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AN IMMERSIVE VIRTUAL LEARNING ENVIRONMENT FOR WORKER-ROBOT COLLABORATION ON CONSTRUCTION SITES

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ABSTRACT

This paper presents a Virtual Learning Environment (VLE) that simulates the collaboration between a construction robot and a construction worker in order to support training in worker-robot teamwork on construction sites. The VLE presented in the paper utilizes a semi-autonomous remote-controlled demolition robot named Brokk. This paper describes the use-case robot (Brokk), system setup and configuration, and the learning scenarios. In this VLE, the trainee learns about the robot's various components, safety management, functions of the robot's control box, and general guidelines used during common demolition tasks. Importantly, this VLE is developed based on adult learning theories in general—and andragogy principles in particular. In addition, we augment the VLE with useful features from existing VLEs. The effectiveness of the developed VLE will be evaluated with construction workers based on knowledge and performance assessments.

1 INTRODUCTION

The construction industry is one of the largest industries in the world economy, accounting for 13% of the world's GDP. However, the industry is challenged by low productivity rates, safety concerns, and labor shortages. In fact, the construction industry has not kept pace in terms of productivity rates (6% increase) compared to other industries such as the manufacturing (760% increase) and the agriculture (1510% increase) (McKinsey 2017). Furthermore, the North American construction industry accounts for 19.2% of total occupational fatalities (BLS 2018). This backdrop provides the context for pushing change in the construction industry. According to the McKinsey Global Institute's report, the construction industry has a tremendous opportunity to overcome the challenges by infusing technology and innovation (McKinsey 2017). Examples include: ground robots such as bricklaying robots which can build by placing materials together based on a construction map; aerial robots such as Unmanned Aerial Vehicles (UAVs), which can also place bricks to a specific location using external localization systems (Ardiny et al. 2015). Thus, construction workers will have to reskill and upskill to interact effectively with new technologies. With the advancement of construction automation, new technology-enhanced learning environments can be developed and implemented to support workers' reskilling and upskilling.

Existing learning and training programs in the construction industry mainly consist of lecture-based trainings, on-job trainings, and apprenticeships (Moon et al. 2018). Many of the lecture-based trainings are

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based on the implicit assumption that knowledge is transmittable. Thus, in a typical training, information on how to complete the tasks is delivered to the construction workers; subsequent to this, workers are expected to perform the task in situ based on the information conveyed to them. There are however drawbacks to such training approaches, especially as it relates to the ineffectiveness in enhancing learners' conceptual understanding and their ability to use their skills flexibly in unfamiliar situations. Further, essential work trainings changes from one construction project to another (Teizer et al. 2013). Moreover, on-the-job trainings provide the worker the opportunity to practice the tasks using the real construction equipment; however, these training are often hazardous, time intensive, and expensive (because of the operation and maintenance costs of specialized equipment and the need for employing experienced supervisors and assessors) to implement widely. Besides, the trainee needs considerable practice with the equipment to learn how to operate it efficiently and safely (Wang et al. 2007).

To address these issues, Virtual Learning Environments (VLEs) have been offered as an alternative to these traditional learning programs. VLEs have demonstrated their value as they are a much more flexible (and impose less risks) alternative to most forms of on-the-job training. Although several VLEs have been developed for construction training, most have narrowly focused on safety training; only a few VLEs touch upon aspects of robot-worker collaboration. In this paper, we propose a novel VLE using a demolition robot named Brokk. For the purpose of this paper, a robot is defined as a programable or reprogrammable machine with varying degrees of automation (International Federation of Robotics 2014). Consistent with this definition, Brokk is considered a robot since its power management software controls the system automatically and sets the motor speed to accommodate workplace conditions. Moreover, the Brokk's software provides a precise positioning of the arm systems based on the demolition type.

The median age of the labor force in the North American construction industry is 42.6 years (BLS 2019). As such, learning programs geared towards construction workers ought to be based on adult education principles. The need to pay attention to learning theories is consistent with the increased interest in training workers for future skills needs. The basis of adult learning theories is that adults have different characteristics and learn differently from younger learners. Accordingly, our proposed VLE is designed based on andragogy learning principles. Andragogy, one of the concepts of adult learning theory proposed by Malcolm Knowles, is characterized as "a new label and a new technology" (Merriam 2001). Against this backdrop, we aim to offer a VLE which is undergirded by important elements of effective adult learning. Along with basing our work in theories of adult learning, we also draw from and build upon previous VLEs to incorporate characteristics considered useful in previous VLEs (for a review, see Moon et al. 2018).

The rest of the paper is organized as follows: In section 2, objectives and research questions of the paper are introduced. In section 3, a review of adult learning theories, along with related works on VLEs developed in the construction industry and robot-included VLEs in other industries are presented. Section 4 provides an overview of the system setup and the virtual environment and the learning scenarios developed for training. Section 5 discusses how the training scenarios adhere to the assumptions of andragogy principles. Further we explicate how this training overcomes the limitations and incorporates useful features of existing VLEs. By way of conclusion, in Section 6 we summarize the design and development of the VLE. Further, we bookend the conclusion by highlighting our plans for future evaluation studies with the VLE.

2 OBJECTIVES AND RESEARCH QUESTIONS

The objective of this paper is to design a novel robot-included Virtual Learning Environment (VLE) for human-robot collaboration on construction sites. This VLE is designed to understand the impact of cyberlearning program on construction workers' knowledge gain and knowledge transfer, trust in automation, and safety behaviors during human-robot collaboration in comparison to the traditional methods. Since the construction workers are included in the adult learner category, the design and development of a VLE should consider adult learning theories. At the same time, such efforts should also adapt the useful features of existing VLEs to improve the training's effectiveness. Specific research questions for this study are as follows:

- How can the VLE adapt andragogy and self-directed learning approach in the development of the learning scenario?
- How can a novel VLE adapt the useful characteristics examined in the existing robot-included VLEs?

3 CONCEPTUAL FOUNDAITONS

3.1 Adult Learning Theories

Pedagogy is defined by Knowles (1980) as the “art and science of helping children learn”. In contrast, Andragogy is a theory of adult learning proposed by Knowles (1968), based on five assumptions. In this area, researchers have tried to recognize adult learners' characteristics and attributes in the development of learning programs. The five assumptions of andragogy are as follow (Merriam 2001):

1. An adult has an independent self-concept who can direct his or her learning.
2. An adult has a reservoir of life experiences, which can be a rich resource for learning.
3. An adult has learning needs closely related to changing social roles.
4. An adult is problem-centered and interested in the immediate application of knowledge.
5. An adult is motivated to learn by internal rather than external forces.

One of the limitations of existing VLEs in the construction industry is that they do not incorporate learning theories in the design and development of learning and training programs. Most VLE’s have been developed to reproduce the same real-world experience to provide the opportunity to practice the same skills in a VLE without accounting for how learners learn. Indeed, the literature identifies problems with this way of learning as learning extends beyond executing routine tasks or gaining implicit knowledge. A body of literature supports the notion that learning requires adapting knowledge and skills in unexpected situations, formulating solutions, obtaining and evaluating information, and defining problems (NLS 2013). In this regard, principles and assumptions of adult learning theories need to be implemented in the novel learning program. Importantly, according to these theories, adults learn differently from younger learners. Thus, traditional programs such as lecture-based and text-oriented training methods may not align with their learning needs (Knowles 1980).

Although there is some debate about the definitions of andragogy and pedagogy, andragogy continues to serve as the base for learning programs developed for adult learners (Henschke 2015). One of the ongoing concerns relates to the extent to which andragogy's assumptions can be applied to adults. As an example, some adults may not prefer learning mapped along self-directed learning approach (andragogy); rather, they may have a preference for teacher-directed learning approach (pedagogy). Knowles addressed this issue by proposing a continuum ranging from pedagogy to andragogy (Merriam 2001). Therefore, while a VLE may be driven by principles and assumptions of andragogy, it may not be completely based on the pedagogy or andragogy principles.

3.2 Existing Virtual Learning Environments

Several VLEs have been developed in the construction industry; yet, most of them have focused exclusively on safety training. Moreover, several VLEs for robot incorporated work sites are designed for various industries, including mining, manufacturing, shipbuilding, and healthcare. A novel VLE should consider limitations and useful characteristics of existing VLEs. The prototypical VLE includes features such as: visualization tools and controllers, navigation methods, learning scenarios, and virtual environments simulated in training programs.

3.2.1 Visualization Tools and Controllers

One of the main features of existing VLEs is the medium through which users can visualize the simulated environment. Many of the initial VLEs have used PC monitors to visualize the environment and keyboard and mouse as the user interface (Goedert et al. 2011; Rezazadeh et al. 2011; Zhao et al. 2009). However, monitors do not provide immersive learning experiences. Others have used a power-wall as the visualization method in order to provide immersive and realistic experiences. However, power-walls only allow a third-person view to the trainee (Li et al. 2012; Sacks et al. 2013; Zhao et al. 2015). Recent VLEs have used Head-Mounted Displays (HMDs) as the visualization tool (Jeelani et al. 2020). HMDs are capable of offering both first-person and third-person views, which can provide a sense of presence in the simulated environment; however, only a few researchers have utilized both first- and third-person views in their VLEs (Goedert et al. 2011). When the trainees experience both views in training, they can be more aware of their interactions with other workers and/or machines.

3.2.2 Navigation Methods

Many robot-incorporated VLEs require the trainee to be stationary during the training (Altenhoff et al. 2012; Bredl et al. 2015; Watanuki et al. 2008). Usually handheld controllers are used to navigate in the VLE, which can inhibit the natural interaction between humans and the robot. Other VLEs allow the trainee to walk around in the environment; however, the walking boundaries are often limited (Chan et al. 2011; Grabowski et al. 2015; Smith et al. 2009). Therefore, a controller-free navigation method should be considered in the VLE in order to allow trainees to freely operate the robot.

3.2.3 Learning Scenarios

Many researchers in the construction industry have proposed VLEs in the format of tutorial-like games which provide pre-determined sequences of conditions (Fang et al. 2014; Goulding et al. 2012; Luo et al. 2016). These learning scenarios lack interactivity since the trainee has no opportunities for collaborative interactions with other workers and equipment. However, some of the robot-included VLEs in other industries have developed interactive learning scenarios that promote "learning while doing" (Le et al. 2015; Van Wyk et al. 2009). This is one of the useful features that should be appropriated for the design of a novel robot-included VLE for the construction industry.

3.2.4 Virtual Environments

The majority of existing VLEs have not incorporated other virtual workers in the simulated environment; thus, limiting the trainees' interactions to the robot (Gregor et al. 2015; Giorgio et al. 2017; Lucas et al. 2007; Orr et al. 2009). Since construction sites are dynamic spaces within which multiple forms of interactions occur between multiple workers, the proposed VLE should simulate other construction workers in the VLE. Besides, many of the existing VLEs are confined to and simulate indoor VLE without attending to outdoor operating environments (Landorf et al. 2017; Pérez et al. 2019). Crucially, since construction sites are mostly outdoors, a robot-included VLE should provide realistic elements and conditions common to a construction site, including uneven surfaces, dust, realistic shadows, and various weather conditions.

To summarize, many researchers have studied the application of VR in various industry-based trainings. However, there is a lack of robot-incorporated VLEs in the construction industry. What's more, most of the construction-related VLEs have focused on the safety training. Furthermore, many of the recent VLEs require the use of a handheld controller as the navigation tool while the user is stationary. Existing VLEs providing both first- and third-person views are far and few between. Many VLEs have used tutorial-like games format, failing to provide interactive learning scenarios. Most of the VLEs have followed traditional sequences for the learning material without offering opportunities for learning by doing. In addition, many of the existing VLEs are cast in indoor environments without simulating more common construction scenarios—outdoor operating scenarios.

4 METHODOLOGY

In this section, the tools, models, and learning scenarios are discussed. In section 4.1, the robot used in this VLE is introduced. Then, the system setup and configuration, such as the game engine, the VR equipment, navigation systems, and user tracking tools are presented in detail. In section 4.4, learning scenarios and assessments, which are designed based on the principles of adult learning theories and useful characteristics of existing VLEs are described.

4.1 Use-case

The robot used in this VR-based training is a demolition robot named Brokk. A demolition robot was selected based on the industry adoption trends, level of technology development, frequency of use in construction projects, and potential impact on construction productivity and safety. Brokk has been used in many different industries, including but not limited to construction, tunneling, mining, metal processing, cement, security and rescue, and nuclear. Demolition robots have provided critical services in extremely dangerous situations such as the clearing of Ground Zero after 9/11 and assisted in containing the Fukushima nuclear disaster in March 2011. Brokk has been used for various demolition tasks from the destruction of a concrete building to the delicate tasks of building renovation. Due to its size, the robot can be operated in confined spaces where other construction equipment cannot go. While the robot comes in different models and shapes, the most frequently used models in the construction industry include Brokk 110, Brokk 170, and Brokk 200. In this research, we use Brokk 110, which has a 19.5 kW Brokk Smart Power electrical system and has a 360-degree working radius (Brokk 2020). Brokk, similar to other construction robots, is a non-social machine-like robot. Since the worker operates the robot remotely, the type of human-robot interaction is non-physical. The communication method between the worker and the robot is digital code-based through the control box. The automation level is semi-autonomous given the fact that a human operates the robot using a control box. The VR simulation, developed to simulate human-robot collaboration in various demolition tasks, includes seven modules to learn how to collaborate with this robot efficiently and safely.

4.2 System Setup and Configuration

The VLE is developed using the Unity 3D game engine framework, which can run on a typical PC with Windows operating system (Figure 1). Unity 3D game engine allows the integration of different components, including 3D models of construction sites, 3D model of the robot, and virtual avatar of the trainee and other construction workers. The system consists of the VR training on a PC, which runs Windows 10, with an NVIDIA GeForce GTX 1080 graphics card. The HTC Cosmos Elite Head Mounted Display (HMD) is the visualization platform for the Virtual Environment (VE). The HMD and a headphone connected to it provide a first-person view and sound effects to the trainee. Furthermore, the trainee uses a VIVE Cosmos controller and the control box of the robot during the modules as the user-interaction tool. The control box is programmed using the Arduino DIY. The serial communication is used to provide data communication between the control box and the VR-based training program. Although the control box's software is different from the real one, the physical shape is the same as the Brokk's original control box. The HMD is integrated with a VR treadmill using an application programming interface (API) to provide the navigation system. Virtuix Omni is used as the VR treadmill, designed to allow participants to walk within the VLE (Figure 2). The treadmill has a bowl-shaped surface that requires the user to wear low friction shoes for movement. The simulator can track the trainee's position, speed, and length of stride using inertial sensors.

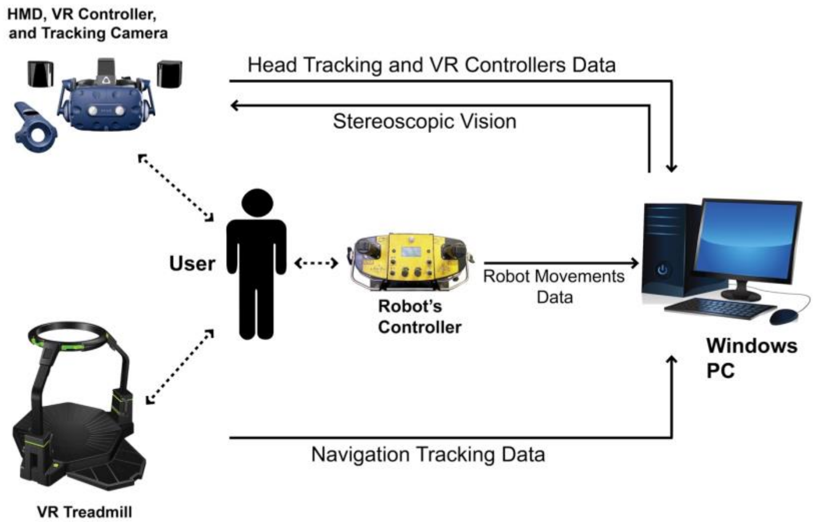

Figure 1: System setup

Figure 2: VR treadmill

4.3 The Virtual Environment

The displayed virtual environment simulates a construction site of a four-floor building. The construction site is modeled in Revit software and exported to a ".fbx" file format for increased compatibility with Unity 3D. Every component of the 3D model is presented as a GameObject in the Hierarchy window of Unity 3D. The properties of each GameObject can be adjusted in the inspector window. Textures and materials are added to the GameObjects to make the environment realistic. Moreover, a set of construction equipment is added to the scene from the Unity Asset Store. The 3D models of the Vive controller and the user's avatar are added by using SteamVR Plugin, imported from the asset store. Then, a canvas and a text box are created as the child of the controller GameObject. The learning information is provided to the trainee through the text boxes. A box collider is attached to each GameObject in the VE. Unity game engine uses this collider to simulate the physical collision between objects in the real world. The collider for the worker's avatar is also used for event triggering during the learning scenarios. In addition to the colliders, the Rigidbody component is attached to the GameObjects to react to real-time physics. Unity 3D simulates the reactions to forces and gravity, mass, drag, and momentum by using the Rigidbody component. The 3D model of the Brokk is designed in 3D Max and imported as a ".fbx" file to Unity 3D. Three types of joints, fixed joints, hinge joints, and configurable joints, are added to the robot's arms to model its movement. Since a construction site consists of workers executing different tasks, virtual workers are added to the environment to simulate a real construction project. Destructible objects are modeled in Rhino 3D to allow the simulation of demolition tasks in the VLE. By applying a specific amount of force to those GameObjects and event triggering feature of the colliders, the GameObjects can get demolished gradually. Furthermore, the VLE includes sounds of both a construction site and of the robot; these sounds enhance the sense of presence (Lu and Davis 2016).

4.4 Learning Scenarios

The developed VLE consists of seven learning modules. As recommended by Radianti et al. (2020), the learning materials are displayed in a text box attached to the controller GameObject in all the modules. In case the trainee is not able to read the text, the trainee can listen to the narration by using the Vive controller. At the end of each learning module, the trainee is evaluated by means of some tasks in the VLE. Following which, the trainer gives feedback based on the trainees' performance. We now discuss each of the seven learning modules.

In the first module, basic information about the robot is presented. The trainee starts the scenario in a construction site and can see the robot in front of him/her. The learning materials are displayed on the board (Radianti et al. 2020). First, the purpose and applications of the robot are introduced. Then, the trainee learns about the different components of the robot. Various components are highlighted, and animations illustrate the range of movement for each component. As mentioned in section 4.1., Brokk has various models, so the differences and commonalities between them are summarized for the trainee. After these steps, multiple boxes appear under the board, each representing the names of the robot's components (Figure 3). If the trainee points to these boxes, each component's detailed information will be presented on the board along with the animation of the highlighted elements. The trainee has the freedom to walk around the robot, examine different parts of the robot, and watch the movements and detailed information to get familiar with the robot. At the end of the module, for assessment, the trainee is tasked with answering questions about the components by pointing the controller to the components mentioned in the question. By using the ray-casting and event-triggering features, the trainee is provided feedback automatically.

In the second module, the trainee learns how to safely operate the robot. First, information about how to safely power the robot is presented. Then, the trainee learns power cable management, that is, the cable: should not be on a wet surface or sharp objects; should be behind the robot; and should not be close to the outriggers. In the learning scenario, the cable is initially in a dangerous position. However, with the guidance of the VR-based training program, the trainee learns how to move it step by step to a safe position by picking up the cable and positioning it via the controller. Thus, the trainee learns power cable management by doing, which is one of the crucial principles of adult learning theories. In the next section, the trainee learns about safe operator positioning. As illustrated in Figure 4, trainees are exposed to the concept of the danger zone around the robot. The boundary of this zone depends on a number of factors, such as the height of the robot's arm. These boundary conditions are introduced to the trainee through the use of Unity 3D's animation feature. If the trainee enters the danger zone, the screen turns red and trainees are signaled to exit the zone. In addition, a virtual worker enters the danger zone during the learning scenario, in order to illustrate the consequences of violating the danger zone boundary. Since a box-collider component is attached to the user's avatar, if the trainee walks to the danger zone, he/she will be hit by the robot's arm. Considering the fact that many demolition scenarios require positioning the robot on an inclined surface, the robot operator should be cognizant of threshold for safely positioning the robot (30 degrees limit for the safe operation on inclined surfaces). This is illustrated via a contrast between two types of ramps, one with a slope lower than the safe limit and the other with a slope higher than the safe limit. The trainee will see that the robot topples on the ramp with the steeper slope allowing him/her to learn about the 30 degrees limit for the safe operation on inclined surfaces. In the last section of this module, the trainee learns the most critical points about workplace inspection; for instance, whether or not the robot can be maneuvered to fit in the workplace, and assess other workplace conditions such as overhead (ceiling) and the lighting condition. For the assessment section of this module, two key areas are targeted: (1) positioning the cable in a safe condition and (2) knowledge of safety issues for operation.

Figure 3: Module 1 (Robot Introduction)

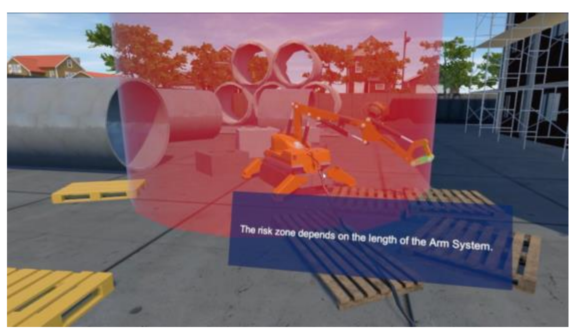

Figure 4: Module 2 (Safety Management)

In the third learning module, the trainee learns how to use the control box to operate the robot. This module is not in an immersive virtual environment since the user needs to see the control box. After getting familiar with the control box, the trainee wears the HMD in the next learning modules without needing to see the controller. The trainee learns how to start the control box and perform the functions of each button step by step. The trainee is able to use the control box to move the robot in a VE presented on screen. In the assessment section of this module, the trainee is assessed on their ability to use the control box to perform various operations with the robot.

In the fourth module, the trainee learns how to start the robot using the controller box using a pre-startup checklist. Before starting the robot, some key steps need to be followed: check the hydraulic oil level, ensure that there is no oil leakage, and inspect for loose objects on the robot. Also, the emergency stop button of the control box should be checked. In this module's assessment, the trainee is asked to execute the pre-startup checklist and mention the issues that must be addressed.

In the fifth module, the operating positioning of the robot is introduced. It is essential to correctly position the robot in order to facilitate the demolition and prevent unnecessary damage to the machine. The demolition robot should not be too close to the work object, the distance between the robot and other objects in the demolition site must also be considered. Moreover, the robot's arms should not be fully extended. Besides, the angles between the arms should be within an acceptable limit. The trainee moves the robot to the safe operating condition with the guidance of the VR-based learning program. In the assessment part of this module, the trainee is tasked with positioning the robot in a safe operating condition.

In the sixth module, trainees are provided opportunities to learn how to move the robot. Now that the trainee has learned the functions of the control box, the trainee practices moving the robot and its different parts via three activities. The first activity centers around using the robot to kick a soccer ball. A virtual soccer ball is given to the trainee, and he/she is asked to place the ball in a specified zone by using the robot (Figure 5). This exercise provides practice opportunities around different activities: moving the robot, using the outriggers to position and stabilize the robot, and moving the arm system to kick the ball. In the next activity, the trainee is asked to move the robot through a pipe. This task is designed to help the trainee learn how to navigate the robot through confined spaces. In the last activity of this module, the trainee is tasked with positioning the robot on an inclined surface. Since demolition scenarios frequently happen on sloping surfaces, the trainee needs to practice positioning the robot on these types of surfaces. Given the practice-oriented nature of this module, there is no corresponding assessment.

In the final module, the general recommendations about the demolition of concrete slabs, floors, free-standing walls, beams and columns are presented. The direction of the demolition tool and the demolition process is vital to learn. Not only is the demolition sequence important, but also the starting points of the demolition. These general recommendations are exhibited to the trainee by highlighting and animating the robot and the work objects. After the learning scenario, the trainee can practice demolishing objects using various strategies to experience the consequences of each approach (Figure 6). In the assessment of this module, the trainee is asked to demolish an object to evaluate the trainee's performance in following the expected rules.

Figure 5: Module 6 (Practicing Robot Movement)

Figure 6: Module 7 (Practicing Demolition)

5 DISCUSSION

5.1 Integrating Adult Learning Theories with the VLE

As mentioned in section 3.1, one of the limitations of existing VLEs in the construction industry is that they have not incorporated learning theories in design and development of their learning programs. As the construction workers are adults, principles and assumptions of andragogy need to be considered and implemented in our novel learning program. Andragogy, which refers to a theory of adult learning proposed by Knowles (1968), includes five guiding assumptions (Merriam 2001).

The first assumption is that an adult has an independent self-concept who can direct his or her learning. In this regard, the trainees can go back and forth at their own pace and direction in the learning scenarios. The trainee can either stop or repeat the learning procedure to redo the tasks. During the training, the trainee can learn by doing and experience the consequences of each decision. As an example, the trainee can move the robot and demolish a wall by implementing various strategies. If the trainee performs incorrect actions or fails, there will be no cost and damage to both the robot and the trainee. Hence, the trainee has the opportunity to experience the training through a self-directed approach.

The second assumption is that an adult has a reservoir of life experiences, which can be a rich resource for learning. This characteristic is infused in different modules of our VLE. A construction worker has a basic knowledge of power cables, interactions on construction sites, and the demolition procedure. Thus, by asking the trainee to manage the power cable based on the guidance provided, the trainee can also draw on previous experiences to augment learning. Further, based on the worker's interactions on construction sites, animating the accidents in the danger zone can stimulate the previous life experiences. These experiences lead to transfer the information from working memory to long-term memory. Dewey (1938) argues that "learning occurs when individuals connect the new experiences with the previous ones to create meaning". In this regard, since the construction worker has experience in demolition, the transforming of experience leads to meaningful learning.

The third assumption is that an adult has learning needs closely related to changing social roles. Our VLE ensures that the training is of close relevance to his/her job goals. Concerning the advancement of automation in the construction industry, workers need to acquire new skills to work with new technologies.

The fourth assumption is that an adult is problem-centered and interested in the immediate application of knowledge. As a person matures, the applications of learning become more problem-centered. Our VR-based training introduces skills that are immediately applicable in a demolition project. Hence, the trainee understands that the application of the learning material is immediate.

The fifth assumption is that an adult is motivated to learn by internal rather than external forces. Construction workers need to move up the career ladder. Hence, in line the fifth assumption, we embrace the notion that workers are motivated to gain new skills and knowledge in their field of expertise in order to adapt themselves to the advancement of the construction industry. Thus, by giving an introduction of the Brokk robot and its essential applications in the demolition area, we hope to pique construction workers interest in this area and help facilitate understanding of its relevance.

As mentioned in section 3.1, in recent years, there have been debates about Knowles' assumptions of Andragogy. One of the ongoing concerns relates to the extent to which andragogy's assumptions can be applied to adults. some adults may not prefer learning mapped along self-directed learning approach (andragogy); rather, they may have a preference for teacher-directed learning approach (pedagogy). To address this issue, Knowles proffered a continuum ranging from pedagogy to andragogy (Merriam 2001). With this consideration, at the end of each module, the trainer's feedback is provided to assist the trainees who lack some of the characteristics mentioned in andragogy.

5.2 Adapting useful features of previous VLEs

Limitations and useful features of existing VLEs have been considered in the design of our learning program. Moon et al. (2018) reviewed the robot-included VLEs in different industries and recommended adapting existing VLEs' useful features in the development of a novel VLE. In the case of visualization tools, the use of both first and third-person views have been recommended. In this regard, the trainee can use the third-person view while learning the control box's functions to move the robot. This view is useful for learning dynamic human-robot interaction. In other modules, the trainee has a first-person view using HMD to facilitate immersion.

Another recommendation is the implementation of a controller-free navigation system. To achieve this, the trainee can hide the learning texts and hang the VR controller from control box to work with the Brokk's control box. In addition, the VR treadmill has been used as the navigation tool; therefore, the trainee does not need to use the controller for navigation, which inhibits the natural interaction between humans and the robot.

In terms of designing learning scenarios, it has been recommended that scenarios should not consist of training in only pre-determined conditions. In this VLE, the trainee has the freedom to use the robot in different situations while employing different strategies in operation and observe the consequences of each decision in a realistic simulated environment. This feature promotes the concept of "learning while doing." Besides, virtual construction workers have been modeled to simulate the dynamic interactions that are common to a construction site.

Moreover, the construction sites' unique characteristics have been considered during the development of the VLE. The physical behavior of each object has been defined; thus, the trainee can get realistic feedback during the operation of the robot. While the construction projects mostly happen outdoors, the VLE needs to provide a realistic display condition. In the design of this VLE, elements common to a construction site, such as dust, uneven surfaces, realistic shadowing, and weather conditions are simulated to provide a realistic training environment.

Mueller and Strohmeier (2011) reviewed the system design elements of VLEs to define the characteristics of a successful VLE. Their key recommendation—further research should concentrate on providing fine- and medium-granular VLE design characteristics. Based on the level of development of this VLE, this qualifies as a medium-granular VLE. Regarding the range of validity, since adult learning theories (universal context) and useful features of existing VLEs (contingent on VLE) have been used in the development of this VLE, it cannot be categorized in only universal or only contingent validity group. However, contextual contingencies of the VLE feature have not been overlooked in the development of this VLE. As mentioned in section 4.4, future efforts include evaluation of the VLE with construction workers.

6 CONCLUSION

In this paper, we present a novel VLE that simulates the collaboration between a construction robot and a construction worker. The design and development of the VLE is driven by theories of adult learning theories. Moreover, we augment the VLE by extracting and incorporating useful features from existing VLEs. In addition to presenting the design and development of the VLE, we also provide coverage of the following: the system setup, including user tracking, visualization platform, and navigation system. Furthermore, we also discuss the interaction techniques used in the development of learning scenarios. In the next step of this research, we plan to evaluate the VLE in user studies. Moreover, we will be conducting comparative evaluations of traditional hands-on training and the VR-based training. We have developed assessments which will be administered to participants to measure the effectiveness of the two training approaches. We will measure learning by assessing participants' knowledge growth from pre- to post-test. To evaluate trainees' performance, a hands-on test will be used where participants will be tasked with completing various exercises using the Brokk. In addition, there will be a pre- post-training survey about trust in automation to measure the change of attitudes about automation and confidence in ability. The overarching goal of this project is to understand the impact of VLE on construction worker's knowledge gain and knowledge transfer, safety behaviors during the human-robot collaboration, and trust in automation compared to the traditional method.

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REFERENCES

Altenhoff, B. M., Sewall, A. S., Shannon, B., Duchowski, A. T.: Effects of haptic feedback and stereoscopy on a surgical training task in virtual reality (2012)

Ardiny, H., S. Witwicki and F. Mondada, "Construction automation with autonomous mobile robots: A review," 2015 3rd RSI International Conference on Robotics and Mechatronics (ICROM), Tehran, 2015, pp. 418-424, doi: 10.1109/ICRoM.2015.7367821.

Bredl, K., Groß, A., Hünniger, J., Fleischer, J.: The avatar as a knowledge worker? How immersive 3Dvirtual environments may foster knowledge acquisition. Lead. Issues Knowl. Manage. Volume Two 2, 222 (2015)

Brokk Inc. (Last accessed May 2020). https://www.brokk.com/us

Chan, J. C., Leung, H., Tang, J. K., Komura, T.: A virtual reality dance training system using motion capture technology. IEEE Transac. Learn. Tech. 4(2), 187–195 (2011)

Dewey, J. (1938). Experience and education. New York, NY: Touchstone.

Fang, Y., Teizer, J., Marks, E.: A framework for developing an as-built virtual environment to advance training of crane operators. In: Construction Research Congress 2014: Construction in a Global Network, pp. 31–40 (2014)

Goedert, J., Cho, Y., Subramaniam, M., Guo, H., Xiao, L.: A framework for virtual interactive construction education (VICE). Autom. Constr. 20(1), 76–87 (2011)

Giorgio, A., Romero, M., Onori, M., Wang, L.: Human-machine collaboration in virtual reality for adaptive production engineering. Procedia Manuf. 11, 1279–1287 (2017)

Goulding, J., Nadim, W., Petridis, P., Alshawi, M.: Construction industry offsite production: a virtual reality interactive training environment prototype. Adv. Eng. Inform. 26, 103–116 (2012)

Grabowski, A., Jankowski, J.: Virtual reality-based pilot training for underground coal miners. Saf. Sci. 72, 310–314 (2015)

Gregor, M., Polcar, J., Horejsi, P., Simon, M.: Factory virtual environment development for augmented and virtual reality, World Academy of Science, Engineering and Technology. International J. of Computer, Elec., Auto., Control and Info. Eng. 9, 2433–2437 (2015)

Henschke, John A. EdD, "FOCUSING ON THE SIX MAJOR THEMES IN THE GLOBAL PERSPECTIVE OF ANDRAGOGY: A JUNE 2015 UPDATE" (2015). IACE Hall of Fame Repository.

International Federation of Robotics (2014) World Robotics: Industrial Robots.

Jeelani, I., Han, K. and Albert, A. (2020), "Development of virtual reality and stereo panoramic environments for construction safety training", Engineering, Construction and Architectural Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/ECAM-07-2019 0391

Knowles, M.S., The modern practice of adult education. New York: Cambridge, The Adult Education Company (1980).

Landorf, C., Ward, S.: The learning impact of a 4-dimensional digital construction learning environment. Int. J. Soc. Behav. Educ. Econ. Bus. Ind. Eng. 11(5), 1158–1163 (2017)

Le, T., Pedro, A., Park, S.: A social virtual reality-based construction safety education system for experiential learning. J. Intell. Rob. Syst. 79, 487–506 (2015)

Lee, A., Yang, U., Son, W., Kim, Y., Jo, D., Kim, K., Choi, S.: Virtual reality content-based training for spray painting tasks in the shipbuilding industry. ETRI J. 32, 695–703 (2010)

Li, H., Chan, G., Skitmore, M.: Multiuser virtual safety training system for tower crane dismantlement. J. Comput. Civ. Eng. 26, 638–647 (2012)

Lucas, J., Thabet, W., Worlikar, P.: Using virtual reality (VR) to improve conveyor belt safety in surface mining. In: 24th W78 Conference Maribor 2007 & 5th ITCEDU Workshop & 14th EG-ICE Workshop: Bringing ITC knowledge to work, pp. 431–438 (2007)

Lu, X., Steven Davis, How sounds influence user safety decisions in a virtual construction simulator, Safety Science, Volume 86, 2016, Pages 184-194, ISSN 0925-7535, https://doi.org/10.1016/j.ssci.2016.02.018.

Luo, X., Wong, C.K., Chen, J.: A multi-player virtual reality-based education platform for construction safety. In: 16th International Conference on Computing in Civil and Building Engineering, pp. 1637–1643 (2016)

McKinsey Global Institute: A future that works automation, employment, and productivity, January 2017. McKinsey & Company (2017)

Merriam, S.B. (2001), Andragogy and Self-Directed Learning: Pillars of Adult Learning Theory. New Directions for Adult and Continuing Education, 2001: 3-14. doi:10.1002/ace.3

Moon S., Becerik-Gerber B., Soibelman L. (2019) Virtual Learning for Workers in Robot Deployed Construction Sites. In: Mutis I., Hartmann T. (eds) Advances in Informatics and Computing in Civil and Construction Engineering. Springer, Cham

Mueller, D., Stefan Strohmeier, Design characteristics of virtual learning environments: state of research, Computers & Education, Volume 57, Issue 4,2011,Pages 2505-2516,ISSN 0360-1315,https://doi.org/10.1016/j.compedu.2011.06.017.

N. Lead States, Next generation science standards: For states, by states (2013).

Orr, T. J., Mallet, L., Margolis, K. A.: Enhanced fire escape training for mine workers using virtual reality simulation. Min. Eng. 61,41(2009)

Pérez, L., Eduardo Diez, Rubén Usamentiaga, Daniel F. García, Industrial robot control and operator training using virtual reality interfaces, Computers in Industry, Volume 109, 2019, Pages 114-120,ISSN 0166-3615, https://doi.org/10.1016/j.compind.2019.05.001.

Radianti, J., T. Majchrzak, J. Fromm and I. Wohlgenannt, "A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda", Computers & Education, vol. 147, p. 103778, 2020. Rezazadeh, I.M., Wang, X., Firoozabadi, M., Golpayegani, M.R.H.: Using affective human machine interface to increase the operation performance in virtual construction crane training system: a novel approach. Auto. in Constr. 20(3), 289–298 (2011)

Sacks, R., Perlman, A., Barak, R.: Construction safety training using immersive virtual reality. Constr. Manage. Econ. 31,1005–1017(2013)

Smith, S., Ericson, E.: Using immersive game-based virtual reality to teach fire-safety skills to children. Virtual Reality 13(2), 87–99 (2009)

Teizer, J., T. Cheng, Y. Fang, Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity, Automation in Construction 35 (2013) 53–68. doi:10.1016/j.autcon.2013.03.004.

U. S. Bureau of Labor Statistics. Injuries, illnesses, and fatalities. (2018) Available at https://www.bls.gov/iif/.

U. S. Bureau of Labor Statistics. Demographics. (2019) Available at https://www.bls.gov/iif/.

Van Wyk, E., De Villiers, R.: Virtual reality training applications for the mining industry. In: Proceedings of the 6th International Conference on Computer Graphics, Virtual Reality, Visualization and Interaction in Africa, pp. 53–63. ACM (2009)

Wang, X., Dunston, P.S.: Design, strategies, and issues towards an augmented reality-based construction training platform. J. of Inf. Tech. in Const. (ITcon) 12, 363–380 (2007)

Watanuki, K.: Virtual reality based job training and human resource development for foundry skilled workers. Int. J. Cast Met. Res 21(1–4), 275–280 (2008)

Zhao, D., Lucas, J., Thabet, W.: Using virtual environments to support electrical safety awareness in construction. In: Winter Simulation Conference, pp. 2679–2690 (2009)

Zhao, D., Lucas, J.: Virtual reality simulation for construction safety promotion. Int. J. Inj. Control Saf. Promot. (2015)

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