing on training applications.

Choi et al. (2015) surveyed and analysed 154 papers on VR applications in manufacturing from 1992 onwards. The analysis focused on the application of VR during the development of new products. It showed a significant reduction of costs over time. The authors state that VR technology achieved a return on investment and maturity that enables VR applications to benefit manufacturing companies.

Damiani et al. (2018) analysed 39 papers on industrial Augmented Reality (AR) and VR applications to investigate the current state of the technologies. They state that multiple applications have been successfully tested in real industrial settings and fulfil actual industrial demands. However, only 22% of the identified applications are used for training purposes.

Hasan et al. (2017) reviewed multiple papers on Virtual Reality training applications in maintenance, assembly procedures, welding, and construction training. The authors state that VR training can be used to reduce training costs and could even be used without a trainer.

Patle et al. (2019) reviewed multiple training simulators in the process industry. The author argued that VR has become an integral part of plant operators' modern training and stressed that improved safety, productivity, and environmental protection are the major benefits of VR training.

This research builds upon a systematic literature analysis on simulation-based training in manufacturing, for that 202 applications have been identified (Knoke et al. 2021). The research shows an increase in VR training within the last decade.

A similar paper on the requirements towards industrial AR applications has also been published by the authors of this research (Quandt et al. 2018). While the cost-effectiveness of AR systems is still an issue, operational and administrative issues have moved into the spotlight.

Multiple review papers have been identified. These reviews show that the maturity of industrial VR applications has changed over the decades from a gimmick for technology enthusiasts towards a widely accepted tool with benefits in various areas. However, the maturity of VR technology is still very limited, which impacts the stakeholders' technology acceptance. The authors further elaborate on technical maturity of VR applications in training in the following section.

3 Analysis of Requirements and Challenges

Recommendations towards a user-friendly interface design require knowledge of the current state-of-the-technology and its limitations. Therefore, this paper analyses multiple industrial VR applications regarding statements on technical limitations and challenges. Taking into account the technical limitations of the hardware elaborated in this section, the design of the user interface is a crucial factor in achieving user acceptance. Therefore, the authors elaborate on user interface design guidelines for virtual enviroments in Section 4.

Earlier publications emphasised the quality and cost as a major downside for the acceptance of VR applications (Mujber et al. 2004, Fernandes et al. 2003). Fernandes et al. (2003) also link a low simulation quality to a low immersion and describe the lack of intuitive movement options as a factor that further reduces immersion and training capabilities. In a comprehensive review of VR applications in various contexts, Halarnkar et al. (2012) identified five main challenges for developing and using VR: cost, usability, software limitations, programming capabilities and aspects of interface and design of the applications.

The Kickstarter campaign of the Oculus Rift in 2012 started a hype that resulted in a new wave of commercial interest in VR, causing a significant increase in quality and a decrease in hardware prices (Rose 2018). Now, multiple companies offer commercial VR systems. Current VR HMD systems include:

- Oculus (Quest 2, Rift S)
- Valve Index
- PlayStation VR
- HTC Vive (Pro, Cosmos Elite)
- HP Reverb
- Pimax Vision

More recent publications describe the creation of quality content as the most significant limitation towards a wide distribution of VR training (Büttner et al. 2017, Zhang 2017, Liagkou et al. 2019, Scott et al. 2020). Liagkou et al. (2019) describe the need for a standardised scenario design to reduce the time and cost requirements. Wolfartsberger et al. (2018) stress that CAD models are often available but need to be converted to be used in VR applications.

However, there are still multiple technical limitations that negatively impact the stakeholders' technology acceptance. Wolfartsberger et al. (2018) state that inaccurate collision detection and realistically implementing haptic feedback are significant challenges for interaction with virtual objects. Zhang (2017) argues that any HMD system that requires a user to use artificial devices such as a keyboard or controller to move within the virtual environment can break the immersion. The author also states that HMDs cause motion sickness after longer periods of use, that haptic feedback is mostly unsatisfactory, that interactions with the training simulation are limited by hardware and design, and that any implementation of simulation-based training must consider the individual characteristics of its users. Büttner et al. (2017) report that HMDs are too heavy and that the user experience is hindered by either a cable or limited battery capacities. Moreover, the acceptance among workers is sometimes hindered by hardware issues causing limited trust in the system or the fear of being controlled (Büttner et al. 2017). For the training of maintenance tasks, Scott et al. (2020) studied the technology readiness of companies and user acceptance of virtual environments. The framework they developed includes organisational factors and the learning situation in close connection with the design of the learning environment.

The limitations caused by the technology maturity can be summarised in a cause-and-effect diagram and sorted into the categories of measurements, materials, methods, machines, personnel, and environment (Figure 2).

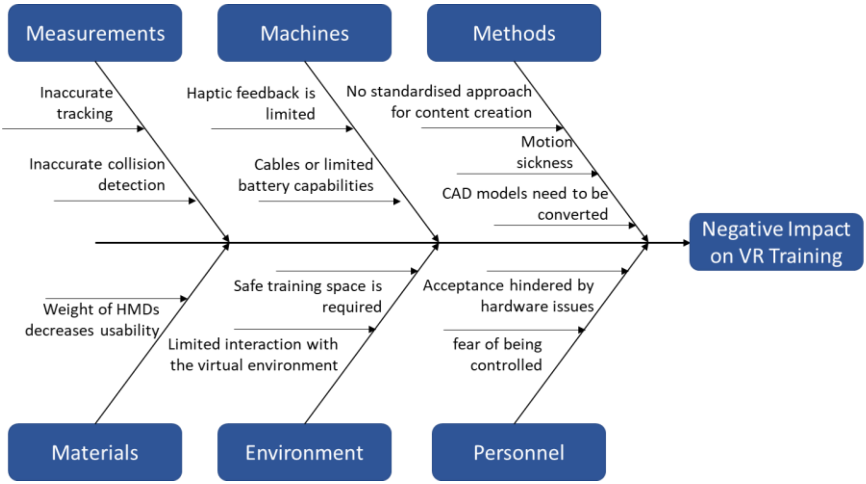

Figure 2: Technology maturity-related challenges of VR Training

Many of the aforementioned causes affect the user's interaction with the VR system. Inaccurate tracking leads to poor recognition of the users' interactions with the virtual environment. Cables prevent users from moving freely, and the weight of the headsets directly affects users' comfort during use. These technical limitations must be taken into account when designing the user interfaces, since user immersion and user acceptance depend to a large extent on the design of the user interface. The technical characteristics of the current hardware turn out to be a limiting factor for the design of the user interface and, therefore, cannot be disregarded.

4 Guidelines for user interface design of VR environments

Multiple sources list design guidelines that can be applied to user interfaces for VR systems.

ISO 9241-110 includes seven principles for the interaction design of interactive systems. The principles aim to improve the usability of the system regardless of the technology used. The individual principles are suitable for the user’s tasks, selfdescriptiveness, conformity with expectations, learnability, controllability, and use error robustness and user engagement.

Further usability principles for the design of interactive systems come from Nielsen (2020). In his ten usability heuristics, Nielsen (2020) gives general recommendations for interactive systems design. Examples include avoiding errors, e.g., by having users confirm an action or limiting the user interface from the essential information through an aesthetic and minimalistic design (Nielsen, 2020). Similar guidelines represent Shneiderman's eight golden rules of interface design. Like Nielsen's heuristics, these include recommendations to provide users with system-side feedback on the current status or reduce users' cognitive load by providing only relevant information. In his fundamental interaction principles, Norman guides human-system interaction usability, which essentially corresponds to the previously mentioned guidelines (Norman 2016).

The described guidelines refer to the design of currently dominant graphical user interfaces for 2D screen environments. Mixed Reality (MR) applications pose extended requirements for user interface design due to the high number of possible interaction forms, hardware configurations, and the possibility of addressing different senses (Dünser & Billinghurst 2011, Vi et al. 2019). Furthermore, in the context of the user experience of immersive technologies, the enabling of a sense of presence, which is related to the degree of immersion, as well as effects of motion sickness, are mentioned (Mütterlein & Hess 2017).

With this in mind, Vi et al. (2019) analysed existing guidelines and contributions for developing user interfaces for Extended Reality (XR) applications and derived eleven guidelines. These guidelines are related to the user experience of HMDs in XR environments and were correlated and adjusted with the usability guidelines of ISO 9241-110, Nielsen and Shneiderman. Therefore, for this research, the guidelines provide a reasonable basis for evaluating a VR-based training environment. These guidelines take into account, among other things, the technical maturity of the available VR hardware and thus address the previously described limitations for the design of user interfaces. The evaluation of the guidelines of Vi et al. (2019) on a practical example is still pending. With this paper, the authors want to contribute to the application of these guidelines and to establish a relation to a VR-based training example. This article cannot provide a complete evaluation of the guidelines based on user studies. In the following, a short summary of each guideline is presented to describe the respective contents, as these guidelines are discussed against the developed VR training environment in chapter 5.3. (Vi et al. 2019).

1. Organise the Spatial Environment to Maximise Efficiency: This guideline addresses the efficient use of three-dimensional space in XR applications. Content must be placed to the users in such a way that the additional space is used optimally, while at the same time the cognitive load of the users remains low and the physical movements are in proportion to the task.

2. Create Flexible Interactions and Environments: The designers need to consider different experience levels of the users and possible physical limitations. Ease of use and general satisfaction with the solution can be increased by adapting the settings to the users' needs.

3. Prioritise User's Comfort: This guideline addresses the user's comfort regarding physical, mental, and environmental influences on the user experience in an immersive environment. The designers can reach this by respecting distances when fading in virtual content, avoiding motion sickness, taking into account the hardware manufacturer's specifications, and producing a suitable environment for using the XR solution.

4. Keep it Simple: A virtual environment's particular challenge is to find the balance between enhancing the virtual experience and overwhelming the user. The information density in the field of view should be kept as low as possible.

5. Design Around Hardware Capabilities and Limitations: Designers must adapt the features of the solution to the hardware used and emphasise the strengths of the respective hardware to minimise the influence of the hardware limitations on the user experience.

6. Use Cues to Help Users Throughout Their Experience: Cues and sufficient user guidance can reduce the risk of overwhelming users. These cues include, for example, the use of directional cues to point out objects outside the direct line of sight. Furthermore, designers should make it easier for users to choose actions by providing concrete hints about the next steps or possible actions. In this context, designers should avoid the overuse of notifications.

7. Create a Compelling XR Experience: The application designers can intensify the user's immersion in the virtual environment by combining visual, auditory, and narrative elements.

8. Build Upon Real-World Knowledge: The design of virtual environments, interactions, and elements should be based on familiar patterns from the user's real-world environment to understand the application. Specific references extend to the interaction design with virtual objects in analogy to real objects of the same kind that actions trigger an expected reaction of the virtual objects.

9. Provide Feedback and Consistency: Consistent implementation of the feedback functions can make the possibilities of the application clear to the users. In particular, this involves the visual representation of different statuses of interactions, the display of results of an action or interaction by the user.

10. Allow Users to Feel in Control of the Experience: The application should gain users' trust by giving them control over the virtual environment's actions and reactions. Users should always be able to undo an unwanted action or leave an undesirable situation.

11. Allow for Trial and Error: Operator errors should not have irreversible consequences. An essential point in this context is the possibility of reversing actions by the users if errors happen in the application. In this way, users' anxiety in using the application can be reduced, and the discovery of system functions can be made possible.

5 Discussion of technical challenges and design guidelines

The identified technical challenges and design guidelines are discussed against a VR application on electrical safety training developed and implemented in collaboration with industrial stakeholders in 2020 (Figure 3).

Figure 3: VR training on electrical safety

5.1 Introduction to the training scenario

The scenario is intended for the safety training of young professionals, as well as a supplement to the yearly safety training of electricians that are mandatory in Germany (VDE 0105-100:2015-10) and multiple other European countries.

The scenario teaches the general safety rules for electrical safety on practical examples to provide an interactive and more engaging learning experience than a conventional lecture. The safety rules are implemented as steps that must be performed to progress within the training simulation safely. The most important steps are:

- To disconnect completely.
- To prevent reactivation.
- To make sure that the installation is dead.

These steps are also covered within the briefing of the scenario as basic learning targets for the training. A support function can always be activated to hint towards the next steps. From previous experiences, the best training results are achieved when the VR training is combined with a brief lecture on the topic. Therefore, the presented scenario consists of a tutorial and the actual exercise.

The tutorial is intended to teach the basic movement and object manipulation functions. The trainee must move towards a specific location and is tasked to pick up a screwdriver from a table and put it on a tool board, which completes the tutorial.

The exercise is to replace a broken electric engine on the shop floor. The task briefing is performed by a female foreman in case the audio help is activated. The steps are described in the following.

Read job ticket: The first step is to advance towards the table and read the job ticket. It hints at the location of the damaged engine.

Tool selection: The trainee is supposed to select the right tools for the job. The tools suspended on the wall can be grabbed with the virtual hands and put into snap zones within the toolbox (Figure 4). However, some tools are not required or are unsafe. The tools that must be put into the toolbox to advance to the next step are:

- a padlock,
- an interlock for fuse deactivation,
- a screwdriver for electric maintenance,
- a multimeter,
- a warning sign for ongoing maintenance activities.

Figure 4: Tool selection

View part number: After the tools are selected, the next step is to exit the room and locate the broken engine on the shop floor. The job ticket indicates that the engine is in field M2 (see Figure 5). The number corresponds to red markings on the pillars within the factory. The engine can also be found by looking for a broken part that emits smoke. It also has a worker standing next to it with a spare part. The trainee must then view the part number to identify the corresponding control cabinet and fuse. The number (N22M3) is written in red below the socket (see Figure 5). It indicates the number of the control cabinet (N20), the switch row within the cabinet (N22), and the fuse (M3).

Figure 5: Area designations on the shop floor

Open control cabinet: Before the engine can be repaired, it must be disconnected. Therefore, the trainee must locate and open the control cabinet located close to the starting area. Both doors must be opened.

Deactivate fuse: Inside the control cabinet, the fuse that corresponds to the broken engine must be deactivated.

Secure fuse: The deactivated fuse must then be secured against reactivation with the fuse interlock followed by the padlock.

Close control cabinet: After the fuse is secured, the control cabinet doors must be closed.

Attach warning sign: The next step is to attach a warning sign outside the control cabinet.

Ensure that the engine is disconnected: After the engine is disconnected, the trainee must ensure that the installation is dead. Therefore, the trainee should first use the screwdriver to unscrew one screw from the engine cover. The screwdriver will snap in position and can be pulled up to loosen the screw. Then, the cover must be removed and placed to the left. The multimeter can then be placed on top of the cover next to the broken engine. It will snap into position as well. Afterwards, an interface can be used to configure the multimeter setting. It must be set to detect alternating voltage. The measuring tips can then be placed inside the engine to create measurements. All connected contacts must be checked. Afterwards, the multimeter must be switched off and placed back into the toolbox.

Replace broken engine: The broken engine is replaced by touching the new engine on the palette. This action automatically replaces the broken engine.

Open control cabinet: After the new engine is in place, the trainee must again move to the control cabinet and open it.

Reactivate fuse: Inside the control cabinet, the security measures (interlock and padlock) must be moved back into the toolbox so that the fuse can be switched back on.

Close control cabinet: The control cabinet must then be closed.

Remove warning sign: The warning sign must be removed from the door of the control cabinet.

Check functionality: After the fuse is reconnected, the trainee must ensure that the installation is working. Again, this is done by moving back to the engine, moving the cover to the left side, and placing the multimeter right on top. The multimeter must again be set to detect alternating voltage. The measuring tips can then be placed inside the socket to create the measurement. It should measure different voltages depending on the placement of the measurement tips. Afterwards, the multimeter must be switched off and placed back into the toolbox. The cover must then be placed back onto the engine. The exercise is completed by moving back to the briefing room.

5.2 Discussion of technological challenges

The VR training scenario has been tested in two scenarios:

- Tests alongside the development have been performed by researchers (n=2) in a lab environment with Valve Index HMDs,
- Tests with the final build have been performed by industrial trainees (n=15) in a VR training room with HTC VIVE Cosmos Elite systems.

The test results allow for a discussion of the technological challenges identified in chapter 3 and the maturity of the applied VR hardware.

The training focuses on the procedural knowledge required for maintenance tasks. Haptic feedback is not a requirement. Nevertheless, the trainees experienced difficulties detecting the controller location on both types of devices when the connection to the base stations was impaired. An error was reported when the controller network of the Valve Index interfered with the Wireless Local Area

Network connection when both networks were sending at approximately 2.4 GHz.

Another interoperability issue occurred when the training scenario that has been initially developed for the HTC Vive Cosmos Elite was used with a Valve Index system. The different controller layouts of these systems caused the menu to pop up when the controller was squeezed, making a reconfiguration necessary.

The training scenario uses warping as the only movement option. Although warping lowers the occurrence of motion sickness, some trainees reported slight dizziness. The weight of the HMDs was not an issue due to the relatively short individual training time. However, the HMDs tend to heat up during long usage periods.

In general, the VR hardware received very positive feedback, although the described issues show that the technology is still in a relatively early stage and heavily suffers from interoperability issues.

5.3 Discussion of guidelines

This section evaluates the guidelines from Vi et al. (2019) based on the experiences made with the VR training scenario.

Guideline 1: Organize the Spatial Environment to Maximize Efficiency

The relevant objects are grouped at three locations: Tools are collected at a tool bench, the maintenance is performed at a damaged part within the factory, and the damaged devices are disconnected at a control cabinet. At these locations, all objects are placed to be clearly visible.

Although the orientation within the virtual environment is part of the task, the users' movement and orientation within the virtual space are free and not predictable. The virtual factory environment has been separated into zones as it is common practice in larger factories (Figure 5). During the testing, no user had severe issues navigating the factory once the movement controls were understood.

Guideline 2: Create Flexible Interactions and Environments

Multiple options are available to adjust the VR training scenario to individual needs. A customisation screen allows selecting the scenario, the language, pathfinding, visual, and auditive assistance (Figure 6).

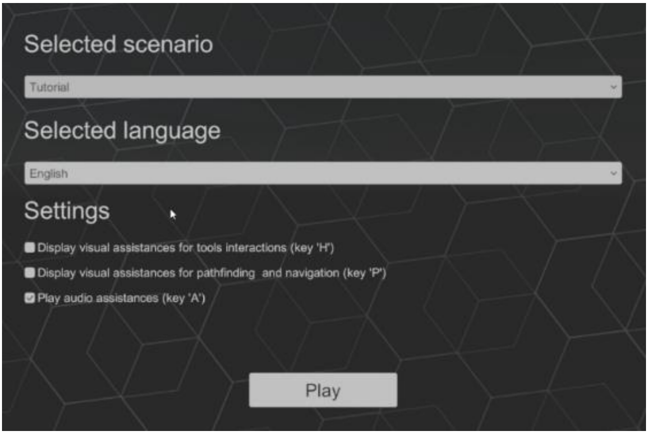

Figure 6: Customisation screen

Every user of the VR training within the test had at least an initial understanding of the task and the required steps. Because the VR training was performed under the guidance of a real trainer, the visual assistance and the pathfinding assistance (Figure 7) were used mainly for debugging. Nevertheless, the assistance functions are expected to provide viable guidance for new users.

Figure 7: Movement tutorial

Guideline 3: Prioritize User's Comfort

The user can move within the virtual space by walking, but the task requires movement between greater distances within the virtual environment. The training has been designed with warping as the only traversing option to minimise motion sickness (Figure 8).

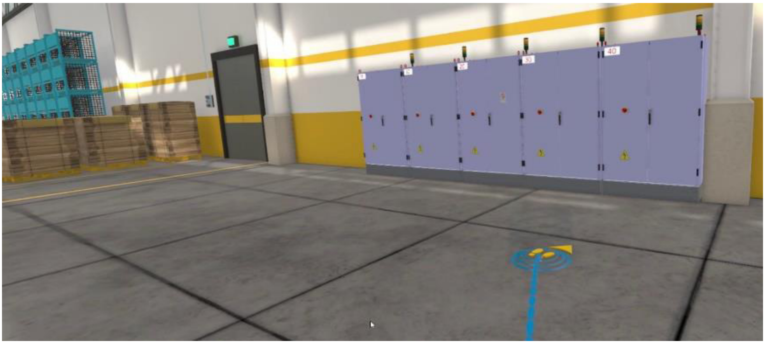

Figure 8: Movement by Warping

It is important to integrate warping or similar functions to prevent motion sickness or other forms of distress in industrial VR training applications.

Guideline 4: Keep it Simple: Do Not Overwhelm the User

The training has been designed to provide training on safety rules for electrical maintenance under realistic circumstances. The user receives audio and notifications intended to induce a moderate amount of stress to train the recollection of the safety rules in a stressful situation. Therefore, training purposes may require a design to challenge a trainee intentionally.

Guideline 5: Design Around Hardware Capabilities and Limitations

Hardware limitations have been less of an issue during the VR training scenario than the available 3D assets and development budget. Some of the hardware-related issues have been discussed in Section 5.2.

Guideline 6: Use Cues to Help Users Throughout Their Experience

The training is augmented with optional visual and auditory cues that guide the trainee to the next step. The auditory cues are given by a virtual foreman that conveys and further describes the task. The visual guidance is displayed as ghost objects that indicate the target position of objects and tools (Figure 9).

Figure 9: Optional visual guidance

Although guiding functions were included, the training personnel preferred to guide the trainees during the VR training.

Guideline 7: Create a Compelling XR Experience

The guideline appears to be generic yet important for immersion. The VR training has been designed to convey a realistic experience of an actual maintenance task. The story is set by a character acting as a foreman who provides the task and asks the trainee to solve it as fast as possible. The training is further augmented by ambient noises and decorative objects that build the scenery.

Guideline 8: Build Upon Real-World Knowledge

Combining real-world knowledge must be considered an obvious requirement for any industrial training simulation that intends to train cognitive skills. Training can only be performed if the design of the virtual experience corresponds to its real counterpart. The maintenance safety scenario has therefore been designed in collaboration with an industrial end-user and training personnel.

Guideline 9: Provide Feedback and Consistency

The VR maintenance training scenario features a broken electrical engine and aims to provide consistent feedback. For example, the trainee receives a simulated shock effect via auditory and visual cues if electrified engine parts are touched. The shock effect does not appear if the engine is disconnected.

It has been established that an industrial training simulation requires a certain functional fidelity towards the trained task (Alessi 2000, Hathaway & Cross 2016). Otherwise, the trained skills would not be transferable to the real system.

Guideline 10: Allow Users to Feel in Control of the Experience

This guideline can only partially apply to training scenarios. For didactic purposes, it can be beneficial to visualise the consequences of mistakes to the trainee. These consequences can include scenes that occur because of the users' actions but are now out of the users' control.

For instance, during the VR maintenance training simulation design, the trainers requested an injured coworker to appear if the trainee fails to install warning signs.

Guideline 11: Allow for Trial and Error

A major benefit of simulation-based training is learning about the system's behaviour through a trial and error approach. Compared to errorless learning, training through a trial and error method is considered to allow for an easier transfer into practice (Jones et al. 2010).

6 Summary

The analysis has shown that Virtual Reality (VR) still suffers from issues that indicate a relatively low technological maturity. Nevertheless, VR technology has already been improved greatly and can provide an actual benefit in industrial practice. VR is currently emerging into industrial training practice, which indicates a considerable demand and potential for the technology to grow. Hardware costs were the focal challenge of VR in the earlier years that is now mostly resolved. The next layer of challenges includes multiple issues such as standardisation and interoperability in hardware and content creation. The effort required for the creation and customization of content for VR training is a major challenge. Companies that intend to implement VR training in their vocational training usually require external resources. Inter-organizational barriers and a lack of standardization hinder future content updates in VR applications .

This research has also discussed guidelines from Vi et al. (2019) as a possible design framework for VR training scenarios. The results indicate that some guidelines are beneficial; others are relatively generic or only partially apply to the design of training simulations for industrial applications. These findings can be observed for the development of virtual environments for industrial use cases in a very similar way in the context of AR applications (Stern et al. 2020). The technical maturity of the available hardware as well as the lack of explicit guidelines for the design of three-dimensional user interfaces pose great challenges for the development of usable virtual applications. Further insights into the acceptance, especially with regard to the design of user interfaces of VR-based training, must be gained by testing the developed systems in practice. Formal user studies can provide further insights into the design of VR training environments. The users' requirements depend strongly on the application case, but the guidelines offer an useful orientation to avoid basic mistakes in the design of virtual applications. Therefore, the authors aim to evaluate developed VR training with users in a formal user study to draw further conclusions on usability and user experience. Furthermore, a user study would provide further insights on the general design of XR applications and the effectiveness of the applied guidelines.

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