Application of Virtual Reality in Task Training in the Construction Manufacturing Industry

R. Barkokebas[a], C. Ritter[a], V. Sirbu[a], X. Li[b], and M. Al-Hussein[a]

[a]Department of Civil and Environmental Engineering, University of Alberta, Canada
[b]Department of Mechanical Engineering, University of Alberta, Canada
E-mail: rdbarkokebas@ualberta.ca, critter1@ualberta.ca, sirbu@ualberta.ca, xinming1@ualberta.ca, malhussein@ualberta.ca

Abstract –

Automation in construction manufacturing is becoming increasingly common due to the drive for higher productivity and increased quality. One important consideration in the implementation of automation is the training and maintenance of the equipment. This study proposes an approach to assess the training for assembly/disassembly and maintenance of machines developed for the construction manufacturing industry by using immersive virtual reality (VR). The application of VR allows the collection of data such as the time required to complete the task, the distance travelled, the identification of ergonomic risks (e.g., awkward body posture), and the layout effectiveness, as well as the observation of multiple users performing an identical task under laboratory circumstances. Moreover, VR significantly reduces the costs associated with real mock-ups and the time required for implementation as it allows testing machine designs in a virtual environment that mimics the machine's real operation setting. To demonstrate the proposed approach, a case study (i.e., VR experiment) is conducted. The primary objective of the case study is to use VR to assess the effectiveness of training using the VR environment for maintenance, and the complexity of the task (i.e., the amount of time needed to understand the task). The VR experiment is performed inside an office room dedicated exclusively for that purpose where participants can move freely, and interactions with the virtual environment are possible through the utilization of a headset and wireless controllers. During the experiment, information is collected both by manual observation and automatic extraction of data from the computer. Based on the analyses of the data collected, the average time to complete the task is determined, and potential areas of design improvement are identified.

Keywords –

Virtual Reality; VR; Maintenance; Automation; Training; Construction; Manufacturing;

1 Introduction

The implementation of visualization, communication, and information technologies by the construction industry has been confirmed as a powerful approach to optimize and integrate industrial processes [1]. Virtual Reality (VR), for instance, has proven to be an integrating tool that supports communication between different stakeholders as well as decision-making processes, especially during the design phase [2]. In the past years, several studies were conducted to investigate the application of VR in the construction industry, focusing on a variety of areas such as virtual prototyping [3–5], ergonomic analysis (e.g., detection of unsafe body motions and unsafe worker behaviour) [6–8], safety hazard detection [9–13], construction equipment training [14–19], and educational purposes [2,20,21].

In terms of training, VR offers the possibility of effective training while reducing significantly cost and safety risks related to mock-ups [16,22]. Investments in training strategies are essential to ensure that employees are continuously improving their skills to accurately and safely perform tasks [23]. According to Rezazadeh et al. 2011 [16], VR can assist training since, by utilizing VR, the user has the sensation, to some extent, of performing the activity as he/she would perform it in reality. Besides the mentioned capability, VR also allows users to practice how to perform a task/activity without pressure due to costs, the inability to complete the task, and risk of hazards inherent to real mock-ups [24]. In terms of the impact of the presentation medium used to provide safety training, Leder et al. [25] compare an immersive VR and a Microsoft PowerPoint presentation. Results obtained conclude that the investment on costly equipment for VR safety training is not cost-effective since Microsoft PowerPoint developed with realistic figures and scenes has a similar impact on user risk perception and learning outcomes [25].

The application of VR technologies to educational purposes is also explored by researchers. Sampaio et al. [2] use 3D modelling techniques and VR to develop models to represent several construction processes. Based on the results obtained, it is determined that introducing 3D models and VR techniques in schools assist students to learn and prepare them to use these technologies in their professional practice. Pan et al. [20] perform a state-of-art research on the concept of VR applied to learning, training, and entertainment, and concludes that the application of VR can enhance, motivate and stimulate learners' understanding of certain events. In addition, it is identified that learners learn faster and are happier using virtual environments than they are when using conventional learning methods [20]. Goulding et al. [21] investigate the utilization of VR to provide a risk-free environment for training construction tasks. The primary goal of Goulding et al. [21] is to stimulate multidisciplinary learning between different construction professionals during the design phase, since faulty work, safety, and health issues are often caused by decisions taken in this stage.

In light of the information provided, it is noted that research has been carried out in the area of VR and the construction manufacturing industry; however, there is still a research gap on VR applications with emphasis on training, especially in terms of machine assembly/disassembly tasks. In this context, the aim of this paper is to design and test a VR experiment to evaluate how two training techniques (i.e., VR experiment and a printed instruction manual) impact the performance of a user conducting a maintenance task.

2 Methodology

This project is the first phase of a larger experiment that will test the effectiveness of VR on training in a construction manufacturing setting. This phase was done to validate the design of the experiment. The overall outline for the project can be seen in Figure 1. This paper will cover the section labelled 'experimental design and testing phase'.

2.1 Experimental Design and Hypothesis

The hypothesis to be tested by this experiment is that users carrying out a maintenance task for the first time in real life will be more successful after completing a training sequence in a virtual reality training environment than users trained by reading an instruction manual. The first run of the experiment was done to analyze the success of the experimental design in testing this hypothesis and to determine whether there were factors that had not been previously considered that should be designed for in the full run of the experiment.

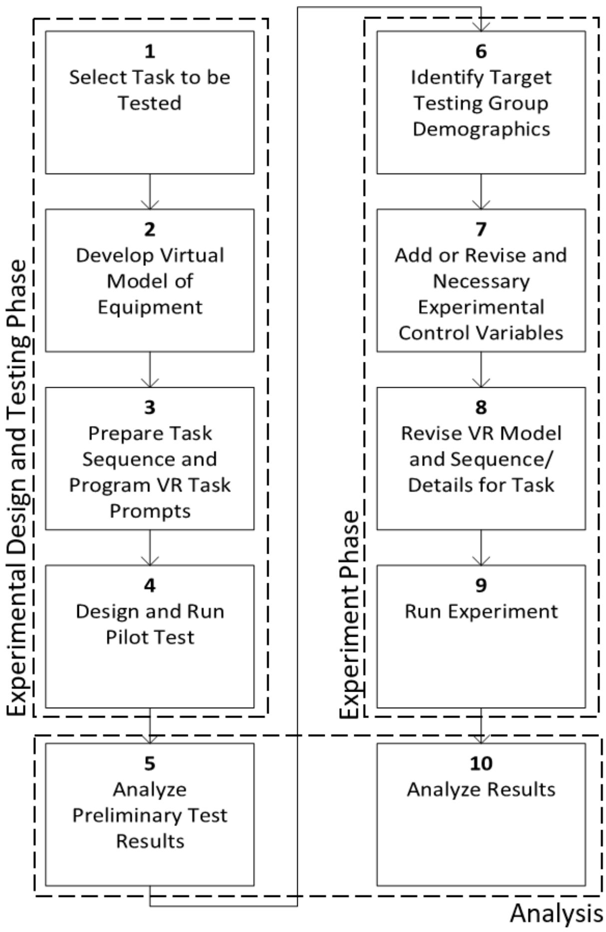

Figure 1. Project outline for testing the effectiveness of virtual reality training for tasks in construction manufacturing and equipment maintenance

2.2 Virtual Environment Design

The VR application used for this experiment was built on the Unity game engine and assets were created using 3DS Max and Photoshop. Standard game engine asset creation workflow was used including using low poly models with baked normal maps and textures to improve performance. Programming was done inside Unity using the C# language. The headset used was an HTC Vive with one hand controller and the application was run on a powerful desktop using a GTX 1080 ti video card. The active physical area of the application was 8' × 8'.

The application itself was developed by a multidisciplinary team including mechanical engineers, construction engineers, a programmer and one digital artist. The 3D model of the machine was based on

SOLIDWORKS files of the real-life machine that was built in our lab. In this way we were able to perfectly match the real life machine that was used for this experiment with the virtual one.

2.2.1 User Experience

An account of the user experience of the VR application is as follows. The user spawns facing the machine fully assembled (since it is to be disassembled first). The controller can have various tools attached to it; however, to begin, it has a placeholder for a hand. To the left of the user is a table with tools that can change the controller placeholder. This is pictured in Figure 2.

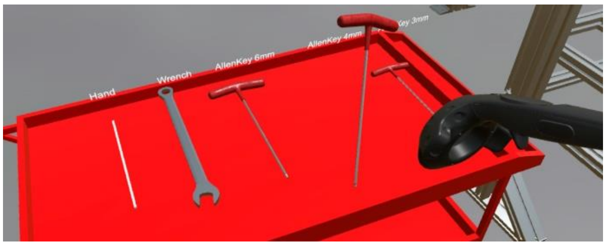

Figure 2. Tool selection in VR environment

Behind the user is a table onto which disassembled parts can be arrayed before they are put back together. This table is seen in Figure 3. The task to be performed next is highlighted in yellow, as can be seen in both Figure 3 and Figure 4, for reassembly and disassembly steps, respectively.

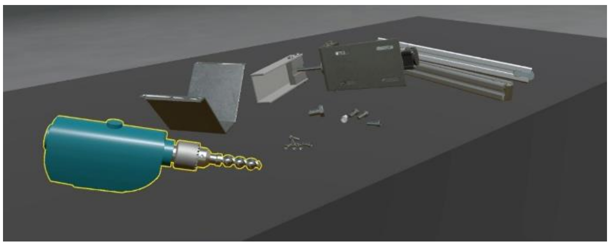

Figure 3. Prompt for the next step of assembly in the VR environment

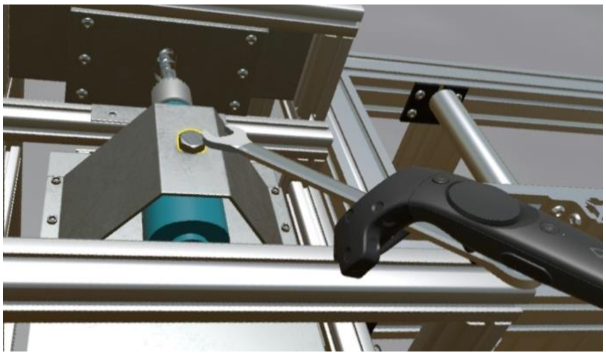

Figure 4. Disassembly prompt with tool in the VR environment

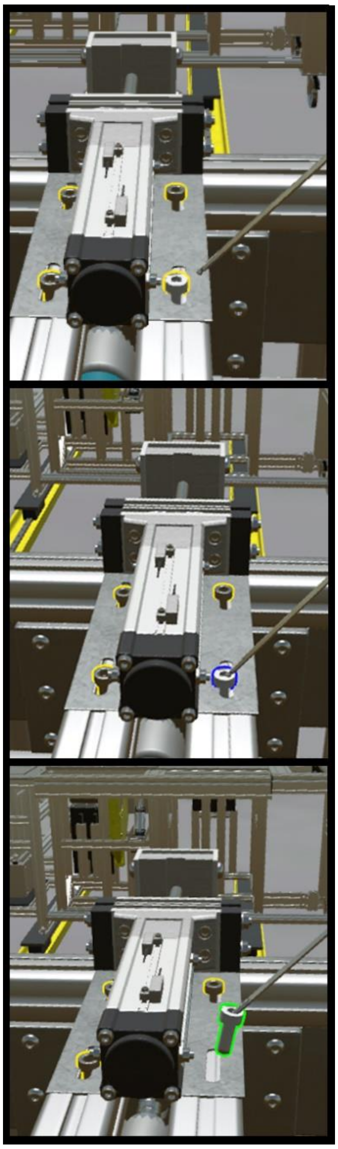

Figure 5. Sequence of colour prompts in the VR training environment

The first step is to take apart screws that connect the top clamp of the machine to the frame. Before detaching the screws, the correct tool must be selected; therefore, as the user first spawns, the tool needed to unfasten these first screws is highlighted in yellow on the table to the left of the user that contains the tools. The user must place the controller (with the hand placeholder) over this tool (that is highlighted in yellow) and activate the controller trigger button. The controller swaps the hand placeholder with the tool and now the screws of the clamp are highlighted in yellow. The user must place the tool in the correct place over one of the screws and activate the controller trigger. Now the screw is attached to the tool and can be moved away from the machine and placed on the table behind the user. When the controller is placed over any yellow part, that yellow part turns blue in order to signify that the controller is touching that part. Parts turn green when the user activates the trigger and the step is completed successfully. This sequence of colour prompts can be seen in Figure 5.

In this manner, by always highlighting the next part in yellow, by giving feedback when the controller is in the right place in blue and highlighting completed steps in green, the user always knows what to do next and whether they are doing things correctly. Over the course of the VR application the user is guided through one full disassembly and one full assembly, and, in theory, he/she would gain a solid understanding of these processes.

2.2.2 Advantages

In theory, the VR training application has the potential to be more engaging from the point of view of the user. VR enables him/her to experience the physicality of the space in relation to the physicality of their own body. In the VR environment the user can freely look to observe the machine and its parts from the same angle and point of view as they would in real life. Moreover, they have ability to reach with their hand into the space and as such they gain an understanding of their own ability to reach into various parts of the machine and to possibly make observations in regard to safety or ease of use that would be impossible to arrive at by looking at a photograph, a technical drawing or written instructions. Moreover, due to the design of the training module, the user is only ever concerned with what to do next and can focus on tasks knowing that the training module will guide them along. The experiential qualities of VR applications are unique and can lead to insights that cannot be arrived at through other means. This allows designers or industrial machinery to test user experience and behaviour in relation to machine operation in ways not previously possible.

2.2.3 Disadvantages

Disadvantages mostly revolve around technical limitations. These include the inability to observe one's body in the space. Currently most VR applications do not allow the user to observe their own hands and body. At best, it is possible to create a 3D model of the user, but even in that case there is a disconnect between one's sense of one's real body and the virtual avatar that acts as a stand-in. Moreover, our application does not account for the user's actual hands. The controller has a placeholder for those instances when the user must use their hands. This is a poor substitute, especially in a training module where using one's hands to put parts together and take them apart is the key component. In order to address this problem, the researchers would have to implement a motion capture system that accounts for hand motion. Hand motion capture is technologically challenging and an area in which advances are being attempted by specialists in that field.

2.3 Experiment Setup

The experiment was carried out in a research facility for three days. Volunteers were randomly assigned to either learn in the VR training environment or by reading an instruction manual. They were then each given six minutes to study the material or use the VR training system. A participant completing the VR training portion can be seen in Figure 6. Next, they were taken to see the physical model for the first time and were tasked with completing the same steps as they were trained. Participants were notified that they would be recorded and scored based on their ability to complete the task, but were not told how aspects of their performance would be weighted when determining their score. Additional instructions on how to perform the task (e.g., bolts do not need to be fully tightened) were given to all participants.

Figure 6. Participant completing the virtual reality training activity before the evaluation activity

2.4 Participants

In total, seventeen people participated in the experiment. Based on how they received instructions to perform the task, they were randomly (as mentioned in the previous subsection) divided into two groups: (1) VR and (2) instruction manual. The VR group had five male and four female participants, while the instruction manual group had five males and three females. All participants were part of the same research group as the authors—the majority of participants, fourteen in total, were graduate students (either master or doctoral students) and three were part of the administrative team. All participants have an engineering background with the exception of two participants, one from each group, and all were under forty years old.

2.5 Data Collection and Analysis

Once the training portion of the experiment was completed, the participants were asked to complete the task on a prototype of the machine. Participants were timed (disassembly time, reassembly time, and total time), as well as marked on the quality of the work completed. This information was used to analyze the differences between the learning methods and performance. A participant completing the last step in the assembly of the prototype machine can be seen in Figure 7.

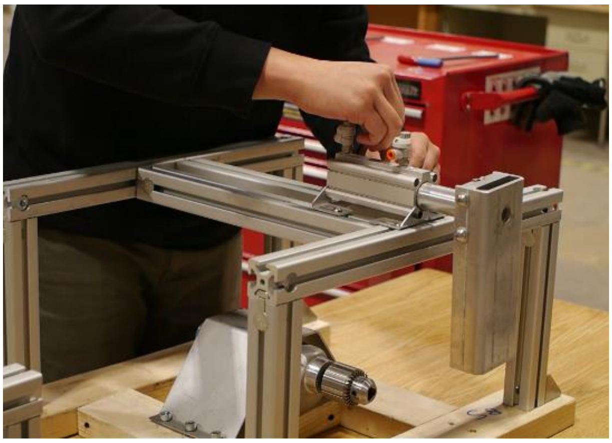

Figure 7. Participant completing the assembly of the prototype

Table 1 shows the number of participants trained in the VR environment or by reading the instruction manual split by gender and by the qualitative aspects of their performance in the experiment, including the final state of the equipment and their organization while completing the task.

Table 1. Count of participants split by training method, gender, and qualitative results

		Count	
		Virtual Reality	**Instruction Manual**
Gender	**Male**	5	5
	Female	4	3
Final State of Equipment	**Operable**	5	7
	Inoperable	4	1
Organization	**Organized**	5	7
	Unorganized	4	1

Table 2 shows the average time taken to complete the task for the participants based on their training type and results. In general, the participants trained using the VR were slower at completing the task. Another interesting observation is that the participants who were able to assemble the prototype so that it was operable again were faster than the ones who left it in an inoperable state.

Table 2. Average time to complete task split by training method, gender, and qualitative results

		Average Time (mm:ss)	
		Virtual Reality	**Instruction Manual**
Gender	**Male**	14:53	11:54
	Female	22:47	16:57
Final State of Equipment	**Operable**	16:31	12:18
	Inoperable	20:45	24:16
Organization	**Organized**	18:40	14:03
	Unorganized	18:03	12:03

3 Results and Discussion

This preliminary run of the experiment allowed for the identification of several parameters that should be identified and possibly controlled for in the next set of experiments. These parameters include the complexity of the project, the deviations from the script in the VR environment that can occur during the test, and the age, experience, and profession of the people completing the experiment.

Figure 8 shows the relationship between the time to assemble/disassemble the equipment in the test. It can be seen that there is little to no correlation between these times for the population tested in this phase of the experiment. This may be due to the simplicity of the task and we expect to see an increased correlation to these times if the complexity of the task is increased.

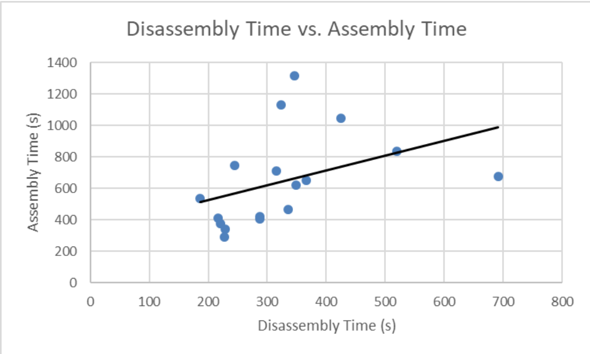

Figure 8. Test results showing the relationship between the time to disassemble and assemble the equipment for each participant

Most of the volunteers were graduate students with undergraduate degrees in engineering. This background would indicate that these volunteers are comfortable with quickly learning through demonstration or reading and analyzing problems.

The complexity of the task is another important factor to consider in the design of the experiment. The task that was used for this demonstration was relatively simple and, given some time, it can be expected that even without the training participants would be able to complete the task. This prompts a separate research question—at what level of complexity does VR training start to outperform text-based training methods, if at all?

Another important observation was the deviations from the VR script. One example of this was how some bars often fell apart when participants loosened them too much, but in the VR training the same bars could simply be slid out of the way. One of these bars can be seen in Figure 9. This prompts an important question regarding the time required to prepare the VR training and what should be included, because as the complexity of the task increases more deviations from the planned path are possible.

4 Limitations and Future Work

This investigation was limited by a relatively small number of tests, as well as by limited diversity in the test group, since all the participants were employed in an office setting and most were graduate engineering students. In the future, the experiment will be expanded to include a demographic that is more aligned with that for whom the VR training technology is to be developed.

Future testing will also be expanded to include more possible deviations from the expected scenario to increase how realistic the VR experience is for the users. Tool orientation, pressure, and level of looseness or tightness that should be accomplished in the disassembly and assembly of the prototype were also issues for the participants. There are several possible solutions to this that could be investigated, including animations of the tools when the right location is selected in the VR environment, or VR options that produce haptic feedback and allow for better tool orientation in the environment.

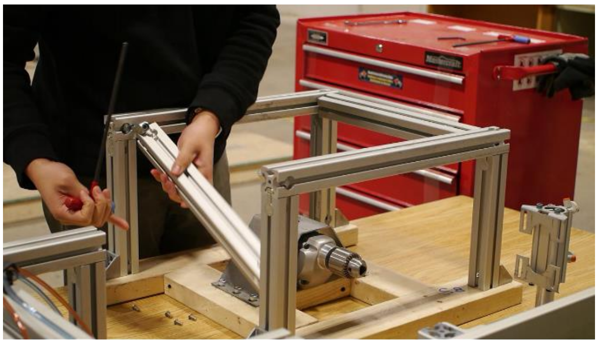

Figure 9. An example of one deviation from the VR script that occurred in the test

5 Conclusion

As mentioned, this experiment was done to validate the experimental design for a larger evaluation of the effectiveness of VR training on construction manufacturing and maintenance tasks, which will be continued in the future. This test will be repeated with a more applicable and diverse demographic and the task will be modified based on the results of this test. The complexity of the task will be adjusted and the ability for users of the VR to view the proper tool orientation and use will be added.

Since in this test, while the number of participants was limited, the VR users were on average slower and less successful at completing the task, it can be concluded that adding more technology to the training method may not always be necessary; however, more testing needs to be done to determine if, with an increasing task complexity and length, the VR training method may become more effective than traditional training methods.

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