Virtual Reality-based safety training in Human-Robot Collaboration scenario: User experiences testing

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Abstract. Robotic safety is an imperative topic, especially in Human-robot collaboration (HRC). The main objective of safety training in Virtual Reality (VR) is to visualize the safety-related regulations, standards, and guidance for robotics operators. We believe that this is the best approach for explaining the complex language used in various directives and standards. The primary aim of the paper is to introduce the VR-based safety training environment and provide a user experience evaluation for the developed system. The user experience test consisted of a usability test survey based on System Usability Scale (SUS) and an open discussion questionnaire regarding VR application and its elements. The result of the survey presented acceptance of the system by an average SUS score of 80%. Open discussions indicated that VR-based safety training is favored over traditional methods and provides a memorable experience. VR characteristics such as a sense of presence and interactive visual environment uncovered the transformation of abstract regulation terminologies into tangible safety measures and concepts such as hazardous areas, working zones, and collaborative levels. Lastly, the paper discusses the potential improvements of the system and the possibilities of utilizing VR for industrial training purposes.

INTRODUCTION

Collaborative robots can automatize repetitive and high-effort tasks and can reduce human task load by providing physical assistance [1], and therefore may potentially improve the working conditions of human workers. On the other hand, humans have better cognitive capability and can therefore supervise robots' operation or transfer new skills to the collaborative robot [2], thus adding a certain level of flexibility to the process and contributing to the effective accomplishment of a broad range of manufacturing tasks. During the last decades, the research interest towards human–robot collaboration (HRC) solutions has been one of the key interests in the field of robotics. The human-robot collaboration research envisions a situation where semi or fully-automated processes could be combined with human dexterity and flexibility without the complexity, and inflexibility [3, 4, 5]. Adaptation of HRC in the field of the manufacturing industry aims to increase the flexibility of factory lines and optimize the efficiency of resources. However, employing industrial robots with high speed and enormous forces forms various problems [6] when we want to reduce the fences and allow human-robot collaboration. There are multiple ways to ensure user safety. Most of these are related to the technical safetyfication of the system. However, in order to be productive, the users need the training to understand what types of collaboration they can foresee in their work, or when they are expected to stay clear from the robot working zone. Each breach of the safety border (e.g. user steps into the safety-guarded area) will likely cause an emergency stop for the robot, and a loss of productivity. For this, we propose a virtual robotics safety training concept and an example of a Virtual Reality (VR)-based safety training for the operators.

LITERATURE REVIEW

Human-robot collaboration is traditionally divided into four categories of interaction based on the proximity and duration of interaction [3, 5, 6]. Malik et al. [5] illustrated the levels of interaction as follows: In the Coexistence mode the human and the robot have independent tasks, and they do not share the workspaces or working envelopes of each other. In the synchronization mode, human and robot share a common workspace and a joint goal. However, only one of them is present at the shared workspace at any instance of time and performs the job alternately. In Co-operation mode, the human and robot both have shared tasks in the shared workspace, but they do not work on the same component. In the Collaboration mode human and robot work on the same component at the same time. Within these collaboration levels, there has been a multitude of research for improving safety, and communication between human and robot. In regards to safety in human-robot collaboration, several attempts have been made in the field of vision systems, sensor fusion, and Artificial Intelligence (AI) / Machine Learning (ML) tools usage [4]. The communication between the human and the robot is not yet intuitive, fast, or flexible. Emerging technologies such as Augmented Reality (AR) [7, 8, 9], Virtual Reality (VR) [10], and Mixed Reality (XR) [8] are seen as good solution candidates for increasing the communication between human and the machine during the design, commission, and operation phases. In particular, the multi-modal communication involving AR, haptics, and audio was found promising by [7]. Malik et al. argued that the use of time-based continuous simulations could offer safe virtual space for testing and validation thus easing the design of complex HRC systems. They proposed a technological development in VR for the design of human-centered production systems and develops a unified framework to integrate human-robot simulation with VR. Mattson et al. [11] introduced three-step approach for the design of cognitive automation. They highlighted the assumption that it is important for the operator to be part of the designing of the work cell and operational modes of the automation system. Burova et al. [12] introduced a VR concept for maintenance training.

So far VR has been used very successfully in introducing the environment, providing additional information, and ensuring ergonomics. Less emphasis has been put on really using the VR environment for training the users to work in collaboration with the robot systems. This research introduces Robotics safety training based on VR environment and proceeds to evaluate its content with a small user study.

RESEARCH SETTING AND RESEARCH METHODS

This study utilizes Virtual Reality (VR) technology for a safety training concept that is intended for the manufacturing sector. The test case of a VR-based safety training application is defined in the human-robot collaboration pilot-line assembling a diesel engine [10, 13]. In this part of the research, the aim is to verify the validity of the content deployed into the VR system and collect experiences from the user group. The study is conducted in Tampere University Human-Robot Collaboration pilot-line where user can perceive in practice the diesel engine assembly. The VR system which is utilized in this study consists of HTC Vive pro wireless headset, two HTC Vive controllers, and a powerful gaming PC with NVIDIA GTX 1050Ti.

Before beginning the experiment, the user was asked to fill consent form, and the target of the experiment was discussed with them. First, the instructor verbally familiarizes the user with how to work with VR Head Mount Display (HMD). Next, the user was instructed on how to navigate the virtual world and how to access and interact with the various instructions. As a guideline, it was requested to follow the safety training checklist in VR, then he/she will cover all aspects of training. During the test, an instructor always monitors users to avoid any possible harm during the test, e.g. bumping into objects in the environment. Finally, it was required to follow consequent steps to finish the procedure of the experiment. The structure of the experiment consists of three phases as illustrated in Figure **??**:

1- The video of the assembly of the engine is demonstrated where user can familiarize themselves with the assembly scenario. Another point of this demonstration is to remind user what kind of communication exists in the system between the robot and the operator regarding safety measures.

2- Second, user perform VR application in the laboratory without any time limits. That can assist them in perceiving every element of the application and benefit from a feeling of presence in a one-on-one scale system. User can act freely and walk around in this experiment.

3- Finally, the user needs to answer two surveys immediately after the experiment. The questionnaires are discussed in the USER STUDIES chapter. It is worth mentioning that the second survey is performed by open discussion and user preferred to do it as a voice recording manner.

INTRODUCTION TO TECHNICAL SYSTEM

For the implementation of VR application, the UNITY game engine is selected as it is a popular platform for developing VR. The environment for the visualization of applications requires 3D models. In this case, the whole pilot-line is simulated in the manufacturing simulation software Visual Components v4.4. The dimensions of the entire system are measured, and each element of pilot-line is modeled on a 1:1 scale. The software has a vast library of factory components and the majority of robot vendors, which helped us to improve the speed of CAD design procedure. In addition, the diesel engine's 3D model is captured by the Romer Absolute Arm 7525E 3D scanner, which gave us a detailed replica of the engine in our system. Afterward, the pilot-line model was imported to UNITY in 3DMaxs format. The file size was bigger than expected, but it is worth having that detailed simulation where it can give user a better feel of presence in the experiment.

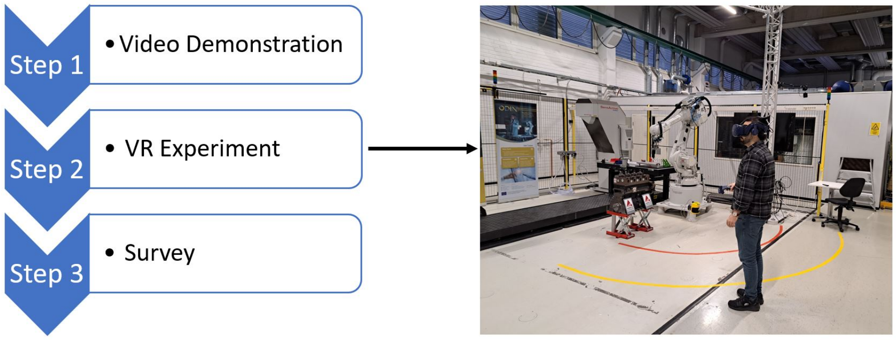

FIGURE 1. VR Study Process Chart.

Next step, the overall system for VR application is initiated with open access OpenXR package. That can assist in the fast implementation of the camera's and VR controller's action. Regarding improved feel of presence, it is decided to implement a human avatar against simple visualization of the controller. A free humanoid avatar model is integrated for this purpose, and with the help of Unity's animation rigging package, the whole skeleton of the avatar is structured. That leads off with two benefits, first, it gives us the opportunity to utilize the head bone structure and placement of the VR camera to the eye-level of the avatar, so the proportion of the body could be visualized more realistically. Second, the colliders are defined around hands, wrists, and forearms where actions regarding close proximity of the engine could be simulated in detail.

There are three types of 3D visualization components implemented in this VR application - Instructions, visualizations, and animations, which are presented next.

Instructions

Instructions are implemented in User Interface (UI) Panel (OpenXR package) as texts give information to the user based on different scenarios. Buttons in the same panel are used for confirmation actions or for continuing to the next procedure. Initially, to provide a clear view for an operator, all of these panels are hidden. However, every panel is accessible at any time of simulation through dedicated tool-tips. Tool-tips demonstrate the location of important instructions based on a real scenario for the user, and by triggering these, the user can have access to all instructions related to the topic. Different topics are represented in these as instruction format. For example, if the user faces different borders such as warning and danger zones, the instruction will tell what would happen in a real system, and how the user can avoid or resolve this situation. The theory of these instructions is based on the application of pilot-line and collaborative level of the system, which is based on ISO/TS 15066 [14]. Another example is the demonstration of different systems' status with tower lights as in a real work cell. The tower lights follow color coding from IEC 60204-1 [15]. This instruction help user to be aware of the system's status and remind user of what can trigger them Fig. 2.

Visualizations

Visualizations in this application target to enhance user awareness regarding surrounding elements, which are not visible at all to the user in a real work cell. The first group is for border visualization. In this case in our pilot-line we integrated a safety laser scanner to dynamically monitor operator presence in different locations. Regarding, speed and separation level of collaboration in ISO/TS 15066, two areas can be defined. The first area is a danger zone, which monitors the operator's location in close proximity to the hazard zone. This area is strictly prohibited to violate, and in case of violation, the robot should be stopped immediately. The second area is a warning zone, which is far from the hazard zone, but still, needs to monitor the operator's intention to approach the hazard zone. In this area, the robot's speed should be decreased. Positions of these borders should be calculated with respect to ISO 13857 [16]. These two borders are implemented in an arc shape with a laser scanner, which in VR is represented respectfully Fig. 3. In

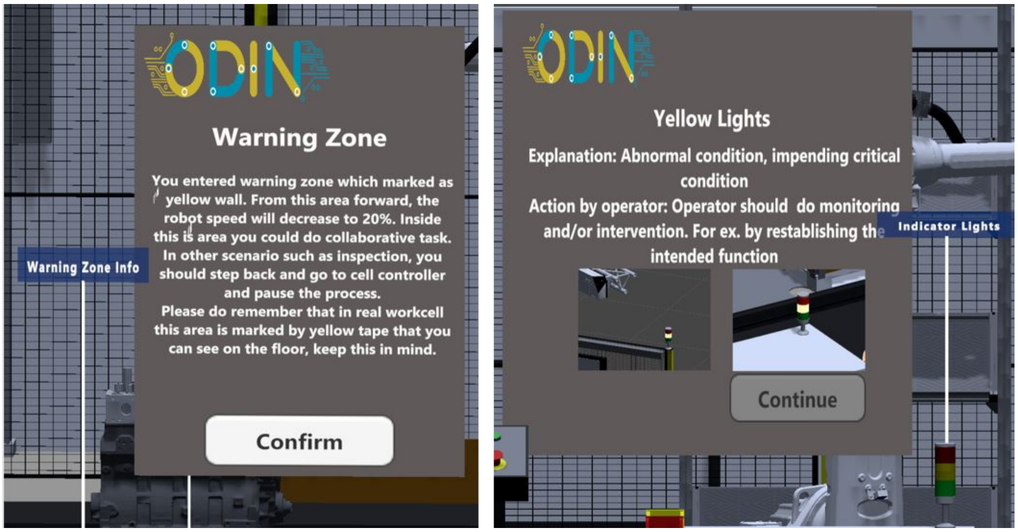

FIGURE 2. Left: Safety border Info, Right: Light Indicator Info.

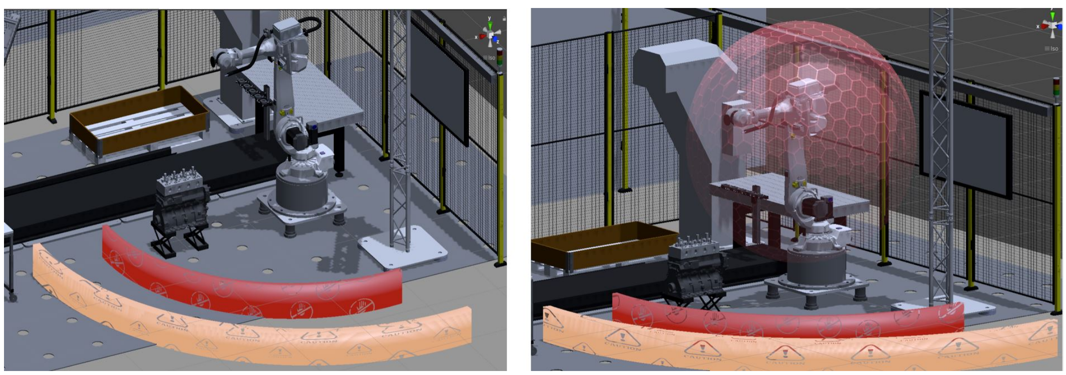

FIGURE 3. Left: Safety border visualization, Right: Robot's working space.

case of any violation of these borders, an arc shape wall would arise from the ground to increase the awareness of the operator about his/her position relative to these areas.

The second element is dedicated to the robot's working space which is referred to as maximum space technically Fig. 3. Normally users are not aware of this area as they are not familiar with the robot's envelope which is provided in technical specifications. This demonstrates robot reachability in work cell and where user can be severely harmed if entered into this restrictive area. This area is represented in 3D sphere space with expanding animation to demonstrate the full reachability of the robot. It worths mentioning that this area is designed with transparent texture so it gives the impression that the user can enter this area, and experience feel of danger in close proximity to the big industrial robot.

In addition to visualizations, audio warning by human simulated voice is implemented to supplement these visual cues. The audio works as a warning message when user has interaction with borders or violates them. For instance, if the operator violates the warning zone the following message will be read for the user "You reached the warning zone, now the robot operates at a slower speed."

Animations

The purpose of the integration of animation is to demonstrate robot movements and the operator's actions in the real-case assembly of the engine. Here user can perceive the timeline of robot actions and trajectory of robots and

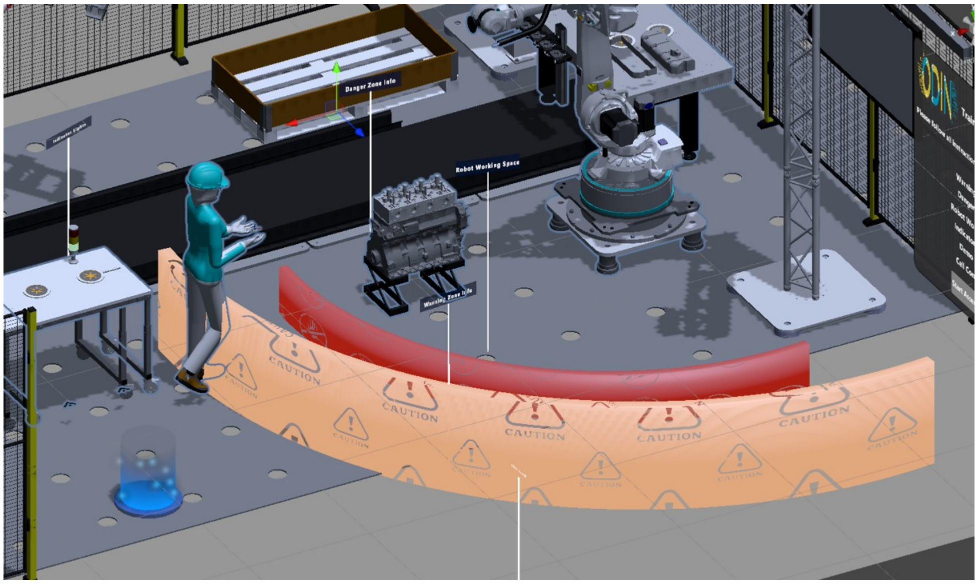

FIGURE 4. Borders interaction in assembly demo.

intention, how the movement of the operator during assembly can trigger the safety system and what impact it has on the robot's work cell status. Animation of operator and robot movements comes from the simulation software. To reduce development process time the "Process Modelling" feature of Visual Components software is utilized. Later on, animations are exported to Blender software to create more realistic representations. Thereafter, the Blender animation can be utilized in UNITY and can be managed to trigger the action of animation based on different events with C# script. Safety borders interact with the operator in animation and act accordingly as user itself violates them Fig. 4. This can increase awareness of violations respected to assembly stages. Additionally, light animation would be triggered respectively based on the location of the user relative to the safety borders. This is the simulation of tower lights that demonstrate the robotics system status in a real environment.

USER STUDIES

The user group for the study consisted of 7 students from the Collaborative Robotics course at Tampere University, and 3 company representatives who had certifications in machinery safety. The user group had gained knowledge about Machine Directive [17], ISO 10218 parts I and II [18, 19], and ISO/TS 15066 which are regarding identifying hazards in robotic work cell design and mitigation plan for risks, and different collaboration levels of human-robot collaboration cell. The reason for the focused user group, in this case, was that the prior understanding of the standards, and their complexity is clear to the users. They could focus on the validity of the content and the user experience on how the content is shown to them. The user study was done according to the non-medical research ethics guidelines. All participants were legal age and volunteers. All volunteers signed the consent form prior to the participation. No personal information was collected during the user study. All participants were allowed to stop the experiment at any time.

In the user study, the following two user experience surveys were utilized. The first questionnaire was based on a well-known usability scale survey [20], which is extensively employed in the research community to validate the usability of their systems such as technologies and software. The second survey was designed specifically regarding this VR application to obtain user feedback and suggestions regarding the general aspect of training and elements integrated into the application. The list of questions is in Table 1.

For analyzing the first survey, each user's System Usability Scale(SUS) score is calculated based on [20]. Additionally, Bangor in [21] presented how the overall SUS score can be evaluated, and for comprehending the scores, we utilized the "Acceptability Range". The mean value of the SUS score is 80 %, which represents that the VR system is acceptable by the users or by adjective rating falling between good and excellent. The maximum and minimum

TABLE 1. Open discussion survey

Question number	Question
Q1	Did you benefit from the visualization of hazardous areas? Why?
Q2	Did the audio warning assist you to understand the border's limit? if not, how it should be improved?
Q3	What do you think would be beneficial regarding the level of collaboration instructions?
Q4	Was the robot working space beneficial? if not, how would you improve it?
Q5	Does the application cover sufficient safety measures? What additional measure is needed to be added?
Q6	In general, do you recommend virtual safety training over traditional (video, text) training?

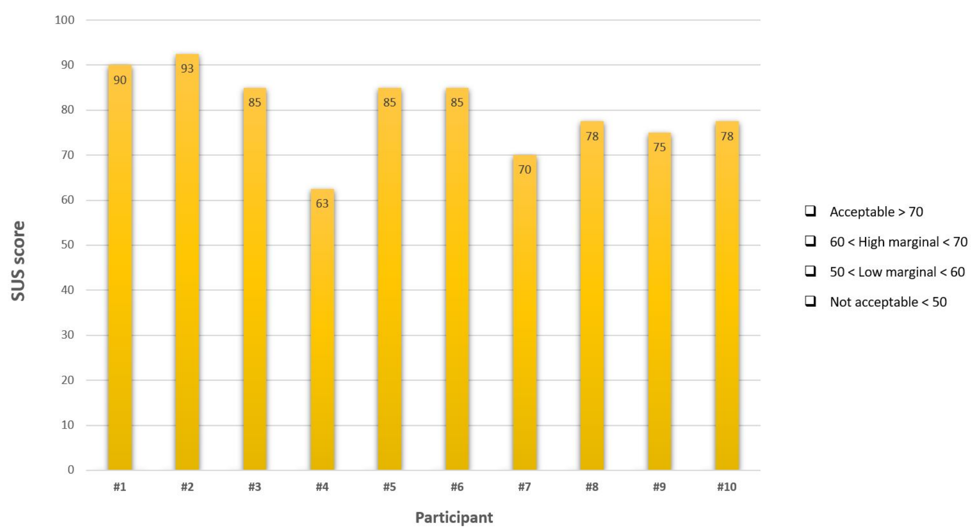

FIGURE 5. SUS score and acceptability for individual participant.

score in this study is 93 % and 63 % respectively. Fig. 5 demonstrates each individual's score from the usability scale survey and the result of their acceptability.

The results of the second questionnaire indicate that visualization of safety training greatly captures the essence of the experiment and clearly conveys messages regarding safety know-how in collaborative workcell. In regard to visualization of hazardous areas, participants mentioned that the visual cues clearly indicate all working areas (i.e., warning, danger, and robot working zones), and users benefit from the 3D feature instead of 2D representation in traditional materials. This enabled the users to continuously be aware of the surroundings as well as "feel" their exact location with respect to the areas. Participants discussed that the interactive characteristic of visualization such as moving borders vertically while violating the hazard zone yields a better grasp of the working areas. It defined "where to go and where not to go, much better than marking on the floor." In addition, it would trigger their curiosity to check what went wrong and what are the appropriate instructions in a given scenario.

In parallel to visual cues, the audio speech was found helpful. It further emphasized on the respective instruction and acted as a reminder of the violation. In cases where the borders were not aligned with the user's visual field, the audio speech complimented the safety instructions. The open discussion on audio speech suggested that it could complement other elements of the system such as text instruction, as readability could be affected by VR headset resolution and cause eye strain. In addition, participants mentioned the use of real human voice instead of computer-aided audio speech. The tone of the computer-aided audio speech within the virtual environment caused an "awkwardness" sensation for some users and gave the impression of unnatural simulated command. In case of violation of hazardous areas, participants were keen to hear a beeping sound in addition to the audio speech warning. This would assist users in focusing on why it happened and referring to instructions if needed.

Furthermore, the results showed that the visualization and interactive environment simplified the instruction and understandability of the level of collaboration. Users fully grasped the knowledge about the speed and separation monitoring zones. The perceived knowledge helped the users to acknowledge the consequences (i.e., robot motion limitations) and how it would affect the operation performance. The interactive environment and audio warnings regarding robot speed reduction or stoppage reassured users of dynamic monitoring of the operator's presence. Further, it yielded a sense of collaboration and act of freedom compared to physical limitations such as fences in workcell. Robot working space was another pressing concern among participants. The sphere representation as a visual cue of the robot's working space emphasized on how visual safety training could underline the threat from the robot. Users argued that the "robot working envelope is hard to imagine." With this approach, all participants stated that with the aid of visualization there is no need to imagine how far the robot's arm may reach and evidently signified the no-go zone.

The reduction of mental workload and visualization of intangible working areas introduced further immersive enhancements to the system. Some users proposed a demonstration of the robot's arm movements and reachability alongside the sphere representation of the robot's working zone. Such visualization at the beginning of the experiment was favored. In addition, most participants emphasized the integration of functions of the emergency stop button. One solution that came up was the utilization of animations in a way that the robot's movement would stop if the emergency stop button was triggered. Afterwards, the user could be instructed on how to resume the operation after such a situation. For the completion of robots' movement visualization, users proposed the integration of audio speech with respect to the relation between robot motion and violation of borders. More importantly, users claimed that the height of the participant could affect the perception of some 3D elements, therefore, in further development, it can be considered to resolve this issue.

In general, the VR system was preferable by the participants compared to the traditional method. There was a consensus of opinion that visualization of safety measures carries valuable advantages in the context of safety training. Participants stated that virtual safety training could compel trainees to avoid bypassing the training stages as it requires active interaction to complete each part. One participant mentioned that the trainee could lose focus in the traditional method, and un/intentionally skip part of the training since the user may perceive that the message was realized. In addition, VR safety training could be more memorable due to the continuous sense of presence and proactive behavior in the system. VR application carried a gamification sense, making it exciting for users to request to try the experiment again. Another matter is that the realistic development of moving elements and animations is favored strongly. In this regard, 3D and spatial elements seem to affect user comprehension.

CONCLUSION

In this study, we examined virtual safety training to encounter the safety aspect of communication between human and robot. The VR HMD hardware is utilized for creating interactive and immersive visual content for the user. For creating a user experience study, the HRC use case of diesel engine assembly in our laboratory is defined with a focus on speed and separation monitoring regarding collaboration level. The VR application is dedicated to the safety training phase as proposed in [10]. Therefore to validate the content of the application, the users selected for the study were already familiar with the safety aspect of HRC with respect to machine directives and standards. Our results suggest that integrating visual and audio cues into virtual safety training is beneficial for delivering clearer instructions to the user. Visual representation of borders and animations clarify the required user actions regarding the different statuses of the robot. In addition, audio warnings provide adequate messages whenever hazardous events are triggered.

This application is more focused on a more immersive experience, as a user should perceive safety distances clearly and visually. However, with the integration of full-body avatar and a walk-in place locomotion system (in this case, a simplified version), the chances of motion sickness could be initiated. Scholars conducted an empirical study and investigated the causes and measures of motion sickness in virtual reality in [22, 23]. Therefore, for further study of VR safety training with a larger audience and with engine assembly use case, this factor needs to be considered and tested, for instance by [24]. One solution that could eliminate motion sickness is to decrease the time period of training and divide training objectives into smaller tasks with a shorter time period.

In order to validate the content from an academic laboratory to an industrial-level environment, the virtual safety training could be examined in small industrial sector use cases. Therefore, the application can be studied with two targeted groups, one with safety experts of the factory and another with operators who work on HRC shop floor. Additionally, the assembly training phase alongside safety training, will analyze the effectiveness of VR safety training in complete assembly scenarios. The study could benefit by comparison of VR training with the traditional methods, and investigating the impact of operator mistakes regarding violation of hazardous areas.

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