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Virtual Reality Substation Training Tool For Industry Workers

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"You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete."

Buckminster Fuller

Acknowledgments

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Kindly, Alberto Carvalho

Resumo

Executar tarefas especializadas, operar maquinaria ou materiais perigosos requer um conjunto especializado de conhecimentos. Frequentemente isto significa treinar operários!

Adquirir este conhecimento envolve riscos e muitas vezes a alocação de pessoal especializado para ensinar, o que pode significar atrasos e consequentes perdas de dinheiro para as empresas.

Aqui entra a ferramenta de treino em Substações, um sistema de realidade virtual que com o uso de dois sensores inerciais (controlo das mãos) permite o controlo e manuseamento dos mais diversificados objectos, ensinando assim novos funcionários de uma forma mais segura e controlada num cenário de manutenção numa sub-estação.

O trabalho de investigação evidencia que esta nova técnica de ensino funciona e motiva os utilizadores a aprender os procedimentos propostos. Todos os utilizadores sentiram que melhoraram o seu conjunto de habilidades, muito pela possibilidade de tentativa/erro e pelo sistema que possui indicações curtas e fáceis de seguir. Graças à utilização dos dois sensores inerciais foi possível recolher informação de cada uma das sessões de treino, o que permite transmitir aos utilizadores no final informação mais precisa de todo o seu desempenho.

A solução final (protótipo) irá permitir à EFACEC treinar técnicos, explorando múltiplos casos e evitando os já mencionados problemas que advêm do uso dos métodos tradicionais.

Palavras-chave: Treino de Operadores, Substação Eléctrica, Realidade Virtual, Sensores Inerciais, Procedimentos Perigosos, Ambiente Seguro.

Abstract

Performing specific tasks or operating hazardous machinery or materials requires a specialized skill set. Often this means training workers!

Such task involves risks and many times the assignment of specialized personnel for teaching, what could mean delays and consequent money lost for the companies.

This is where the Substation Training Tool comes in, a Virtual Reality system that with the use of two inertial sensors (hand control), will allow the control and handling of a multitude of objects, teaching new employees in a safer/controlled way for a scenario of maintenance in a substation.

This research evidence that this new learning methodology works and motivates users to learn the proposed procedures. All the users felt that they had improved their skill set, a lot due to the possibility of trial/error and to the system which has short and easy to follow indications. Due to the used inertial sensors it was possible to collect data from each training session, providing more efficient final feedback for the users.

The final prototype will allow EFACEC to train technicians, exploring multiple cases and avoiding all the mentioned problems that come with the traditional training methods.

Keywords: Operators Training, Electrical Substation, Virtual Reality, Inertial Sensors, Dangerous Procedures, Safer Environment.

Abbreviations

VRSTTFIW	**V**irtual **R**eality **S**ubstation **T**raining **T**ool **F**or **I**ndustry **W**orkers
VR	**V**irtual **R**eality
AR	**A**ugmented **R**eality
PPE	**P**ersonal **P**rotective **E**quipment
UI	**U**ser **I**nterface
App	**A**plication
OCB	**O**utdoor **C**ircuit **B**reaker
RMU	**R**ing **M**ain **U**nit
HMD	**H**ead **M**ounted **D**isplay

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CHAPTER 1

Introduction

This chapter introduces the reader to the agenda of this master thesis containing six sections. Throughout this chapter I will present my motivation and the framework of the document.

1.1. Motivation

Electricity and the inherent risks associated with its use in the built environment have long since been a priority for the electrical utilities who must work in this environment. By its nature, virtual reality has the advantage of being safe for both the user and equipment. Besides, it offers the user an opportunity to be exposed to a range of scenarios and conditions that either occurs infrequently or are hazardous to replicate. The master thesis objective is contribute to fill that gap, VR Trainee is a virtual reality system assisted by motion sensors, for workers to train scenarios which occur every day at electrical substations, as are example the REN, EFACEC and EDP facilities [**1**].

1.2. Context

A considerable amount of data indicates that industry urgently needs to change its training methodologies, as seen in the literature [**26**], especially the dangerous ones like the agriculture, mining, construction, aviation, healthcare and electrical sectors or where working relationships or conditions create particular risks [**55**]. The electrical industry includes several dangerous work scenarios; thus, training workers in this context using Virtual Reality (VR) or Augmented Reality (AR) is suitable option. Therefore, the advantages of using VR technology are:

. **Security:** it will help to reduce the number of security breaches, incidents by more than 25%. According to Ford [**33**], the introduction of VR in the manufacturing process, caused the injury rate to fall by about 70%.

. **Operational Errors:** : studies indicate the reduction of errors by more than 90% [**50**]; when AR-VR training applications are used.

. **Retention:** : research work suggests that the retention rate will rise by 80% [**57**]; if the introduction of AR-VR methodologies is appropriately done.

. **Adaptability:** studies show the gradual increase in the number of companies that use training methodologies and gamification models as one of the leading learning priorities. Mohsen Ghobadi and Samad Sepasgozar [**39**] says that only 7% of businesses are using VR in their sector. It is expected that this number will increase since 23% of companies have plans to use VR in the next three years. This is true, at least for the "high consequence" sectors, where organizations face a high level of regulatory and compliance requirements.

. **Training Time:** it reduces training time by more than 50% [**37**], with regular and efficient practices in training modules, ensuring significant cost reductions and optimizations of human resources. Over time, this number can increase, based on technological adaptability that gradually increases over time.

1.3. Research Questions

The development of the project associated with this dissertation was made with Fraunhofer Portugal Research Centre for Assistive Information and Communication Solutions (FhP-AICOS) in collaboration with EFACEC Power Solutions. The project aimed to produce a Virtual Reality training tool that helps workers to acquire the necessary skill set without putting their lives in danger; Thus, this research focuses on enhancing the learning process, evaluating all the necessary procedures to work in an electrical substation and collecting data useful for the employee and EFACEC. The main goal of this dissertation is to test the following hypotheses:

⇒ How effective is this type of training compared to traditional methods?

⇒ What kind of impact does this application have on companies and their employees?

⇒ Does it contribute to personal or collective knowledge enrichment?

⇒ Does collecting data during sessions help the company and the employee in a training process?

1.4. Objectives

This master thesis intends to offer a new learning methodology through a simulation of real scenarios occurring in electrical substations in a virtual world. The objective is to reduce the negative impacts of the traditional methods and better training workers in the execution of high-risk tasks. Additionally, it is an interactive solution, motivating users during all the process and tracking their individualized profile.

1.5. Research Methodology

This section introduces the research methodology, explaining the different types of research used along-side this document. Each presented method was responsible for better organization and conduction of the work.

1.5.1. Exploratory Research

With the theme and objectives defined, I carried out exploratory research. This research is used when looking at an understanding of the nature of the problem, alternative hypotheses and other information that can be used. It allows increasing the knowledge of the problem, defining the focus and how to analyze the study, understanding the criteria used. It allows to raise hypotheses and discover unknown characteristics on topics where I do not have any knowledge [**40**]. So at this early stage of my research, I can increase my knowledge by analyzing documents and websites, quantitative research. Whenever is required observation and interviewing people, the investigation will be based on qualitative research.

1.5.2. Research Paradigm and Methodology

The research process produce answers to my research questions in order to achieve the proposed research goals. Therefore, my approach for this study was based on the Continuum Epistemological paradigm. This double approach (positivist / interpretive) requires the use of qualitative and quantitative methodologies (Figure 1.1).

- **Qualitative Research:** Based on small samples, providing insights and understanding of the problem context [**51**]. It takes place when trying to understanding the phenomenon under study and the aim is to describe or interpret it. Researchers must observe, describe, interpret and appreciate the environment and the phenomenon, always without trying to control them [**48**]. The objective was to understand better the surroundings and the particularities of the technology being studied in this dissertation.

- **Quantitative Research:** The process of collecting observable and quantifiable data, based on the observation of facts or events that exist independently of the researcher [**48**]. All data is quantifiable and can be translated to numbers, opinions and information to be classified and critically analyzed, using statistical methods [**38**]. The objective is to quantify data and generalize the obtained results to the target users [**51**]. These data are used to enrich and evidence the growth/quality of my technology. I will use them too for carrying out usability questionnaires, divided into five stages: (1) construction of the questionnaire; (2) pre-test of the questionnaire; (3) procedure and monitoring of questionnaires; (4) data collection and processing; (5) analysis of the results.

Table 1.1. Qualitative vs Quantitative Research [**24**].

	Qualitative Research	**Quantitative Research**
Objective Purpose	.Exploratory research to establish a base of insights on a key topic area. .Understand underlying motivations, attitudes and perceptions. .Provide insight into problem definition, providing hypotheses and language for subsequent quantitative evaluation.	.Quantify data and generalize results to the target audience. .Measure the incidence of motivations, attitudes, and perception. .Benchmark and track data over time. .Predict future behaviours (with caution). .Understand differences between target audience segments.
Sample	.Small and narrow. .Not statistically projectable.	.Large and broad .Usually statistically projectable.
Methodology	.Focus groups, in-depth interviews, ethnographies, shop-along,etc. .Can be in-person, by phone, or online.	.Surveys conducted by phone, online/mobile, or email.
Data Collection	.Semi-structured, using discussion guides. .Can evolve throughout the study.	.Highly structured questionnaires. .Few changes (if any) throughout the study. .Wide variety of question types, both close and open-ended.
Data Analysis	.Non-statistical, generally non-numeric. .Focusing on concepts and images. .Includes content analysis, observations.	.Numeric and statistical. .May include advanced analytic techniques.
Reporting Outcome	.Directional in nature. .Not projectable to the total target audience. .Often used to develop a sound understanding as a basis for nature research.	.Reports are graphical. .Representative of the target audience. .Provides guidance for business decisions and course of action.

1.6. Structure

Four elements compose this dissertation, and it is divided into five chapters and an annexe, as schematized in Figure 1.1.

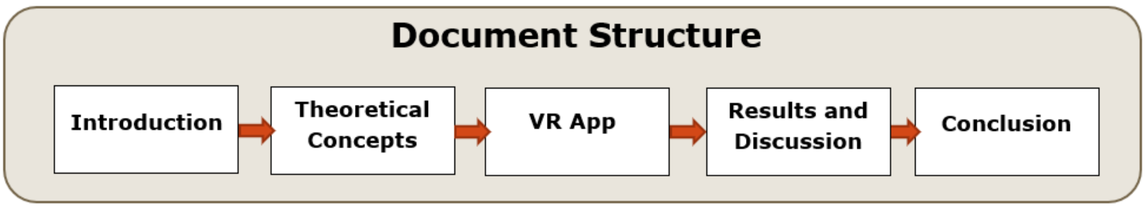

Figure 1.1. Dissertation structure.

The present chapter introduced the context and motivation, which lead to the development of this project. Additionally, a review of the literature and the main objectives were also presented. Chapter 2, the Theoretical Concepts, provides background concepts and principles. The methods used in this research are introduced in Chapter 3 which thoroughly presents and explains the developed Virtual Reality application, or for other words, the VRSTTFIW. Chapter 4 summarises a description, results and discussion of the conducted studies. Finally, Chapter 5 highlights the more relevant conclusions and points to future work directions.

CHAPTER 2

Theoretical Concepts

This chapter contains the essential theoretical background to develop this project; it is composed of five sections. The first section includes the substation description, the necessary personal protective equipment (PPE) and the procedures to be trained. Next, the second and third section presents some notions about the VR that were used in the development of the application and other solutions context respectively. Section four, summarizes the used motion sensors. Finally, the last section discusses forms of interaction with the VR, using movement or controller.

2.1. Electrical Substation

A substation is part of the electrical generation, transmission and distribution system. The substation is responsible for transforming voltage from high to low, the reverse, or perform other essential functions. Moreover, between the power stations, wherever energy is generated and the shoppers, power could flow through many substations at completely different voltage levels [**23**]. Thus, a substation could embody transformers to vary voltage levels between high transmission voltages and lower distribution voltages. It is additionally attainable at the interconnection of two totally different transmission voltages.

Elements of a Substation: Figure 2.1, usually they have switching, transformers and protection/control equipment. In larger substations, circuit breakers are used to interrupt any short circuits or overload currents which can occur on the network or for maintenance actions. Smaller distribution stations might use re-closer circuit breakers or fuses for defense of distribution circuits. Capacitors, voltage regulators and reactors are other kind of devices that may be situated at a substation.

FIGURE 2.1. SE EFACEC Arroteia (60 kV).

2.1.1. Circuit Breakers

Outdoor solutions [**5**] composed of medium voltage circuit breakers encapsulated in enclosures designed to measure, Figure 2.2. These solutions are developed according to the most demanding international standards and can withstand the most adverse atmospheric conditions.

In addition to the circuit breaker, they include electrical transformers as well as control, measurement, protection and signaling.

Construction: Outdoor circuit breakers (OCBs) are made entirely of welded or screwed coated steel plates with high resistance paint. Optionally it can be built-in stainless steel sheet and coated with polyurethane paint.

Characteristics:

- Safe and reliable;
- Placement in outdoor areas with adverse conditions;
- Compact design;
- Ideal for all Medium Voltage applications;
- Excellent dielectric properties;
- Excellent electrical arc extinguishing properties;
- Easy installation;
- Ease of manoeuvre;
- Increased electrical and mechanical life;
- Maintenance-free;
- Several options available;
- Consisting of 2 distinct compartments: - Medium voltage compartment, where crossings are chosen, current and voltage transformers (optional) and the vacuum circuit breaker; - Low voltage compartment, where relays are installed protection, the elements of obligation, control and signalling.

FIGURE 2.2. Circuit Breaker.

2.1.2. Compact Outdoor Frames

The Compact Ring Main Unit (RMU) of SF6 insulated exterior [**13**] is an extensible solution or not (according to specification customer) that can be complemented with several extensible modular options, measurement or remote control facilities. All involved parties are protected under SF6 insulated tank. This solution, Figure 2.3, is equipped with an SF6 cut-off switch and vacuum cut-out circuit breaker. This equipment is designed for distribution networks up to 12 kV in the most adverse conditions being widely used in tropical, arid or saline outdoor areas. It can also be used in elevated areas up to 1000 m above sea level.

Characteristics:

- Compact outdoor frame with SF6 insulation;
- Equipped with SF6 cut-off switch;
- With vacuum cut-out circuit breaker;
- Insensitive to environmental conditions;
- Resistant to the internal arc;
- Increased electrical and mechanical life (class E3 M2);
- Stainless steel tank;
- Possibility of remote control and connection with SCADA systems;
- Resistant to corrosion.

Figure 2.3. Compact Outdoor Frame.

2.1.3. Disconnectors

Horizontal Disconnector: These disconnectors [**15**] are of the type of two or three rotating columns, with an opening (SHD) or double side opening (SHCR), with separate poles, for outdoor installation, Figure 2.4. They can be supplied with manual or motorized control, local or remote. Closing and opening are carried out by rotating the movable contact arms in a horizontal plane.

Characteristics:

- Up to 245 kV;
- Up to 50 kA (RMS) / 4000 A;
- Easy installation and maintenance;
- IEC / ANSI certification;
- Resistance to seismic phenomena;
- Operation under the ice;
- Double side opening or central opening.

FIGURE 2.4. Horizontal Disconnector.

Vertical Disconnector: This disconnector [**18**] is of the rotating vertical opening type for outdoor installation. It consists of three insulators, two fixed (support) and a connecting rod, Figure 2.5. The operation is carried out employing a motorized command and, optionally, can be supplied with manual control.

Closing and opening are performed through the rotation (SVN) or translation (SVL) of the connecting rods and mechanisms. The rods transmit a rotation in the axis at the beginning of the op closing and a movement of rotation in the vertical plane during the transition between the open and closed positions.

Characteristics:

- Up to 245 kV;
- Up to 50 kA (RMS) / 3150 A;
- Easy installation and maintenance;
- IEC / ANSI certification;
- Resistance to seismic phenomena;
- Operation under the ice;
- Supply option with attached earth knife.

Figure 2.5. Vertical Disconnector.

Pantograph Disconnector: These disconnectors [**16**] are of the pantograph type, Figure 2.6, with separate poles, for installation outside. They can be supplied with manual or electric control. The connection and opening are carried out by moving the contact arms in a vertical plane. These devices are simple in design and easy to assemble.

Characteristics:

- Up to 420 kV;
- Up to 50 kA (rms) / 4000 A;
- Easy installation and maintenance;
- IEC / ANSI certification;
- Resistance to seismic phenomena;
- Operation under the ice.

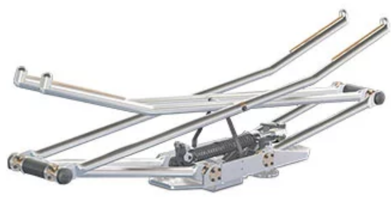

Figure 2.6. Pantograph Disconnector.

Semi-Pantograph Disconnector: These disconnectors [**17**] are of the semi-pantograph type, with separate poles, for outdoor installation, Figure 2.7. They can be supplied with manual or electric control. Connection and opening are carried out by displacing a single articulated arm. These appliances are simple in design and easy assembly. The articulated design gives it a high mechanical resistance to stresses short-circuits electrodynamics, enabling high performance to be achieved.

Characteristics:

- Up to 550 kV;
- Up to 63 kA (RMS) / 4000 A;
- Easy installation and maintenance;
- IEC / ANSI certification;
- Resistance to seismic phenomena;
- Operation under the ice.

FIGURE 2.7. Semi-Pantograph Disconnector.

2.1.4. Personal Protective Equipment

Working in an electrical substation is a dangerous activity, workers need to select the suitable PPE, Figure 2.8, in order to conduct his maintenance activities safely. Above is presented the list of the usual PPE used during the interventions in these scenarios.

. **Dielectric Gloves** (only for consignment maneuvers).
. **Helmet with a coloured visor** (only for consignment maneuvers).
. **Fireproof Clothing** (only for consignment maneuvers). It can be represented by only a long-sleeved coat that will be worn during the (de)consignment periods.
. **Helmet without visor**.
. **"Normal" gloves for mechanical protection**.
. **Metal-free safety shoes**.

FIGURE 2.8. Personal Protective Equipment (PPE). Same order as listed before, starting on the Dielectric Gloves and ending on the Metal-free safety shoes.

2.1.5. Working Tools

Besides the PPE, to execute the required procedures for the maintenance, a lot of tools are necessary, Figure 2.9. So in this subsection they are presented and schematized.

- **Tension detector with insulated rod** (only for consignment maneuvers).
- **Land Game** (only for consignment maneuvers).
- **Stick for land collation** (only for consignment maneuvers).
- **Universal Tools Box**.
- **Isolated Ladder**.

FIGURE 2.9. Working Tools. Same order as listed before, starting on the Tension detector with insulated rod and ending on the Isolated Ladder.

2.1.6. Procedures

To operate inside the substation and correctly execute the maintenance tasks is necessary a set of procedures. Below is presented a seven sequence of maneuvers for the consignment of a transformer panel, using the SE EFACEC Arroteia (60kv) as an example (for the Station Single-Line Scheme check Figure 2.10). Before listening to the procedures is essential to mention that the example consignment allows working in every equipment since the disconnector 60 kV (exclusive) to the cables exit 15kV from the transformer(inclusive).

1º Turn off the 15 kV circuit breaker. In the cell corresponding to the panel to be assigned, this circuit breaker is mechanically locked in the open position and a key comes out to be able to operate the 15 kV disconnector.

2º Open the 15 kV switch in the cell corresponding to the panel to be assigned.

3º Turn off the 60 kV circuit breaker, corresponding to the panel to be assigned, this circuit breaker is mechanically locked in the open position and a key comes out to be able to operate the 60 kV disconnector upstream of it.

4º Open the 60 kV disconnector, corresponding to the panel to be assigned, this disconnector is mechanically jammed in the open position (the circuit breaker key is stuck, only comes out when it closes); The key is released to be able to operate the earth disconnector in the 15 kV cell of the cable arrival.

5º Close the earthing switch on the 15 kV side, in the cell corresponding to the panel to be assigned.

6º Place the removable 60 kV earth next to the 60 kV disconnector on the voltage-free side.

7º Delimit the assigned area with plastic chains or signal tape.

Disclaimer: These procedures are presented in the Single-Line Scheme, Figure 2.10. Appendix B.1 has a sequence of images where it is possible to quickly understand what parts of the Single-line scheme corresponds to the ones in the substation.

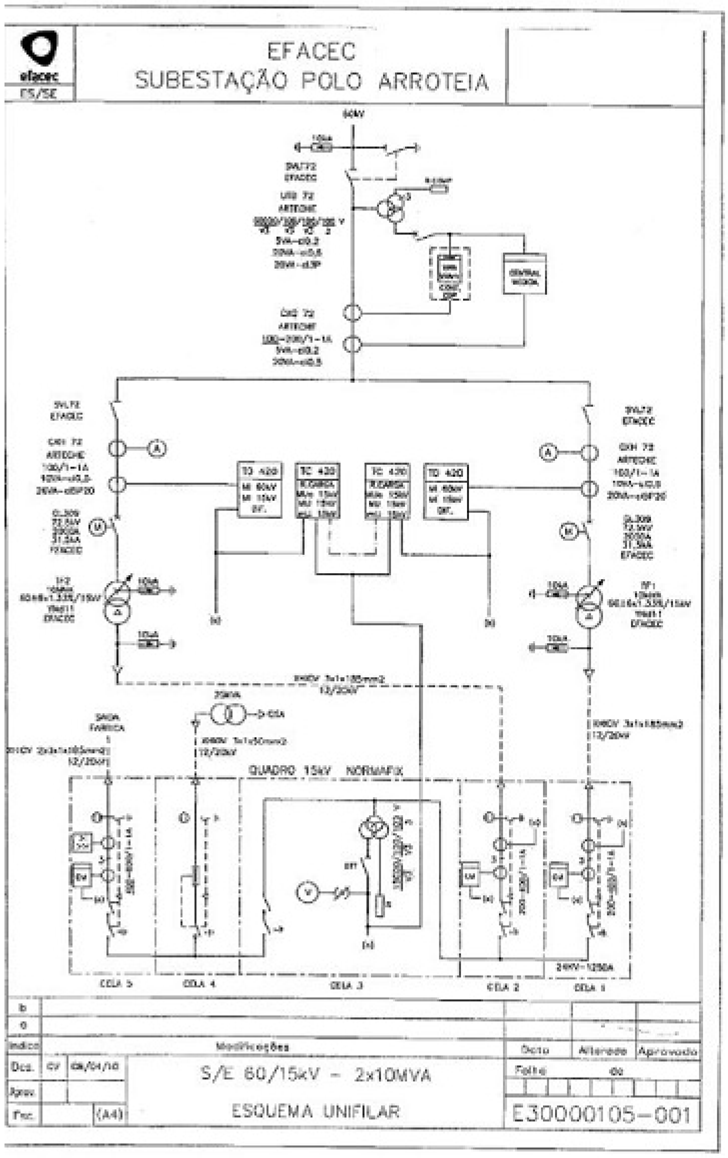

FIGURE 2.10. Single-Line Scheme.

2.2. Virtual Reality as a Training Tool

Virtual Reality systems as training tools are an effective and reliable teaching methodology. They were easily proven with the diversity of applications in distinct areas, such as health, engineering, science and general use. Important to note that in [**43**], the authors analyzed a total of 99 papers whose educational software was a VR system. For my case study, I will only focus on the engineering part.

2.2.1. Engineering Education

Virtual environments are widely used as training simulators in engineering. The popularity of VR can be attributed to the attractiveness of its use in preparing engineering students for industrial situations in the real world, allowing them to make early decisions on the project in an economical way [**53**]. It provides engineers with a better understanding of the project and helps facilitate changes whenever necessary. Also, it helps to reduce time and cost, which affect many modern design processes [**54**].

FIGURE 2.11. Real engineering laboratories and their representation in VR.

Next, several cutting-edge applications are described. Figure 2.11 presents images of virtual environments selected for this purpose, Power block [**28**], Robotic arm CRS [**31**], Robotic cell for glueing shoe soles [**56**] and Industrial picking robot [**41**]. For example, the teaching of civil engineering was aimed at [**36**]. To motivate and engage young students; Furthermore, it allow them to understand planning issues, often restricted by their current knowledge. So [**35**], the authors created a VR platform and introduced civil engineering to students through a VR game. The results obtained show that VR is a relevant tool for this type of education, as it allows participants without prior training to interact correctly with the platform. The authors of [**28**] presented a VR application to promote the teaching of electrical engineering. They designed and developed online labs that students could access remotely using VR. These projects allowed students to use virtual breadboards and virtual instruments to perform simple electronic laboratory work. The created application had realistic prototypes of 3D models of all equipment, in addition to electrical components relevant to laboratory tests. Virtual environments like this can be used in conjunction with other study materials, allowing students to learn and participate at home or work. Additionally, it minimizes teachers or employers' concerns about the time, cost and risk of dangerous experimental strategies. Another approach was presented in [**31**], where the authors created a VR system for education and training in robotics. The application was equipped with interaction based on visual and haptic feedback and contained a built-in physics mechanism. The robotic arms can be controlled by a virtual pendant or programmed to follow specific instructions. The results of using this application indicated that users trained in this system were better equipped to complete tasks on real robots, compared to colleagues who used traditional training methodologies. Similar approaches, with similar results, were also presented in [**56**] [**47**].

To facilitate the process of creating virtual models of existing machines, the authors presented a new method of acquiring a 3D model based on the digitization of images

[41]. Besides, the authors presented ViMeLa in [45]. This project aims to enrich study programs by implementing a VR-based tool for teaching and learning in higher education. ViMeLa provided a VR space, where students can experiment with simple machines that allow them to make mistakes and learn, with no consequences in the real world. A similar example was presented in [42], where the authors described a system for learning the internal operations of an intelligent factory, following Industry 4.0 concepts.

2.3. Other Solutions Context

VR systems as a teaching methodology are widely disseminated in the most different areas. It is proven that the use of this technology guarantees the gains that I identified in my goals.

Below I list some direct competitors Figure 2.12, explain in what consist their solutions and give an overview of what differentiates my solution from theirs.

FIGURE 2.12. Screenshots of competing VR applications. Starting on left: Digital Engineering and Magic, 3DInternet and SANERGRID.

Digital Engineering and Magic [9], have developed the project HV Electrical Substation VR Training for electricians. The purpose of this training tool is to give attendees the ability to explore High Voltage (HV) electrical substation equipment. Attendees learn each HV unit individually due to the disassembling mode. The training is intended to anyone interested in electrical engineering; Is required to know the basic electrical principles. This solution only runs on the Oculus Quest or the HTC Vive Oculus Rift, using the respective hand controllers.

3DInternet [3] creates fully interactive game-like simulators for the Energy Industry. The presented solution, substation training for utility workers [25], has the same purpose of my solution. However, this one was developed only for computer, using the standard controllers (keyboard and mouse).

SANERGRID [20] is specialized in the creation of virtual reality solutions for industry, creating immersive demonstrations. They have created a virtual demonstration of an electrical substation, but it is now a training tool. Also they use as standard the virtual reality headset Oculus Gear VR 324 and a Samsung Galaxy phone, charging extra costs for using other equipment.

Mechatraining solution [46] is a training tool for electrical maintenance. Using the Oculus Quest, this solution allows the attendee to simulate the use of tools, measure the electric current, and perform other procedures in order to work with the required electrical components.

All these projects have two things in common, they are available for a limit number of displays/platforms, and they all use standard controllers. The developed solution is differentiated from them, since besides the head-mounted display (HMD) for VR it uses two inertial sensors [**32**], explained on section 2.4, instead of the standard controller that usually comes with the VR system. It is also compatible with all the majority of the HMDs in the market.

2.3.1. Traditional Controllers

As already exposed in section 2.3, the vast majority of applications presented, as far as controllers are concerned, Figure 2.13 have limitations. They do not allow tracking all types of movements that I intend to use, real-time evaluation is limited, and data collection is very residual.

FIGURE 2.13. Usual controllers: Start at the top from the left: Playstation Move; Wii Controller; Kinect System; Head Mount Display (buttons or analogical controller).

At this time, my only assurance was that I wanted to use a VR headset. Before choosing what HMD to use I needed to choose one controller for the hands. The usual controllers that accompany the VR systems do not comply with my requirements, so I needed an alternative controller. On table 2.1, I synthesize the existing controllers.

Table 2.1: Traditional Controllers Specifications.

Controller	Portability	Measurement	Difficulty
Keyboard + mouse	Yes	Static/Residual	Easy
PlayStation Move	No	Residual	Easy
Wii	No	Residual	Easy
Kinect	No	Human Behaviour/Movement tracking	Easy
HMD + analogical	Yes	Eye-tracking/Residual	Medium

From all the controllers I presented the only who is capable of measuring human behaviour is the Kinect, but to be used with the VR requires too many devices, what increases the total cost of the final solution. Would be required to have the Kinect, a computer, and an HMD running simultaneously to deploy the solution. Another important point would be the quantity of effort to deploy the solution; since would require the developer to learn how to use the Kinect and all the necessary algorithms to work with him and tracking human behaviours.

So, motion sensors were used to interact with the system. Since Fraunhofer developed a motion sensor, called IoTiP and algorithms to monitor human-motion, this was integrated into the system as explained in section 2.4, since it requires less effort and allows to achieve the intended results.

2.4. IoTiP by Fraunhofer Portugal

Pandlet or IoTiP is a hardware platform developed by Fraunhofer Portugal to measure human motion and environmental context. It includes a set of sensing capabilities and an Android API that allows the seamless integration of external hardware into Android's platform.

2.4.1. Hardware Framework

The modules created with the IoTiP hardware framework [**32**] are composed by a set of building blocks (dots) that when "glued" together create new devices and functionalities. The base dot needed in any device is the IoTiP CORE, which contains: a Bluetooth 4.0 interface; a 16MHz ARM M0+ processing unit; support for QI wireless charging; and Inertial (IMU) and Environmental (EMU) Measurement Units, Figure 2.14.

FIGURE 2.14. IoTiP: sensor + bracelet

Regarding the measurement's units, the IMU contains three inertial sensors:

- Accelerometer with 16 bits resolution, 4 kHz sampling rate and 2 to 16 g range;
- Gyroscope with 16 bits resolution, 8 kHz sampling rate and 250 to 2000 º/s range;
- Magnetometer with 14 bits resolution, 100 Hz sampling rate and 4900 µT range.

2.4.2. IoTiP Core

IoTiP Memory, is an extra memory block that allows recording two weeks of inertial data at 100 Hz (using a standard 4GB micro-SD card). It also includes a micro-USB plug for wired charging.

Communication: To establish the communication between a sensory node, such as the IoTiP platform, Figure 2.15, and a data collection device, such as an Android smartphone, a complete communication protocol was designed and implemented on top of Bluetooth Low Energy. The protocol allows the devices to exchange information using previously defined formats, through a header and payload structure. Any device that implements the designed protocol may replace the Android device or the IoTiP platform, without requiring adjustments to the peer device.

IoTiP Firmware: The described solution requires the firmware to be generic and not implement any specific functionality on its own. Instead, it should provide access to as many features as possible and be able to be configured, at runtime, to perform as many tasks as possible. Currently, the implemented firmware supports the use of four modules – General Purpose Input/Output (GPIO), Pulse Width Modulation (PWM), InterIntegrated Circuit (I2C) and Universal Asynchronous Receiver/Transmitter (UART). The I2C module enables the communication with all of the IoTiP on-board sensors, as well as any external I2C or TWI sensors that may be added. The UART module allows wired communications with other devices, such as GPS modules or microcontrollers. The PWM and GPIO modules enable the IoTiP to be used in a myriad of situations and contexts, from simple port switching to the control of servo motors.

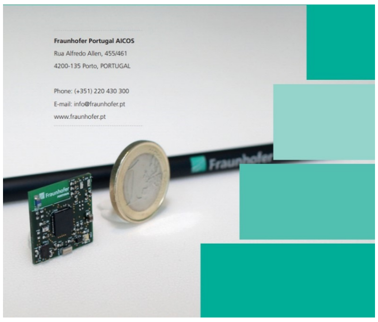

FIGURE 2.15. IoTiP hardware vs coin size.

Android API: The API is composed of a collection of classes that encapsulate the functionalities offered by the IoTiP platform. Instances of these classes may be used to easily interact with the IoTiP modules and collect data from theirs sensors. The developer is also able to program the sensor to perform predefined tasks whenever a GPIO event is detected.

2.5. Hardware and Development

To work in a Virtual Reality environment, first, a VR Headset is required. I present the used model in subsection 2.5.1. The developed virtual world is a copy of a real substation and the users interact with their virtual objects with their own hands. So I define two things:

1) It is necessary to have a functional 3D Hands Model, subsection 2.5.2, in order to handle objects and perform the maintenance procedures;

2) I want to have as much as possible the virtual world similar to the real one, so we decided to use a 3D Scanner technology, subsection 2.5.3, to capture the real world, or in other words, the substation and all the equipment's where is supposed to perform the training.

2.5.1. Virtual Reality Headset

A head-mounted device provides virtual reality for the user. These headsets are widely used in video-games and other applications, like simulators and trainers. They are composed by a stereoscopic head-mounted display, which provides separate images for each eye, stereo sound and head motion tracking sensors. Some headsets also have eye tracking sensors or extra gaming controllers. My solution uses the HMD, Figure 2.16, with the IoTip sensors, instead of these standard controllers.

FIGURE 2.16. Used Virtual Reality Headset.

The reasons why this VR display was selected and not another device, was due to his price, comfort and versatility. Specifications about the most common and used displays on the market can be consulted on table 2.2, the last one presented is the chosen display.

Table 2.2: HMD Specifications.

Display	Comfort	Versatility	Price
Google Cardboard	Low	Yes	From 5 to 13 euros
Oculus Quest	Very High	Yes	From 250 to 340 euros
Oculus Rift	Very Hight	Yes	250 euros
Vive Cosmos	Very High	Yes	Starting at 463 euros
Samsung Gear VR	Very High	Yes	130 euros
Denver VRC-23	High	Yes	20 euros

2.5.2. VR Hands Model

Known that an intuitive and easy-to-interact system is required and that must be easy to customize and be used by any type of VR Headset, I used a model that complies all the mentioned requirements.

The software used to develop the App was Unity, so I needed to select a hands model compatible with it. During my research for the right model to use, I discard other options, like some paid models from the Unity Asset Store [**8**] and free models from the cgtrader [**4**]. The free ones were also valid for me, but they were not fully integrated with the Unity engine, which would require more effort from me on the development phase.

The Oculus Hand Models [**12**], schematized in Figure 2.17, is the system I implemented in the final solution. These hands solved the problem of interacting with the virtual world and perform the required tasks. They usually work using special gloves or the oculus controllers, but since they are straightforward to customize, it was possible to change these controllers to the IoTiP sensors.

Two of these sensors are required, one in each wrist. Each of them corresponds to the right and left hand, respectively. These sensors include a gyroscope and accelerometer, and using an algorithm is now possible to use the hands in the virtual world to handle objects and interact as if it was real. It is not possible to control each finger individually.

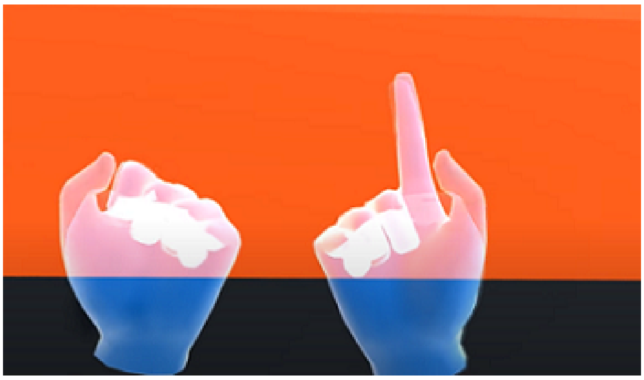

FIGURE 2.17. Oculus Hand Models.

2.5.3. 3D Scanner App

The 3D Scanner allowed to capture real models from the equipment in the substation easily. After some research, I put together a set of 3D scanner programs available [**52**]: Trnio, Qlone, Scandy Pro, Heges, Sony 3D Creator, Capture and Display.land. I have realized some tests with the display.land app and validate it to be used to capture the substation models. I share it with EFACEC, they started some tests and mean while, the App become deprecated.

To overcome the setback, the used software was 3DF Zephyr [**2**], having a free version with a limit of 50 images, was enough to build this solution. To construct the models, first was necessary to take some pictures of the objects with different perspectives.

EFACEC, the entity who have access to the substations, exported the outcome to the Zephyr software and generated all the final models to be used in the engine. In Figure 2.18 I present the first test whit this technology, where a model from a motor was made.

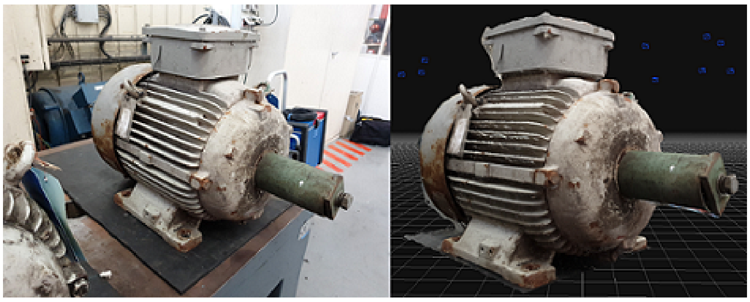

FIGURE 2.18. Motor Real Model Vs 3D Motor Model.

CHAPTER 3

VR App

This chapter introduces the developed application. I start this chapter by presenting the partners, Fraunhofer Portugal, the company where I developed the master thesis and EFACEC the technical partner. Namely who they are, our technical meetings and the outcomes necessary for the development of the solution.

Afterwards, all the five main features of the solution are summarized. Starting with the first part, the customization, where I explain how the user can fully customize his training and select the necessary equipment. The second part I mention how the AI behind setting the procedures works. In the next section, it was presented all the interactions in the system and explained the mechanics behind them. The fourth section presents all the UI presented in the VR App and the choices made. In the last section, I explain how the evaluation is done during the training, presenting to the user the final score. This last step is done by a simple verification of every step made by the user during his training.

3.1. Contextualization

My dissertation was made in Fraunhofer Portugal, Center for Assistive Information and Communication Solutions – AICOS [**7**], founded by Fraunhofer-Gesellschaft, the largest organization for applied research in Europe. AICOS conducts applied research and development dedicated to building tomorrow's information and communication technologies today. They create cutting-edge innovation based on end-user insights, leading to the deployment of technological solutions that have a positive impact on people's lives.

On the beginning of my dissertation, I only knew that I wanted to create a VR training app for the hazardous industries, using some of the AICOS technology. So I needed to find an industry interested in my solution. Fraunhofer had a significant impact on this issue since they have the contacts and help me to find a suitable technology partner. My Fraunhofer Coordinator and I had some internal meetings to discuss this topic and video calls with some contacts.

So the technical partner of this master thesis is EFACEC [**6**], a Portuguese company with a vast international presence with its technology in the areas of Energy Products, Systems and Mobility.

At this moment I already knew some existing solutions, their strengths and weaknesses due to my previous research, Chapter 2, so I prepared a small presentation to show the potential of this training tool, who was presented to EFACEC new business team. From this first meeting, they told me that they were interested in having this type of training tool for maintenance tasks. The message was passed on, to the sector where the application would best fit. Then the responsible for that team cameback to us, Fraunhofer, to have the first technical meeting.

Due presentations were made and the discussion about possible areas where this type of solution could be implemented started. The outcome was training in a substation scenario, and they gave me the first insights to start working on the development of the solution. A set of technical documents were shared with all the information about the substation and the procedures to work.

EFACEC created a shared place where if necessary, I could contact them, to expose some doubts and present them the last updates quickly. Furthermore, I had about three more meetings with them where some important feedback came out; they transmitted to me all the requirements I should include in the final solution. I schematized these same requirements as bullet points on table 3.1.

Table 3.1: Application Requirements.

Requirements	Priority	Implemented
Inertial Sensors	Critical	Yes
Customization	Very High	Yes
Insert Personalized 3D Models	Low	No
Main Maintenance Procedures	Critical	Yes
Tools/Equipment Selection	Critical	Yes
Guidance System	Critical	Yes
Teleport System	Critical	Yes
3D Hands Interaction	Critical	Yes
Using Tools Simulation	Medium	Partial
System Evaluation	Critical	Yes
Data Acquisition	High	Partial
Substation House Model	Low	No
Save Data to Web Portal	Very Low	No
Android/IOS Compatibility	Medium	Yes

3.2. System Flow

Before starting the VR App development, I schematized all the system flow. Here is possible to check step by step all the transitions between screens and functionalities, Figure 3.1.

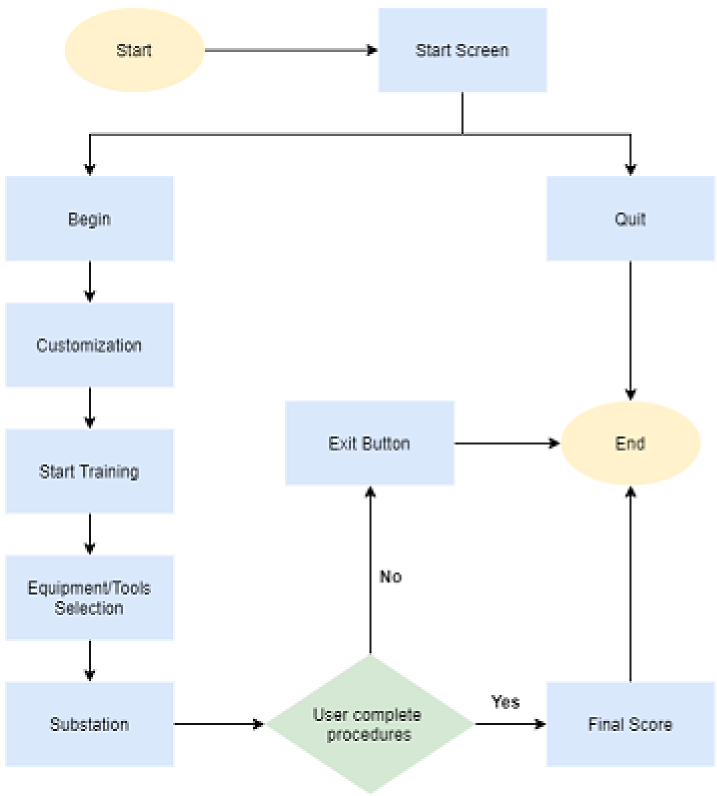

FIGURE 3.1. VR App Flowchart.

3.3. Customization

Customization as shown in Table 3.1, is one of the requirements that EFACEC transmitted to me to be necessary to have in the App. Thus, it is possible to customize the energy potency entering in the substation, the number of transformers and switches present in the scenario and select the procedures, from a list of seven elements, that the user wants to simulate in the system. Besides that, it is possible to configure the guidance level during the session, here three options are available: 1) Full Help; 2) Semi Help; 3) No Help.

In this solution it will be possible to select which are the 3D models to use in the training program. Trainees can choose the standard version (currently the one available in the VR App) or the custom version (insert there own 3D models).

All the mentioned customization components are grouped in one screen, Figure 3.2.

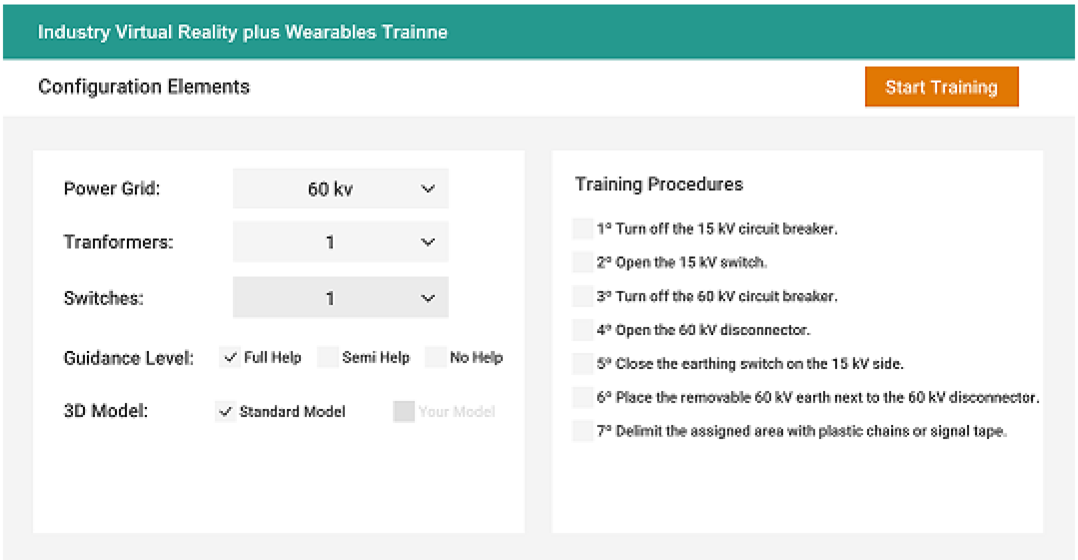

FIGURE 3.2. Configuration Elements.

When this primary configuration of elements is finalized the user can press in "Start Training" button, and a new screen pops up. This screen asks the user to select the necessary EPI's, Figure 3.3, and tools, Figure 3.4, to conduct the previous select procedures. The arrows buttons must be pressed to navigate between the two different lists. After selecting the necessary EPIs tools, the user can press the "Continue" button, and the training scenario is loaded.

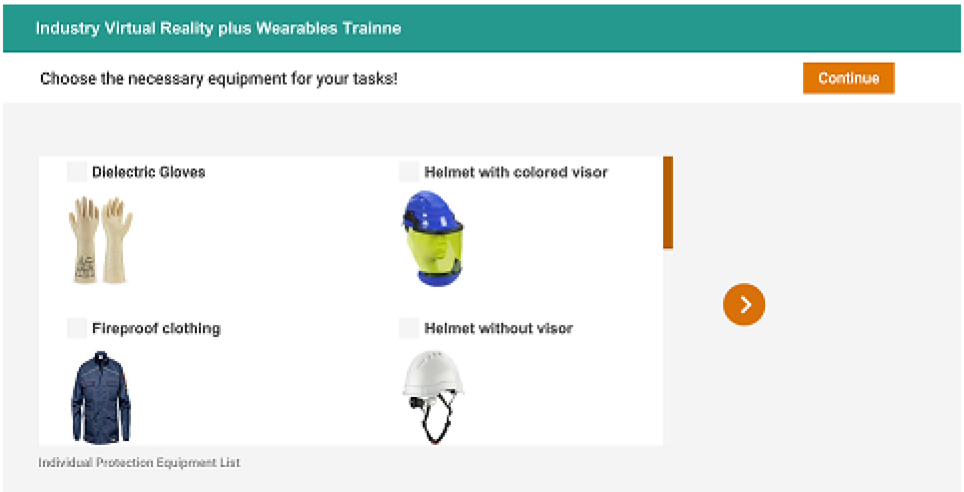

FIGURE 3.3. Screen: Individual Protection Equipment selection.

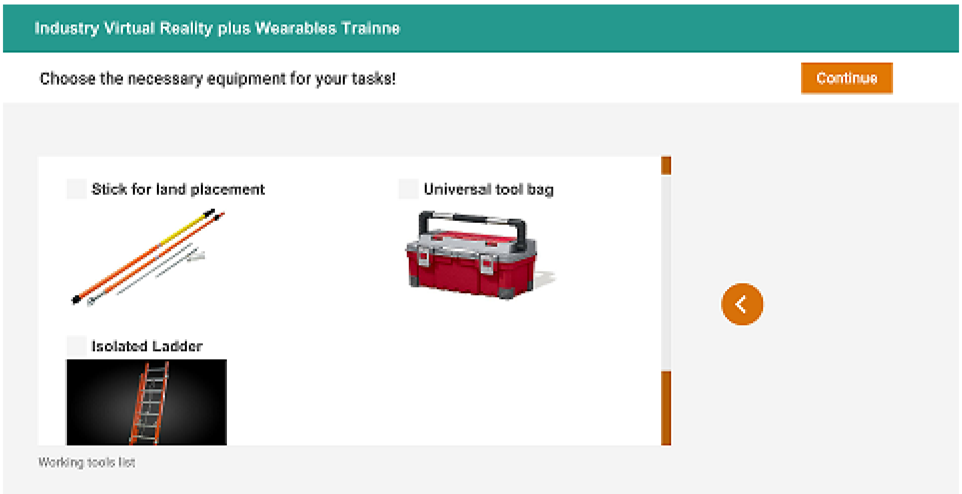

FIGURE 3.4. Screen: Working Tools selection.

Disclaimer: Workers that work in these dangerous conditions must mandatory know the necessary tools and equipment to conduct the maintenance activities. This selection will be reflected in the final evaluation, section 3.7.

3.4. AI - Setting Training Scenario

As explained in subsection 2.1.6, the seven presented procedures allow the technical personnel to work in every equipment present in the substation. With this information in mind, an algorithm responsible for setting the training scenario was created. How does it work? Picking the procedures selected by the user and the other elements inserted in the customization area, a new scenario is displayed. The algorithm controls things like the distribution of the navigation platforms, equipment present in the substation, and the order of the instructions to complete the necessary maintenance.

The idea behind this type of generation is to challenge the user to improve his skill set, no repeating the order of the elements (training program) showed to him on the screen. For more detail, this procedure is explained using pseudo-code on appendix A.1.

3.5. Interaction System

The developed solution has different types of interaction, more precisely three. In this section, I present and schematized how they are implemented and how the users work with them.

3.5.1. Interaction on the customization screen

The customization screens are the only place where the VR controller is used, Figure 3.5. It was chosen because it is easier to use to interact with UI elements, like checkbox, dropdowns and buttons. This controller is a small command with few buttons and a joystick. Users only need to press one of the top buttons, and a small arrow will appear, then they only need to manipulate the arrow with the joystick and select the desired elements for their training. When the arrow is over the desired element it is necessary to press one of the possible buttons to confirm the selection.

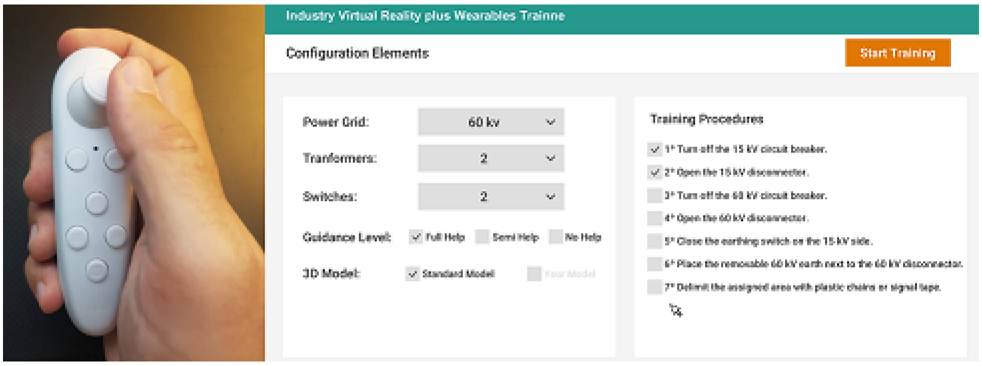

FIGURE 3.5. Interaction with Customization Screen.

3.5.2. World visualization/Teleport

Users visualize the substation world as if they were there. This kind of realism is only possible due to the Virtual Reality technology, that is the VR headset.

Around the substation on the ground exist a determined number of platforms, Figure 3.6, used to navigate through the scenario by teleportation. How does it work? The user operating the VR device must focus the platform from three to four seconds. Reached this timer threshold, he is transported from the existing platform to the locked one. Users know when they are locking the platform because there is a pointer, which represents the position they are looking at and the same pointer increases in size when it is over the target platform.

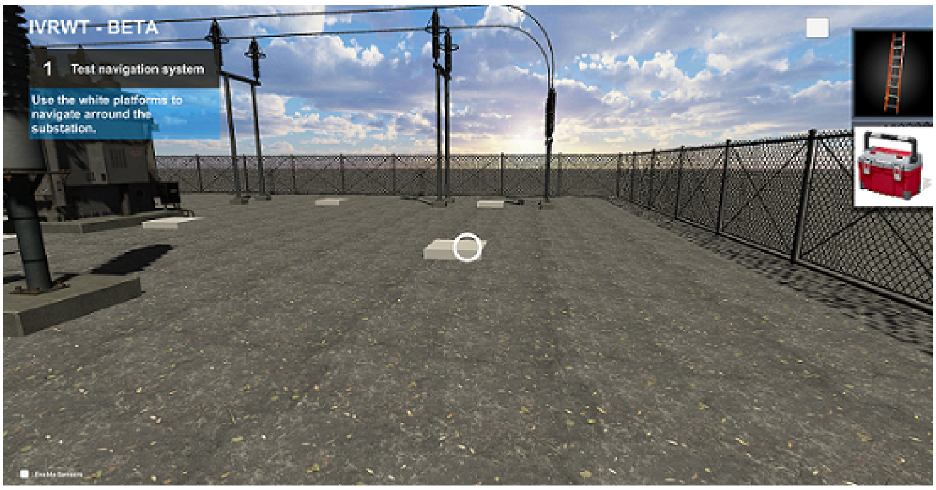

FIGURE 3.6. Teleport System.

3.5.3. Hands to Manipulate Objects

The manipulation of objects is critical since it is the main objective along-side the identification of the electrical components to perform maintenance. Furthermore, the user simulates a real scenario without being in danger of life. This manipulation is done using our own hands represented in the App as white hands, Figure 3.7. The hand's control was previously explained on subsection 2.5.2, so here I will focus on what happens in the virtual world, moreover how everything is processed in real-time. When a piece of maintenance equipment is locked, the hands emerge. The user is then challenged to perform tasks like opening the transformers cases, push levers to release keys, insert keys, signalize equipment. The substation plant is always available, to access it the user must only press the top button of the VR headset, same thing to hide. If the right equipment were selected in the customization menu, they would be automatically available if necessary. The selected tools are always displayed at the right of the screen.

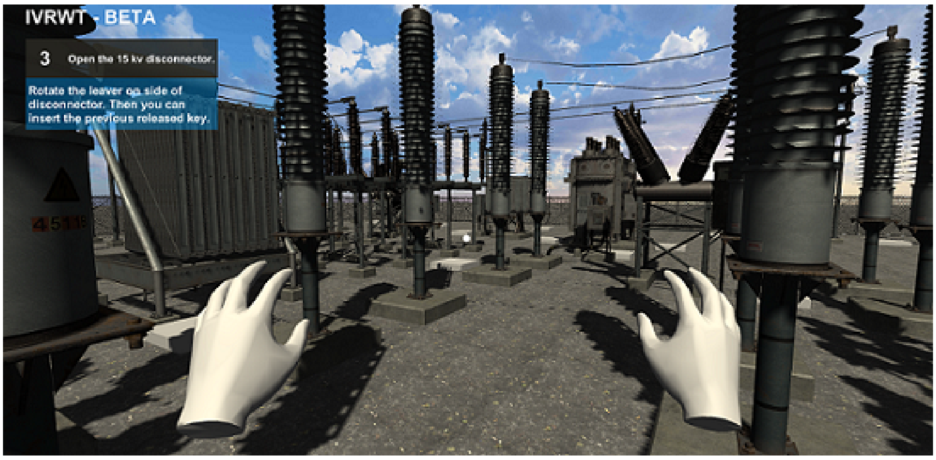

FIGURE 3.7. 3D Hands: For object manipulation.

3.6. User Interface

I choose a simple and clean UI for the application. My objective was allowing easy reading and that everything necessary was always in the sight of the user. For these choices I followed the UI Design best practices, "10 interaction design rules you must never break" [**30**].

All these practices are schematized on table 3.2, where it is possible to confirm the ones used in the solution.

Table 3.2: Design Rules.

Rules	Used
Visibility of System Status	Yes
Match between System and Real World	Yes
Consistency and Standards	Yes
User Control and Freedom	Yes
Error Prevention	Yes
Recognition rather than Recall	Yes
Flexibility and Efficiency of Use	No
Minimalist Design and Aesthetic	Yes
Help Users Recognize, Diagnose, and Recover from errors	No
Help and Documentation	No

How are the implemented rules visible in the solution? Let us start by the visibility of the system status; the rule tells us: "give your users appropriate information, hints and context so they know where they are within the system at all times". Taking this rule into consideration, a hints interface has created to guide the user throughout the training, as shown in Figure 3.8. With this, the user always feels in control and knowing what to do next.

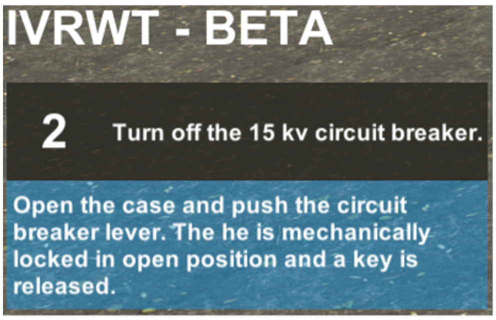

FIGURE 3.8. Left image: Objectives Interface; Right image: Hints Interface.

Match between System and Real World, "system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order". Simple text phrases were used instead of complicate terms, to describe what is necessary to be done or what will happen afterwards, an action is realized by the user.

Consistency and Standards, ”users should not have to wonder whether different words, situations, or actions mean the same thing”. Two types of consistency exist: internal and external. Internal consistency refers to patterns in the application, so keep the colours for the same concepts, in every screen. In external consistency icons that users find familiar with, buttons and the options symbol are adopted, as presented in Figure 3.9.

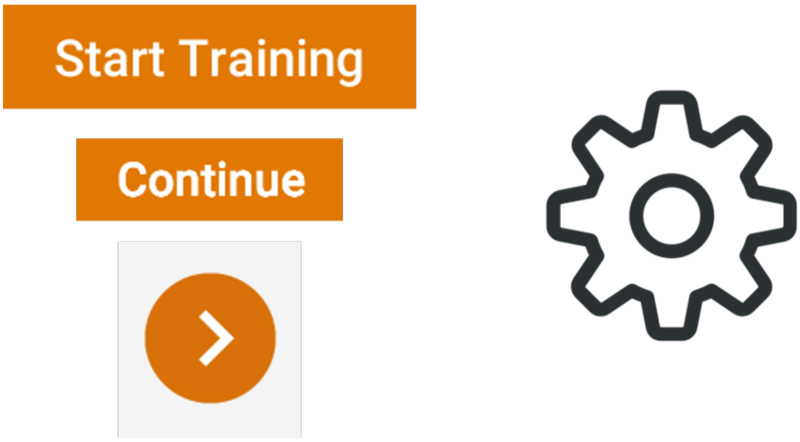

Figure 3.9. External Consistency: Some familiar elements.

User Control and Freedom, ”users often choose system functions by mistake and will need a clearly marked “emergency exit” to leave the unwanted state without having to go through an extended dialogue. Support undo and redo”. This rule adopted as long as possible; for example if someone opens a menu by accident or chooses the wrong configuration is possible to correct it and undo the mistake. However, in what concerns the maintenance tasks, this rule cannot be applied, since it has not supposed to undo mistakes. In real life, mistakes mean dangerous actions and the objective is for the user to learn with these mistakes in this safer environment so that in real scenarios, the trainee will not make mistakes.

Error Prevention, ”even better than good error messages is a careful design which prevents a problem from occurring in the first place”. When designing this solution I try to predict all the possible errors and avoid to use error dialogues. All the detected errors where solved. I only use one dialogue message for a particular case, sensors battery warnings or related errors, Figure 3.10.

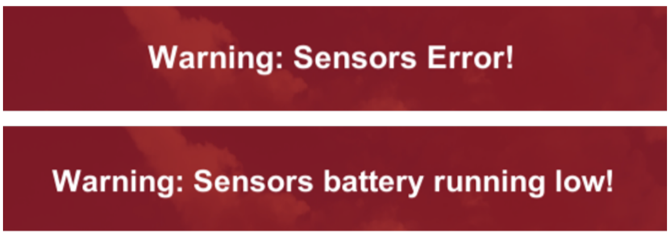

Figure 3.10. Sensors Warnings.

Recognition rather than Recall, "minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for the use of the system should be visible or easily retrievable whenever appropriate". Instructions are available during all the training session, even when help is disabled it is always possible to consult the plant of the substation and users' respective position, Figure 3.11.

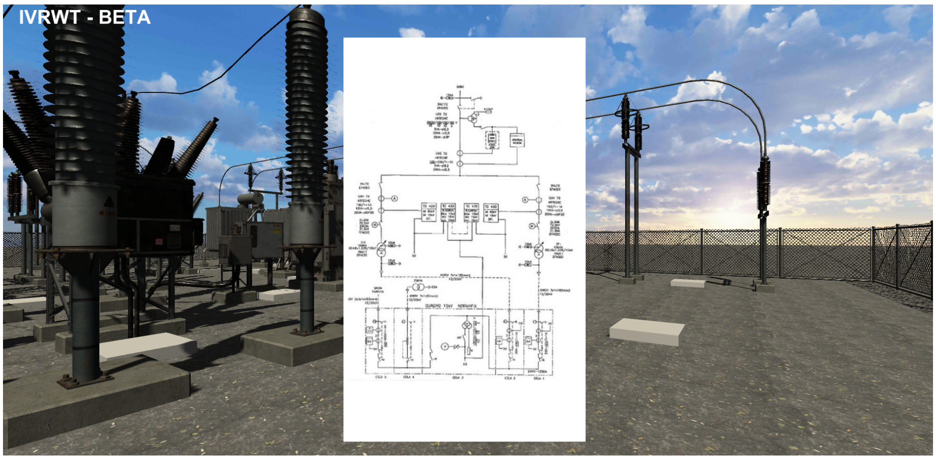

Figure 3.11. Substation: Power Plant.

Minimalist Design and Aesthetic, "dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility". The solution only contains the necessary information; no irrelevant information is displayed to the users.

3.7. System Evaluation - Final Score

To finalize the training, users must enter the substation house. Then a fade-out effect is activated, and the pop up with the overall performance is showed, Figure 3.12. For this purpose a score script is created, evaluating first the selected security equipment and tools according to the selected procedures for the training (the pseudo-code is available in Appendix A.2). Then every step required in the maintenance of single equipment or multiple ones is checked and translated to information that is available in the final score component. Text written in red means that the user failed in that step, in apposite green text means that he has completed the task with success. Besides all the steps information, it is also showing the user an overall performance in percentage.

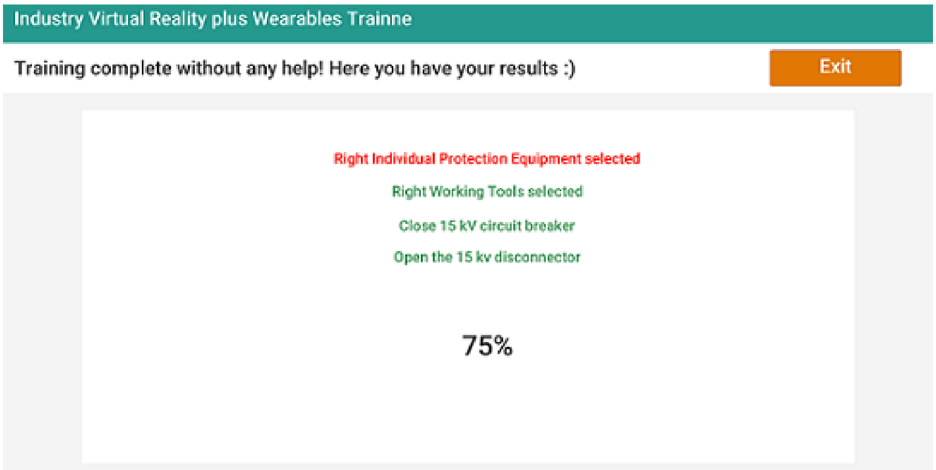

FIGURE 3.12. Screen: Final Score.

CHAPTER 4

Results and Discussion

In this chapter, the results yielded for each experiment, and the App validation tests with users are presented and critically analyzed. In this analysis, the existing competitors were used to expose solution weaknesses and uniqueness.

4.1. Usability Tests

At the begin of my dissertation, the objective was to test the developed solution with EFACEC personnel, that are the final users of my solution. Due to the Covid-19 situation, these planed tests could not happen. I needed to come up with a new plan for the tests.

The purpose of the Usability Tests [**49**] was to validate when users test this App; if they follow all the presented steps and learn from them. So, non-professional users can also preform these tests. I did not test the App with EFACEC or in alternative with FRAUNHOFER personnel since I was always working from home. As an alternative, the solution was to test with friends and relatives. The usability scales in paper were not used and instead an online version plus some additional questions to be answered using the web browser were created. For this purpose, I used Mentimeter App [**11**]. The usability scale had some questions inverted, where is supposed to disagree instead of agreeing strongly. This is purposely done to avoid automated answers that could bias the study.

Although my usability tests were less formal, I have created a protocol to be followed. There, it was detailed which parts of the application must be tested. It is impossible to ask people to test all the functionalities in the application; because that required to much time. So, a script for the customization screen, asking to introduce the signalized data was given to them. Every tester had the same session, training in the same conditions and testing the App for the first two procedures. Since my teaching system is equal for all the procedures, it was enough for acquiring the necessary information.

The solution was tested by a total of ten people, six male and four female, with ages between 25 and 60.

During these tests, my only intervention was at the beginning, before starting each session, giving them all the required equipment and if necessary, explain how to use it. From there until the end of each tester session, my function was to observe and only in "blocker" cases try to help, influencing their experience the less as possible. Just to mention this only happened in one test.

4.1.1. System Usability Scale Results

The standard System Usability Scale [**19**] was adopted, and an online version was created, for the persons who test the solution to give feedback, Figure 4.1 and Figure 4.2.

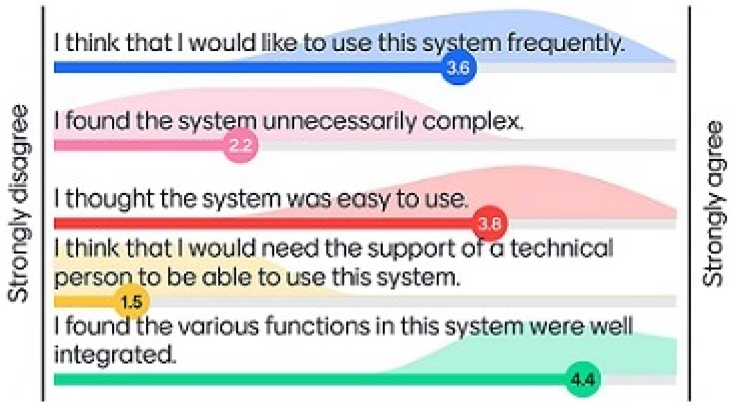

FIGURE 4.1. Usability Scale - Part 1.

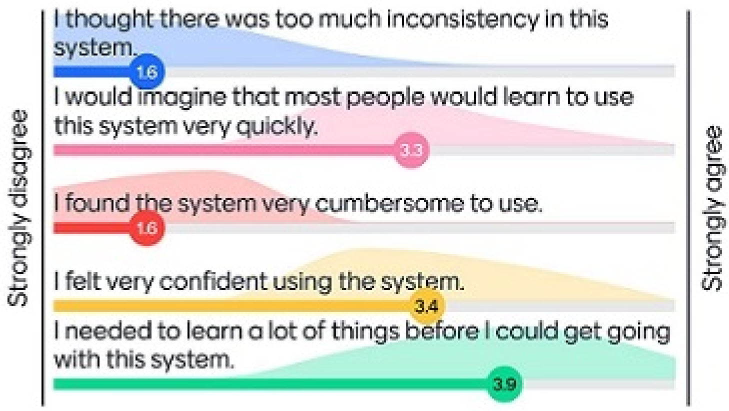

FIGURE 4.2. Usability Scale - Part 2.

4.1.2. Other Questions Results

Besides the Usability Scale, more questions were added to better know about the current state of the developed VR application. So, the next questions and individual results are the outcomes of these extra queries.

The first question to evaluate if the customization screen and all the instructions during the training session were easy to understand and follow, so one question related to this issue was created, Figure 4.3.

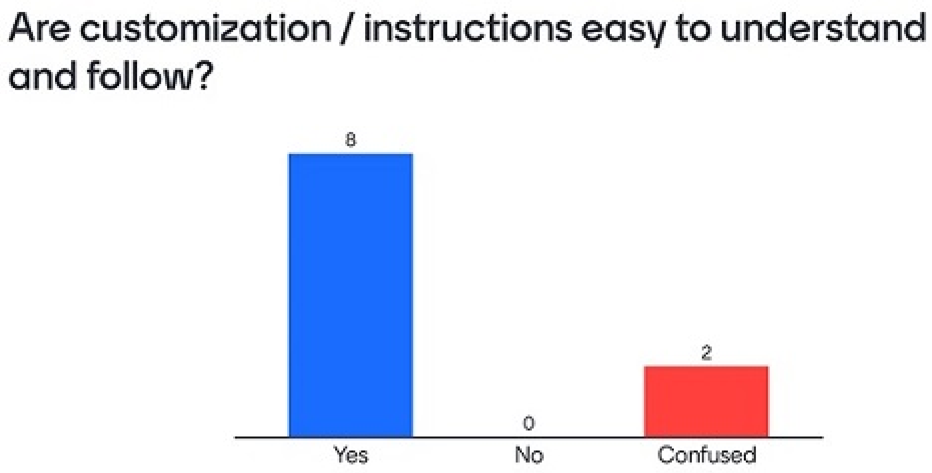

Figure 4.3. Question Number 1.

The developed solution is all about teaching a set of procedures that required specific skill sets, so for me was critical to know if the message is passing and somehow users are learning the proposed concepts, Figure 4.4.

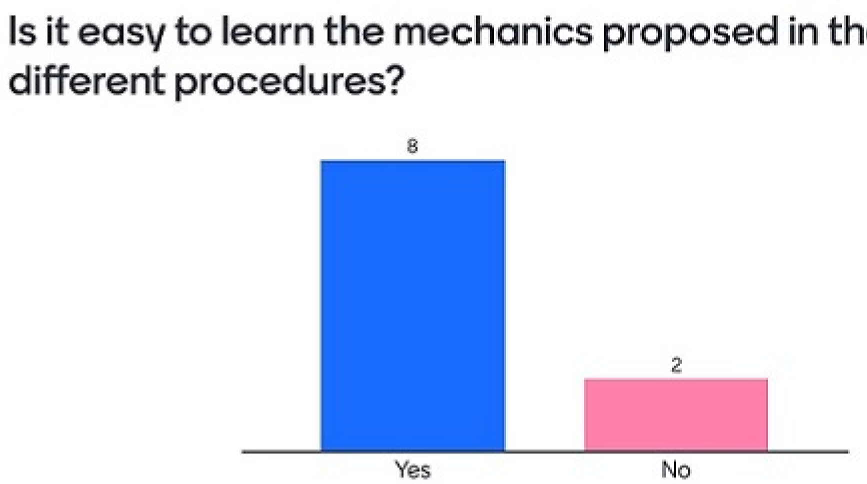

Figure 4.4. Question Number 2.

Throughout the research for this master thesis and this document, Virtual Reality as a teaching method is a real advantage over the traditional methods, section 2.2. This question was to assess if users have the same opinion and VR is a good training tool, Figure 4.5. Reminder: With traditional methods I mean images, schemes and illustrations in books.

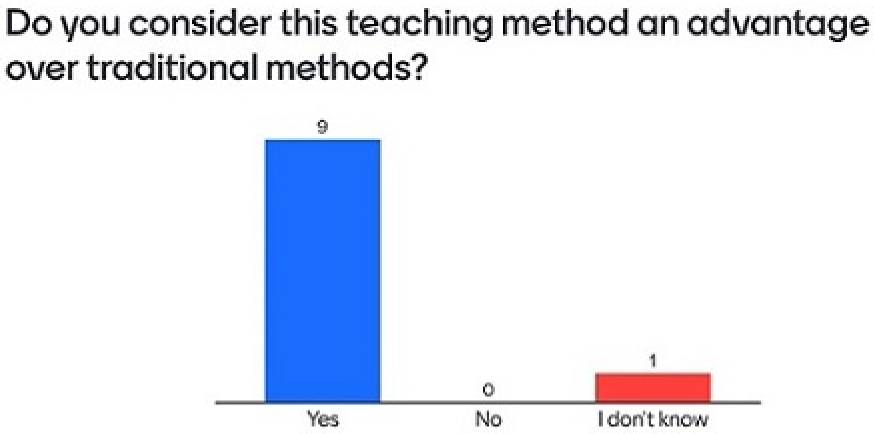

FIGURE 4.5. Question Number 3.

Mentimeter as a functionality named "world cloud", that builds a frame with all the words inserted by the testers. Volunteers were asked to describe the solution in one word. Everyone could insert more than one word. The outcome is this frame, Figure 4.6.

FIGURE 4.6. World Cloud: App in one word.

4.2. Discussion

The results indicate that Virtual Reality as a teaching methodology, depicted here by my solution, "VR Substation Training Tool", is effective and help trainees to achieve the purposed assignments quickly.

By analyzing the obtained data from the results, this idea can be supported and aligned with other research studies. The results from the Usability Scale tests claim that users would like to use the system (overall of 3.6 out 5), and that, the system was easy to use (overall of 3.8 out 5). Moreover, users responded that, would learn to use this system very quickly (overall of 3.3 out 5), and only a few answered that the system was cumbersome to use (overall of 1.6 out 5). They felt very confident using the system(overall of 3.4 of 5). The question, "Is it easy to learn the mechanics proposed in the different procedures?", had eight answers as "Yes" versus two as "No". To the question "Do you consider this teaching method an advantage over traditional methods?", nine answered as "Yes", zero as "No" and one as "I do not know". With these results, the first research question is answered, VR is viable as a teaching tool. This is also in line with previous research studies, where it is showed by other authors that VR is an effective and reliable technology, Section 1.2 and Section 2.2. "A relatively small VR device can even act as a whole science lab", "With VR, they are not limited to word descriptions or book illustrations; they can explore the topic and see how things are put together" [**27**].

The previously mentioned data, also justifies that using this solution improves personnel procedures, responding to other of my research questions. A reflection of this is also the results from the question "Are customization/instructions easy to understand and follow?", where I obtained eight "Yes", zero "No" and only two "Confused" answers. Why am I saying this? If users understand what is necessary to be done and how to do it, clearly they are learning something. These are excellent signs since along the last months some iterations in the UI design were made to give a clean look and keep it simple as most as possible. Thus, VR solutions help users to learn the expected content; the data says that it is accurate and other existing solutions and studies are saying the same. GE Grid Solutions [**22**] says "Teaching an operator how to replace a high-voltage circuit breaker... would usually involve many paper manuals and weeklong practice runs at a substation training centre, with a team of about six people on hand to operate the crane. With virtual reality, it takes 20 minutes to practice this task" [**44**]. Other analyzed article says and I quote, "Once in place, AR and VR can speed the on boarding of new workers and improve worker productivity, by offering more immersive, on-the-job training" [**10**].

Another research question of this master thesis is "Does it contribute to personal or collective enrichment?", let us talk first about the individual part. Yes, it does. All the data collection points in this direction. What about the collective improvement? Besides, not having data to confirm this question, both situations, personal and collective, are related. What does this mean? So the target users are working all in the same company, if the solution contributes to the individual enrichment, for sure, it will also contribute to the collective [**34**]. "AR and VR also allow them to retain the knowledge of an ageing workforce" [**10**].

The results need to be the supported by a technical person to be able to use this system (overall of 1.5 out 5), should be taken into account when considering the deployment of the solution. Consequently, a proficient user should, be present the first time the user is using the equipment to explain the setup. User will need to use three pieces of equipment, the VR headset in his head, the two inertial sensors, one in each wrist and a controller only for the customization part.

Another essential result is the one related to the system development where it was expected people to give feedback about how the system was well integrated (overall of 4.4 of 5). Furthermore, if the system does not have inconsistencies, here the question was the inverse. Therefore, the expected result was strongly disagreed (overall of 1.6 of 5). The developed solution has similar results when compared with other competitors [**9**] [**25**] [**46**]. This statement is based on the questionnaire results but also when comparing the developed scenario with other solutions.

Some unexpected results occurred in the question from the usability scale; I need to learn many things before I could get going with the system (overall of 3.9 of 5). There are two possible explanations for this outcome; one is that the majority of the population is not accustomed to this type of technology and with the combination of the inertial sensors it requires some time for them to learn how to work with the system. The good news is that the results also show that the system is easy to learn, so when users overcome and assimilate all this knowledge, this is no longer a problem. On other hands what could also contribute for this could be all the substation vocabulary and concepts, since the volunteers did not know too many things about this world, maybe they needed more time to assimilate everything. Although people mentioned that the system had too many things to be learned before going on with the system, they mentioned that the presented complexity was necessary for the solution. The results from the "I found the system unnecessarily complicated" (overall of 2.2 out 5), sustains my statement.

About the research question "Does collecting data really help the company and the employee in a teaching process", I will focus only on the employee part, everything related with companies are excluded from the conducted usability tests. I conclude that data collected during the training sessions, due to the inertial sensors, section 2.4, was vital for all the teaching process. Despite sensors are collecting motion data, it is only used to control objects; this type of data is not being saved or analyzed yet. For the final screen where the feedback with all the steps and the final overall score is showed to the user it is used the data coming directly from the App. This topic has so much potential [**29**], being the primary function that separates the developed solution from the others [**20**] [**9**] [**14**]. There is a solution that does some training performance analytics [**21**]. Additionally, they have a portal where all this information is available. However, they do not use inertial sensors so they cannot track the same data as the developed solution. Regarding all this, further work on data acquisition will be critical; more data means that users will be more aware of all their movements and where they need to put more effort to improve. The same applies to the company; they will have more data about there employees and will manage all their working force more effectively, reducing eventual errors.

Due to the lack of data related to company context and their employees, was impossible to respond to my research question ”What kind of impact does this application have on companies and their employees?” As explained in section 4.1, Covid-19 situation made it impossible for me to conduct the tests in an Industry context, namely with EFACEC and their employees. Despite this setback, the results from the possible tests give me hope that the solution will have an impact both for the company and employees. Off course, further research is needed to establish this statement , so tests for this context are planned shortly wherever the situation improves or normalizes. Nevertheless, the developed solution works as a teaching tool, and procedures are easily assembled, contributes to personal enrichment and all the data collected helps the users during the training journey.

CHAPTER 5

Conclusion and Future Work

5.1. Conclusions

Nowadays, traditional teaching methods are not enough for specialized training personnel. All sectors are searching for new training solutions. Industry, in this case, the Electrical sector, is searching to replace the old traditional methods by new ones and more efficient. Virtual Reality and Augmented Reality are new teaching techniques, proven by the literature, that are effective and capable of replacing the significant methods being used by the industry.

However, literature tell us that already exist some new solutions with these new technologies; they have some gaps in what monitoring users actions and scenario customization concerns.

Initially, this dissertation provided a broad overview of substation complex, necessary equipment and procedures. Then was introduced Virtual Reality as a training tool, using engineering education as an example and doing cross-reference with the traditional controllers. Thus, other existing solutions were contextualized and compared. Next, the IoTiP specifications were explained, namely the hardware framework and the sensor core. To close chapter two, Virtual Reality development is introduced, presenting the used headset and other technologies like the VR hands model, 3D Scanner and how the inertial sensors are working in the App to control objects.

The following chapter presents the "VR App", and all the work realized in the development of the solution. Starts by describing the system flow, schematized using a flowchart. The customization area is presented, and the interaction system, the user interface and how the system does the trainee performance evaluation (final score).

The developed solution was evaluated through a questionnaire and a usability scale. A set of 10 users run tests and answer to the questionnaires. The obtained results are represented and discussed next.

With this master thesis is possible to conclude that VR works well as a teaching methodology and users feel comfortable and motivated using this solution. Users can train with help and suggestions from the system and later try again without assistance, challenging them-selves to improve. The customization tool gives to the chance to customize the training scenario for each particular case, or in other words, for a specific substation.

5.2. Final remarks on the research questions

Throughout this document, I tried to respond to all my research questions. The rebuttal of those questions, stated in Section 1.3 is quickly summarized below (complete version in Section 4.2):

- **How effective is this type of training compared to traditional methods?**

As explained before, this research evidences that this new methodology is adequate and the future of learning, special in dangerous contexts.

- **What kind of impact does this application have on companies and their employees?**

I could not evaluate this type of impact, because usability tests were made in casual users and not with technical personnel. When the covid-19 situation improves and lets me, I will conduct new tests as was planned at the begin of this dissertation.

- **Does it contribute to personal or collective enrichment?**

Individual enrichment influences the collective one, during my studies was proved that this solution has the potential of teaching users what is proposed. So is the fact that this App contributes to the technical improvement of both parts.

- **Does collecting data really help the company and the employee in a teaching process?**

For me, this is the critical point of my solution, the one who differentiates from the others. All the results showed that data has a significant impact on all the learning process; without this component, how would the students know the main aspects of their training? The final feedback would be incomplete.

5.3. Future Work

This dissertation leaves some unsolved problems. Thus, additional development effort will be applied in the future. The description of some of the ideas to explore are detailed in the following paragraphs.

Enable customized 3D models. It was decided to leave this feature out of the thesis working plan because the used standard model was enough for users to learn all the necessary procedures to work in the substation maintenance. I would be back soon to this issue to add more diversity to the App in order to trainers add their station's 3D models if they considered necessary. With this, it is possible to create different types of substations.

Add training inside the substation house. The seven procedures presented in the current solution resolve the large majority of the necessary maintenance, so we leave the training inside of the substation house out of the solution and only focus on training in the substation exterior. As future work, it will be added the equipment models for the house. The procedures are already implemented, as mentioned before.

Improve the interaction with the levers. Due to the Covid-19 situation, it was impossible to map the 3D model for the transformers leavers, since I could not travel to EFACEC to realize the 3D capture. As an alternative, more abstract models were created and added to the application.

Add more procedures to the solution. Since the focus was to add the essential procedures to be trained, the ones that allow realizing almost every kind of maintenance, some tools currently present in the application were left without use. So with this issue, it is intended to add more procedures, allowing users to use all the tools currently available in the VR application.

Test the solution at EFACEC. As mentioned in chapter 4, Covid-19 did not allow to conduct the planned tests with some EFACEC personnel. These tests were replaced with new ones, only with relatives and friends. Thus, once again, when possible new tests will be conducted, before releasing the solution to be used as a learning method.

Appendices

CHAPTER A

Pseudo Code

A.1. AI - Setting Training Scenario

The data from the customization and EPI/Tools screens is saved in the SessionConfigurations when the continue button is pressed. Then a new scene is open and this script will be launched on the start function and generate all the training scenario.

Example:

```
SessionConfigurations;
Procedures List;
GameObject tools Array ;

start function

for i = 1; i less then NumberOfTranformers in SessionConfigurations; i++
   instantiate one tranformer prefab

for i = 1; i less then NumberOfSwitches in SessionConfigurations; i++
   instantiate one switche prefab

for i = 1; i less then NumberOfProcedures in SessionConfigurations; i++
   Add procedure i to the Procedures List

for i = 1; i less then totalOfTools in SessionConfigurations; i++
   enable gameobject in the array position i

if fullHelp in SessionConfigurations is true
   set active all help elements
else if semiHelp in SessionConfigurations is true
   set active only the task, without the description
else
   turn off all help elements
```

A.2. Final Score

This script will check every step made by the user. This information is shown as text. If a step is completed the text is showed with green colour and if not in red colour. An overall score is also presented in the form of a percentage.

Example:

```
SessionConfigurations;
User;
CompletedSteps;
TotalSteps;
FinalScore;

if the right Individual Protection Equipment selected in SessionConfigurations is true
   write the respective text with green colour and add one to CompletedSteps
else
   write the respective text with red colour

if the right tools selected in SessionConfigurations is true
   write the respective text with green colour and add one to CompletedSteps
else
   write the respective text with red colour

if procedure number one completed in Users is true
   write the respective text with green colour and add one to CompletedSteps
else
   write the respective text with red colour

... same thing for the remaining procedures

TotalSteps = number of selected procedures in SessionConfigurations;
FinalScore = CompletedSteps/TotalSteps * 100
```

CHAPTER B

Substation Related Schemes

B.1. Understanding Arroteia Substation

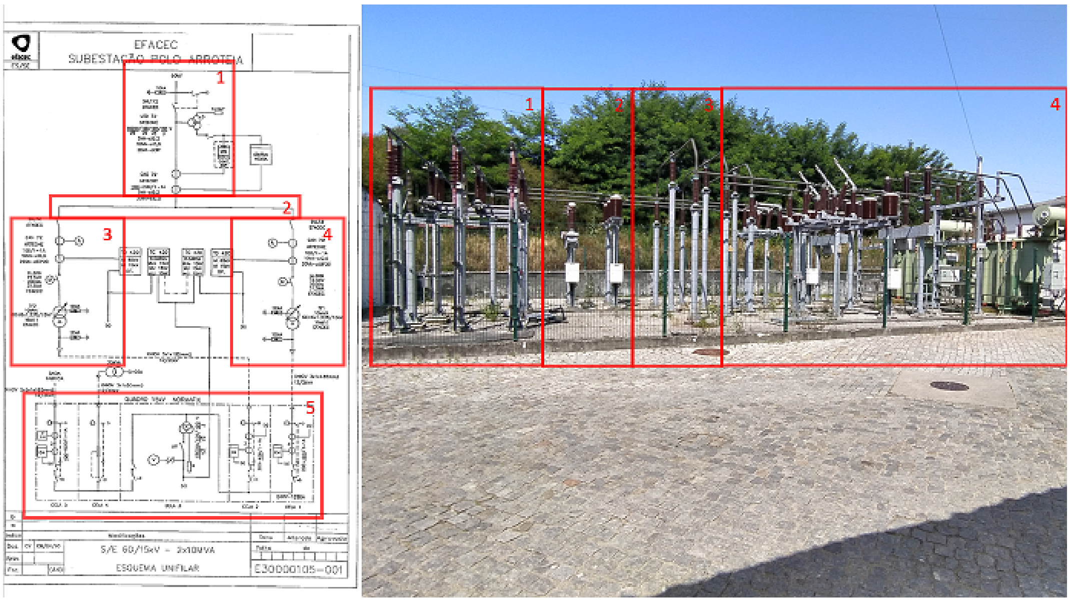

FIGURE B.1. Understanding Arroteia 1.

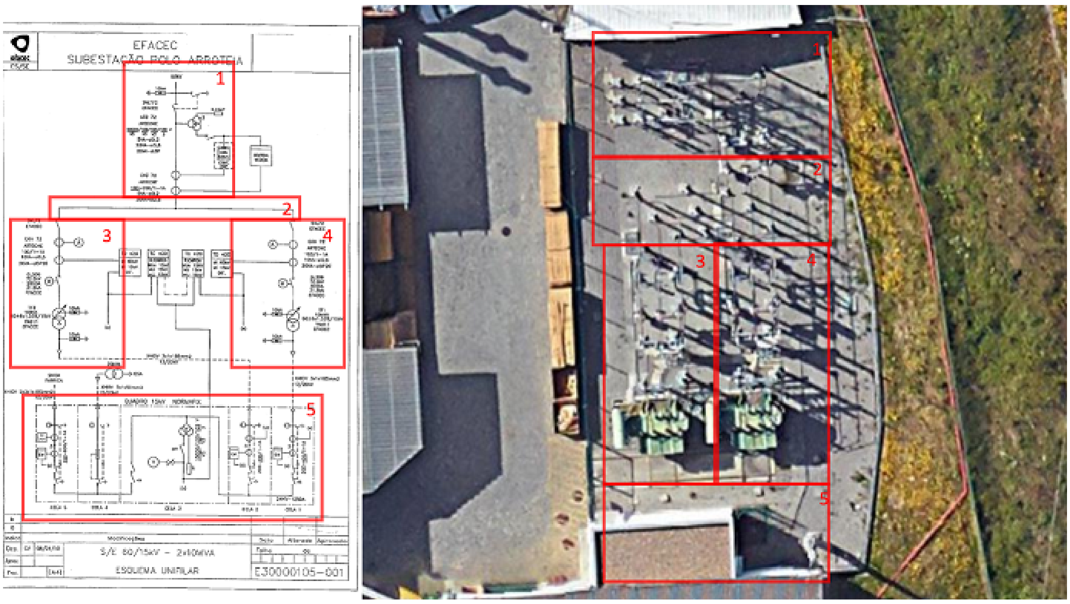

FIGURE B.2. Understanding Arroteia 2.

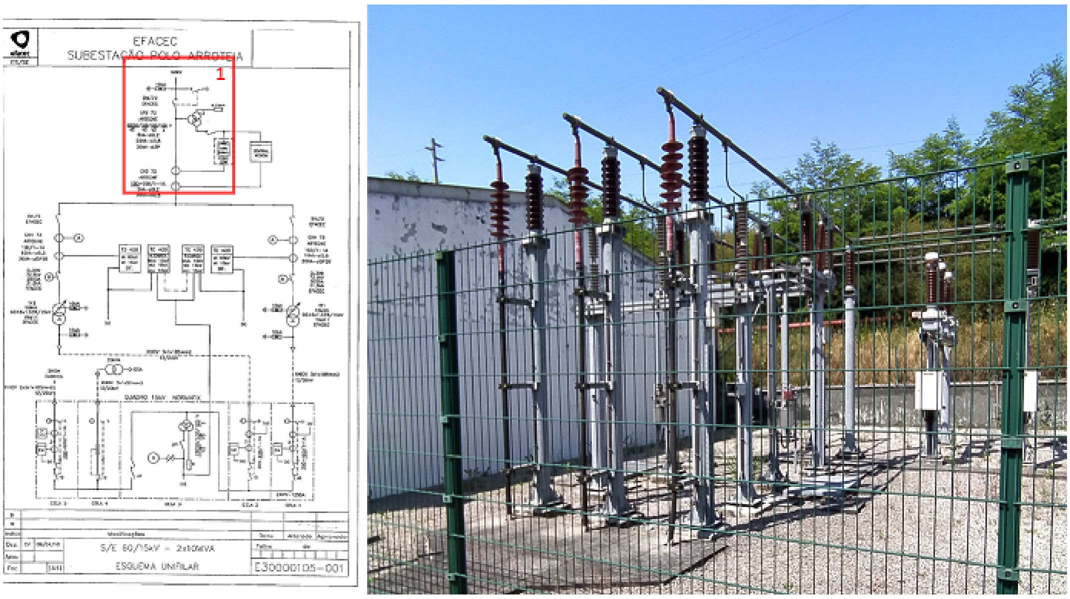

FIGURE B.3. Understanding Arroteia 3.

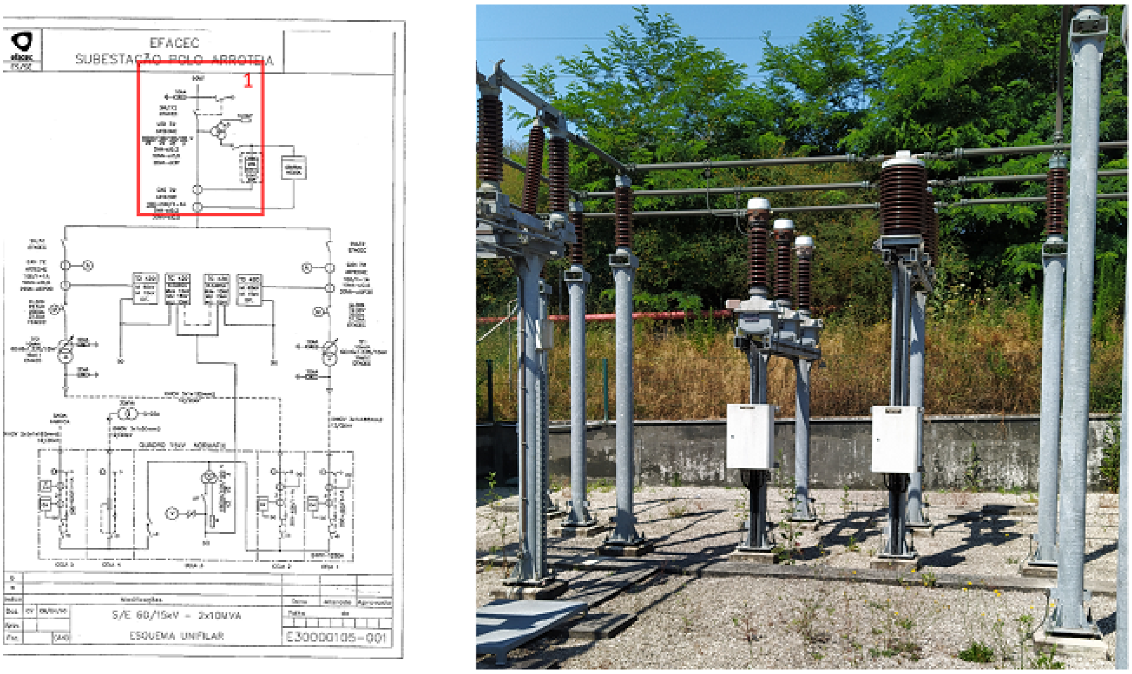

FIGURE B.4. Understanding Arroteia 4.

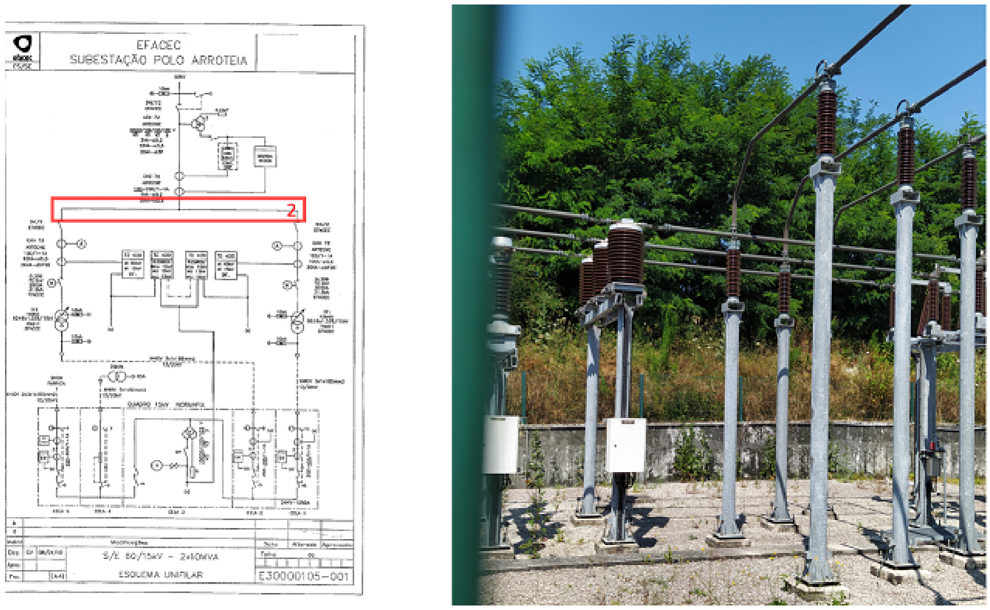

Figure B.5. Understanding Arroteia 5.

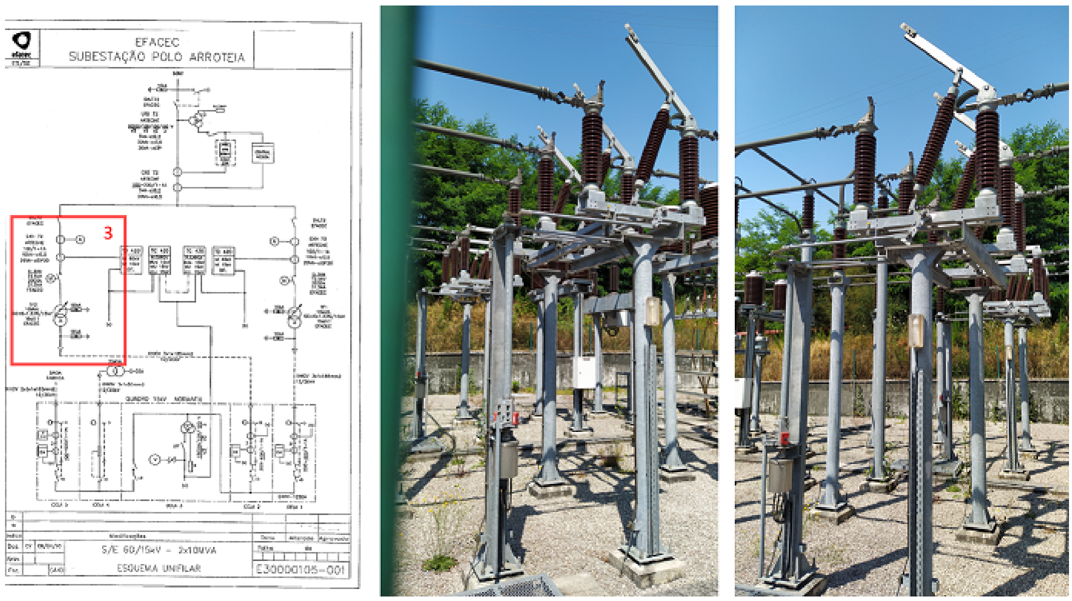

Figure B.6. Understanding Arroteia 6.

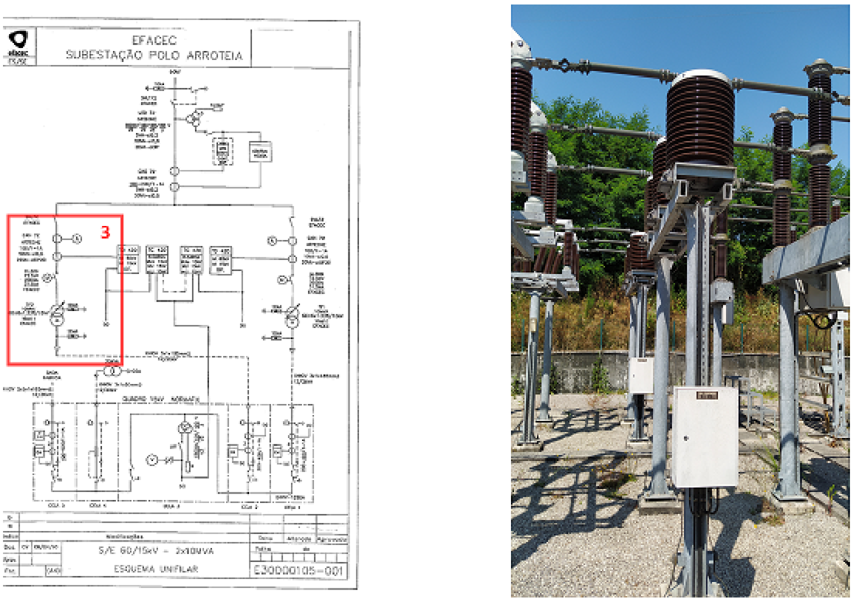

FIGURE B.7. Understanding Arroteia 7.

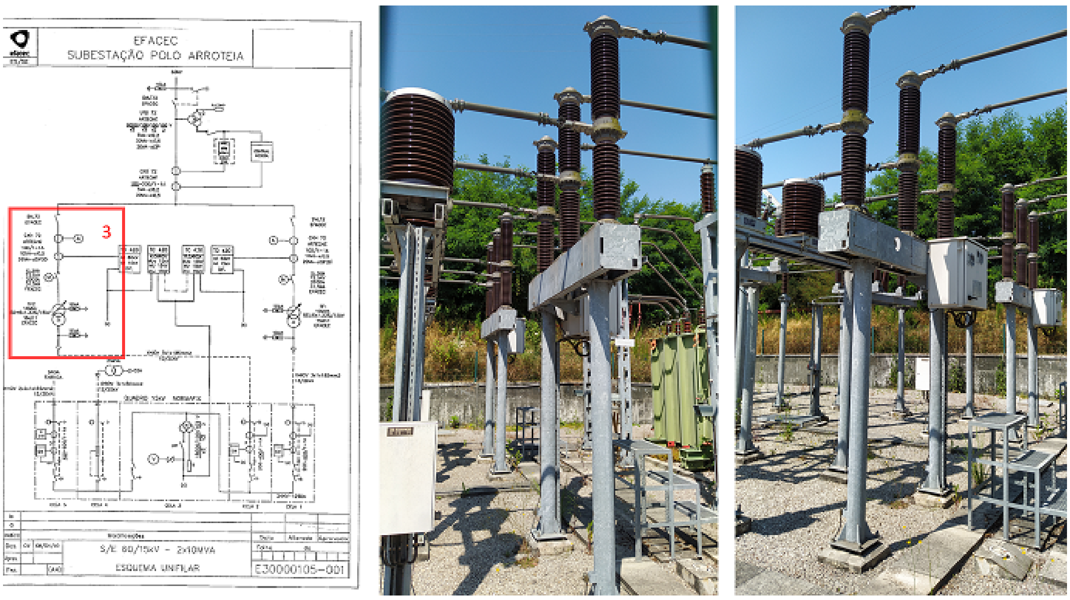

FIGURE B.8. Understanding Arroteia 8.

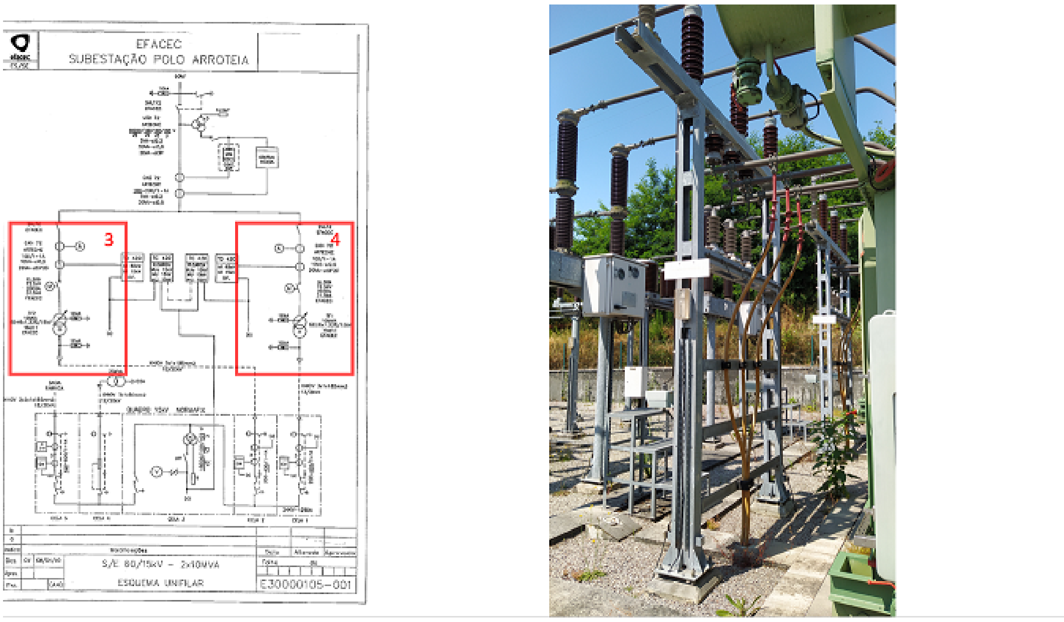

FIGURE B.9. Understanding Arroteia 9.

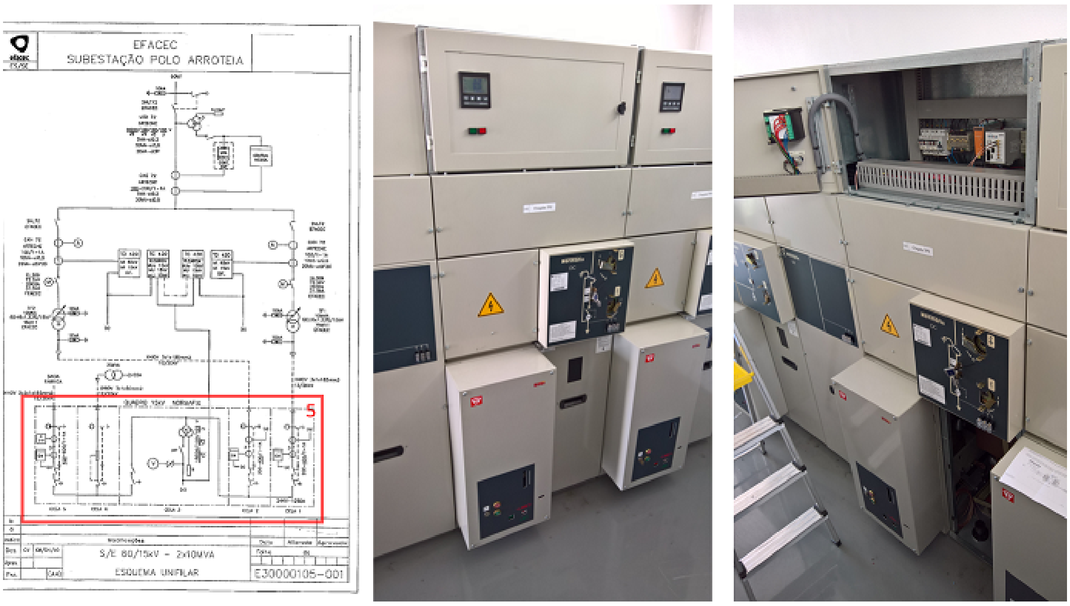

FIGURE B.10. Understanding Arroteia 10.

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