IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received July 28, 2021, accepted August 10, 2021, date of publication August 23, 2021, date of current version August 31, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3106826

Study of Interaction Methods in Virtual Electrician Training

FILIP GÓRSKI, DAMIAN GRAJEWSKI, PAWEŁ BUŃ, AND PRZEMYSŁAW ZAWADZKI
Faculty of Mechanical Engineering, Poznan University of Technology, 60-965 Poznań, Poland

Corresponding author: Damian Grajewski (damian.grajewski@put.poznan.pl)

This work was supported by the European Union from the European Regional Development Fund within the Smart Growth Operational Program 2020–2024. The project is executed within the priority axis ''Support for R&D Activity of Enterprises'' of the National Center for Research and Development under the contract POIR.01.01.01-00-0463/18. Research was also partially financed by the Ministry of Science and Higher Education, Republic of Poland, under the project 0613/SBAD/4679.

ABSTRACT Virtual, Augmented and Mixed Reality technologies can be applied to improve competences of serviceman, or generally employees dealing with technical systems. The paper describes results of a first stage of development of a VR training system dedicated to electricians, working for one of Poland's major electricity providers. Three methods of interaction with the virtual environment and three navigation methods have been implemented in the presented application. To choose the best method of interaction and navigation in the training application, 30 electricians tested different combinations of methods in two training scenarios. Each participant went through the scenario twice, using two different navigation modes for the same interaction mode and scenario. The time of each pass was measured and the participants filled in a questionnaire to give feedback on their subjective impressions of using a given mode. Based on the gathered data analysis, the best interaction and navigation methods have been selected. These initial results will improve interaction and navigation at the next stage of the application development and implementation in the enterprise.

INDEX TERMS Virtual reality, training application, interaction.

I. INTRODUCTION

Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) fall into the group of ''free'' technologies, i.e., they do not have a strictly defined range of applications. Based on this assumption, VR can be used in any area of professional activity and everyday life. In some applications, e.g., in mechanical engineering [1], [2], electrical and energy engineering [3], education and training [4], medicine and medical education [5], military [6] and entertainment, VR facilitates the streamlining of certain processes.

This paper presents the results of the first stage of work on creating a flexible VR-based system designed to build, maintain and improve competences of employees dealing with maintenance and service of electrical infrastructure. The project is implemented in cooperation with an energy industry company. The work described in the paper concerns the selection of effective interaction methods in the VR system, taking into account the specificity of work of technical service employees and the activities performed by them. Research has been carried out on various interaction techniques for the training of technical service employees. A test training scenario has been developed and a study has been conducted on a group of thirty participants in order to recommend the most effective interaction techniques when performing various activities.

The associate editor coordinating the review of this manuscript and approving it for publication was Andrea F. Abate.

II. VIRTUAL REALITY IN INDUSTRIAL TRAINING

Apart from extensive use in the entertainment industry, VR systems are applied to simulate specific parts of the existing, physical reality. They are inextricably linked with the phenomenon of immersion in the virtual world, which allows the user to deeply engage, enabling more effective learning [7]. VR systems used for education and training can be based on mobile devices [8]; however, limited computing power of such devices compromises the quality of both graphics and interaction methods. In order to achieve a more natural interaction with the virtual environment, many modern VR solutions use PCs and HMDs (Head-mounted displays) alongside dedicated controllers which allow real-time tracking of users' hands and getting input from various buttons.

Industrial training is one of the most important and prominent applications of VR, as indicated in many cross-sectional studies, e.g. [9]–[11]. This was also confirmed by the work carried out previously by the authors [12], [13]. The use of VR techniques allows employees to learn and practice proper response to emergency situations in a controlled and safe environment. Visual and auditory stimuli in a virtual environment allow the user to maintain interest in the training, as well as facilitate storage of information and consolidation of skills related to the performed work [11]. Effective industrial training using VR is one of the methods to increase production efficiency in industrial enterprises implementing the concept of Industry 4.0 [14], [15]. The need to use virtual simulation becomes particularly justified where training cannot be delivered in a real workplace (e.g., there is no physical equivalent of the workplace available only for training) or this possibility is very limited (only during downtime) [16]–[18].

Analysis of VR solutions used for industrial training oriented at workplace activities shows that they can support training in the implementation of procedural tasks [19]. The implementation of a procedural task should be built as a series of activities undertaken by a trainee, leading to achievement of a specific goal (e.g., correct arrangement of parts in an assembly), in a specific order and according to an established procedure, assessed considering the duration and accuracy of the performance. Tasks of this type are common in the servicing of energy installations.

Examples of solutions dedicated to the energy industry can be found in scientific publications and industry portals focusing on the topic of VR applications in industrial training. Scientists at ExxonMobil Research Qatar, in cooperation with EON Reality Inc., have developed a VR platform for training engineers and operators of oil platforms and modern gas pipeline installations for gas transport [20]. The ExxonMobil 3D Training Environment solution allows its user to create various training scenarios and personalized exercises which duplicate key procedures of use, maintenance and safety, at particular installations.

A similar solution has been created by EON Reality for BP (British Petrol - oil and gas company) [20]. The Operator Essentials Training platform provides interactive training for engineers and operators of oil processing plants in operation and maintenance as well as implementation of critical tasks (e.g., in the event of a failure).

The Digital Engineering and Magic company has developed the Electrical Substation Training Platform for virtual training in operating high voltage power substations [21]. The solution provides exercises designed according to various scenarios (recognition of tools used in the substation, recognition of devices present in the substation, crisis management, improper use of equipment, removal of root causes of common accidents).

4Experience (Polish developer of VR applications) has developed a VR system for Tauron Polska Energia S.A. (Polish company from the energy sector). The solution, referred to as the VR work simulator, is an interactive training platform dedicated to electricians. The training familiarizes the employees with the design and operation of the switchgear and the equipment used in maintenance, servicing and inspections [22].

III. MATERIALS AND METHODS

Two VR scenes have been developed for the study: a virtual electrical substation (ES) and a virtual live-line work (LLW). In each of the scenes, a different scenario has been implemented: a switching operation scenario in the virtual ES, and a live work scenario in the virtual LLW.

The experiment was aimed to establish a ranking of interaction techniques in the virtual environment, based on feedback from a group of at least thirty electricians.

A. HARDWARE

Two popular VR headsets have been used in the experiments: Oculus Rift CV1 and HTC Vive. These are similar class devices – apart from different shapes of controllers and the greater tracking field of the HTC Vive, the differences between them, from the user's point of view, are insignificant. They have similar controllers, featuring:

- motion tracking (sensors built into the controller),
- trigger under the index finger,
- grab under the middle / ring finger,
- touchpad / analog stick under the thumb,
- menu button and additional buttons under the thumb.

Two experimental stations have been created. One of them corresponds to a stationary training station, where the workspace is unrestricted and the user can move freely. The other station corresponds to a mobile training station, where space is limited by dimensions of the interior of the vehicle in which the VR system will be installed.

Test stand no. 1 has been equipped with the HTC Vive with controllers and a wireless extension (Fig. 1). These devices are connected to the computer wirelessly. Two base stations in version 1.0 were used. The tracking area was approximately 3.5 × 3.5 m. The wireless headset gives the user freedom of movement, without the need to pay attention to the signal or the power cables. In addition to the headset, the station is

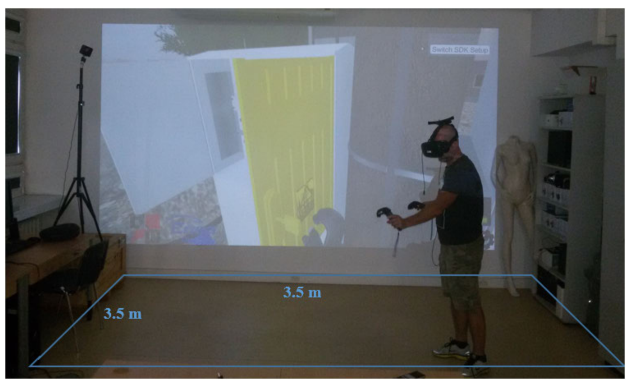

FIGURE 1. Tracking space at test stand No. 1.

equipped with two projection devices: a monitor and a 3D projector projecting the image onto the wall and enabling a view of the application's operation.

Test stand no. 2 has been equipped with an Oculus Rift with Touch controllers and three tracking stations (Fig. 2). The space tracking movement was about 2 × 1.3 m. Here, the user uses a HMD equipped with a cable, which negatively affects the ergonomics of work. Due to a small tracking space, the user uses methods of artificial movement (i.e., navigation) more often, so the marks given to individual navigation modes are more reliable. The stand has been equipped with a 3D TV to view the application.

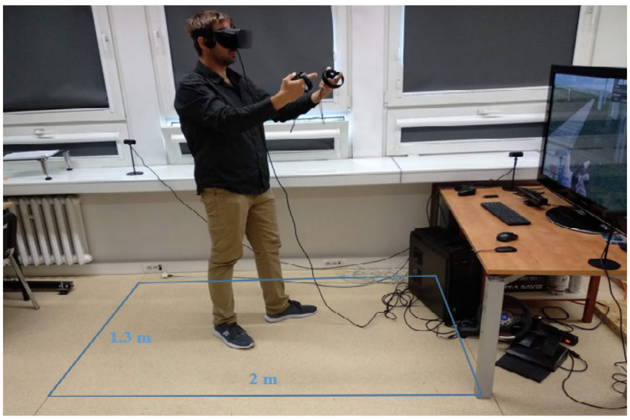

FIGURE 2. Tracking space at test stand No. 2.

B. SOFTWARE

The programming work has been carried out in the Unity software version 2018.2.20f1, licensed under Unity Pro. To build two VR applications, which are implementations of two training scenarios, in addition to the Unity 3D engine itself, a set of plugins and content available through the built-in software store (Asset Store) or through the so-called Unity package manager have been applied.

Both VR applications have been equipped with the same GUI which allows the user to take the following actions:

- switch to one of the three interaction modes available,
- switch to one of the three navigation modes available,
- change or disable the 3D avatar of the character,
- enable / disable visibility of the 3D controller model in the application,
- change the weather scenario and time of day (three modes available: sunny day, rainy afternoon and moonlit night),
- record the procedure time (a simple mechanism with the stopwatch functionality, start and pause manually activated, automatic termination when all tasks are completed by the user),
- reset the location of non-stationary objects in the event the user places them outside the scene (which may be the result of a physics engine error).

C. TRAINING SCENARIOS

The implementation of a given training procedure takes place step by step. The user receives information about subsequent tasks via the so-called master. The master is an animated character who gives the user tips on what to do next. These guidelines are provided in the form of drawings and instructions on a board (flipchart) or in the form of hints in a speech bubble above the master's head. Once a task (typically, a simple or more complex activity, e.g., moving a switch, screwing a screw, etc.) is completed, the subsequent task is signaled by a sound and a change in the displayed information (updating texts and drawings). Upon completion of the last step in a given procedure, the final sound signal is given and the user receives congratulations from the master.

To sum up, the user follows the procedure below:

1. Reads the instruction for a task.
2. Moves to the place where the task is to be performed in a given 3D scene.
3. Performs an action or group of actions – e.g., uses a stationary object (e.g., a lever, switch, door), or lifts a non-stationary object (a tool, key, cable end, etc.) and uses it on another stationary or non-stationary object.
4. Reads the instruction for the subsequent task – upon positive verification of the previous task.
5. Repeats the above mentioned steps until the procedure is completed.

1) SCENARIO 1 - SWITCHING OPERATIONS AT THE VIRTUAL ES

Scenario 1 simulates the procedure of preparing the system for the switch off of a 110 / 15kV transformer. The source material for developing the procedure is a graphic and text document developed by employees of the energy company. The situational plan of the 3D scene at the moment the user starts working in the application is shown in Figure 3 (the building is not translucent in the actual application – here, it has been made so for completeness of the image).

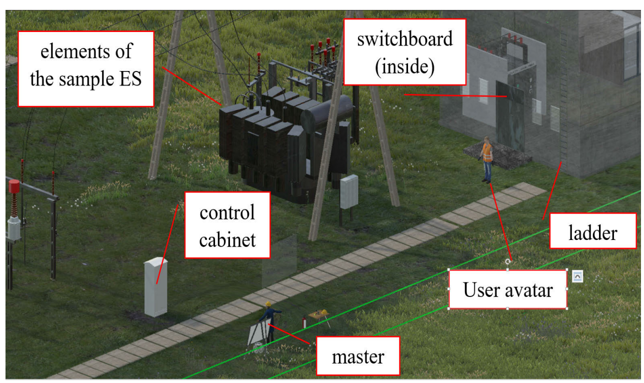

FIGURE 3. Initial state of the 3D scene – scenario 1.

The first scenario consisted of 10 steps. These activities included, among others, lifting the key to the control cabinet, placing it in the lock and turning it to open the lock. Other activities included operating switches and levers inside and outside the building. Details on the steps of the procedure in accordance with scenario 1 and the actions performed are presented in Table 1.

TABLE 1. Scenario 1 actions.

Step no.	Step command	Grab and move actions	Use actions
1	Grab key and open control cabinet.	1	0
2	Block the ATS 110 kV and 15 kV (setting: horizontal), switch on the 110 kV coupling (setting: vertical).	0	3
3	Lock the Automatic Voltage Regulation (AVR) of transformer TR1 and transformer TR2 (setting: horizontal).	0	3
4	Go to the building. Change the settings on the transformer. Set TR1 and TR2 to 16.00.	0	2
5	Go to the control cabinet. Switch on the 15 kV coupling (setting: vertical).	0	1
6	Go to the building. Switch off transformer 1 on the 15 kV side (setting: horizontal).	0	1
7	Turn off transformer 1 on 110 kV side (use red button in control cabinet).	0	1
8	Go to the building. Open the TR 1 rail disconnector on the 15kV side (lever down).	0	0
9	Open the transformer disconnector TR1 on the 110kV side. Use the red button at the top.	0	1
10	Enable the Automatic Voltage Regulation (AVR) of the TR2 transformer (setting: vertical).	0	1

2) SCENARIO 2 - LLW STATION

Scenario 2 implements one of the standardized procedures carried out at low voltage and being part of training delivered to electricians at the training ground of the company – the "TR1" procedure, i.e., placing a non-live cable in a live distribution device. The situational plan of the 3D scene at the time the user starts working in the application is shown in Figure 4.

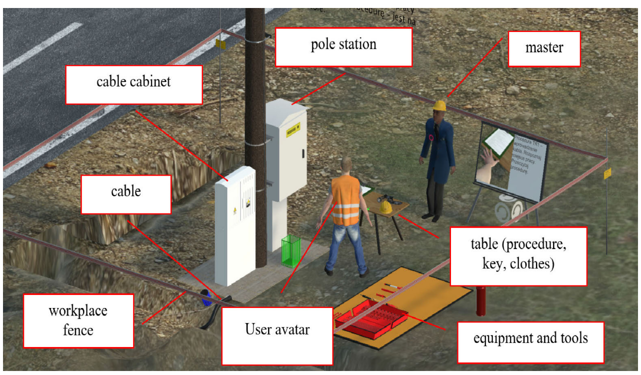

FIGURE 4. Initial state of the 3D scene –scenario 2.

The second scenario consisted of 15 steps, the first of which was to read the procedure by picking up the clipboard on which it was saved. Other activities included interactions related to moving virtual objects, opening control cabinets, and placing elements such as fuse covers and cables in designated places. As in scenario 1, the steps of the procedure and the actions performed are listed in Table 2.

TABLE 2. Scenario 2 actions.

Step no.	Step command	Grab and move actions	Use actions
1	Get acquainted with the workplace and read the procedure - it is on the table.	1	0
2	Put on (by pressing button) a helmet and work gloves.	0	1
3	Take the key from the table and open the cable cabinet.	1	1
4	Throw away unnecessary elements from the cabinet and the surrounding area.	3	0
5	Remove the damaged sign, take a new one from the table and install it.	2	1
6	Take the ratchet wrench and tighten the screws in the cabinet on the bottom bar.	1	1
7	Use plastic sheets and fuse covers to insulate the work area.	20	0
8	Strip the insulation from the end of the cable - using a knife. Take a voltage meter from the table and use it at the end of the cable.	3	0
9	Place the cable cover over the end of the cable and guide it into the conduit in the ground.	2	0
10	Remove the cable cover and strip the insulation from the ends of the cable wires.	2	0
11	Take the sheet covers and attach them to the uninsulated ends of the cable wires.	4	0
12	Remove the insulation from the protective-neutral wire (yellow -green wire) and the connection point.	0	2
13	Insert the wire into the cable clamp (on the left side) and tighten with a torque wrench.	2	1
14	Put the cover back on the connection point.	1	0
15	Connect the other wires as the one before (isolate, connect and insulate).	9	9

D. INTERACTION MODES

Based on the literature, especially review and classification papers [23]–[26], describing various possibilities of interaction, as well as on the expert knowledge of team members, three interaction modes have been identified for research:

a) basic mode (A) – interaction (using, grabbing, etc.) is done by touching the object and pressing / holding one button, referred to as the trigger (located under the index finger).
b) basic+ mode (B) – interaction is done by using the pointer, i.e., at a distance, as well as by using the trigger button only.
c) medium mode (C) – interaction with stationary objects (doors, levers, buttons, fixed objects) is similar to that in the basic mode; gripping and moving objects as well as climbing is performed using the grab button, located under the middle / ring finger on the side of a controller handle.

In many VR applications, use of the so-called advanced mode can be observed. It is the medium mode extended by the pointer, activated by an additional button on the controller within reach of the thumb. The advanced mode offers complex interaction options, but is only convenient for advanced users of VR systems. Considering little experience of the study group in the use of VR, this method of interaction has been abandoned.

E. NAVIGATION MODES

Similarly to the identification of interaction modes, based on scientific papers [24], [26] and the expert knowledge of team members, three modes of navigation in the virtual scene have been distinguished (in addition to moving on one's own legs within the space of tracking a given headset). All of them require the use of a touchpad / analog stick available under the user's thumb. The navigation modes are as follows:

a) Free movement (1) using the touchpad / analog stick, equivalent to using arrow buttons or WASD keys on a keyboard. Using both hands doubles the maximal movement speed.
b) User teleportation (2) to any visible location (within a limited range) using the touchpad / analog stick (activation of the teleport pointer by touch, indication of the desired location by moving the controller, i.e., by hand, activation of the teleportation by pressing). Operated with the right or left hand.
c) "7-mile steps" (3) – moving while standing still, only with specific movements of hands equipped with controllers (the so-called "Move in Place" mode); activated by pressing the touchpad / knob (only motion tracking); additionally, by pressing the touchpad / knob, the natural movement can be multiplied by a specific factor (1 meter in the real world corresponds to 5 meters in the VR scene); activated with the right or left hand.

IV. PLAN OF EXPERIMENT

Two of the most suitable navigation modes were assigned to each of the interaction modes A, B and C, according to the expert knowledge of the authors. Thus, each person tested in one approach went through the scenario twice, using two different navigation modes for the same interaction mode and scenario. A detailed plan of experiments and division of groups is shown in Figure 5.

The course was similar for both training scenarios, except that in scenario 2 there was a change in the experimental group for each of the test persons, according to a "+1" algorithm. So, for example, a five-person group testing scenario 1 (switching operations) on HTC Vive in the interaction mode A (basic) tested scenario 2 (LLW) on Oculus Rift in mode B (basic+) in the second round. Another group of five testing scenario 1 in mode C (medium) on Oculus Rift tested scenario 2 in mode A (basic) on HTC Vive in the second round. Each electrician used a given VR system twice, once in each of the two rounds.

A two-week break was planned between successive rounds, which was primarily aimed at clearing the muscle

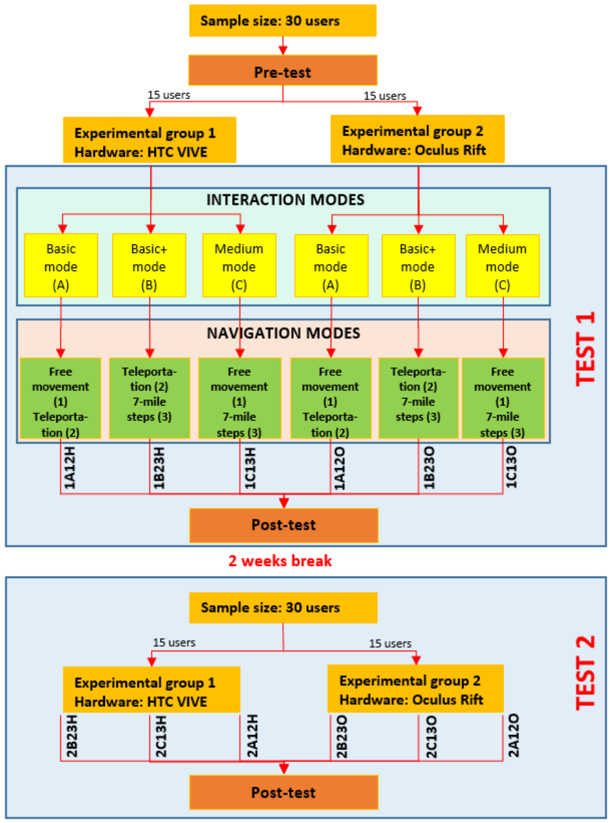

FIGURE 5. Plan of the experiment.

memory of the operation of the VR system, built in the first round. This approach was taken to make the performance of scenarios independent of the order in which the use of the VR equipment was taught, so that the final assessment could be more reliable. The break also served to cool down the so-called "wow effect" [27], accompanying immersion in a VR system for the first time. In this way, the second round could be considered more binding in terms of assessment of the technology itself and the merits of the application.

Work was planned for a group of 30 electricians from various regions/areas of the company's operations in Poland. It was a specially selected (quantitatively and qualitatively) representative sample of the company's employees, volunteering for the test procedure. The experiment was spread over ten days in two rounds of five working days, separated by a two-week break. As a result, each electrician approached the VR system twice, with a two-week interval (the ES scenario was implemented the first time, and the LLW scenario after 14 days). Every day, six electricians from various company branches were tested, two at a time, simultaneously at two test stands. Within one round, each electrician performed the following activities:

- VR equipment operation training,
- 1st test run: one navigation mode assigned to a given interaction mode,
- 2nd test run: another navigation mode assigned to the same interaction mode.

Within a round, the training scenario, the VR equipment used (test stand), and the interaction mode (one out of three), tested by the same electrician, remained unchanged. The two test runs differed only in the navigation mode. The scenario, equipment and interaction mode tested by the same electrician changed in the second round.

As each interaction mode was assigned two navigation modes, over two rounds and a total of four runs, each electrician tested and evaluated: two different scenarios, two interaction modes, three navigation modes and two different configurations of the VR equipment.

Four researchers took part in the experiment. Before each round, the team leader introduced the topic and demonstrated how to use the HMD and controllers as well as the application itself and its purpose. A complete scenario run in the given interaction and navigation modes was explained to the participants before they commenced the test. The overall time of the test was measured. All the major interventions on the part of the researchers, related to the operation of the equipment or the application itself, as well as errors and side effects, were noted down. In cases of serious symptoms of simulator sickness, the experiment was discontinued and resumed only at the participant's explicit request.

After completing a scenario for the first time, there was a break of several minutes. The test participants who experienced any symptoms of simulator sickness completed a questionnaire and took the second attempt only at their own request. After a short pre-training of the other navigation mode, the second test run was made. Due to high complexity of scenario 2, only its first half was carried out, i.e., up to and including the stage of isolating the work space (after this operation, the time measurement and the experiment were stopped).

Upon completion of the test (one or both runs, depending on the symptoms of simulator sickness), the participants completed two questionnaire surveys: a cyber-sickness survey and an application evaluation survey. The latter differed between the rounds; after the second round, it took into account a comparison of the two hardware systems and interaction modes (thus, it examined whether the participants remembered the previous round of tests).

V. METHODOLOGY OF SURVEYS

A. PRE-TEST

As part of the preliminary study, the following activities were carried out before the actual experiments began:

1. The participants were informed about the course of the experiment, its purpose and possible health effects;
2. They were requested to complete a personal questionnaire;
3. They were interviewed to provide information on seniority, work progress, duties, etc.;
4. Information was obtained from the participants on their health condition, including, without limitation, whether they suffered from a condition which might trigger or intensify the symptoms of simulator sickness (e.g. motion sickness, fear of height and space, problems with the labyrinth, etc.), and on the consumption of agents which affect the nervous system (caffeine, alcohol, etc.); information was provided on possible symptoms of simulator sickness;
5. The course of the experiment as well as the hardware and software used were presented, and the participants were requested to provide information on their previous experience with the VR technology.

B. POST-TEST

The post-test research consisted of two surveys: a substantive assessment of the interaction methods in the application and a cyber sickness survey. The assessment survey questionnaire was completed after a given participant finished work on a given day. The cyber sickness survey was completed on a similar basis, except in the case when clear symptoms [28] occurred while using the application; the test would be then discontinued at the participant's request and the questionnaire completed. If there were no clear symptoms or signals from the participant, both questionnaires were completed at the end of the workday. Any significant differences in the symptoms of cyber sickness after each of the rounds on a given day were marked on the questionnaire.

The interaction methods in the application were assessed based on a multiple choice test. The survey questions can be classified into one of the four groups below:

1. Overall assessment of the VR application.
2. Technical assessment of the application (various aspects of software and hardware).
3. Assessment of the usefulness of VR in training electricians.
4. Comparative assessment of various navigation and interaction methods.

Answers to almost all the questions in groups 1-3 were given on a 5-point Likert scale, for easier comparison of results. Questions in group 4, examining the participants' preferences regarding the interaction methods and the location tested, were of the multiple choice type with two possible answers (additionally, the option ''I don't know'' was provided). Answers to them were used to create a ranking of interaction and navigation techniques.

The cyber sickness survey was conducted using a commonly applied simulator sickness questionnaire [29]. This questionnaire was completed jointly with the researcher, to avoid any doubts as to what each symptom meant. The application and interaction assessment questionnaire was completed by the participant himself, while the researchers responded to any queries where necessary.

VI. DATA GATHERING AND RESULTS

The research was carried out on a group of:

- 30 participants implementing the ES training scenario,
- 30 participants (the same persons) implementing the LLW training scenario.

For the purpose of a detailed analysis of the experiment results, a database was developed storing the following data for each participant:

- registered times for both scenarios,
- recorded interferences (hints),
- implemented interaction modes,
- implemented movement modes,
- equipment on which the procedure was carried out (Oculus / Vive),
- official duties of the electricians,
- age,
- assessment of the interaction mode (based on a questionnaire),
- assessment of the movement mode (based on a questionnaire),
- assessment of the controllers (Oculus / Vive).

Two participants failed to complete the two runs of scenario 1 due to symptoms of cyber sickness. For the same reason, two participants failed to complete the two runs of scenario 2. As a result, these participants were not able to assess the modes of interaction and movement in Test 1 (ES scenario). It was similar in the case of Test 2 (LLW scenario).

In the summary, a preliminary interaction and navigation ranking for scenarios 1 and 2 was established based on the results obtained from 28 trials (Table 3).

TABLE 3. List of participants conducted scenarios 1 and 2.

Group ID.	Test 1	No. of participants of test 1	Test 2	No. of participants of test 2
1	1A12H	5	2B23O	5
2	1B23H	5	2C13O	5
3	1C13H	4*	2A12O	5
4	1A12O	5	2B23H	4*
5	1B23O	4*	2C13H	5
6	1C13O	5	2A12H	4*
*cyber sickness symptoms				

The comparative assessment of the navigation and interaction methods studied was based on an extensive analysis of:

- the implementation times of the scenarios in specific modes,
- the number of hints given,
- assessment of the application by the participants, provided through the questionnaires.

The questionnaires are extremely important from the point of view of the entire project because the electricians will be the end users of the developed training solution. Another important aspect concerning the effectiveness of training is the educational effect (better performance in the second run of the same task). For its measurement, only the two runs of scenario 1 have been analyzed. Scenario 2 has not been used because it was necessary to shorten it - the last steps were not performed. The first participants reported that it is taking too long and they started to feel uncomfortable after performing step 10 from scenario 2 (see Table 2 for details). After analyzing framerate, a slight, but observable frame drop was found starting from this step. It may be due to the wires physics and limited computing power. After taking that into account authors decided that the rest of participants will only perform the first 10 steps.

In addition, as part of the analysis of the experiment results, a ranking of the VR equipment used for testing has been developed and the final average ratings of both VR applications expressed by the participants have been presented.

Only the methods of interaction and navigation were taken into account when analyzing results of experiments and survey. Notation of data got simplified, by removing part of it that was responsible for used HMD. Consequently, data for e.g. 1A1O and 1A1H are presented as 1A1.

A. INTERACTION AND NAVIGATION IN ES

The ranking of navigation methods for the ES scenario has been developed on the basis of an analysis of the average times of task implementation in specific modes of movement, including interaction modes (Fig. 6), and a subjective assessment by the participants (Fig. 7).

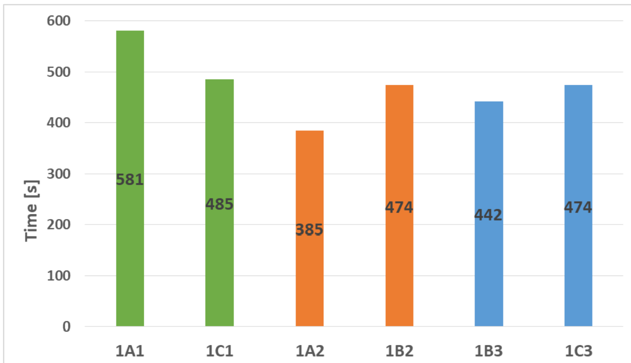

FIGURE 6. Average task completion time in correlation with the navigation method and interaction mode used (ES).

The average times achieved in the teleportation (1A2 and 1B2) and 7-mile steps (1B3 and 1C3) modes are at a very similar level, while navigating in the free movement mode (1A1 and 1C1) took the participants longer. A comparison of the additional interaction modes used shows that the results for the basic+ (1B2 and 1B3) and medium (1C1 and 1C3) modes are very similar. An exception is the basic mode, with a clear discrepancy between the teleportation (1A2) and the free movement mode (1A1), to the advantage of the former. The authors attribute the poor result for the free movement mode to the necessity of covering long distances.

When it comes to the subjective opinions of users (Fig. 7), only three participants indicated the free movement mode as the best and most effective (one vote for 1A1 and two votes for 1C1). The teleportation and 7-mile steps modes were ranked quite similarly to each other.

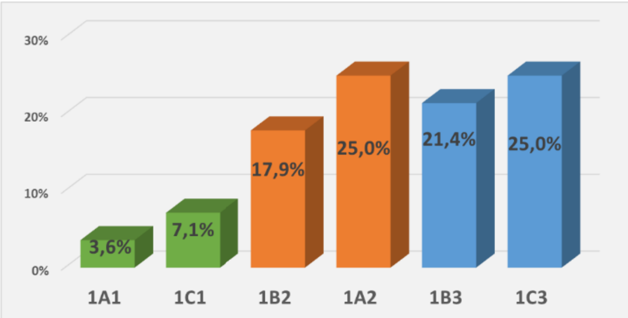

FIGURE 7. Navigation ranking including interaction mode (ES).

The assessment was probably affected by the need to travel considerable distances in scenario 1, which entailed a longer duration of the task performance. Additionally, in some participants, it caused slight discomfort and mild symptoms of simulator sickness.

B. INTERACTION AND NAVIGATION IN LLW

Considering that the course of scenario 2 was shortened, the average times of completion in correlation with the method of movement are presented broken down into single runs. In route 1 (as presented in Fig. 8), the electricians implemented modes 2A1, 2B2 and 2C1, so two of them (2A1 and 2C1) were free movement modes. Therefore, in the first route, there was no time recorded for the 7-mile steps mode.

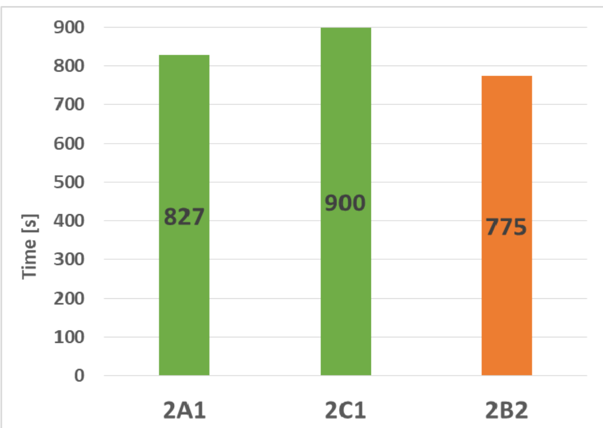

FIGURE 8. Average task completion time in correlation with navigation method and interaction mode (LLW route 1).

An analysis of the times shows that implementation of the scenario in the free movement modes (2A1 and 2C1) took much longer on average. In addition – in the case of the 2C1 mode – a more difficult form of controller support (medium) was used, which clearly extended the run time.

In the shortened run 2, the electricians implemented modes: 2A2, 2B3 and 2C3, so two of them (2B3 and 2C3) were the 7-mile steps mode. Therefore, no time was recorded for the free movement mode in this run (Fig. 9).

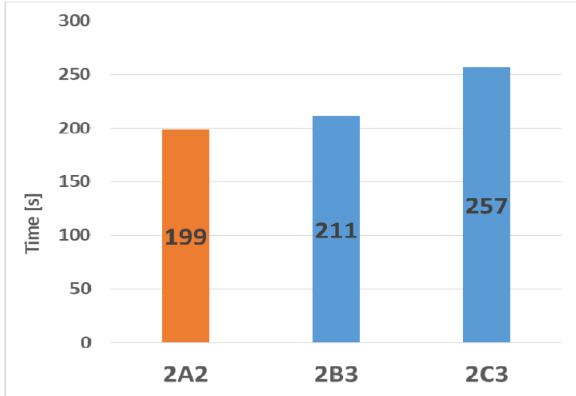

FIGURE 9. Average task completion time in correlation with navigation method and interaction mode (LLW route 2).

In this case, the implementation of the shortened LLW scenario in the teleportation mode (2A2) took less time, although it was carried out by a smaller sample of respondents (7 people), which could affect the final results. In addition, in this mode of movement, the electricians implemented the scenario in theoretically the easiest mode of interaction – basic (A). As in the first run, a clearly worse time was noted for the medium mode (2C3).

The assessment of navigation modes is based on the opinions of 28 respondents (Fig. 10).

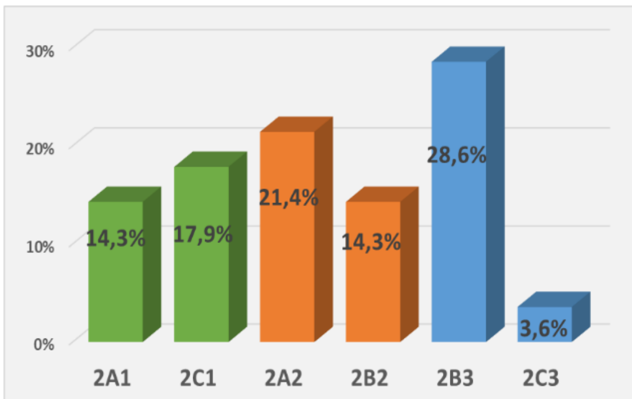

FIGURE 10. Ranking of navigation methods including interaction modes (LLW).

Unlike in the ES scenario, there are no clear differences between specific modes of navigation. However, with the interaction mode taken into account, the C-medium mode (2C3) is much worse for 7-mile steps.

The ranking is probably influenced by the small working space of the LLW station (no need to move over greater distances), which meant that in the free mode, it was basically enough to move on participants' own legs, without triggering artificial movement using controllers.

VII. RESULTS ANALYSIS AND DISCUSSION

Based on the developed rankings of navigation methods for each of the scenarios (for the ES and the LLW), the following conclusions have been formulated regarding the navigation methods:

1. For training scenarios implemented on a virtual ES, the free movement mode is not recommended due to simulator sickness it causes and a lack of positive user reviews. The recommended default navigation mode is teleportation, with the option of alternatively switching to 7-mile steps.
2. No explicit negative selection can be made for the LLW training scenarios. Nevertheless, for compatibility with the main functionality of the system (ES), it is recommended to provide teleportation and 7-mile steps as two possible navigation modes, to be selected by the user. During training, users are advised to use walking on their own legs for as long as possible.

In the case of LLW, the teleportation mode – both the size and sensitivity of the teleportation marker – must be adapted to the working field. The same applies to sensitivity in the 7-mile steps mode – it should be definitely smaller in small working fields, so as not to cause sudden jumps of the character's avatar.

The final interaction ranking is based on:

- an analysis of the average implementation times in correlation with the interaction modes,
- subjective feedback from 28 participants who used different modes of interaction.

In one of the questions of the second survey, completed after the implementation of the LLW scenario, the users were requested to indicate the interaction mode which, in their opinion, was more effective and easier to use.

It is worth noting that out of the 28 respondents, where each respondent tested two interaction modes:

- 9 respondents compared the A - basic mode (scenario 1 - ES) with the B - basic+ mode (scenario 2 - LLW),
- 7 respondents compared the B - basic+ mode (ES) with the C - medium mode (LLW),
- 2 respondents compared the B - basic+ mode (ES) with the A - basic mode (LLW),
- 2 respondents compared the C - medium mode (ES) with the B - basic+ mode (LLW),
- 8 respondents compared the C - medium mode (ES) with the A - basic mode (LLW).

Detailed results are presented in Figure 11. The question in the survey concerned the preferred of the two interaction modes. Almost 40% of respondents (11 participants) indicated the basic mode (A). The same number of respondents selected the basic+ mode (B), and only 6 participants pointed to the medium mode (C).

It should be borne in mind that due to the limited time of the experiment, each user had only two runs with different interaction modes (none of the users evaluated all three modes). Therefore, a classic pair-wise comparison was made, i.e., the method known as Paired Comparison Analysis was used as part of the AHP (Analytical Hierarchy Process) method [30]. Comparison in pairs is considered ideal where

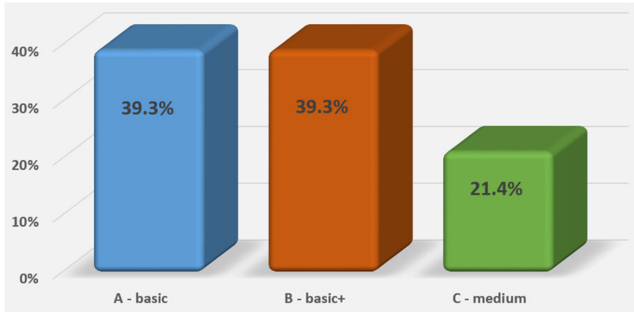

FIGURE 11. Evaluation of tested interaction methods.

the choice is subjective and not based strictly on objective premises [31]. The authors are aware of the limitations of this method. Nevertheless, following discussions in the expert team and literature analysis [32], a decision was made to use it to evaluate the selected navigation methods and interactions using controllers.

To sum up, taking into account the average times of scenario implementation in correlation with interaction and navigation methods and user assessment, as well as the specifics of the work of technical service employees and activities performed during the training, a final recommendation can be formulated. The complex interaction mode (C-medium) should be discarded, and the A-basic and B-basic+ methods should be used as effective methods of interaction in the virtual reality system. Further work should be done on the concept of the indicator appearing in mode B, as it is needed only in certain situations where precise manipulation is required (e.g. increasing voltage). According to the authors, it should be set to default mode A, with the option to be turned on when needed, either with the help of an additional button on the controller or automatically, at a specific step of a scenario.

The obtained results allow to state that the virtual reality technology has great potential for effective implementation in the training practice of an enterprise. Nevertheless, many aspects need improvement, and many positive user reviews are also related to so-called the "wow" effect.

From the point of view of the main goals of the project, the general assessment of the suitability of VR technology for training in their work area issued by electricians is very important (Fig. 12). Such usefulness was positively assessed by almost 90% of electricians testing ES application. What's more, 54.5% of respondents expressed the opinion that VR can largely replace traditional training, bypassing some manual activities. The pole station application was assessed more cautiously in this respect - 41.4% determined the suitability to a large extent and definitely more (55.2%) to a moderate degree. Nevertheless, in the overall assessment after the implementation of the second scenario no one stated that the VR technology is useless (one of the possible choices in the survey), which, according to the authors, proves the positive reception and attitude of electricians to

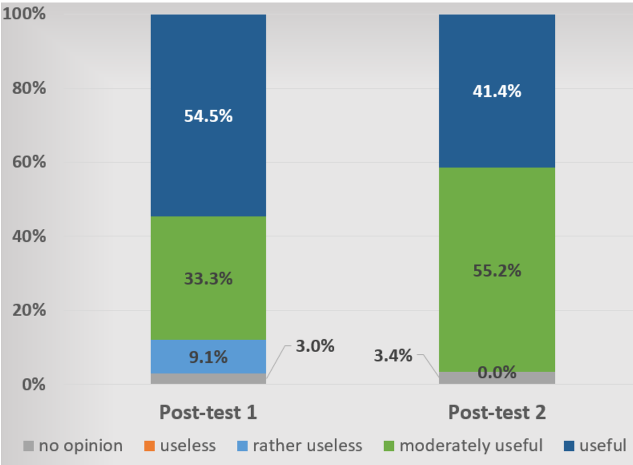

FIGURE 12. Assessment of the suitability of VR technology for training in the work of electricians.

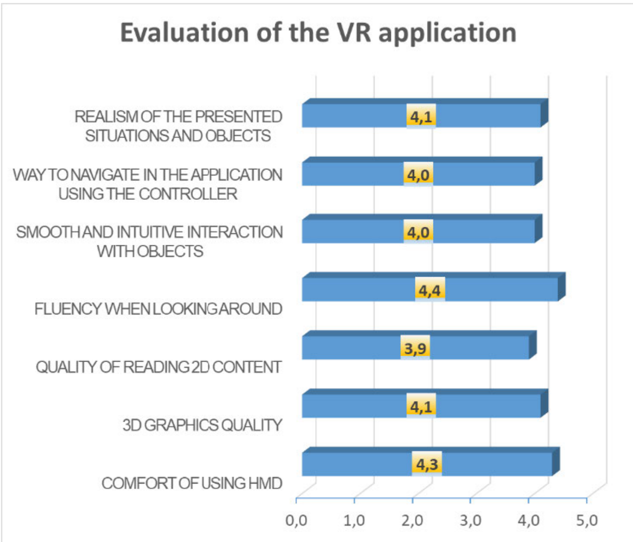

FIGURE 13. Evaluation of the VR application.

this innovative form of training. On this basis, the authors infer that the VR technology has great potential for training in this area.

The above results show considerable implementation potential of the VR technology in the energy sector. The enthusiastic approach of the study participants and their readiness to use it in everyday work is especially important.

VIII. CONCLUSION

As a result of the tests carried out on two different VR applications, recommendations have been developed regarding the interaction and navigation methods. Two navigation methods (default - teleport and alternative - 7-mile steps) and one interaction method (default - basic mode with the option of turning on the indicator) have been selected.

Users rated both applications. The average ratings for both applications are shown in Figure 13.

The average technical rating of ca. 4.0 is a very good result, given that the application is not graphically refined (although interaction with objects is complex at times). It still contains relatively many errors (graphical and in the operation of the physics engine), which will be eliminated at further stages of the development. Overall potential of VR has been assessed positively on the basis of the tested applications, and almost all the electricians expressed a great desire to participate in further development of the system and use the VR technology in their daily work. The initial versions of the demonstration applications have been assessed as promising, and great potential is seen for future implementation of the VR technology in the enterprise. The sample of respondents could be larger, but the authors and the company believe that it was representative for the given purpose, and tests on a larger group are planned in the further stage of training system development.

The presented results were used in the construction of a prototype training system, which finally will contain a total of over a dozen substations of the substation and several medium and low voltage stations, plus an appropriate number of scenarios using the conclusions of the research. At the time of writing the article, the system is in the process of implementation in the enterprise as a tool for training new employees.

It is also planned to conduct research on a larger group of users (more than 100), working in various professions, in order to generalize the obtained results. The presented research focused only on proper method of interaction and navigation in training application dedicated for electricians, but it can serve as a starting point for future research in field of interaction techniques for training applications in virtual reality. The authors plan to conduct research to determine how selected interaction and navigation methods affects effectiveness of training.

REFERENCES

[1] P. Buń, F. Górski, and N. Lisek, "Comparison of manual assembly training possibilities in various virtual reality systems," in *Proc. Int. Conf. Innov., Eng. Entrepreneurship*. Cham, Switzerland: Springer, 2018, pp. 398–404.

[2] F. Górski, P. Buń, P. Zawadzki, and R. Wichniarek, "Knowledge management in open industrial virtual reality applications," in *Proc. Int. Sci.-Tech. Conf. (MANUFACTURING)*. Cham, Switzerland: Springer, 2019, pp. 104–118.

[3] P. N. A. Barata, M. R. Filho, and M. V. A. Nunes, "Consolidating learning in power systems: Virtual reality applied to the study of the operation of electric power transformers," *IEEE Trans. Educ.*, vol. 58, no. 4, pp. 255–261, Nov. 2015.

[4] P. K. Buń, R. Wichniarek, F. Górski, D. Grajewski, P. Zawadzki, and A. Hamrol, "Possibilities and determinants of using low-cost devices in virtual education applications," *EURASIA J. Math., Sci. Technol. Educ.*, vol. 13, no. 2, pp. 381–394, Dec. 2016.

[5] J. Herron, "Augmented reality in medical education and training," *J. Electron. Resour. Med. Libraries*, vol. 13, no. 2, pp. 51–55, Apr. 2016.

[6] K. K. Bhagat, W.-K. Liou, and C.-Y. Chang, "A cost-effective interactive 3D virtual reality system applied to military live firing training," *Virtual Reality*, vol. 20, no. 2, pp. 127–140, Jun. 2016.

[7] J. Parong and R. E. Mayer, "Learning science in immersive virtual reality," *J. Educ. Psychol.*, vol. 110, no. 6, pp. 785–797, 2018.

[8] T. Cochrane, "Mobile VR in education: From the fringe to the mainstream," *Int. J. Mobile Blended Learn.*, vol. 8, no. 4, pp. 44–60, 2016.

[9] A. H. Abulrub, A. Attridge, and M. A. Williams, "Virtual reality in engineering education: The future of creative learning," *Int. J. Emerg. Technol. Learn.*, vol. 6, no. 4, pp. 4–11, 2011.

[10] S. Choi, K. Jung, and S. D. Noh, "Virtual reality applications in manufacturing industries: Past research, present findings, and future directions," *Concurrent Eng.*, vol. 23, no. 1, pp. 40–63, Mar. 2015.

[11] N. Gavish, T. Gutiérrez, S. Webel, J. Rodríguez, M. Peveri, U. Bockholt, and F. Tecchia, "Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks," *Interact. Learn. Environ.*, vol. 23, no. 6, pp. 778–798, 2015.

[12] D. Grajewski, F. Górski, A. Hamrol, and P. Zawadzki, "Immersive and haptic educational simulations of assembly workplace conditions," *Procedia Comput. Sci.*, vol. 75, pp. 359–368, Jan. 2015.

[13] F. Górski, P. Zawadzki, P. Buń, and B. Starzyńska, "Virtual reality training of hard and soft skills in production," in *Proc. 23rd Int. ACM Conf. 3D Web Technol.*, Jun. 2018, pp. 1–2.

[14] D. Romero, J. Stahre, T. Wuest, and D. Gorecky, "Towards an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies," in *Proc. Int. Conf. Comput. Ind. Eng. (CIE)*, 2016, pp. 1–11.

[15] H. Schroeder, A. Friedewald, C. Kahlefendt, and H. Lödding, "Virtual reality for the training of operators in industry 4.0," in *Proc. IFIP Adv. Inf. Commun. Technol.*, 2017, pp. 330–337.

[16] A. Bhatti, Y. Khoo, C. Bing, A. J. Douglas, S. Nahavandi, and M. Zhou, "Haptically enabled interactive virtual reality prototype for general assembly," in *Proc. World Automat. Congr. (WAC)*, vol. 8, 2008, pp. 1–6.

[17] R. Cheng, "Dig this: I operated a giant excavator from 2,500 km away," CNET Mag., New York, NY, USA, 2015.

[18] A. Seth, H.-J. Su, and J. M. Vance, "Development of a dual-handed haptic assembly system: SHARP," *J. Comput. Inf. Sci. Eng.*, vol. 8, no. 4, Dec. 2008.

[19] J. Rodriguez, T. Gutiérrez, E. J. Sánchez, S. Casado, and I. Aguinaga, "Training of procedural tasks through the use of virtual reality and direct aids," in *Virtual Reality and Environments*. Rijeka, Croatia: InTech Open, 2012.

[20] *Augmented Reality Adventures in Energy*. Accessed: Jul. 8, 2021. [Online]. Available: https://eonreality.com/use-cases/augmented-virtual-reality-energy/

[21] *Virtual Reality for Electric Power Industry*. Accessed: Jul. 8, 2021. [Online]. Available: https://www.digitalengineeringmagic.com/

[22] *Tauron VR Work Simulator—Professional Skills Training*. Accessed: Jul. 8, 2021. [Online]. Available: http://www.4experience.co/portfolio-item/tauron-vr-work-simulator-professional-skills-training/

[23] X. Shao, X. Feng, Y. Yu, Z. Wu, and P. Mei, "A natural interaction method of multi-sensory channels for virtual assembly system of power transformer control cabinet," *IEEE Access*, vol. 8, pp. 54699–54709, 2020.

[24] K. Rogers, J. Funke, J. Frommel, S. Stamm, and M. Weber, "Exploring interaction fidelity in virtual reality: Object manipulation and whole-body movements," in *Proc. Conf. Hum. Factors Comput. Syst. (CHI)*, May 2019, pp. 1–14.

[25] J. Jung, H. Park, D. Hwang, M. Son, and D. Beck, "A review on interaction techniques in virtual environments," in *Proc. Int. Conf. Ind. Eng. Oper. Manage.*, Bali, Indonesia, vol. 9, Jan. 2014, pp. 1582–1590.

[26] E. Bozgeyikli, L. Bozgeyikli, R. Alqasemi, A. Raij, S. Katkoori, and R. Dubey, "Virtual reality interaction techniques for individuals with autism spectrum disorder," in *Universal Access in Human-Computer Interaction. Virtual, Augmented, and Intelligent Environments* (Lecture Notes in Computer Science), vol. 10908, M. Antona and C. Stephanidis, Eds. Cham, Switzerland: Springer, 2018.

[27] T. Reunanen, M. Penttinen, and A. Borgmeier, "'Wow-factors' for boosting business," in *Advances in Human Factors, Business Management, Training and Education*. Cham, Switzerland: Springer, 2016, pp. 589–600.

[28] U. A. Chattha, U. I. Janjua, F. Anwar, T. M. Madni, M. F. Cheema, and S. I. Janjua, "Motion sickness in virtual reality: An empirical evaluation," *IEEE Access*, vol. 8, pp. 130486–130499, 2020.

[29] P. Bimberg, T. Weissker, and A. Kulik, "On the usage of the simulator sickness questionnaire for virtual reality research," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces Abstr. Workshops (VRW)*, Mar. 2020, pp. 464–467.

[30] A. Muhammad, A. Shaikh, Q. N. Naveed, and M. R. N. Qureshi, "Factors affecting academic integrity in E-learning of Saudi Arabian Universities. An investigation using Delphi and AHP," *IEEE Access*, vol. 8, pp. 16259–16268, 2020.

[31] Accessed: Jul. 8, 2021. [Online]. Available: http://www.mindtools.com/pages/article/newTED_02.htm

[32] Accessed: Jul. 8, 2021. [Online]. Available: http://www.sciencedirect.com/topics/engineering/paired-comparison

FILIP GÓRSKI received the Ph.D. degree in engineering in the field of additive manufacturing technologies. He is currently an Associate Professor with the Faculty of Mechanical Engineering, Poznan University of Technology. He has authored more than 40 publications, including three books. He has participated in many research projects also as the grant holder, including research and development projects performed in cooperation with industrial companies. He has authored several software solutions implemented in industrial companies. He specializes in virtual reality in industrial applications, 3-D printing technologies, CAD/CAM/CAE systems, and reverse engineering techniques.

DAMIAN GRAJEWSKI received the Ph.D. degree in engineering in the field of virtual technologies in training and education. In 2018, he successfully defended the Ph.D. thesis entitled "Study of tactile interaction in Virtual Reality using Delta robot." He is currently a Research Assistant with the Faculty of Mechanical Engineering, Poznan University of Technology. He has participated in many research projects, including FP6, FP7, education, and training (LLP) programmes. He has authored more than 30 publications. His research interests include virtual reality, haptic technology, CAx systems, product, and process design.

PAWEŁ BUŃ received the M.Sc.Eng. degree majoring in machine diagnostics and measurement systems from the Faculty of Mechanical Engineering, Poznan University of Technology, in 2013, where he is currently pursuing the Ph.D. degree in mechanical engineering.

Since 2015, he has been a Research Assistant at Poznan University of Technology. His research interests include the use of virtual and augmented reality systems, position tracking, visualization, interaction methods, and their impact on the immersion and knowledge transfer.

PRZEMYSŁAW ZAWADZKI received the master's degree in mechanical engineering specializing in industrial computer science, in 2007, and the Ph.D. degree in engineering in the methodology for design automation with the use of knowledge engineering tools, in 2016. He is currently an Assistant Professor with the Faculty of Mechanical Engineering, Poznan University of Technology. His research interests include a wide scope of the engineering design process, using CAx and virtual reality systems, and reverse engineering methods and 3-D printing techniques in prototyping. In his work, he has a strong focus on the implementation of knowledge-based engineering methods.