Case Study on Mobile Virtual Reality Construction Training

M. Wolf[a], J. Teizer[a], J.-H. Ruse[a]

[a] Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Germany
E-Mail: mario.wolf@rub.de, jochen.teizer@rub.de, jan-hendrik.ruse@rub.de

Abstract –

Recent surveys among construction firms found, a majority has a hard time filling craft worker/hourly positions and salaried jobs. Among the ways they are trying to create more is in-house training. However, existing learning methods have been lagging effectiveness or are outdated. New approaches, like mobile virtual reality, are being investigated. In this paper, the authors describe their approach to a low cost virtual reality training that offers personalized feedback for trainees or workers. The developed approach utilizes elements of gamification for motivational purposes. While the training requirements were gathered in dialogue with leading companies in the construction and engineering industry sectors, the research conducted focused on prototyping and testing the novel learning concept. As a result, the authors developed a mobile virtual reality application that utilizes the Google Daydream SDK that runs on Google Cardboard, Samsung Gear VR, Oculus Go or compatible other inexpensive devices. The application was tested and evaluated by industry representatives. An outlook provides the path forward in research and development.

Keywords –

digitalization, construction safety, personalized feedback, virtual reality, virtual trainings, workforce education and training.

1 Introduction

The construction and engineering industries face several major hurdles at this time. While construction workplace accidents account for a significant number of fatalities and injuries [1] that consequentially lead to a loss in productivity, engineering in general faces another problem: a severe shortage of skilled labor [2].

Over the past decades, researchers and practitioners have attempted to understand and mitigate the underlying precursors of accidents in construction [3,4]; with some success the accident rates dropped until they recently started rising again [5]. Among other ways, hazard recognition is one of the first steps in effective safety management [6-8]. However, results on the effectiveness across the globe have shown that up to 50% of construction hazards remain unrecognized despite that training and certification are provided [6-12]. Among the contributing factors for such poor hazard awareness are worker's paying attention on their task, ignoring predominantly some types of hazards, and having low capabilities in "visual search". Latter means the initial detection and then identification of hazards is a very challenging human task [13]. It is particularly difficult considering that construction sites are very complex and dynamic, where one worker's attention to all the present details can often be overwhelming.

Examples of such work environments are building and industrial construction sites or larger vs. smaller work spaces. No or no recent training, no or unclear tool box meetings before work begins, imprecise work station preparation, and inadequate site conditions or staffing are some of the most common reasons that challenge worksite safety behavior. The recent example of a partial refinery explosion shows, unsafe work preparation, unclear instructions, or using the wrong tools for the wrong task can result in a tragedy [14].

The objective of this study is to leverage mobile virtual reality construction training. The preliminary research effort designed training in two virtual environments: hazard detection in a virtual building construction site and a flange training scenario in a virtual training center of a chemical plant operation. The next section presents a brief background on safety training and flange coupling. This is followed by an explanation of the virtual gaming environment that was created and tested. Results are shown and an outlook of future work is presented.

2 Background

Safety is a major concern in the construction industry. Besides numerous other approaches on hazard awareness, training has one of the highest positive impact factors in reducing fatalities. In the literature as well as in the praxis exist several different teaching formats, such as self-, hands-on-, supervised- learning. Generally, the level of awareness aimed at implies knowledge on possible hazards and safety regulations. These are strictly defined in most countries, like in Germany by the BG Bau [15], an official organization responsible for establishing and enforcing construction safety rules.

While workers in the chemical industry are constantly confronted with the installation or maintenance of piping and the respective connections, these works can only be executed once normed guidelines and instructions are followed [16-17]. Problems arise or continue to exist if no or only limited trainings for executing work tasks are provided. This may happen less in the chemical industry because training has been part in their core business processes. The fragmented construction industry though has a continuous problem with adequate workforce training.. There, knowledge on safety and health is hardly ever refreshed in greater depth once primary education as an apprentice has ended [5]. For this reason, several researchers started investigating new methods, particularly on using Virtual Environments (VE's) for hazard awareness [6,18-19,20]. Although a full scientific validation of VE for safety education and training is a very challenging task considering that mature practical solutions seem far to be reached, all of these approaches claim that VE will provide safe and more effective training, at reduced time and cost. An additional example is, the right way to work with flange connections in the chemical industry is typically taught on a single day and is usually viewed by the trainers and trainees as a basic training. But especially larger diameter flange connections can challenge work crews, so that an adaptive VR training and instruction guide could help workers build confidence and provide readily available knowledge in handling the materials and the necessary tools.

3 Requirements and general setup

As mentioned in the introduction, this paper focuses on testing the limits of mobile virtual reality for two different scenarios with very specific requirements. To avoid the accumulation of inert knowledge, the authors want to use immersive virtual reality technology to enhance the experience for the trainee. This offers a safe way to confront the trainees with realistic representations of hazards without exposing them to real dangers.

One of the most relevant requirements, in context of this paper, is the ability to use the trainings on mobile virtual reality devices. Mobile VR devices like the Oculus Go cost around 200 €, with more advanced hardware (Lenovo Mirage Solo, Oculus Quest, etc.) costing around 400 €. This is significantly less than an equally usable stationary VR setup, which costs anywhere from 2000 to 4000€. Low cost and ease of use are centerpieces of mobile VR hardware. These advantages seem highly appreciated by training organizations or departments who need to equip higher numbers of training staff with such technology.

The aim is to offer explorative, immersive experiences at minimal costs. Both virtual trainings aim at a maximum of 15 minutes working time.

As with most virtual surroundings, the visualization of the desired scenes must be believable with a realistic scale between the user and her/his surroundings. As photorealism in the virtual reality cannot be achieved with the limited computing performance of existing mobile devices, the focus is on creating a visually-sound context for the training scenarios.

The first virtual construction safety awareness training orients itself on the regularities from the German Social Accident Insurance (DGUV) and its subdivision for the building trades (BG Bau) [15]. The second scenario is the virtual flange training, which is based on German norms and guidelines for the handling of flange connections [16].

3.1 Virtual safety awareness training

The objective of the scenario was to provide a scene that must show a realistic and valid construction site. Embedded in the scene are typical hazards that can and must be avoided in the real world. To accommodate the scene for regular use in training and to offer some variety, the total amount of hazards must exceed the number of hazards in each session, with an automated, random selection applied at the start of the training. Hazards must be identifiable by the user, preferably by pointing at them and then selecting them with the controller. Head mounted devices (HMD) provide such instruments that even allow for data gathering and post-analysis which and when a hazard was selected.

The user must have full locomotion in the scene to reach all parts of the virtual construction site. When coming closer than the typical safe distance for a particular non-identified hazard – granted the user has line-of-sight – the user needs to be informed that the concerning hazards was not detected and is therefore marked as failure. The safe distance of each hazard depends on the type of hazard and should be automatically applied.

The virtual construction safety awareness training application must record user- and session-specific datasets consisting of the current scene configuration (number of randomly selected hidden hazards with their IDs) and the user's actions in the scene (total time, full completion yes/no, total number of corrected hazards, specific listing of the hazards, their status and association with German safety training regulations). The exact documents considered for the creation of hazards must be at least BG Bau A021 (fire safety), A062 (flammable substances), A064 (pressured gas tanks), B100-1 (work-at-height), B132-1 (ladders), B161-1 (load handling), B172 (electrical equipment), B173 (mobile generators), B181 (excavators) and B202 (hand tools) and each hidden hazard must specify the associated document for later analysis.

3.2 Virtual flange training

The virtual flange training's purpose is to teach and train both patterns of valid screw-fastening on flange-couplings (cf. DIN 1591-4) for novices and experienced work crews. The training must be flexible enough to train on a variety of flange couplings ranging from small (8 screws, DN20) to big (24 screws, DN400).

The virtual flange training is supposed to offer two separate modes. The first mode aims at teaching novices the usage of both the standard crosswise and the alternative pattern of fastening the flange's screws (Fig. 1). In this teaching mode, each step taken should be marked as either correct or incorrect to provide immediate feedback. The trainee must be able to access help functions to learn about the general guideline for the chosen approach [16] and optionally which screw to fasten next. In this training environment, the trainee should not be able to move around freely but be allowed to concentrate on the task at hand. Therefore, the flange should be placed floating in a frontal view to mimic the depiction in the guidelines.

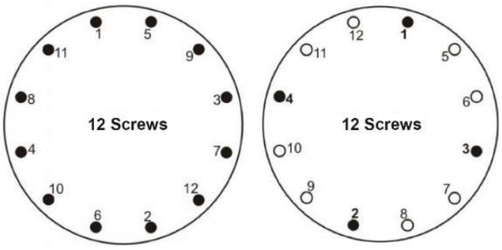

Figure 1. Standard crosswise pattern (left) and alternative pattern (right) [16]

The second "open training" scenario should offer less help, free locomotion and a realistic scenario with a flange connection of two pipes stacked vertically. This should force the trainee to change her/his position and viewing angle similarly to the movement necessary in the real world. The immersion of the trainee in the scene was improved and an option to use the controller in a movement like a ratchet was offered optionally.

The virtual flange training application must record user- and session-specific datasets consisting of the current configuration (e.g., number of screws, choice of training mode, method of fastening), the total amount of time till full completion, the achieved score and the total amount, type and time of occurrence of errors made during the training. Before each training session, the trainee was made aware of the recording, putting her/him under pressure to concentrate on quality and timely completion of the assigned tasks. The different kinds of errors that can occur in this scenario are described in Table 1.

Table 1. Registered events in the flange training application

No.	Error Description
1	User specified the wrong torque number
2	Selected screw was already fastened in the current turn
3	Selected screw is not opposing to the last
4	Selected screw is not one of the two screws orthogonal to the axis connecting the first two screws
5	Wrong sequence in the last step of the standard cross-wise pattern (i.e. not clockwise)
6	Wrong starting point in the last step of the alternative pattern
7	Wrong sequence in the last step of the alternative pattern (i.e. not clockwise)
8	Wrong combination of method and nominal diameter

4 Prototypical implementation

For the preliminary evaluation, the authors implemented two mobile virtual reality applications using the Unity3D Engine and a Samsung S8 in a Google Daydream Headset with its accompanying controller. To run the application on Google Cardboard, Samsung Gear VR, Oculus Go or compatible devices, the Google Daydream SDK was used. In each scenario, the rotational head tracking enables the trainee to look around in the scene, while interaction and movement via virtual teleportation as locomotion method is handled with the controller.

4.1 Virtual safety awareness training

The authors created a virtual construction site in the Unity3D Editor (Fig. 2, top), which has over 70 possible hazards from which each training set is drawn. When looking directly at the controller, tooltips (Fig. 2, bottom) show up to inform the user about the total time in the scene, the amount of found and left hidden hazards in the scene and the button's functions (identify hazard and teleportation).

For each training session, a new set of hazards is selected from the "hazard pool" and all non-selected hazards are "non-existent" in this very training session. The algorithm for the process is displayed in Table 2. As the number of implemented hazards is known (70) and the amount of targeted hazards per scene is known (between 10 and 25), all that is needed to set up an individual scene is a random number *i* to generate. The goal for the trainee is to find all hazards in the construction site, but no further assistance (i.e., highlighting when hovering over objects in the scene) is given.

Table 2. Algorithm for the construction safety training

Step	Description
1	Generate a random number *i* between 10 and 25
2	Generate “”"-many random numbers between 1 and 70 with no doublets allowed
3	Hide all hazards
4	Show all hazards where the generated numbers match the hazard’sIDs

Fig. 3 shows screenshots taken from the user’s perspective when looking at unsafely stacked cable spools and an unsecured falling hazard (Fig. 3, left). When the user identifies the hazard via point&click using the controller, the hazards is resolved, and the desired (safe or healthy) situation is revealed (Fig. 3, right).

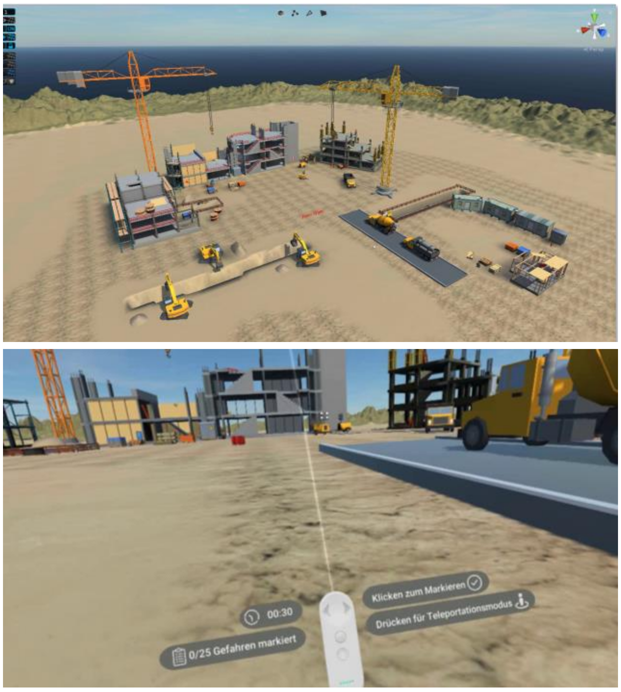

Figure 2. Screenshots with overview over the created construction scene (top) and the user’s perspective using the application (bottom)

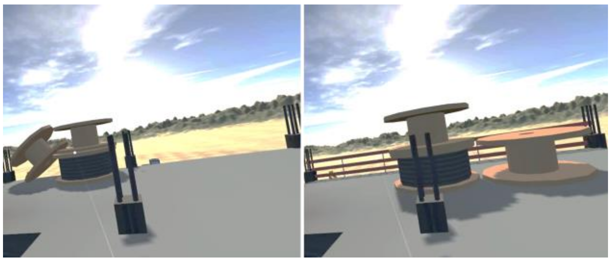

Figure 3. Close calls with crane load: contruction worker (left) and skid-steer loader (right)

4.2 Virtual flange training

The virtual flange training must implement both methods (standard and alternative) of fastening flange connections specified in the German Industrial Standard (DIN 1591-4). For that matter two different algorithms were implemented in C# and used in the training scenes to check a trainee’s input. Table 3 shows the algorithm for the standard method. In short, the standard pattern consists of three rounds with different torque figure. In each round a set of four screws is fastened, starting with two opposing screws and going to the pair of screws that are orthogonal to the first two. This crosswise pattern continues until all screws are fastened with the current torque figure. After a full pass of all three steps, the guideline specifies an “unlimited” amount of clockwise repetitions until each screw passes with 100% torque. In our algorithm a single pass is sufficient.

Table 3. Algorithm for the standard method in the flange training application

Step	Description
1	Start with 30%, 60% and 100% torque
2	Select random screw (< current max. torque)
3	Select opposing screw to the first screw
4	Select one of the two screws orthogonal to the axis connecting the first two screws
5	Select opposing screw to the third screw
6	Repeat steps 2-5 until no screw is left < current max torque
7	Repeat with next torque level starting at step 1
8	Select each screw, starting at screw one and following a clockwise path

Table 4. Algorithm for the alternative method in the flange training application

Step	Description
1	Start with 20%, 60% and 105% torque
2	Select random screw (< current max. torque)
3	Select opposing screw to the first screw
4	Select one of the two screws orthogonal to the axis connecting the first two screws
5	Select opposing screw to the third screw
6	Repeat with next torque level starting at step 1
7	Select each screw, starting at screw one and following a clockwise path

Table 4 shows the algorithm for the alternative method. It is important to note that the DIN-standard specifies the alternative method invalid for nominal flange diameters of less than 200 mm. In consequence to that, once a “smaller” training flange is selected and the alternative method is used, the current try is considered a failure. The alternative method is basically a single crosswise pattern with different torque figures, followed by clockwise fastening with the highest torque figure. Analogue to the standard pattern, the theoretically unlimited number of repetitions until the final torque figure is met is reduced to exactly one in the algorithm.

Each algorithm can be used in each of the two training modes. As the novice mode is supposed to offer a great amount of support functions, the authors created the scene and Graphical User Interface (GUI) as seen in Fig. 4. The user starts at the trainee position (Fig. 4, No. 1) with a frontal view of a flange connection (Fig. 4, No. 2) of a specified size. The score panel shows the current number of correct steps and the score for this session (Fig. 4, No. 3). In the option and help menu (Fig. 4, No. 4) the user can switch between help for individual methods and switch on the help and instruction panel (Fig. 4, No. 5). In the scene configuration menu (Fig. 4, No. 6) the user can set up the size of the flange, the preferred method and the optional "manual ratcheting". Locomotion is disabled in this mode, so that the trainee is surrounded by (optional) information, with her/his task in front.

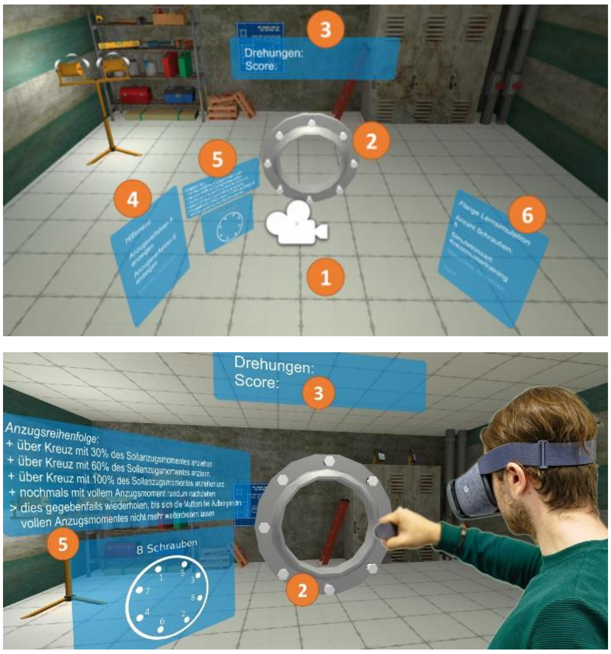

Figure 4. Screenshots with overview over the created scene (top) and the user's perspective (image overlay) using the application (bottom)

Instead of the strict nature and learning-based novice mode, the open training mode offers free locomotion (identical to the construction site scene) and more naturally placed interaction elements. The trainee starts at a standard position (Fig. 5, No. 1), with the task in front of him. The vertical piping elements with the flange connection needs to be fastened (Fig. 5, No. 2). It can be configured with the scene configuration menu (Fig. 5, No. 4), just as the frontal flange view in the novice scene. The idea behind this is, that when handling the flange connection of rather large piping, the task becomes harder, as the exactly opposing screw is not that easy to find. The score panel for the current session is fixed to the opposing wall (Fig. 5, No. 3).

The task in this scene is to choose a flange size, start wrenching and use either the standard or the alternative pattern to fulfill the task. Once the route for a particular method is set after choosing the 5th screw, every error lessens the score.

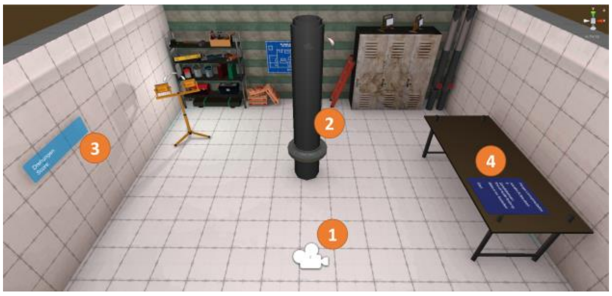

Figure 5. Screenshots with overview over the created scene for the open training

5 Results to demonstration and testing

The prototypical applications were demonstrated at an interdisciplinary internal workshop for experts for digitalization of learning environments and didactics in engineering at the Ruhr-University Bochum, Germany. Many of the attendees had long-term construction or engineering industry experience. They were asked about their opinion after testing either or both of the applications.

On the positive side, the experts mentioned the ease of use due to the nature of the light headsets and the easy way to understand locomotion. The comic-like graphics were easy to understand too and offered not much distraction, while being clear enough to offer orientation and recognition.

Concerning the construction site safety training the experts suggested, instead of revealing the ideal solution for each found hazard, the trainee could be asked to choose from several different suggested solutions. This would offer a better possibility to verify the trainee's deeper understanding.

Data gathered from three exemplary users show what kind of insight instructors can get, when preparing feedback based on virtual trainings. Table 5 lists some of the gathered data, with hazards subdivided by their according BG Bau rules like A021 or B100-1. As one can see, user 1 seems to be at ease with the recognition of hazards in a construction environment with a good time and full completion. Users 2 and 3 did not finish on time, but user 3 found all but one hazard. As the full XML data log contains timestamps for all events, a graphical timeline could reconstruct the events within the training. That would reveal that User 3 was as fast as User 1, but didn't look up to check the load hanging from the crane till the time ran out.

In both applications, the experts found the trainings to be interesting and challenging, while the technical representation left some things to be desired. To address these concerns, performance enhancing measures will need to take place before a larger survey can be conducted. Also, future participants will need to get a precise introduction to the applications and tasks, as the applications are not self-explanatory enough and the overpowering nature of VR to first-time users might hinder this further.

Table 5. Data collected from three exemplary users in the construction hazard awareness training

	Participant		
	1	**2**	**3**
Timestamp	**11/01/2019 15:02:34**	**11/01/2019 15:34:04**	**11/01/2019 16:01:58**
Total time [min]	8:05	15:00	15:00
Full completion	Yes	No	No
Hazards in scene	19	12	17
Correctly detected	19	10	16
A021	1 of 1	1 of 1	1 of 1
A062	3 of 3	1 of 2	3 of 3
A064	2 of 2		2 of 2
B100-1	2 of 2	2 of 2	3 of 3
B132-1	3 of 3	1 of 1	
B161-1	1 of 1	1 of 1	0 of 1
B172	1 of 1	1 of 1	2 of 2
B173	3 of 3	1 of 1	3 of 3
B181	1 of 1	1 of 1	
B202	2 of 2	1 of 2	2 of 2

6 Conclusion and outlook

This study described a novel approach towards a low-cost virtual reality training that offers individual feedback for trainees or workers. The approach utilized elements of gamification for motivational purposes. With requirements gathered in dialogue with industry leading companies and based on research conducted at the Ruhr-University Bochum the concept at hand successfully created and tested a prototype. While the results are preliminary the authors have shown the complexity of creating virtual reality experiences based on existing safety-related regulations.

In case of the presented applications, the far smaller scenes of the virtual flange training contains more complex interaction elements. Its dynamic algorithms also offer a varying degree of difficulty.

In the rather large construction site scene, the algorithms are based on many elements and regulations. A simple hit or miss strategy which was particularly easy to implement might be enhanced in the future by providing immediate feedback on the hazard type. Similarly, allowing false positive errors might strengthen a trainee's attention to be careful about selections.

In brief, our future work will combine the presented approaches for work place safety and actual work tasks. This will enhance the experience with further interactive elements like dynamic non-player characters and vehicles. The idea is to offer a holistic construction site representation with varying tasks to perform, to lessen the impact of the acclimation time users usually need to accept and cope with their immergence into a virtual environment. Another research topic in this context is the increase or decrease of learning quality due to the immersion in virtual reality. As the applications were created with Unity 3D, a reference group will test the same applications and 3D contents in a non-immersive standard PC configuration. Structured may replace opinion-based surveys.

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