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ORIGINAL ARTICLE

Virtual reality training system for maintenance and operation of high-voltage overhead power lines

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Abstract The maintenance of high-voltage overhead power lines involves high-risk procedures; the accidents involving live lines maintenance can be lethal. This paper presents the architecture and main features of a novel non-immersive virtual reality training system for maintenance of high-voltage overhead power lines. The general aim of this work was to provide electric utilities a suitable workforce training system to train and to certify operators working in complex and unsafe environments. The developed system has three components: the virtual warehouse, interactive 3D environments, and a learning management system. The workforce training system consists of thirty-one maintenance maneuvers, including the application of different techniques and equipment designed for various structures. Additionally, the system, using 3D animations, illustrates the safety conditions required before starting the maintenance procedures. To fit the worker's different skill levels, the system has three operation modes: learning, practice, and evaluation, which can be accessed according to the trainee's level of knowledge. The system is currently used to train thousands of overhead power lines operators of an electric utility in Mexico. The system has demonstrated to be a cost-effective tool for transferring skills and knowledge to new workers while reducing the time and money invested in their training.

Keywords E-learning · Interactive training · Virtual reality · Power distribution systems · High-voltage overhead power lines maintenance

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1 Introduction

Electricity is a key element in modern society, supporting the cultural and industrial development. Lack of electricity has a high impact on the economy and society. Electricity utilities are responsible for generating, transmitting, and distributing electricity to users. To ensure a continuous supply of electricity, the electricity utilities must have efficient operation and maintenance procedures. Electricity distribution is carried out by means of power lines; these lines require an adequate and timely inspection and maintenance. The maintenance of overhead power lines involves high-risk tasks; accidents involving live lines maintenance can be lethal. In order to reduce the risk and avoid damage to the equipment and personnel, it is important to have a well-trained and highly skilled workforce, so the tasks are performed safely and efficiently in such dangerous environment.

Personnel maintaining and operating overhead power lines (OPL) require a higher level of qualification than those working with underground power lines due to the higher risks associated with the maintenance of high-voltage aerial distribution networks. Some of the inherited issues of OPLs are associated with the aging of facilities, insulation failure, and corona discharge. Even though failures in aerial installations are faster to locate and to be repaired than in underground lines, overhead transmission lines have important disadvantages, where the main problem is the high percentage of outages attributed to them. Additionally, overhead line service interruptions are usually caused by external factors such as weather and vegetation.

The rapid population growth and new real estate developments have put huge pressure over the electric utilities. Companies need to hire constantly new inexperienced people to cover the constant increase in electricity demand while maintaining low the percentage of customer minutes off-supply (CMOS) (Engström 2007). Furthermore, electric utilities need to maintain the knowledge of their current workforce updated for operating and maintaining new accessories and equipment. Training of overhead power line operators is an important problem faced by distribution power utilities. For safety and efficiency reasons, to train operators in the dangerous real-world environment is not recommended. Hence, power line operators need to be trained in a simulated work environment which needs to be as realistic as possible. To be effective, the computer-aided training systems require useful user interfaces and better adaptive training methods that can be achieved by incorporating artificial intelligence (AI) algorithms, multimedia, and virtual reality (Gallagher and Cates 2004; Hamilton et al. 2002; Seymour 2008; Seymour et al. 2002).

The application of virtual reality (VR) systems in training processes has demonstrated to be an important and appropriate technology. Many VR-based training applications have been developed. These applications include training for medical surgery (Rosen 1996; Tang et al. 2007; Zhang et al. 2003), manufacture (El-Chaar et al. 2011; Guobin et al. 2010; Wu and Fei 2011), construction (Chun et al. 2008; Blackledge et al. 2011; Webster et al. 1996), teleoperation (Freund and Rossmann 1999; Ou et al. 2002; Shaoqiang et al. 2007; Tang et al. 2009; Tao et al. 2011), military (da Silva Simoes and Ferreira 2011; Moshell 1993; Mukherjee and Tapaswi 2006; Rizzo et al. 2011; Shiau et al. 2007), and power systems (Angelov and Styczynski 2007; Arendarski et al. 2008; Baeta Miranda 2010; Breen Jr and Scott 1995; Coutaz 1987; de Sousa et al. 2010; Feng and Cheng 2009; Galvan et al. 2010; Garant et al. 1995; Kriz et al. 2010; Li et al. 2003; Matsubara and Yamasaki 2002; Mól et al. 2009; Park et al. 2006; Romero et al. 2008; Shaikh et al. 1995; Tam et al. 1998, 1999). VR technologies provide synthetic representations of the real world in which several procedures can be simulated. The use of VR systems tends to be a cheaper and safer solution against previous training methods (Galvan et al. 2010; Kozak et al. 1993). Interactive 3D VR-based training simulators seem to be a more natural learning media than plain documents, blueprints, or fixed videos (Gallagher and Cates 2004; Hamilton et al. 2002; Seymour 2008; Seymour et al. 2002).

This paper describes the development of a non-immersive virtual reality training system for workforce training of the operators of high-voltage overhead power lines. The system was developed for teaching thirty-one different maintenance procedures for high-voltage distribution networks. Section 2 presents a contextualization of VR and its application in the training process for industrial maintenance. Section 3 describes the maintenance of high-tension power lines. Section 4 describes the architecture of the virtual reality training system. Section 5 shows the results of the experiment we design to measure the effectiveness of workforce training using our VR approach. Section 6 presents a case study and the advantages found with the implementation of the system in an electric utility. Finally, Sect. 7 enumerates the conclusions and future works.

2 Virtual reality and its application in training processes

Virtual reality aims to eliminate interaction barriers between users and computer systems. In addition, it attempts to stimulate human senses in order to give an impression of presence inside a 3D computer-generated synthetic environment. Virtual reality can be classified in two groups: non-immersive desktop-based VR and immersive VR. Immersive VR requires head mounted displays, tracking systems, interaction devices such as data gloves or joysticks and multi directional thread mills (Souman et al. 2011) coupled with advanced visualization systems like the cave automatic virtual environment (CAVE; Cruz-Neira et al. 1992). Those special interface devices isolate users from the physical world and provide a deeper sense of presence and immersion. In spite of the fact that immersive application offers a high level of interactivity and realism, nevertheless it requires advanced hardware and software for its implementation. The cost of using professional immersive hardware limits its use in various applications, inhibiting its popularity (Pantelidis 1997). Moreover, the ergonomics and price of such advanced devices remain a great problem that prevents the use of immersive VR in a widely accepted tool within companies (Kozak et al. 1993). Non-immersive desktop-based VR is the most common and inexpensive form of VR, it typically consists of a standard computer screen for visualization and common input devices such as mouse, keyboard, and joysticks for interaction.

Traditional training methods require that workers leave their duties and travel to special training centers located sometimes far away from work place. The latter involves huge costs of transportation and subsistence allowance expenses. There are further motivations and requirements for the search of new innovative workforce training techniques. The following are the most important:

- The urge of a training system that can be integrated into the work environment without the need to travel;
- The need for adaptive training methods to fit different skill levels;
- The need for standardized workforce training procedures within nationwide companies;
- It is imperative for companies the implementation of a flexible training system that can be used anywhere and anytime;
- The need for a fair assessment of the knowledge for certifying workers based on competencies;
- The importance of having standardized maintenance procedures and vocabulary across the country.

Virtual environments have demonstrated potential in the training sector because they offer an approach in which the modern demands of workforce training and the requisites mentioned before can be integrated into one single application. Some important reasons for using non-immersive virtual reality training systems (VRTS) in industrial maintenance are listed below:

- They provide the opportunity of using 3D environments to catch user's attention;
- Little to no-learning-curve;
- They can illustrate some features more accurately since they allow close-up examination of objects;
- Allow trainees to proceed through a procedure at his/her own pace;
- Provide multiple levels of interaction, encouraging participation rather than passivity;
- Allow trainees to explore tools and equipment that would be inaccessible or dangerous otherwise.

2.1 Previous work

There are some researchers that have developed VR-based training applications for the electric power industry. de Sousa et al. (2010) developed a VR training system for maintenance and operation of a hydroelectric energy unit. In their work, they designed a desktop-based application allowing users to train in different modes accessed according to the acquired degree of knowledge. Similarly, research has been done for assessing the effectiveness of VR vocational training when dealing with maintenance, repairs, and diagnostics of complex machines such as transformers and generators in substations (Arendarski et al. 2008; Coutaz 1987; Feng and Cheng 2009; Romero et al. 2008). Other VR training applications have been developed for maintenance of medium-voltage live overhead lines (Galvan et al. 2010; Park et al. 2006), simulation of nuclear power plants for dose assessment (Mól et al. 2009), and operation of control rooms (Coutaz 1987; Feng and Cheng 2009; Matsubara and Yamasaki 2002).

Based on our own previous VR effectiveness studies (Israel et al. 2001, 2011; Pérez et al. 2004), we decided to develop the VR training system for maintenance and operation of high-voltage power lines as a non-immersive desktop-based VR application because it was crucial that the workforce training system was available to trainees at their workplace at any time, or even that the system could be accessed from home. An immersive approach would have had as a consequence, the need to build and operate expensive special facilities at each work place.

3 Maintenance of high-voltage overhead power lines

Electricity distribution belongs to the final stage in the delivery of electricity to end users. A distribution network transforms the extra high voltages from the transmission system into the different voltages required by clients. Distribution substations deliver the energy to different individual customers such as sub-transmission customers requiring high voltage, primary customers using voltages ranging from 4 to 13 kV, and secondary customers which are small business and homes using 120 or 240 V. Typically, the network is divided into sub-transmission lines carrying high voltage from 26 to 150 kV between substations, medium voltage from 1 to 30 kV, and low-voltage distribution wiring.

This work focuses on the maintenance of high-voltage sub-transmission facilities, involving working at heights ranging from 50 to 165 ft and requiring the manipulation of heavy equipment. Usually, the maintenance procedures are scheduled in advance, except for contingencies. Linemen repairing malfunctions in the network have to travel to the failure location by different means. Sometimes, high-voltage structures are in inhospitable places, and therefore, workers are forced to walk, and carry heavy equipment. Once linemen are in the work area, they must conduct a security inspection to verify the status of the facilities, and then plan the activities to be performed to carry out the maintenance in a safe way. Some of the commonly performed maintenance maneuvers are:

- Insulator string substitution;
- Lead wire repair;
- Replacement of a damaged structure;
- Installation of accessories like fuses, arresters, and shock absorbers.

The required steps and security preconditions to perform a maintenance maneuver vary according to four main factors:

3.1 The type and configuration of the structure

There are three main types of structures for high-voltage electricity transmission in distribution networks: H-type poles, steel towers, and tapered steel poles. The first two structures are used in rural areas and the last one in urban areas. All structures carry the cable using two main insulator configurations: suspension string and strain insulator. The maintenance work is planned depending on the characteristics of the structure (see Fig. 1).

3.2 The maintenance technique

In the procedure known as bare hand method, the linemen use a conductive suit (see Fig. 2a). The hot stick technique involves the use of specialized tools for live lines called hot sticks (see Fig. 2b). The bare hand technique is often faster since the linemen manipulate the elements with their own hands, but it is riskier because the linemen's suit is raised to the same electric potential as the energized line. Therefore, it is imperative for the workers to stay away from parts at a different potential.

On the other hand, the use of a hot stick is safer because it is fully isolated and prevents the linemen from infringing the minimum clearance distances. However, the operation is more complicated since it has to be performed from several meters away.

3.3 The available climbing equipment

Most often, structures are climbed using their steps, or ropes, or cranes, or even helicopters (see Fig. 3).

3.4 Different work tools

The same goal may be achieved using different work tools, for example, a lineman can hold an insulator string with a line fitting yoke plate, a lever chain hoist, or a rigging tool. Each tool has a different functionality and consequently a different procedure has to be performed.

As it can be seen, maintenance maneuvers besides being dangerous are too varied. For example, the procedure of *changing the insulator string on a suspension type steel tower* can be performed by climbing the structure's steps and then using a line fitting yoke plate. Similarly, this same procedure can be performed with the bare hand technique on a crane basket. An experienced lineman should know all the available combinations and possibilities in order to make good decisions and perform his job in a safer and practical way.

4 Main components, interaction, and system architecture

This section describes the main features and architecture of the 3D workforce training system for maintenance of energized high-voltage power lines (ALEn^{3D} AT). ALEn^{3D} AT is composed of two applications: The first one is a

Fig. 1 Structures for high-voltage electricity distribution: steel tower, tapered steel pole, H-type structure

Fig. 2 Different maintenance techniques: **a** bare hand technique and **b** hot stick technique

Fig. 3 The maneuvers can be done using different climbing equipment

desktop-based VRWTS, and the second one is a Web-based application called AdminWeb (see Fig. 4). The Web application was designed to manage, among other things, information of trainees and metadata of the maintenance procedures. The VRWTS application has two components: the virtual warehouse and the interactive 3D environments, which were designed using a learning approach based on practice (Hillier 2009).

The system is intended to be used by adults with no previous computer skills. Therefore, the GUI has to be intuitive, easy to use, and include the proper terminology.

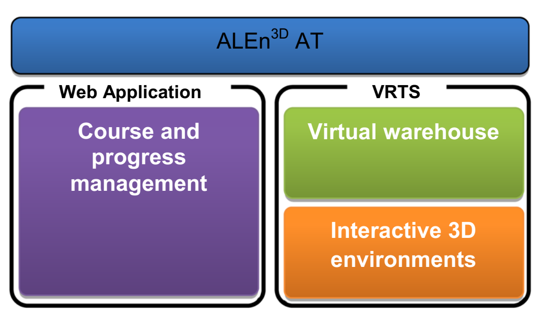


Fig. 4 ALEn^{3D} AT main components

In order to help users to quickly familiarize with the system, all buttons include images that resemble tasks of real-life tools. The graphical user interface is designed taking into account principles of design human–computer interaction (Helander et al. 1997).

4.1 Virtual warehouse

The system includes an interactive virtual warehouse (VW) categorized by equipment, tools, and construction hardware. The virtual warehouse can be utilized by trainees for familiarizing with the equipment without having to visit the actual warehouse, and therefore, it helps to reduce the time spent on training. The VW offers interactive visualization of equipment, allowing zooming and deep exploration of items. Additionally, users can study the detailed operation of components. Technical information, mode of operation, and specifications of each piece are presented to the user (see Fig. 5).

4.2 Interactive 3D environments

By using interactive 3D environments, ALEn^{3D} AT teaches the correct development of maintenance procedures (also known as maneuvers) step by step. The virtual environments are reinforced by current step objectives, contextual information providing knowledge about the procedure shown in the 3D scene, altogether with instructions that aid self-training. Moreover, the system includes additional information regarding an alternative valid procedure, or hints written by experts; this information is available on demand.

The user interaction tasks are divided into three categories: navigation, selection/manipulation, and system control. In ALEn3D AT, these three interaction categories are performed using mouse, keyboard, windows, menus, and icons, which are the standard parts of traditional WIMP interfaces. We do not want the users to waste time figuring out how to manipulate complicated 3D input devices, which is why ALEn^{3D} AT implements widely known WIMP interfaces. We do not want to confound the apprentices navigating inside a real-world limited space, while activities in the virtual world are carried out at different altitudes and involving several workers. Maintenance procedures in OPL integrate the work of several linemen, and all these tasks are represented in ALEn^{3D} AT using multiple virtual cameras and considering the different roles. ALEn^{3D} AT focuses on the importance of cognitive immersion by creating detailed, context-driven virtual environments that integrate environmental sounds and encourage participation for stimulating user senses.

Final users were involved in the cycle of assessing, designing, developing, and validating ALEn^{3D} AT. A process of user-centered design was performed to gain better knowledge of subjects, their needs, expectations, skills, and abilities, and thus develop a proper and useful workforce training tool (see Fig. 6).

The interface has four main interactive elements: information and instructions of the current step in execution, buttons to access security and standard operations,

Fig. 5 Elements of the virtual warehouse

Fig. 6 Workforce training using our non-immersive virtual reality approach

equipment menu, and the 3D interactive canvas (see Fig. 7). When the user clicks a valid 3D element, an animation shows the way the elements have to be installed, how to operate equipment, and the correct location of participants. To fit for different learning styles, the information in ALEn^{3D} AT is presented in both forms: written and audio (Dunn et al. 1989). The virtual scene also contains environmental sound to enhance realism, and each item in the scene has a tooltip with its corresponding standardized name. Depending on their skill level, users can access the different modes of operation: learning, practice, and evaluation. Each mode offers the users different levels of aid and difficulty. The learning mode offers users help, hints, and contextual information about standards. The learning mode guides users to follow a strict sequence of steps and does not allow to skip any part of the procedure. The practice mode offers help and allows the users to move and explore freely along the maintenance procedure. Finally, the evaluation mode requires the user to be more skilled in the maneuvers and offers no help or instructions. The evaluation mode also keeps track and records user errors, when users are enrolled in official courses.

4.3 Course and progress management (AdminWeb)

Along with the desktop-based VRWTS application, ALEn^{3D} AT also provides a Web-based application called AdminWeb (see Fig. 8). The AdminWeb features are similar to those of a learning management system (LMS), except that AdminWeb does not manage material resources or communication services; the system is oriented to administrate courses, trainees, and instructors. Unlike a traditional LMS, AdminWeb allows the creation of content; specifically, it permits instructors to design examinations that can be used later in courses.

Fig. 7 Elements of the interactive 3D virtual environments

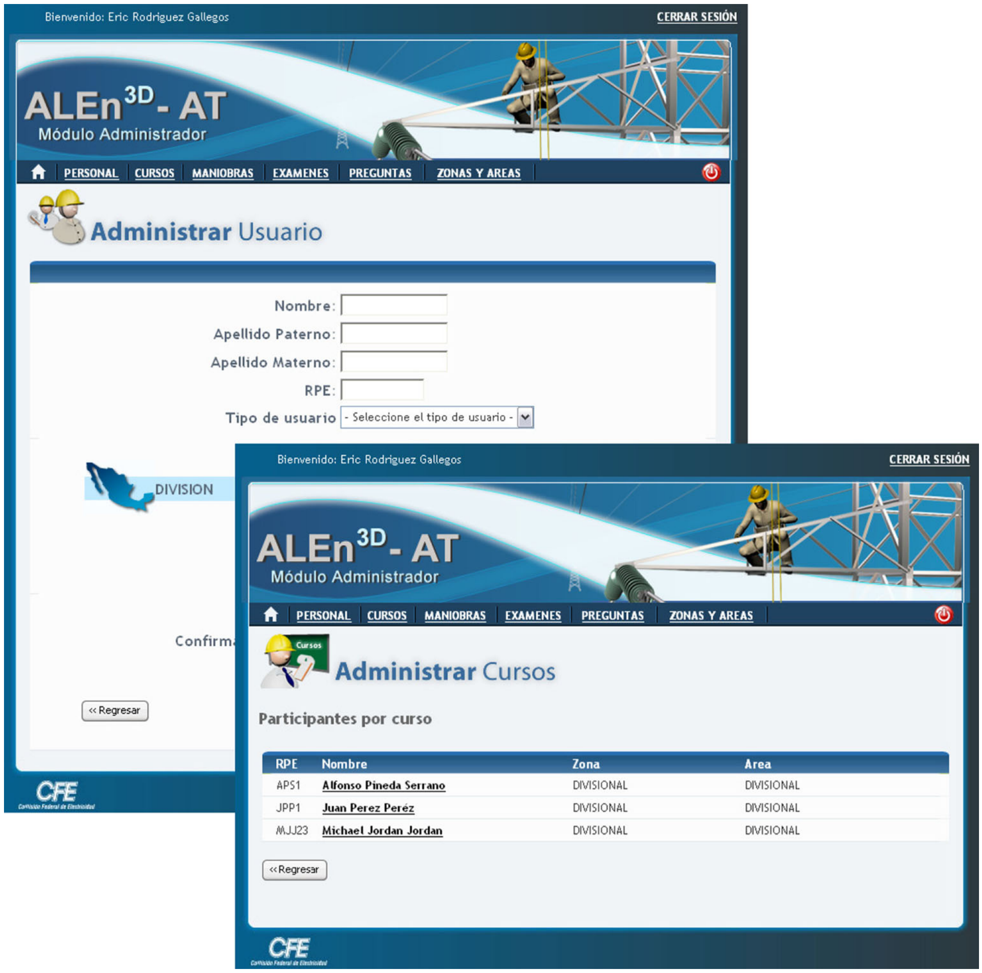


Fig. 8 Course and progress management application (AdminWeb)

4.4 System architecture

ALEn^{3D} AT architecture is based on the hierarchical model view controller (MVC; Coutaz 1987; Cai et al. 2000) software architectural pattern. In this architecture, the model comprises the application data and business logic. The controller mediates input and triggers events. And finally, the view displays information retrieved from the model. In ALEn^{3D} AT, there are two MVC branches: one for the VRWTS application and the other for AdminWeb; both branches share the same database (see Fig. 9). Under the VRWTS controller, there is a child branch corresponding to the 3D scene.

4.4.1 Model

The model is the part encapsulating the system data and multimedia files. It provides routines to manage and manipulate these data in a meaningful way. It also contains routines retrieving data from the model when it is requested from the controller. In ALEn^{3D} AT's VRWTS, the model contains methods to add, remove, and update information about trainees' progress in the database (shared with AdminWeb). Additionally, the model incorporates methods for retrieving multimedia files from the repository according to the business logic.

4.4.2 View

The view receives data from the model (passed to it from the controller) and feeds data to the different objects of the graphical user interface. Data can be text, audio, buttons, and 3D scenes. The view does not modify the data in any way; it sends messages back to controller methods and then displays data retrieved from the model. The 3D scene in the VRWTS is not a simple view; it contains a controller synchronizing events and animations in the 3D canvas.

4.4.3 Controller

In the VRWTS, the controller is also known as orchestrator and it is the medium of communication between user

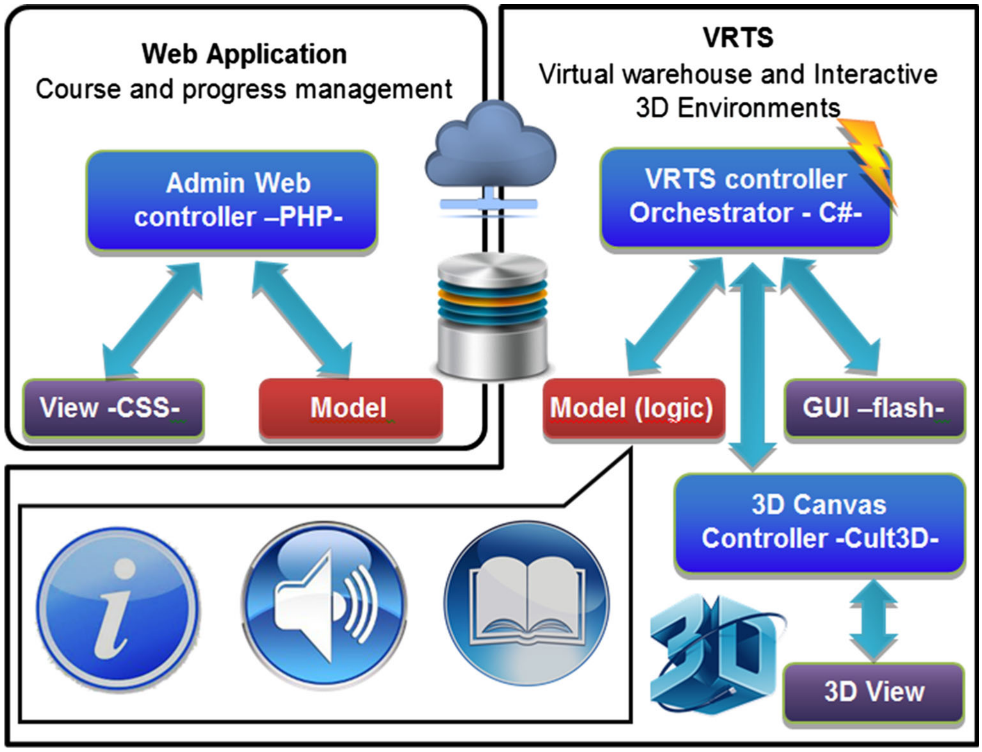


Fig. 9 ALEn^{3D} AT architecture

interface, business logic, and repository of multimedia elements. The orchestrator is responsible for responding to user actions. The orchestrator incorporates callback functions; it also determines the user requests and responds appropriately by triggering different model methods to manipulate data appropriately. The orchestrator receives information from the model and passes it to the view components (see GUI, CSS view, and 3D view in Fig. 9). Regarding the 3D canvas, the orchestrator does not update the 3D view directly; instead, it triggers events in the 3D canvas controller. The events in the 3D canvas controller synchronize sounds and animations into the 3D canvas view. Furthermore, the 3D canvas controller is responsible for stopping and activating events depending on the user actions, and it also sends messages back to the main VRWTS controller (orchestrator).

5 Testing the effectiveness of ALEn3D AT

For determining and quantifying the effectiveness of ALEn3D AT for workforce training, two groups composed of twelve randomly selected apprentices were trained using two different approaches.

5.1 Training

The group GroupTrad attended classroom lessons and a field training. In the classroom, students learned about theoretical aspects of electricity, safety procedures, tools, and materials and equipment needed to perform live lines maintenance. Instructors used photographs, power point presentations, and videos during the class.

The field training allowed students to practice maintenance in a de-energized environment emulating actual facilities. For this task, the group was randomly divided into six two-man teams to learn and practice the tasks of a single maintenance maneuver.

The group GroupALEn was trained using our approach during the first half of the training process. Similarly to GroupTrad, during the second half, the apprentices in GroupALEn formed six teams and attended the field training. Our non-immersive VR approach allowed students to know in advance all the tools and materials as well as the whole maintenance procedure. GroupALEn trainees learned all the standards in a context-driven virtual environment. This provided the student with essential knowledge before they went to the field training.

The two groups were separated at each moment, and they were not allowed to share information. Evaluations were performed in separate facilities (see Fig. 10).

5.2 Evaluations

Once the two groups were trained, they were evaluated in two separate sessions in order to investigate whether or not the students were retaining the knowledge:

1. The first session of evaluation was performed 3 days after the training session and included an examination and a field test. The examination was a theoretical evaluation composed of twenty-five questions. The field test was performed in teams at a field training facility. At the facility, they had to perform the same maintenance maneuver they learned at the classroom.
2. The second session of evaluation included the same two tasks. Since the second evaluation was intended to evaluate whether or not apprentices retained the information, the evaluation was applied 9 days after the training session.

Evaluation outcomes were recorded individually for the theoretical evaluation and in pairs for the field test. The results were averaged per group as follows:

1. Theoretical: Examination results
2. Practical: Field training evaluation. Marks were assigned by a group formed by several experienced general foreman and electrical engineers.

5.3 Outcomes

5.3.1 Immediate evaluation

As shown in Table 1, trainees in GroupALEn got a score of 81 % in the theoretical evaluation and 84.05 % in the practical evaluation. On the other hand, trainees in GroupTrad scored 72 and 69.93 %, respectively. Not only GroupALEn performed 9 % better in theoretical evaluation, but their results in the practical evaluation were also 14.12 % higher.

5.3.2 Knowledge retention

Similarly to results obtained during the immediate evaluation, apprentices in GroupALEn scored 14.16 % better than apprentices in GroupTrad. In addition, GroupALEn results in practical evaluation were 21.62 % better than those of GroupTrad.

It is worth noting that both groups scored above the minimum passing score of 60 out of 100 points. Furthermore, people in GroupALEn increased their theoretical score in the knowledge retention evaluation and both groups improved their performance in the practical knowledge retention evaluation.

6 Results and discussion

Unlike other virtual reality prototypes designed for the energy sector (Angelov and Styczynski 2007; Arendarski et al. 2008; Baeta Miranda 2010; Breen Jr and Scott 1995; Coutaz 1987; de Sousa et al. 2010; Feng and Cheng 2009; Galvan et al. 2010; Garant et al. 1995; Kriz et al. 2010; Li et al. 2003; Matsubara and Yamasaki 2002; Mól et al. 2009; Park et al. 2006; Romero et al. 2008; Shaikh et al. 1995; Tam et al. 1998, 1999), which in general are solutions that have been tested in laboratories or used for small groups of people, ALEn3D AT is currently being used as the official training tool at an electric utility company. The system was specifically designed for the Mexican federal commission of electricity (CFE for its acronym in Spanish), which is a nationwide electricity parastatal. The company is divided into sixteen different geographic regions covering the whole Mexican territory. It is paramount to mention that the system is based on the company's health and safety regulations, as well as in maneuver specifications written by a select group of expert linemen, foreman, and engineers. Consequently, ALEn^{3D} AT is a knowledge resource backed up by the company best practitioners.

ALEn^{3D} AT comprises thirty-one maintenance maneuvers; it integrates 3D scenarios including all types of structures for high-voltage electricity distribution. Moreover, the interactive 3D representations were designed for training workers on different techniques such as the bare hand method or using hot sticks. Likewise, ALEn^{3D} AT includes maneuvers for performing maintenance in circumstances when cranes are available, as well as when workers have to climb the structures to perform the maintenance. Since ALEn^{3D} AT is a heterogeneous group of maintenance procedures with different degrees of complexity, the instructors can easily create courses for trainees with different skill levels.

Table 1 Averaged evaluation scores

Evaluation scores				
Group	Immediate evaluation		Knowledge retention	
	Theoretical (pts)	Practical	Theoretical (pts)	Practical
GroupALEn	81	84.05	85	93.24
GroupTrad	72	69.93	70.84	71.62
Difference	9	14.12 pts	14.16	21.62 pts

In total, the thirty-one interactive 3D environments comprise more than 1000 h of animation. The virtual warehouse is composed of 371 items divided into four categories: live lines equipment and accessories, insulated tools, overhead line hardware, and personal protection equipment. The development of the system took twenty months, and it was developed by a team of ten people. In total, 27,000 man-hours was required to complete the system. The system was released during the first quarter of 2011.

6.1 Workforce training using ALEn^{3D} AT

Live lines maintenance is a high-risk task and demands a comprehensive training, including field practice. This is why ALEn3D does not substitute the traditional training; rather, it is aimed to complement and improve workforce traditional training.

ALEn^{3D} AT can be used both off-line and online when people are enrolled in courses. During the first two quarters of 2011, the system was used off-line for an unspecified number of people. In the meantime, lectures to prepare instructors were held all over the sixteen regions of the country. Finally, in November 2011 the instructors began to direct courses. From November 2011 to July 2015, the system was installed in 3700 different computers, during that period of time 1100 official courses were conducted using ALEn^{3D} AT, in which 4600 workers were trained.

A huge advantage of ALEn^{3D} AT is that it does not require expensive workstations to be used; therefore, it can be installed in regular desktop systems with intranet connection. Furthermore, the use of the system has helped to reduce the cost of training due to transportation and subsistence allowance expenses. Additionally, workers can use the system from anywhere by choosing the off-line mode.

Previously, training new workers in the basic set of skills required to maintain OPLs used to take 6 weeks. Using ALEn3^{D} AT, that time was reduced to 4 weeks, which means that the cost of training, both in time and money, has been reduced by 33 %. Likewise, CFE has found that they are saving about US $950, per course per person. Given that 4600 linemen were trained using the system from November 2010 to July 2015, CFE cut the direct training expenses by US $4,370,000. Additionally, there were extra savings related to indirect costs of not having the personnel during the extra 2 weeks that the traditional training course used to take.

As shown in Fig. 11, in addition to the direct cut in training expenses, ALEn3D AT has helped CFE to reduce health insurance and lost workday's related expenses in a year by year basis in up to 94 %, when comparing expenses with years in which the OPL workforce training system was not in place. Furthermore, the number of accidents has been reduced by 59 % and the working days lost due to accidents have been reduced by 93 %. The later shows the affectivity of our system as presented in Gutierrez-Requejo et al. (2013).

7 Conclusions

In summary, the maintenance of high-voltage facilities involves hazardous activities that must be performed by well-trained linemen. This work aims to provide a tool to learn the methodology and regulations related to live lines maintenance in a risk-free environment. As the results of our experiment with 24 trainees showed, workforce training using ALEn3D AT has a positive effect both in theoretical and in practical evaluations.

In this paper, the design, development, and implementation of a virtual reality workforce training system for the maintenance of high-voltage overhead power lines are presented. The proposed workforce training approach consists of a non-immersive virtual reality application and a learning management system. The virtual reality application is based on the hierarchical model view controller software architecture pattern which makes it modular, extensible, and flexible. The system incorporates an easy-to-use graphical user interface including images and terminology that resemble the real-life tasks and equipment that electricity workers employ.

The developed software guides apprentices step by step through thirty-one different maintenance procedures. All the procedures include contextual information about related regulations and practical hints written by experts. The system offers a learning management module that allows instructors to plan whether the trainees can access the training mode or evaluation mode. Unlike traditional workforce training methods, the system provides different levels of interaction promoting participation rather than passivity.

By reducing thirty-three percent of the time required to train new workers, the proposed training system has proved to be a cost-effective alternative to traditional training methods, but more importantly, it guarantees workers safety during the training stage. In five years, the system was used to train 4600 operators of a Mexican electric utility.

7.1 Future work

We are currently designing an immersive version of selected OPL training procedures. It is important for us to identify which procedures would benefit the most from an immersive experience. We know from previous experiences that in some cases, immersive VR

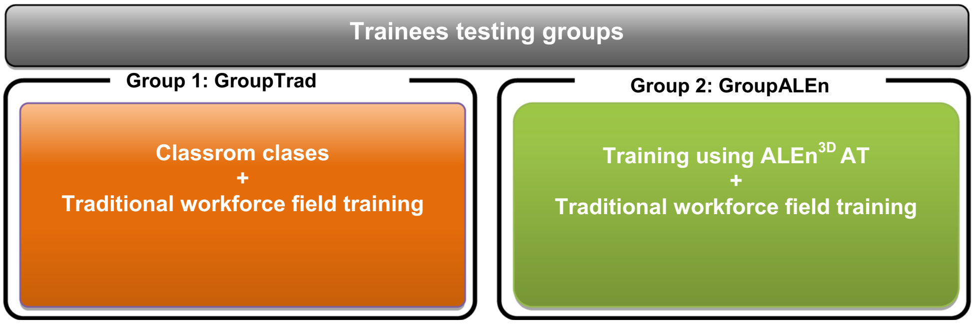
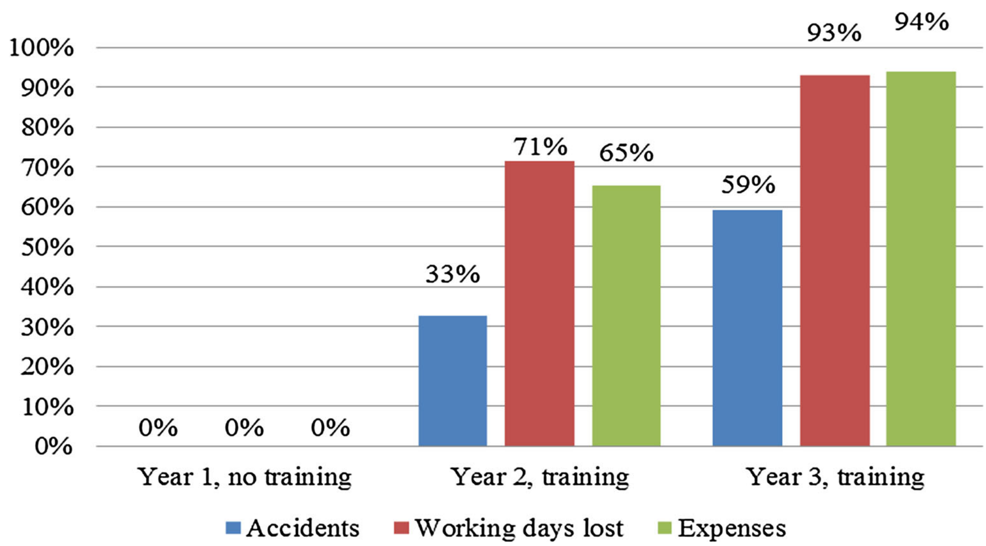


Fig. 10 Two groups of 12 randomly selected people were trained using different approaches

Fig. 11 Percentage reduction in accidents, working days lost, and expenses



applications require users to learn gestures, which takes certain level of adjustment to the equipment needed to create the immersive scenarios. The latter can cause distractions and alienate learners from the main training objective, which is to learn. In the future, we will release immersive VR versions of the training procedures only in the procedures where we can prove that knowledge transfer is effective.

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