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A collaborative, immersive, virtual reality environment for training electricians

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Abstract

This paper presents the development of a multi-user, collaborative virtual reality environment for training electricians to work on the electric power distribution network. Typically, traditional trainings in this field have lots of constraints and don't allow learners to experience a wide set of different equipment that is installed in the network nor bad weather conditions and the different risk analysis that should be performed. With the proposed virtual reality environment, learners will be able to practice several realistic conditions without risking themselves.

Keywords: *Simulator, virtual reality, Electric power distribution system, training*

1 Introduction

More and more virtual reality (VR) applications are hitting the market nowadays and becoming popular. According to Meta, since the release of the official Oculus Quest app store on May 2019, more than 120 applications have earned US$ 1 million in revenue or more, while eight have exceeded US$ 20 million (Lang, 2022). In fact, most of the VR apps available on the Oculus Quest app store and other platforms are games and entertainment. However, both Meta and Goldman & Sachs estimate an expansion of the usage of VR beyond games, in several different areas: education, automotive industry, healthcare, retail, and others (Verdu, 2021) (Bellini, et al., 2016) due to the lowering prices of the Head-Mounted Displays (HMDs). For example, the first Oculus device released in 2016, the Oculus Rift, was sold by US$ 599. Now, it is possible to buy its latest device released, the Meta Quest 2, by US$ 399. By 2024, more than 34 million of HMD installations are expected worldwide (Alsop, 2022).

In the corporate education and professional training fields, VR environments can be a powerful resource to engage learners, increasing the interest in the teaching and learning practices, making the training sessions more effective (Popovici & Marhan, 2008). Additionally, when the real practices in the real environments involve security risks, especially because of possible human errors and environmental factors, the usage of VR environments can help learners to recognize the symptoms and causes of accidents and risk situations, as well as learning to react to mitigate or eliminate such risks (Amokrane & Lourdeaux, 2009). Moreover, Amokrane and Lourdeaux (2009) highlight that, by enabling learners to explore different situations through trial and error whilst avoiding exposure to real risks, VR environments offer an effective strategy for training. Furthermore, with VR environments, learners are able to conduct their own learning, in their own time (Mikropoulos, Chalkudis, Katsisis, & Kossivaki, 1997).

Therefore, it is interesting to notice these pros when using VR environments in professional trainings that involve risks to learners. That is the case with civil construction, as the usage of Personal Protective Equipment (PPE) and the knowledge of the safety rules and procedures are essential, but students and workers in this area are not always aware of them. As a result, there are high rates of work accidents, which lead to increased costs and delays in the delivery of the construction works (Le, Pedro, & Park, 2015). Thus, as a resource to improve safety training in civil construction, Le et al. (2015) proposed a multi-user virtual platform based on Second Life (Second Life, 2023). The virtual platform proposed by Le et al. (2015) was composed of a virtual classroom to share academic material and discuss accident cases and reports, a virtual environment for risk inspection exercises in realistic scenarios in a collaborative manner among learners, and another environment in which first learners individually inspect the scenario and then share their inspections with others.

Another key factor for the adoption of VR in training is when there is difficulty in simulating critical or emergency events or situations in the real world. Along these lines, a multi-user virtual reality environment to train security agents (police officers, firefighters, special agents from the National Nuclear Energy Center) to work in major events, such as the Olympics and the Football World Cup was proposed (Passos, da Silva, Mol, & Carvalho, 2017). The major objective of this environment was to simulate feasible situations that could compromise public safety and explore the actions and responses of security agents in some virtual environments that were identical to the real ones (for example, a football stadium and its neighborhood). Then, security agents must work in the proposed environments in a coordinated and collaborative way, communicating and sharing information to identify potential risks or suspects, guide the public and, eventually, isolate and/or eliminate the risk. The tests carried out with the proposed environments showed that the security agents were able to develop a sense of collaborative actions.

In addition, the agents considered that the adoption of the proposed environments could enhance the training procedures.

One of the other sector that VR can be adopted as well is in the trainings of the electric power distribution sector. Traditionally, trainings in this sector in Brazil consists of formal theoretical and practical classes in training centers that generally represent parts of the electric power distribution network and its components, such as poles, cables, insulators, distribution transformers, switches, among others. However, these trainings are not always able to cover all types of equipment that electricians can face in the distribution network. Furthermore, the training centers do not represent the real characteristics of the environment and the conditions of the distribution network in the field. Often, and for example, during their daily, work routine, electricians must face streets with intense vehicle traffic, trees whose branches are tangled with the cables of the distribution network, consumers who may not be satisfied with the offered service, dogs, bees and other animals that can represent a threat, adverse weather conditions (wind, rain and fog, for example), among others.

Therefore, and knowing the lack of professional trainings that can allow electricians to face situations and conditions similar to what they find in their daily routines, but without exposing them to risks, this article presents a multi-user VR environment that simulates realistic and situations that cannot be practiced in current training centers. This VR environment has been developed by the Instituto de Pesquisas Eldorado and Companhia Paranaense de Energia (COPEL), as part of the Research and Technological Development Program for the Electric Energy Sector regulated by the National Electric Energy Agency (ANEEL) in Brazil. The next sections present some related works, the development of the multi-user VR environment, the major results so far and the concluding remarks. Also, it is important to notice that this is an extended version of a paper from the same authors already published in SBGames 2021 (Tanaka, et al., 2021).

2 Related work

Currently, COPEL has approximately 1,500 electricians responsible for maintaining its electric power distribution network, who carry out mandatory recycling courses every 2 years. For a new electrician, a training course has 40 hours of theoretical, classroom activities and 160 hours of practical activities in the field. In theoretical classes, the adopted methodology follows the traditional classrooms, which usually do not encourage problem solving or interaction between learners due to the large amount of lectures. On the other hand, during the practical activities, trainees have the opportunity to visualize and interact with the network equipment as well as with Personal Protective Equipment (PPE) and Collective Protective Equipment (CPE), get used to the safety procedures, and, therefore, experience situations close to reality and work routine. However, these activities may not cover all the required topics for training qualified professionals, due to restricted physical spaces for training and the limited access to network equipment, since there are many types and manufacturers. In addition, there are risks to the safety of learners and to the physical integrity of the equipment when these training activities are performed on the field with powered lines.

Given the complexity and risks involved in the electric power distribution system, an effective and efficient training is a key piece to ensure safety, reliability and quality of services. Furthermore, when these professionals need to work on any maintenance of the distribution network, if they have been effectively trained, the chances are high that they will adopt good safety practices and use the most appropriate PPE and CPE for each task and, consequently, reducing the risk of accidents. Thus, simulators for training electricians have been developed since the last two decades as tools to enhance learning and increase the awareness of best and safety practices at work. Some of these simulators aim only to visualize isolated electrical installations or equipment whereas others encourage the users to interact with equipment and the environment itself to solve problems. Also, some adopt VR to provide a high level of immersion and realism.

An example of a simple simulator for the electrical system is STOP (de Castro Silva, Sampaio, Leão, Barroso, & Soares, 2011). With STOP, electricians can analyze and interact with single-line diagrams of electrical systems and change the configuration of relays, circuit breakers, power transformers, and other equipment. Moreover, it is possible to simulate faults in the electrical systems and request learners to identify these faults. One of the drawbacks of STOP is that, as the learners only interact with 2D diagrams of the electrical systems, they do not have the experience of interacting with all the equipment present in the systems – for example, a learner may not be aware of how to operate a circuit breaker present in the real system.

Another example of a simulator in this area is Virtual Substation (Silva, 2012), which uses 3D models to represent an electrical substation and its equipment. Although it is possible to interact with these 3D models using joysticks and HMDs, the look and feel of the equipment is not realistic.

A more recent project also to simulate an electrical substation using VR is from Paludo et al. (2017). In this simulator, all equipment were 3D modelled according to a real substation in Brazil and all panels, buttons, switches, disconnectors and other equipment are interactable through motion controllers. Additionally, the learners must select the appropriate PPE and CPE according to the tasks he/she will perform. Moreover, a smart band can be used to monitor the stress level of the learners during the exercises with the simulator and then instructors can further analyze the performance of the learners through generated reports available on a Web-based system (Paludo, et al., 2017).

3 Material and methods

The simulators described in the previous section provide a useful and effective assistance for training electricians. However, none of them aims to train electricians to work in the electric power distribution network, its equipment and components (poles, insulators, cables, disconnectors, distribution transformers, among others). Moreover, none of them allows the electricians to experience common challenges encountered in their day-to-day work in the field. In addition, none of the simulators is multi-user or promotes effective collaboration among the electricians to solve problems. Therefore, the project described in this article proposes the development of a multi-user VR environment for the training of electricians to work in electric power distribution network from COPEL.

In order to understand the teaching and learning demands of both instructors and electricians, identify the "pains" of current trainings and in the electricians' routine, and how a multi-user VR environment can assist the trainings, unstructured interviews were conducted with electricians, safety specialists, instructors and engineers at the beginning of the project. Through these interviews, the importance of safety at work and the proper use of PPE and CPE became clear. Also, the participants of the interviews highlighted that it would be very nice and valuable to have a training that could encourage electricians to practice services that, in the field, have a high rate of accidents and/or cannot be exercised in the conventional trainings. In addition to the interviews, the authors of this paper attended a complete cable splicing training to observe how the current trainings take place and the teaching and learning strategies commonly utilized.

After the interviews and the attendance in the cable splicing training, a brainstorming meeting occurred with electricians and instructors to define what kind of exercises should be included into the proposed VR environment. As a result, the electricians and instructors chose a tree pruning exercise as the first one to implement. In this exercise, electricians should use a chainsaw and a truck with an elevator bucket to reach the branches of the tree that are in conflict with the cables of the distribution network, as this was a typical service with a higher accident rate compared to others.

To prospect demographic data and assess the opinions of electricians and instructors about current trainings and expectations for future trainings, an online questionnaire with open and closed questions was also applied, the latter using a 7-point Likert scale. The questionnaire aimed to understand the perceptions of electricians and instructors about current trainings (and expectations for future training), asking them to evaluate trainings as theoretical or practical, serious or fun, formal or informal, individual or collective, among others. Based on the responses from the questionnaire and the interviews carried out, it was possible to create personas for two representative users for the project: one for an electrician and another for an instructor.

For the development of the project, the Scrum agile framework was adopted with two-week sprints. Also, the Unity 3D game engine (Unity, 2023) was used and associated with the SteamVR plugin (Valve Corporation, 2021) to support VR. The following VR devices are currently supported by the project: Meta Quest 2 (Meta, 2020), HTC Vive (HTC, 2023) and Windows Mixed Reality/Lenovo Explorer (Lenovo, 2022).

The 3D models to represent both the components of the electric power distribution network and the urban scenario were created by a specialized 3D modelling team, based on photos, videos and technical specifications from equipment provided by COPEL. To summarize, 122 models were created. Also, it is worth to notice that every 4 months the 3D models that had been created were reviewed by electricians, instructors and safety specialists, who gave valuable feedback about their visual accuracy and useful hints. For example, when the truck was first modelled, the reviewers noticed that it was too clean, and some dirt on it would make it more realistic. Also, the truck didn't have the emergency lights, which was added to the model later.

To provide a high degree of realism and a feeling of immersion, gestures with motion controllers for interacting with objects present in the VR environment were implemented whenever they were feasible. For example, to start the chainsaw, a user needs to pull the engine's crank and, to cut some branches of a tree, a user must move the chainsaw to hit the branches. There are also gestures to expand and collapse the hot stick and to open and close switches attached to the poles in the virtual scenario by pulling and pushing them with the hot stick from a safe distance.

As the electricians always need to perform the services as a team, each one of them with a well-defined role (for example, in case of a pair of electricians, one will be the executor and the other the supervisor), communication between them in the proposed VR environment is mandatory. Therefore, a virtual radio accessible through a button from the motion controllers was implemented. Then, with that virtual radio, electricians can communicate and coordinate their actions during an exercise just like in real, work situations. The virtual radio makes sense when the electricians are not in the same room, but, instead, are remotely distributed.

Since the beginning of the development of the project, usability evaluations were applied to evaluate its main features, such as the locomotion mechanisms, the interaction with gestures, and the provided resource materials (videos, safety and best practices documentation) inside the VR environment. At first, usability evaluations were done through user tests. However, due to the new coronavirus pandemic and the corresponding sanitary restrictions, since March 2020 the researchers has applied Nielsen's heuristic evaluation (Nielsen, 1994). In short, usability tests were applied to evaluate locomotion mechanisms, gestures with the hot stick and with the chainsaw, and the navigation through the resource materials, whereas the heuristic evaluation was adopted to evaluate the visualization of documents and videos, environment settings and the communication between electricians. In total, 21 volunteers participated in the usability tests and 3 usability experts performed the heuristic evaluations. The major results of the usability tests results were published (Tanaka, et al., 2020).

It is worth noting that all volunteers formally accepted to participate in the surveys and usability tests, giving their acknowledgement of a Free Informed Consent Form (FICF). The FICF explained the objectives of the research and tests and that personal data would be kept confidential, the identity of the participants would be kept anonymous and that the test results would be used exclusively for the purposes of the project. In addition, the FICF reinforced that participation was voluntary and that participants could withdraw from continuing the research at any time.

Finally, in addition to the VR environment, it was implemented a Web-based Management System (WMS) to allow instructors to manage trainings and exercises to be done by a group of electricians and view reports of the execution of exercises, especially the performance of the electricians.

Figure 1 summarizes the architecture to run the whole project. The electrician's PC is a high-end Windows computer, with all the system requirements to support the usage of a HMD and to execute the proposed VR environment. The instructor's PC may be an ordinary computer, just to access WMS through a Web browser. The server's main roles are to host WMS, manage user authentication, handle exercise sessions and share technical documentation and videos among electricians and instructors. Once an exercise session begins, one of the electrician's PCs becomes the host of that session whereas the other electrician's PCs act as clients. When the exercise session finishes, data related to the exercise are sent from the host to the server so that an instructor can analyze the exercise reports provided by WMS.

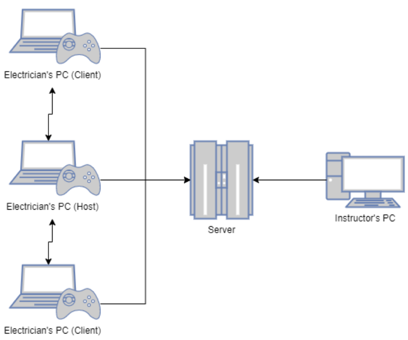

Figure 1. Overall architecture of the project.

It is important to highlight that the proposed architecture relies on network communication. More specifically, REST calls allow the server to communicate with the PCs (both from electricians and instructors) whereas the host-client communication between PCs of the electricians is done through Forge (Bearded Man Studios, Inc., 2022), a Unity 3D network library. Other important aspect to highlight is that, although the diagram on Figure 1 shows only a single host, the architecture support multiple hosts running different exercise sessions, which means that multiple teams can practice exercises at the same time. Moreover, the PCs may be remotely distributed – for example, an electrician may be in Curitiba, whereas his/her teammate is in Foz do Iguaçu, more than 500 kilometers away, but they are practicing the same exercise, each one with his/her HMD and PC connected on the network. Furthermore, the server and the instructor may even be in other locations.

4 Results

4.1 Questionnaires

Figures 2 to 7 show the results of the questionnaire applied among the electricians and instructors from COPEL to identify their perceptions of current trainings and what expectations they would have for future training. In total, 93 volunteers answered the questionnaire, of which 76 respondents were electricians.

Regarding the demographic profile of the respondents, it is interesting to notice that the majority of them is over 30 years old: adding up the age groups, 80.6% of the respondents said they were 31 years old or older, of which 20.4% are in the aged 41 to 50 and 9.7% aged 51 or over.

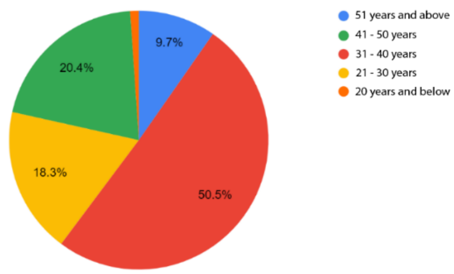

Figure 2. Age group of respondents.

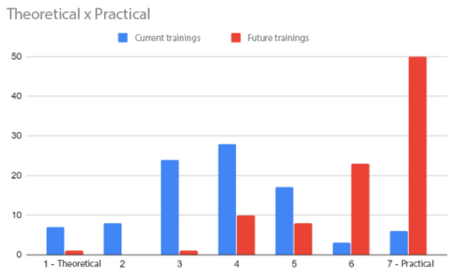

Figure 3. Vision of electricians and instructors about current and future trainings: theoretical x practical.

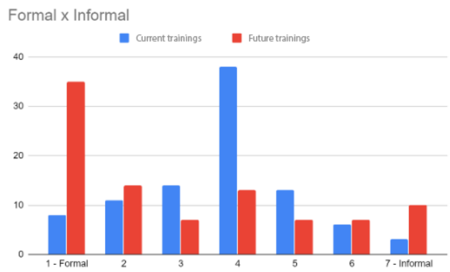

Figure 4. Vision of electricians and instructors about current and future trainings: formal x informal.

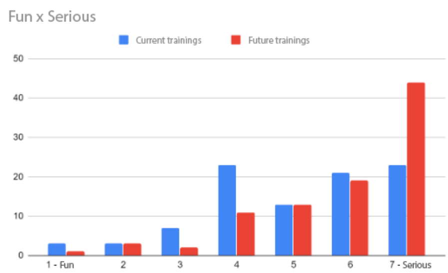

Figure 5. Vision of electricians and instructors about current and future trainings: fun x serious.

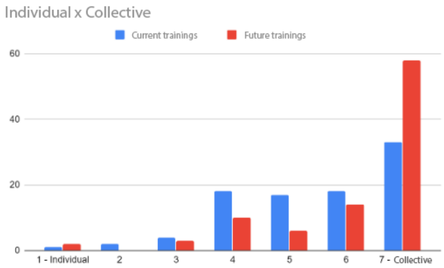

Figure 6. Vision of electricians and instructors about current and future trainings: individual x collective.

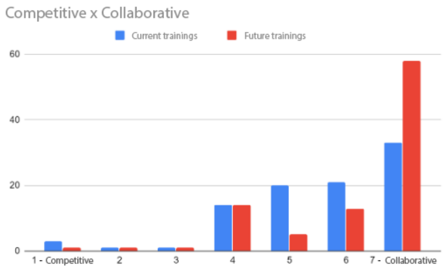

Figure 7. Vision of electricians and instructors about current and future trainings: competitive x collaborative.

Still, based on the results of the questionnaire, it is interesting to notice that the current trainings were considered balanced between theory and practice, but that respondents expected that, in the future, more practices should occur in the trainings, which reinforces the adoption of the proposed VR environment. Between serious and fun, the current trainings were evaluated as more serious than fun and so it was expected that they will continue this way in the future. Additionally, the respondents would like that the trainings continue to encourage collective and collaborative work, as they currently are.

According to the respondents, the major challenges in the current trainings are: “Make a training interesting” (38.7%), “Make a training a reliable source of research for electricians” (33.3%), “Increase the engagement of both electricians and instructors” (9.7%) and “Break the resistance of instructors to use new technologies” (8.6%).

4.2 Personas

Based on the unstructured interviews and the questionnaires, two personas were created for the project, as shown in Tables 1 and 2.

These personas were adopted so that the development team could easily understand the priorities of the items in the backlog according to the needs of the personas and, thus, help to understand how users will use the proposed VR environment. Additionally, these personas reflected a shared vision among all the researchers involved in the project about the main users of the proposed VR environment. To be more specific, every user story added to the development backlog was written using these personas to give to the development team and all stakeholders a clear view of the importance of the stories (and, consequently, of the related functional requirements to be implemented). Therefore, for the development team, having the personas in the user stories/backlog items to clarify how the proposed new functionalities would be useful to the users. And, for other stakeholders, such as the researchers of the project, the personas were a good way to always remember key aspects of the end users, so that suggestions of new features were always discussed and prioritized having in mind whether or not they would be valuable to these personas.

Table 1. Persona to represent electricians.

Samuel, electrician		
Age	Marital status	Job
41	Married	Field electrician
Major characteristics: Zealous, important to follow the rules Always aware at work and with safety Likes to learn and update his skills		
Frustrations: Repetitive training, “more of the same” Lack of practical activities in training I would like to more actively participate in training		
Biography: Since he was a child, Samuel has always been interested in electricity and was fascinated when he saw COPEL trucks in the neighborhood to perform maintenance on the distribution network. At the age of 20, Samuel decided to take an electrician course and never stopped. After working for a few years in private companies, Samuel was hired as an electric power distribution network electrician in 2009. Samuel is highly esteemed by his colleagues thanks to his organization and attention to rules and procedures. In fact, Samuel always warns them about risk factors at work. Also, Samuel takes advantage of each training to clear up doubts with the instructors and to learn more and more. However, Samuel thinks that training is scarce and there is often a short time for them, especially for practical activities.		

Table 2. Persona to represent instructors.

Marcos, instructor		
Age	Marital status	Job
45	Divorced	Instructor
Major characteristics: Self-taught Likes to share everything he learns Communicative		
Frustrations: Electricians not engaged in training Unable to plan different practical activities in training Short term training		
Biography: Marcos has been a low voltage electrician at COPEL since 2005, always acting in a precise, safe and efficient manner in all calls. Because of his positivity, his energy and his willingness to specialize more and more and to share his findings with his colleagues, Marcos was invited to become an instructor at the end of 2015. Since then, Marcos has been trying to improve his teaching-learning materials, but he lacks tools and resources to engage and encourage the active participation of electricians. Additionally, having already gone through a lot of training, Marcos understands when his groups of learners feel frustrated by		

the few practical activities actually carried out in training. To counterbalance, Marcos coordinates a WhatsApp group with his electrician classes to answer post-training questions.

4.3 Development of the VR environment

As mentioned before, the first exercise defined for the proposed VR environment was a tree pruning service in an urban scenario. Thus, the implemented scenario realistically represents a typical street of Brazilian cities, with houses, buildings, sidewalks, cars, traffic lights, traffic signs and trees. Among the elements of the electric power distribution network, 3D models were created for poles, crossheads, low and medium voltage cables, pulley-type insulators (for low voltage), pin- and anchor-type insulators (both for medium voltage) and fuse switches. Additionally, a truck with elevator bucket to access the network equipment and the tree branches. Moreover, the electricians' uniforms, PPE, and CPE required to perform activities with safety were modeled according to their real-world equivalents. The electricians and safety specialists who had contact with the proposed environment mentioned that all the 3D models were visually realistic, which, in fact, provides a great feeling of "being on a street with an aerial electric power distribution network". Figures 8 to 11 show some screenshots of the implemented VR environment.

Figure 8. An electrician and the truck with elevator bucket.

Figure 9. An electrician with PPE and the chainsaw, ready to prune a tree.

To practice the exercises in the proposed VR environment, similar to the real world, a team composed of two electricians is required according to the safety rules. Moreover, each of the electricians in a team must have a well-defined role: a supervisor, who is on the ground giving support, and an executor, who, from the elevator bucket, prune a tree or open or close the fuse switches, for example. In addition, each type of activity requires a set of specific PPE and CPE, such as a helmet, safety glasses, face shield, hearing protection, protective gloves, insulating gloves, safety harness with lanyard, signal cones, among others. For example, to prune a tree using the chainsaw in the elevator bucket, an electrician need to equip himself/herself with the following PPE:

- Helmet
- Safety glasses with grey lenses during daylight (or colorless lenses at night)
- Protective gloves
- Face shield
- Hearing protection
- Safety harness with lanyard

Figure 10. An electrician in the elevator bucket after a L-type prune, being watched by an instructor in observer mode.

Figure 11. Inventory screen to select PPE, CPE and other equipment.

The actions performed by the electricians in an exercise must follow a pre-defined sequence in accordance with manuals and procedures of safety work. For example, in the case of a tree pruning, electricians should perform the following actions:

1. Identify the tree to be pruned and check if there are potential risks that may prevent the pruning (for example, bees).
2. Fill the Preliminary Risk Assessment (PRA) form, to identify the possible risks when performing this task and what actions should be taken to mitigate these risks.
3. Wear the appropriate PPE, as mentioned before.
4. Isolate the working area with signaling cones.
5. While the executor goes up with the elevator bucket and use the chainsaw to select the region of the tree

to prune, the supervisor remains close to the truck to assist the executor.

6. After finishing the pruning task, collect the signaling cones back to the truck.

To provide a wide range of options, the tree to be pruned in the exercise may require one of the following types of pruning: an "L-type" on the left or right branches, a containment pruning on the top branches, a hole or a "V-type" on the middle of the tree. The correct type of pruning depends on how the low and medium voltage cables are passing through the tree branches. Thus, when accessing the branches, the electrician must select the correct region of the tree to perform the pruning and use the chainsaw to cut the branches in this region. In the event of an incorrect choice of region to be pruned, a record is made in the exercise log for later analysis by the instructors.

In addition to the tree pruning exercise, some other exercises have already been implemented: an exercise to open or close fuse switches using a hot stick and a tree cut exercise, which uses the chainsaw too but, in this case, the tree must be cut down in a countryside scenario.

Figure 12 shows a screenshot of an electrician performing the open fuse switches exercises whereas Figure 13 shows the electricians in the countryside scenario, preparing themselves for the tree cut exercise.

Figure 12. Electrician opening fuse switches in the elevator bucket.

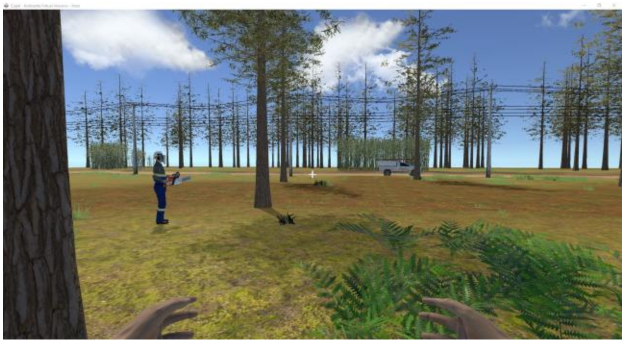

Figure 13. Countryside scenario for the tree cut exercise.

In all exercises, if inappropriate actions are performed, for example, an electrician opens a fuse switch during a service that only a tree pruning was required, or a required PPE or a CPE was missed during a task, a record is added to the log of the exercise that can be later assessed by an instructor. In addition to the record of failures in the exercises, the log of exercises also contains information about the time required to finish the exercise by the team.

To identify what kind of action would be a failure in an exercise, a penalty system was implemented based on the Life Protection Program (LPP) from COPEL. The LPP is an internal initiative conducted by COPEL to inspect, in the field, the correct adoption of technical and safety procedures, during the execution of the activities of electricians, in accordance with the standards of the Occupational Health and Safety Management area of COPEL. The major goal of LPP is to reduce the accident rates and severity among the electricians. Thus, sometimes LPP inspectors accompany the electricians in the field and fill a form/checklist with the technical and safety failures they found. Also, for each kind of failure, the form has a penalty score – the more severe the failure, the higher is the penalty. Additionally, LPP inspectors may suggest the electricians to take refresher trainings, depending on the failures in the field.

After discussions with electricians, instructors and safety specialists, the LPP form was adopted in the proposed VR environment too. In other words, the list of possible failures in the LPP form was converted as triggers in the proposed VR environment which generate penalties for the electricians. These penalties in the proposed VR environment are similar to the LPP and have the same scores, actually. Table 3 presents a summarized version of this penalty score implemented in the proposed VR environment and based on LPP.

Table 3. Penalty scores based on LPP.

Action	Individual/Team	Penalty
No supervisor in the team	Individual	-3
No communication with Distribution Operation Center (DOC)	Team	-7
Preliminary Risk Assessment (PRA) not performed	Team	-7
PRA incorrectly filled	Team	-3
Safety belt and lanyard not used	Individual	-21
Missed helmet	Individual	-7
Missed safety glasses	Individual	-7
Missed protective gloves	Individual	-7
Missed isolating gloves	Individual	-7
Missed PPE (others)	Individual	-1
Open/close fuse switches in the wrong sequence	Team	-3
Remain under suspended load	Individual	-3
Tasks not performed in pair	Individual	-1
Working area not properly isolated	Team	-3

In the field, an electrician who reaches out 21 penalty points in the LPP form may be immediately suspended from her/his activities and a refresher training may be mandatory to return to work in the field. Then, similarly, in the proposed VR environment, it was decided that reaching 21 penalty points in a single exercise should be considered a critical failure in the execution of the exercise so that the team shall start it again. Also, at the end of an exercise, if penalties were applied, a dialog shows to the electricians some hints about the faults.

As an example of how the penalty system was implemented, supposing that two electricians are performing the open fuse switches exercise. At the beginning of the exercise, one of the electricians fills the Preliminary Risk Assessment (PRA) form, but selects a task to be performed that doesn't have any relation with the open fuse switch. Then, when opening the fuse switches, the electrician who is the executor opens them in the incorrect order. As a result, the team will get two faults based on the LPP form (and on the penalty system of the proposed VR environment): PRA incorrectly filled (-3 points) and open/close fuse switches in the wrong sequence (-3 points). As the sum of the penalty points of these faults is lower than 21, the electricians are able to proceed with the exercise until they finish it. However, at the end of the exercise, a dialog will show a hint to pay attention when filling the PRA and to open the fuse switches in the proper order. Figure 14 shows that dialog confirming that the exercise was successfully finished and presenting the hints related to the faults happened during the exercise.

Supposing another example of two electricians performing a tree pruning exercise, but, when jumping into the elevator bucket the executor is not wearing the safety belt and lanyard. According to the LPP and the penalty system, this fault itself generates a 21 points penalty. Then, the exercise immediately interrupts and a dialog shows some safety hints to remember the electricians to use the proper PPE. Figure 15 shows an example of that dialog.

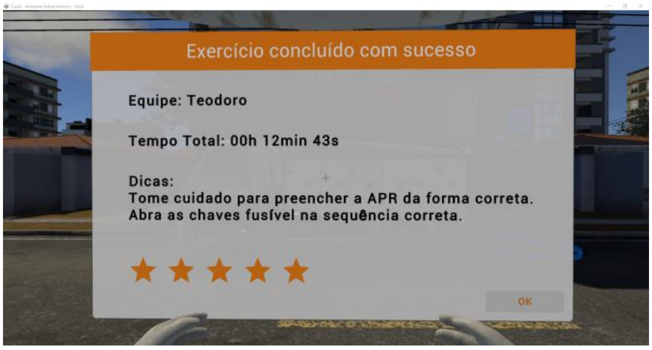

Figure 14. A sample dialog that is shown when the exercise is successfully finished but giving advices to prevent the faults.

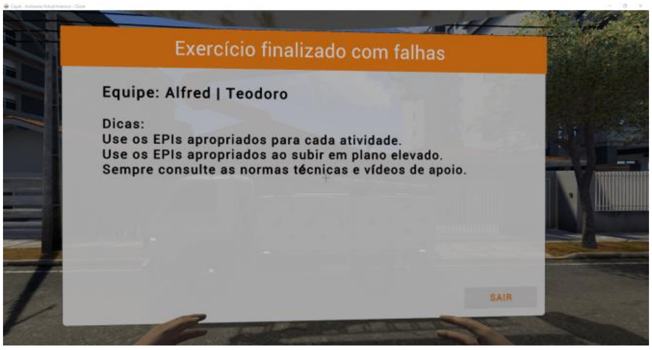

Figure 15. A sample dialog that is shown when the exercise is not successfully finished.

In addition to the penalty score and the exercise logs, instructors can monitor the execution of exercises in real time through the observer mode, as illustrated in Figure 10. In observer mode, instructors can "follow" one of the electricians in the exercise or even navigate through the exercise.

In order to offer even more realism and variables to the exercises, the proposed VR environment also provides different temporal and weather conditions. In other words, the exercises can be performed during the day or at night, in firm weather, with light rain, heavy rain or fog. And those temporal and weather conditions may influence the exercises. For example, a tree pruning can be done during the day with light rain or fog, but not with heavy rain or at night. Thus, at the beginning of an exercise, electricians must evaluate and decide if the required service can be done based on the weather and temporal conditions. If it can not be done, the electricians must inform the Distribution Operation Center (DOC).

Also, some weather conditions may require special PPE when the exercise can be done. For example, in the tree pruning exercise with light rain during the day, the raincoat is a mandatory PPE. If the raincoat is not wore by an electrician, and according to the LPP form and the penalty system, that electrician will get a -1 penalty point – missed PPE (others).

One of the identified difficulties in the usage of the proposed VR environment was the communication between the electricians, the DOC and the Virtual Instructor (IV) – this last one acts as an assistant and gives some hints about what needs to be done in the exercise. To produce the radio voices of electricians, DOC and IV, a free text-to-speech service was adopted. However, there was only one male voice for Brazilian Portuguese and that was applied to electricians, DOC and IV. Therefore, it was a bit difficult to identify who was talking. Thus, after a survey carried out with electricians on the acceptance of the usage of female voices, it was decided to adopt different female voices for the COD and IV and to keep the male voice for the electricians, making it easier to identify DOC, IV and electricians via radio.

Finally, as the majority of electricians and instructors have never used HMDs, a set of tutorial videos were recorded to present the main features of the proposed VR environment and how to use the motion controllers to locomotion and to perform the gestures with the equipment (especially the chainsaw and the hot stick). As these tutorial videos are intended for the electricians and instructors to learn about proposed VR environment, they were published on the Web and can be retrieved both on desktop computers and on smartphones. Figure 16 shows how the tutorial videos look like on a smartphone screen. For simplicity, only portrait view is shown on this paper, but the videos can be watched on landscape orientation as well.

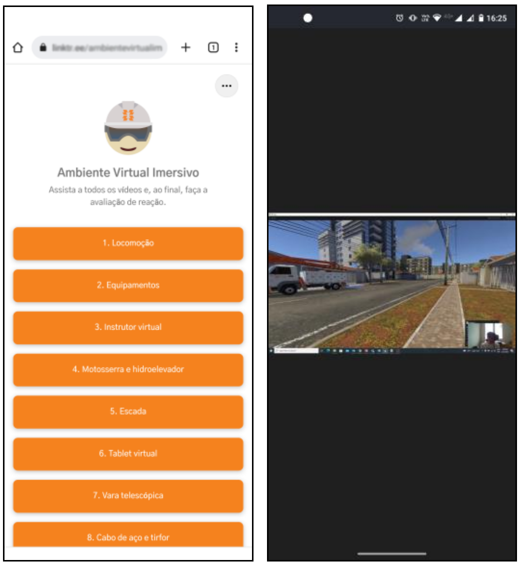

Figure 16. Screenshots of the tutorial videos provided.

To allow the instructors to manage trainings in the proposed VR environment, a Web-based Management System (WMS) was also developed. With the WMS, an instructor can manage the teams of electricians, create trainings (i.e., a list of exercises to be done by the teams), and check performance reports of the teams or individuals.

To create a training in the WMS, an instructor must select the exercises he/she wants that the teams try in the proposed VR environment. And each exercise provide settings to select the weather conditions and also the period of the day (day or night). Figure 17 shows a list of trainings created on the WMS. It is also possible to view in the same figure the weather condition and the period of the day for each exercise.

After a training was created in WMS, it can be assigned to teams of electricians. Then, next time the electricians log into the proposed VR environment, they will see the corresponding available exercises. And, once they perform the exercises, the logs will be registered and can be visualized on the reports provided on the WMS. Several reports are provided on the WMS: by trainings, by exercises, by electrician or by team. And all the reports can be exported as PDF files.

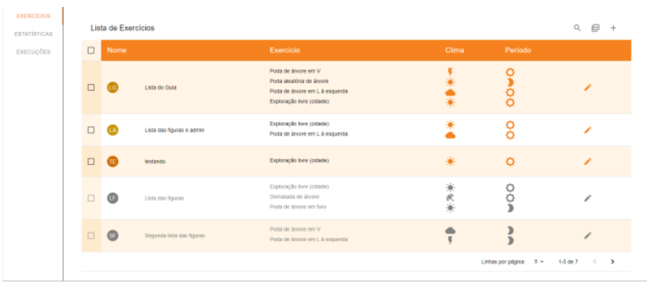

Figure 17. Trainings on the Web-based system.

Figure 18 shows a report of tries of exercises by teams. In this report, an instructor can view details of exercises tries: the teams, date, time to conclude the exercise, weather condition and period of the day set for the exercises and the number of faults. Figure 19 shows an individual performance report. For this report, an instructor and view all exercises tried by an electrician, check the role (supervisor or executor) it performed for each exercise, weather condition and period of the day that was set for each exercise. Also, in case of faults, it is possible to see the log of the exercise and view what kind of fault was committed by the electrician and the applied penalty. In Figure 19, it is possible to see that the electrician had a single fault in the "V-type" tree pruning exercise: missed the safety glasses, which implied a -7 point penalty.

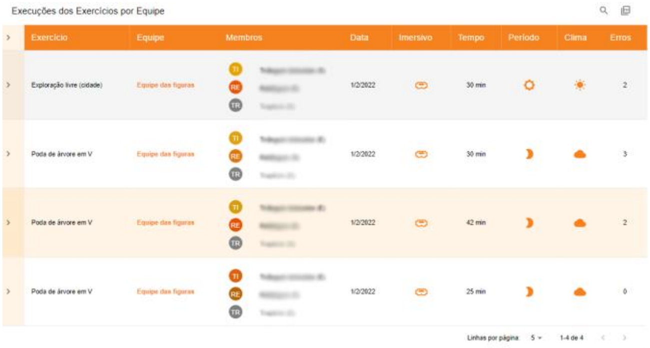

Figure 18. Report of tries of exercises by teams on the Web-based system.

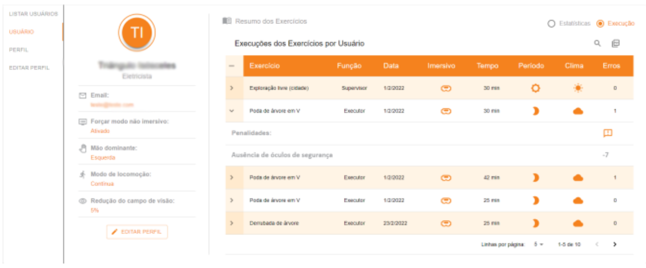

Figure 19. Report of the tries of exercises performed by an electrician on the Web-based system.

With all the information provided in the reports of exercises and trainings, an instructor can identify common mistakes done by the electricians when performing specific actions, if some tasks are taking longer than expected, if the electricians are wearing the proper/expected PPE to perform the actions, and others. In fact, when reviewing these reports with instructors and safety specialists, they highlighted the usefulness of them and that, the results included into these reports could assist instructors to take effective actions in their current trainings to avoid mistakes in the field and to promote safety campaigns that prevent common faults committed by the electricians.

4.4 Usability evaluations

According to the Meta Quest best practices (Meta, 2023), locomotion is one of the most difficult feature to implement in a VR environment and one of the most important to do it well. Otherwise, even the most familiar and experienced VR users may experience discomfort and motion sickness. The same document highlights the importance of carrying out user tests of any proposal for locomotion in a VR environment.

With this in mind, user tests were carried out with 21 volunteers throughout the project to evaluate different methods of locomotion in VR. Detailed results are available in a previous paper (Tanaka, et al., 2020). In short, from these user tests, it was decided to adopt locomotion mechanisms: continuous locomotion with reduced field of view and discrete locomotion, also known as teleportation.

Continuous locomotion is the most traditional method of locomotion in first-person games: through the analog sticks of the motion controllers, users can move forward, backward and sideways, in addition to rotate the user's camera. More specifically, while one of the analog sticks is pressed to one side, the user moves or rotates his/her virtual body to that side continuously. As this type of locomotion causes motion sickness in VR very frequently (White & Stevens, 2018), different approaches can be adopted to mitigate motion sickness and one of them is the reduction of the field of view (Fernandes & Feiner, 2016), which simply adds black borders around the user camera, reducing the field of view to a smaller circle. With this approach, the visual stimuli in the user's peripheral vision are reduced and, therefore, the brain registers smaller discrepancies in the virtual movement and there is a lower tendency for motion sickness during locomotion.

Discrete locomotion or teleportation is performed as follows: the user launches a bolt or arc forward, in front of it, and at the point where the bolt or arc strikes a surface, the user can be immediately and directly transported to it. Despite solving the problem of motion sickness in VR environments by simply eliminating the continuous movement of the camera, one of the main criticisms of teleportation is that it generates a break of locomotion, compromising the feeling of immersion (Boletsis & Cedergre, 2019).

The decision to adopt both continuous locomotion with reduced field of view and discrete locomotion was due to the fact that, in the user tests, discrete locomotion resulted in lower levels of discomfort compared to continuous locomotion. However, according to the participants of the user tests, continuous locomotion was easier to use.

Additionally, knowing that a HMD and motion controllers may not be available to all users and that there are users who are more sensitive to locomotion in VR environments, no matter the efforts to improve locomotion methods to avoid nausea and discomfort, the proposed environment also allows the use in non-immersive mode with a monitor, a keyboard and a mouse or a conventional gamepad.

Another usability test carried out was to evaluate the gestures with the chainsaw (turn on and turn off the chainsaw, accelerate and cut out branches of a tree using the chainsaw) and with the hot stick (expand a section, collapse a section, open and close fuse switches in the aerial network). For this test of the gestures, four volunteers were recruited and the objective was to identify the most comfortable way to perform the gestures: standing or sitting. Thus, users were asked to perform a tree pruning exercise, and open and close fuse switches while standing and sitting, and then answering a satisfaction questionnaire. Figure 20 and Figure 21 show the responses to the questionnaire.

Figure 20. User preference of the chainsaw.

Figure 21. User preference of the hot stick.

From the results found on the usage of the chainsaw, it is noted that there were identical results when performing the tasks sitting and standing for the first three criteria (ease of pruning, time spent x errors, collisions with objects in the real world). In addition, participants did not complain of tiredness in either mode, sitting or standing. However, the incidence of motion sickness was higher with users standing than sitting.

Among the comments made by the participants about the tree pruning with the chainsaw, one that is worth to notice was the usage of the elevator bucket to go up. Two participants described that the vertical movement of the elevator bucket when they were standing caused some discomfort.

Interactions with the hot stick had the highest incidence of negative responses in the questionnaires answered by the participants. The gestures to open and close the fuse switches were considered a difficult task and the participants made mistakes. Also, it was not a task that they could complete quickly, both sitting and standing. In addition, the gestures performed caused fatigue in the participants in both modes (sitting and standing). However, nausea was not observed by the participants in any of the modes.

Possibly, the interactions of opening and closing the fuse switches were difficult because they were performed on the ground in the VR environment, at a considerable distance between the user and the fuse switches in the aerial network. More specifically, these gestures required a great precision of movements in the motion controllers to, first, select a fuse switch and, second, pulling or pushing the fuse switch to open or close it, respectively. In fact, two participants commented that it was very difficult to interact with the fuse switches while on the ground. Thus, if the distance were reduced (for example, the user being on top of the ladder or in the elevator bucket of the truck), these difficulties could be minimized. Also, according to the development team's analysis, relaxing certain implementation rules established to identify whether the user wants to open or close a fuse switch (such as identifying the gesture speed, the height of the hot stick tip, among others), could make it easier to perform these interactions with the fuse switches in an aerial network.

Finally, the last usability evaluation carried out was the heuristic evaluation of the virtual tablet with which electricians access applications to configure the VR environment, COPEL safety and technical standards documents, take pictures, watch videos with safety hints, fill a Preliminary Risk Assessment (PRA) form, among others. Figure 22, Figure 23 and Figure 24 show some virtual tablet screenshots.

Figure 22. Virtual Tablet main screen.

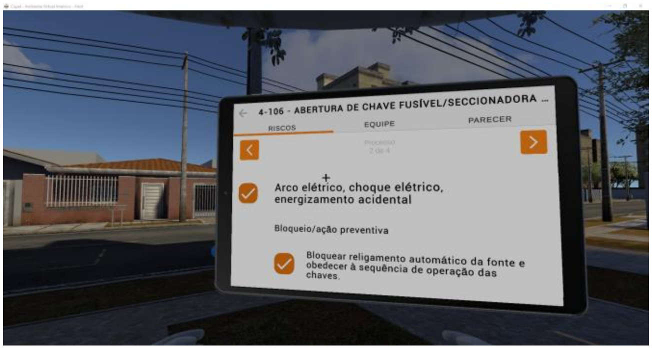

Figure 23. Filling the PRA form in the Virtual Tablet.

Figure 24. Viewing a safety document in the Virtual Tablet.

In total, 19 usability issues were found in the virtual tablet by the usability evaluators. Table 4 presents the number of problems according to the severity ratings.

From the problems classified as “Major” (with severity rating = 3), some are worth to notice. One of them is the impossibility of using the mouse wheel to scroll on the virtual tablet screens, violating the heuristics of Consistency and standards and Flexibility and efficiency of use. Other one was the impossibility of drag-and-drop the cursor of the video player, also violating the heuristics of Consistency and standards and Flexibility and efficiency of use. Some others were the absence of a search function for technical standards documents, violating the heuristics of Flexibility and efficiency of use and Recognition in instead of memorization, and the difficulty and inaccuracy of pressing small buttons on the virtual tablet screen, violating Error Prevention heuristics.

Table 4. Usability problems found in the virtual tablet according to the severity ratings.

Severity ratings	Occurences
0 - Not important - Does not affect interface usage	0
1 - Cosmetic	3
2 - Minor - Low priority problem	7
3 - Major - High priority problem	9
4 - Catastrophe - very serious	0

It is worth to notice that, among the problems found in the heuristic evaluation, seven have already been fixed (of these, three were of severity rating = 3) and the others have already been mapped to be fixed in the next sprints of the development team.

5 Concluding remarks

This paper presented a multi-user VR environment to train electricians to work in electric power distribution networks. The proposed environment has two realistic scenario, one representing a typical street of Brazilian cities and other a countryside road. Also, in both scenarios, there are elements that constitute a typical aerial distribution network, such as poles, crossheads, low and medium voltage cables, fuse switches, insulators, among others. In these scenarios, electricians can practice tree pruning, tree cut, open and close fuse switches.

The feedback from instructors and electricians so far points out that, with the proposed VR environment, it will be possible to practice exercises that cannot be performed very often in the current trainings, but that are part of the routine of electricians in the field. Additionally, the proposed VR environment makes it possible to exercise in different temporal and weather conditions, such as rain and/or at night. Therefore, it is expected that the proposed VR environment can improve the current trainings, enabling electricians to practice situations that frequently cannot be experienced in the current trainings. Moreover, it is also expected to improve the quality of service provided by electricians and reduce the accident rates. And, to assist instructors to identify common mistakes and safety faults, the WMS provides useful reports containing details about the performance of the electricians in the exercises.

It is worth mentioning that, based on the positive comments of electricians and instructors, the proposed VR environment “looks like a video game” and this fact has stimulated everyone's curiosity to participate more and more in the project's research and engage the usage of the proposed VR environment by more and more COPEL electricians, instructors, technicians and engineers.

In addition to use the proposed VR environment for training electricians, COPEL's corporate education professionals who were part of the research team of the project raised the possibility of using screens captured from the virtual scenarios to enhance other materials adopted in training, such as slideshow presentations. Furthermore, the instructors themselves, using the simulator in non-immersive mode, can demonstrate through a big screen in an ordinary classroom how certain procedures must be performed.

Finally, among the future works, new exercises to the proposed VR environment are planned, by including other equipment of the electric power distribution network (for example, a fuse saver) and new scenarios to explore other components of the electric power distribution network that are not aerial, specially the underground network which usage is growing in big cities like Curitiba. Also, the authors are investigating gamification elements (rankings, badges, and others) to increase the motivation and engagement of electricians with trainings using the proposed VR environment, and additional usability studies may be conducted to evaluate the both the penalty system based on LPP and the WMS reports.

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