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Experiences And Learning Outcomes Of Using Virtual Reality In Building Services Engineering Education

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ABSTRACT

Virtual Reality (VR) is a promising learning environment in vocational and higher education as it enables learning by doing. We developed a digital twin (DT) for learning the most common maintenance procedures of an air-to-water heat pump using game engine technology, targeted for students and professionals in the building services engineering industry. 22 HVAC (heating, ventilation and air conditioning) students participated in a user study to evaluate their experience with the DT, their usage preferences, and learning outcomes. Results of an online post-test questionnaire show that participants found the use of the DT easy and useful for learning maintenance procedures, regardless of their previous experience with VR devices or video gaming. More than half of the participants reported preferring to use the DT before practicing with the physical device. Learning outcomes measured with eight questions indicate that most of the students learned the tasks and safety issues correctly and in correct order (72-95% answered correctly). However, the questions measuring the learning related to adjusting the pressure was challenging for almost all students. The functional and task correspondence as well as the visual similarity of the digital twin to the real-world context is important for learning outcomes. The reported perceived usefulness by students for using VR in learning the maintenance procedures was related to realism of working with the digital twin, illustrating the maintenance procedures and tasks, as well as safety issues in the learning phase. The transfer of learning to real maintenance situations could be tested on the physical device.

1 INTRODUCTION

1.1 Background

Virtual reality (VR) systems are gaining increasing interest in training of maintenance and service tasks. In vocational training and in life long learning, experiential learning (Kolb and Kolb, 2005) is a commonly used educational approach in training of maintenance workers (Borsci et al. 2016). The goal of utilizing virtual reality in maintenance training is to achieve an immersive, realistic experience (ibid.). Students can perform tasks and various procedures in virtual, simulated environments that include virtualized physical equipment and systems (ibid.). These virtual counterparts of real equipment are called Digital Twins (Grieves and Vickers, 2017; Jones et al. 2021; Semeraro et al., 2021).

One of the mentioned advantages of using virtual reality in maintenance training is the efficient transfer of knowledge to the real environment (Guo et al., 2020). Also improvement of maintenance personnel safety is highlighted, as VR enables the learning of maintenance procedures and processes before conducting them on site (ibid.). The use of virtual reality in the training, practice, and certification testing of complex and dangerous maintenance procedures, such as high-voltage power line maintenance, has been shown to be a cost-effective tool for training new employees (Ayala García et al., 2016). The number of practice sessions in virtual reality can also be greater than in the real world, and learning procedural skills, which often involve sequential steps as in maintenance procedures, can be effective when implemented in virtual reality (Bailey et al. 2017).

However, the results on transfer of learning may not be similar in all training contexts. In the meta-analysis of XR (extended reality) studies from multiple fields on transfer of training, Kaplan et al. (2021) found that extended XR was as effective as commonly accepted training methods. The most commonly mentioned value of XR is described to be training in circumstances, which are hard to access or dangerous, or where the cost of training may be too high in traditional environment (ibid., Vasarainen et al. 2021).

In recent studies, the effect of the information presentation format during the learning phase on personal workload and task performance has been examined. Shi et al. (2020a) compare the learning of operating instructions for performing pipeline maintenance in an industrial environment using four different methods. They compare two different 2D functional instructions to 3D and VR implementations. The 3D and VR implementation groups performed better on the task than groups who received either of 2D functional instructions, but experienced higher cognitive workload during the memorization phase. Borsci et al. (2016) found that training for car service maintenance with VR/MR resulted in a lower number of unsolved errors and training time compared to traditional training. In addition, the trainees' experienced VR/MR tools to increase the understanding of tasks and procedures.

1.2 Goals of the research

The goal of this research was to examine whether VR is useful as a learning environment in training maintenance tasks in vocational training from the point of students as well as learning outcomes. To this end, we evaluate in a user study the user experience, students' usage preferences, and learning outcomes of using a Digital Twin (DT) of an air-to-water heat pump (AWHP). With DT we here refer to a virtual representation of a real-life system, that uses a game engine to create a realistic high-quality representation of a system. The implemented enables to learn and carry out two of the most important and common tasks and procedures to maintain an AWHP.

There are a number of definitions for DTs (see e.g. Jones et al. 2021; Semeraro et al. 2021). The most typical parts of a DT are the 1) physical products in real-world, 2) their virtual counterparts in VR, and 3) their connections through data and information transfer (Grieves and Vickers 2017). In addition to being used in training of maintenance procedures, DTs can be used as part of more advanced maintenance strategies. Currently, predictive maintenance dominates, but in the future condition-based maintenance and in preventive maintenance are of interest (Errandonea et al. 2020). These advancements have also been taken into account in the competence goals of vocational training, where working in digital environments has been added as a learning goal (Paananen et al. 2023, 6-7). The development of the DT in this work aims to support these new competence goals to give experiences of new digital environments.

2 LEARNING OBJECTIVES AND IMPLEMENTATION OF THE DT

The digital twin of an AWHP was developed in collaboration with the heat pump manufacturer. The goal of creating the DT was to provide training and learning opportunities for common maintenance. The maintenance tasks selected for implementation were pressure adjustment and relief valve testing, cleaning of the strainer, and room cleaning, which were identified as the most common causes of maintenance downtime and were deemed maintainable not only by domain experts, but also by technically competent heat pump owners.

The DT was created using Unity game engine to model the outdoor water source heat pump images in a VR (virtual reality) environment. The game engine enables the creation of realistic 3D environments that can be designed to work with different VR headsets and controllers. Building the VR environment fully customized using Unity tools enabled the creation of an independent end product that can be easily adapted to different usage situations without the need for different licensing terms or fees associated with pre-made commercial VR learning solutions and platforms.

Unity is a popular platform for other VR implementations due to its ease of developing VR headset functionality and its cheap and well-documented platform (Checa and Bustillo. pp. 5509-5510, p. 5519, 2020). An interactive, but linear, process-oriented VR implementation was aimed for as realistic and reality-based interactive implementations have been found to be effective in virtual reality implementations compared to either passive and more affordable models without interactions (ibid., 2020). They are, however, more cost-effective compared to freely exploratory and interactive environments, which are more expensive and time-consuming to develop (ibid., p. 5519).

The use of the DT in a VR environment was designed to support a procedural learning experience that progresses step-by-step according to the maintenance procedure. The DT guides the user with text instructions at each step and explains what to do next. Progress from one step to another requires correct completion of the task steps in the correct order to unlock the next task.

3 METHODOLOGY

3.1 Procedure of the user study

The user study was conducted with HVAC (heating, ventilation and air conditioning) students. Testing was arranged during normal lessons based on voluntary participation. The students came to the test session to the classroom where the used system was set up and used the DT for learning the maintenance tasks. 1-2 researchers were present during the test. Participants were explained the test procedure, informed about the possibility to withdraw from the study at any time, and to inform the researchers immediately if feeling nauseous when using the DT. Researchers guided the participants on how to use the VR system prior to starting the use of DT. In case a participant had problems in progressing in the tasks during the test session, researchers helped the student by giving instructions. In the end of the test session, students answered an online post-test questionnaire with a computer.

3.2 System

The computer used in the test had an Intel Core i5-7500 processor, Intel UHD Graphics 620 and NVIDIA GeForce RTX 2080 TI graphics card, and 16 GB of memory. In the test situation, the VR headset used was the HTC VIVE Cosmos, along with its controllers. One Vive base station was used to track the movement of the controllers and the headset. The application being tested was the digital twin of the AWHP device. The pedagogical approach for learning the maintenance tasks and procedures utilized procedural learning approach.

Figure 1. Test session setup in classroom

3.3 Participants

22 HVAC students participated the user study. All of the participants were men (age m = 16, min 15, max 21). 77% of the participants were first year students, 18% second year students, and the rest (5%) third year students. Participation to testing and answering the questionnaire was voluntary.

Most of the participants (86%) had no prior experience of AWHP maintenance. The rest had some prior experience. 41% of the particpants had no prior experience of using VR systems and 41% had little prior experience. Most of the participants (91%) had at least some experience in video games (computer, gaming consol or mobile games).

3.4 Post-test questionnaire on user experience, usage preference and assessing learning outcomes

The online questionnaire was created using Microsoft Forms. The questionnaire aimed to gather students' experiences using the digital twin for learning maintenance procedures, as well as their preferences for using digital twins in education. Additionally, the questionnaire measured learning outcomes by asking questions related to the maintenance tasks and procedures they practiced with the DT. At the end of the questionnaire, three open-ended questions were asked to gather further development ideas and students' perception of the usefulness of the DT.

Seven questions gathered information on the participants' background, including prior experience on digital gaming and using VR applications as well as on prior experience on AWHP maintenance. User experience was assessed with three statements on a five-point scale (see Table 1). Three questions covered 1) student's concentration during learning of maintenance procedures on the VR device or AWHP (immersion supported by ease of use, adapted from Gavish et al., 2015), 2) ease of use of the digital twin (adapted from Gavish et al. 2015 Tepsa et al. 2022,), and 3) usefulness of the digital twin in learning (Tepsa et al. 2022). Furthermore, preference was asked for learning and practicing maintenance procedures for the AWHP using the DT or the physical device (Table 2).

Learning outcomes were assessed with seven questions covering the tasks and procedures practiced with the implemented DT (Table 3). Multiple-choice questions allowed for selecting multiple answers. For six questions there was only one correct answer. For the question 7, "What do you check in AWHP pressure adjustment?", there were two possible correct answers. All multiple-choice questions also had an option "I don't know".

The eighth question to assess the learning outcomes by using the DT was measured by asking to organize the maintenance procedures in correct order. The question on the correct order of the maintenance tasks had multiple correct orders of tasks, as in real life. Only orders that posed a safety risk - such as disconnecting the mudfilter before turning off the water supply, which would cause water damage - or were logically impossible were considered incorrect when checking the results. For example, pressure cannot be increased without opening the indoor unit front panel. Another example of a hazardous situation would be not closing the valve leading to the outdoor unit before removing the mud filter, as this would cause water to rush out and cause water damage. Also, leaving the valve open after cleaning the mud filter is considered a mistake because the equipment will not function properly. Leaving the main power on before maintenance work was also considered an error, as this could cause a hazardous situation, as well as leaving the main power off after maintenance. An example of a logical error is that it would be impossible to check the pressure adjustment of the internal unit if the front panel had not been opened before the maintenance tasks.

4 RESULTS

4.1 User experience and usage preference

The user experience was measured using four questions. The questions, scales, mean, and standard deviation of answers to three first questions are reported in Table 1.

Table 1. User experience of the Digital Twin

Item	Question	Scale	mean	std
1	Did you focus more on using the VR system or learning the maintenance tasks of AWHP? (N = 22)	1 = Mainly on using the VR system 3 = Equally to using the VR system and learning the maintenance of the AWHP 5 = Mainly on learning the maintenance tasks	3.7	1.20
2	How easy it was to use the digital twin? (N = 22)	1 = Extremely difficult 5 = Exremely easy	4.4	0.60
3	How useful did you find the use of the digital twin in learning the maintenance tasks? (N = 21)	1 = Not useful at all 5 = Extremely useful	4.1	0.65

Most participants reported focusing more on learning the maintenance procedures of the AWHP than using the VR device (Table 1). However, some participants reported that they focused more on the VR device than on learning the maintenance procedures with the DT. About one-third of the participants reported focusing equally on using the VR device and practicing the AWHP maintenance procedures. Focusing more on the VR device usage than on the content and learning is unpreferable. This could be reduced by either including in the test procedure or the VR implementation a learning phase for usage of the devices and controls prior to the learning phase of the maintenance procedures.

The use of the digital twin was perceived easy by most participants (95%), and none found it difficult to use. Most participants (86%) also found the use of the digital twin useful in learning the AWHP maintenance procedures. We also investigated by cross-tabulating whether there is a correlation between prior video game experience or prior experience using VR devices and the perception of usefulness and ease of use. Neither prior video game experience nor prior experience of using VR devices had significant effect on the perceived usefulness and ease of use.

Additionally, participants were asked about their preference for using the digital twin or the physical device in practicing the AWHP maintenance procedures (Table 2). More than half (59%) of the participants preferred using the digital twin first for learning and then continuing the learning with the physical device. 14% of participants would only use the digital twin in learning the maintenance tasks, while 18% of the participants would prefer to use only the physical device in learning.

Table 2. Preference of DT or physical device in learning and practicing

Preference	% of answers
First digital twin and then physical device	59%
Digital twin	14%
Physical device	18%
I don’t know	9%

4.2 Assessment of learning outcomes

Table 3 summarizes the learning outcomes measured with the multiple choice questions. Learning outcomes are at least somewhat satisfactory for 5/7 questions, varying from 72% to 95% correct answers.

Table 3. Learning outcomes based on multiple choice questions

Item	Question	Correct answer	I don’t know
5	What do you do before carrying out the maintenance tasks?	73%	5%
6	How do you adjust the pressure of an AWHP on the physical device?	14%	73%
7	What do you check when adjusting the AWHP pressure?	9%	
8	What do you do before removing the mud filter**?**	82%	5%
9	What do you do to the mud filter after removing it?	95%	5%
10	Why is it important to keep the space around the AWHP clean?	77%	5%
11	What do you do after succesfully completing the AWHP maintenance?	72%	14%

However, the two questions (6 and 7, see Table 3) related to pressure adjustment were difficult for the participants.The reason for confusion can be that the digital twin had two separate extra buttons for adjusting the pressure and the color of these extra buttons was not consistent with the color of the real buttons (see Figure 1). Therefore the implementation of the DT was different from the physical model in this respect. Reason for this difference was that the buttons were in a tight space inside the heat pump model, close to each other. With the used VR controllers, such situations cause difficulties in control because the controller selects the adjustable object based on the hand position. In future implementations, in case similar controllers are used in interaction, the color coding of these buttons to adjust the pressure should follow the colors in the actual device or strong zooming into the actual buttons should be enbled to remove the need for separate buttons. The learning outcome in this task shows that such interface design solutions have a significant impact on the transfer of learning to the real world. In design of DTs, it is essential to ensure that the student's mental model corresponds to the actual implementation of the physical device.

Figure 2. Implementation of the UI for pressure control

In the question asking for ordering of maintenance tasks, 73% of participants ordered the maintenance tasks in the right order. 14% of participants made one error, either logical or causing a hazardous situation, but otherwise ordering the tasks correctly. 9% of participants ordered some of the tasks in correct order. One participant ordered the tasks randomly.

4.3 Perceptions on usefulness

An open-ended question about the usefulness of the digital twin was included for collecting qualitative feedback from the participants. The responses were thematically analyzed. Three themes related to perceived usefulness were identified: realism, illustration, and work safety (see Table 3).

Table 4. Emerging themes in answers related to the usefulness of learning in VR

Categories of themes	Examples of coded descriptions	Frequency of mentions
Realism	A situation corresponding to a real maintenance situation A sense of agency in performing maintenance	5
Illustration	Illustrates the sequence of maintenance operations Illustrates the functionality of the system	4
Work safety	Shows where there are safety risks Provides an opportunity to practice operating procedures without safety risk	2

The most often mentioned theme related to usefulness was realism. Respondents mentioned similarities between learning with a digital twin and a physical device. In addition, maintaining the DT was felt to be similar to maintainance of the physical system. One of the participants described the experience as "able to practice like in real life". The second most often mentioned theme was illustration. Respondents described the DT as illustrating the system quite realistically and illustrating the maintenance work beforehand. Practicing the maintenance with DT was described to help both in understanding the system's operating principle as well as in understanding the maintenance procedure sequence and its precise execution. Work safety emerged as the third theme raised by the respondents. DT was mentioned to help in identifying and learning about work safety risks. One participant highlighted the feeling of safety for the student in the learning situation: "you can practice system maintenance without any physical harm."

5 SUMMARY

In this study we examined the user experience and learning outcomes of using a digital twin (DT) for learning the two most important maintenance tasks of an air-to-water heat pump. The participants assessed the DT easy to use and useful for learning. Over half of them preferred first using DT and then the real system for learning the maintenance tasks. The amount of prior experience of video gaming or using VR solutions did not have a significant effect on the perceived ease of use and usefulness of the DT. Realism of performing the maintenance, illustration of the functionality and maintenance operations, as well as safe operation in learning phase and learning about safety risks were mentioned by participants to contribute to the perceived usefulness. Learning outcomes were measured with a post-test online questionnaire. Learning was on satisfactory level, except for a task where the physical device and the implemented DT were not consistent with each other due to interaction related challenges. This highlights the importance of realism of the digital counterpart compared with the physical system. To measure the transfer of learning to real world from training with a DT, instead of the online questionnaire a test on a real device could be conducted to test the learning of the maintenance procedures.

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