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ENGINEERING SCIENCES

Virtual Reality for Monitor and Control of Electrical Substations

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Abstract: This project presents the results obtained from a new strategy based on Virtual Reality techniques, which intends to minimize the operational issues caused in electric power substations due to the lack of spatial and functional information on the traditional operation interfaces. For this purpose, a three-dimensional interactive virtual reality environment was built in a realistic and accurate way regarding an energy supplier substation in Minas Gerais – Brazil and subsequently implanted it in its operation center for tasks related to its functioning. Lastly, tests were applied to operators to obtain results aiming at the contextualized problems.

Key words: Electrical substation, spatial and functional information, substations operation, virtual reality.

INTRODUCTION

In the electrical sector, the energy suppliers have continuously employed efforts which intend to improve the quality and continuity of their power supply to their customers (Bernardon et al. 2016).

However, supply interruptions are inevitable for various reasons, particularly: execution works in system expansion, preventive and/or corrective maintenance on the grid's components, or even human errors in the operation of the national interconnected system (Porto et al. 2017).

In the context of human errors, statistical analysis shows that these errors in a system correspond up to 90% of the total failures (Peng-Cheng 2012).

Historically, in Brazil, major blackouts that occurred in the national interconnected system are related to human error in its operation. In this regard, a situation that deserves mentioning is a blackout occurred in 1996, which affected 9 states for 100 minutes due to a maneuver failure (Gomes 2004).

In these circumstances, identifying the factors that influence the operators' performance is necessary to identify problematic aspects that raise the potential occurrence of human errors (Embrey 2000).

Therefore, methodologies related to the analysis of human reliability on critical Engineering Systems can help the search of improvements in the national interconnected system operation process. The objective of these methods is to analyze the factors that contribute to the occurrence of human mistakes and to determine their probability. The model utilized in this study must be built and validated by empirical data, for instance, the operational experience and results based on simulators usage (Podofillini & Dang 2013).

In this respect, the HEART (Human Error Assessment and Reduction Technique) methodology elaborated by Williams 1986, and later consolidated by Bell & Williams 2016 assumes that any reliability in a task's performance can be altered according to the presence of error-promoting conditions or performance factors. According to this guideline, one of the main error-causing conditions related to the operation of Engineering Systems is based on the absence of an interface to transmit spatial and functional information to the operator in a way that he/she can readily assimilate.

Contrasting this problematic, the application of Virtual Reality techniques aims to develop a more intuitive interface that maximizes the interactivity, usability and naturality aspects during the action process (Kirner & Kirner 2011).

Under this context, the Virtual Reality became the main technique to break the interaction barrier in the 2D space. It allows its user to manipulate information that is similar to the real space while being favored by the immersion feeling, which is the major characteristic in these environments, for it being the responsible of producing the feeling of presence in the virtual world (Landberg 2000).

This way, facing the scenario of the difficulties dealt in the electric system's operation process and the potential of the Virtual Reality field, this research has the objective to develop and evaluate a system based on Virtual Reality techniques that allows transmitting spatial and functional information in the process of electric power substations operation.

For this purpose, the premises of this research are: a) To investigate the state of the art of the operation process of electric power substations; b) To create methods and interface control styles that reuse the mental model from the operator regarding the traditional operation process; c) To carry out usability analysis and apply evaluation and observation forms.

Lastly, having in mind that the main current systems for this practice do not bear the resources that promote the view of functional spatial information, a factor that is considered an error-promoting condition, the motivation behind this research is based in the search for improvements in the operation process of electric power substations, reduction of the error incidence possibility and greater safety and efficiency.

STATE OF THE ART

Electric system operation

The operation of the electric system has always been a very complex activity. Initially executed in a local level by station operators who, most of the time, do the operation directly on the machinery, and generally in a mechanical and manual way. The evolution of the machinery and, mainly, the increase in the systems' tension levels brought the possibility and the necessity to execute the commands remotely. Afterwards, the operation interfaces migrated, throughout this evolution, abandoning the objective of executing the operation directly on the electric system's machinery and sought to offer interfaces supported by computers and built on single-line diagrams. Nowadays, except for small-sized electric systems and simple substations that do not have machinery with electrical commands, the "natural" operation interface are systems based on computers with single-line 2D diagrams (Prado et al. 2014).

For the operating system to reach its objectives, the information regarding the machinery's status needs to be provided to the various interested sectors, simultaneously maintaining the data integrity and the access' safety. To allow the provision of the system's information, generally, the computer which executes the operation software will be connected to the company's network (Alves 2014).

State of the art of the operation interfaces of the electric power substations

For all the users of the operation centers, the natural operation environment is the 2D interface, single-line diagrams. Most of these users, mainly the new hires, barely know the stations they operate into. Normally, they are technicians who come directly from the technical courses to be trained directly in the control rooms. When they are taken to the stations, they face an unfamiliar and strange environment and may have difficulties in finding the correlation between the 2D operation interface and the actual station's environment, thus not promoting the association of the operation mechanisms with the real field scenario (Prado et al. 2014). Figure 1 shows an example of the current operation interface.

HEART methodology

The HEART method – Human Error Assessment and Reduction Technique, Bell & Williams (2016), assumes that any trustworthiness in the performance of a task can be modified according to the presence and the strength of error-promoting conditions.

The methodology identifies nine generic kinds of tasks and proposes nominal values for the corresponding human mistakes probability, and besides that, it relates the main error-promoting conditions that have a great influence on the tasks' performance.

Each error-promoting condition has a value associated to the impact it can cause. This value is based on an extensive analysis of human performance literature.

It is worth calling attention to the error-promoting condition number 5 called "Lack of means to transmit spatial and functional information to the operator in a way that he/she can easily assimilate" that has a value of 9,

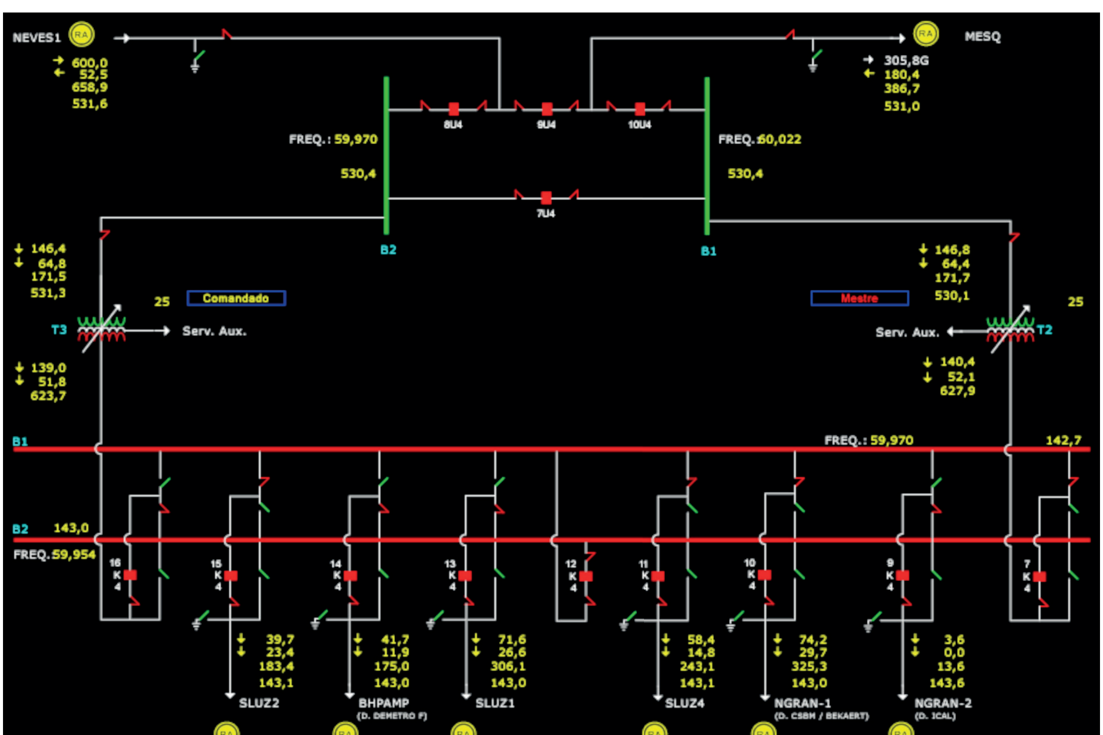

Figure 1. Single-line diagram of the energy electric company of Minas Gerais (CEMIG).

being considered high in a scale between 0 and 17 related to the impact that it could cause.

This error-promoting condition involves the problematic of this presented article.

Virtual Reality

The term Virtual Reality (VR) was released at the end of the 80s by Jaron Lanier, artist and computer scientist, who managed to blend two antagonistic concepts in a new and vibrant concept able to capture the essence of this technology: the search for the fusion of what is real with the virtual (Tori et al. 2006).

There are many definitions of the term "Virtual Reality" which involve general and/or technological aspects. As for Byrne 2009, Virtual Reality is a computer technology that offers its user the illusion of being in a three-dimensional space with the ability to interact with this 3D space.

Whereas for Kirner & Kirner 2011, Virtual Reality is an advanced interface for computer applications that allows its user the movement (navigation) and real-time interaction, in a three-dimensional environment, allowing the usage of multi-sensory devices for its acting or feedback.

Lastly, Cardoso et al. 2007 state that Virtual Reality is a computer system used to create and artificial environment, where its user has the impression of not only being inside this given environment, but also being able to navigate on it, interacting with its objects in a natural and intuitive way.

In the definitions of the Virtual Reality term, it is possible to understand its formation in three basic principles.

Interactivity: It is related to the computer's capacity to detect its user's actions and react instantly, modifying the application's aspects.

Involvement: The idea of involvement is linked to its motivation grade to a person's commitment to a given activity. The involvement can be passive, like reading a book or watching television, or active, like participating in a game match with a partner. Slater 2003, reports that involvement or interest relates to content, not form.

Immersion: immersion stands for the objective level of sensory fidelity provided by a VR system, whereas presence is the subjective psychological response of a user experiencing a VR system (Slater 2003).

RELATED WORK

There are several pieces of research that propose the usage of Virtual Reality in many aspects associated with electric substations, being: a) Training of Substations Operators; b) Methodologies for virtual substation development.

In the training of substation operators' field, some works are worthy of mention, such as Wang & Li (2010), which is based on a Virtual Reality system development connected to a database, designed for operators' training purposes in substations' control rooms. Finally, the authors reported that when utilizing this system, the operators fully understood proper equipment operation in different conditions, as well as effectively improved response time in emergency situations.

In the same aspect, the work of Ribeiro et al. (2014), presents a system of Virtual Reality for operators' training in power systems substations. The proposal intends to reduce training time for new operators and increase ongoing training effectiveness. Using the simulation, the operator can visualize information captured by the supervision system and simulate operation procedure, not exposing the system to risk situations, avoiding injuries of any kind.

Another work that can be highlighted is the system conceived by Yang et al. (2014), destined for failure detection training by partial discharges. The system provides various tracking patterns and allows failure and instrument simulation algorithms to be packaged in separated components, enabling new detection pattern attachments in order to extend system functions. Guangzhou's power supply training center was benefited from the installation of this system, being presented qualitative results emphasizing good outcomes in the training process.

Regarding the methodology for virtual substations development, Meng & Kan (2010), propose a flexible development manner for creating a Virtual Reality environment structure for Electric Power Substations. The work focuses in developing a system to enhance a Virtual Reality Game Engine. Since most of Game Engines do not possess units dedicated to elaborate electrical power substations, modules were designed to complement the Engine and to reduce costs in the fabrication of these substations. The structure developed has methods for capturing real values to the equipment's state.

In this work, the authors have not reported this implementation in a real utilization scenario. Neither have they highlighted the possibility of substation equipment's control, nor the development of solutions for integrating tools with traditional operation interface, favoring the reuse and association with the operating mental standard model.

Another relating research, Pessoa et al. (2017), presents an authorship tool using spherical panoramas for the construction of immersive Virtual Reality (VR) environments linked to the concept of extended panoramas. The tool was utilized to build an immersive environment based on a real substation, and equipment data were consulted through communication with the substation data acquisition system. The possibility of control and equipment operation that constitutes the substation was not reported.

Thus, based on quoted associated works, It is noticeable that - even presenting different action scopes in the electrical power substations area – is possible to observe in the analyzed works the importance of developing interfaces that present spatial information relevant to the purpose's domain, and as consequence providing a more natural and intuitive human-machine interface with the reality experienced.

DESCRIPTION OF THE VIRTUAL REALITY SYSTEM DEVELOPED TO THE OPERATION OF ELECTRIC POWER SUBSTATIONS

The proposed system consists of a realistic virtual environment that represents 44 electrical substations from Minas Gerais (CEMIG) equipped with interfaces for both monitor and control.

Through an elaborate internal architecture, data regarding the machinery's status (on, off, electrical measurements) that compose an energy provider's substation are received and processed in real-time through WebService. Having this information, the virtual environment is updated representing accurately the status of the substation's devices, allowing commands to be sent in real field action.

In this context, it is possible to provide a new approach to control and operate devices from the electric power substation through the usage of VR techniques, granting greater immersion and more intuitive interactions.

Another pertinent aspect is that the operators areable to navigate through various ways, exploring and viewing the electrical components' conditions in order to control the substation more safely.

Thanks to the virtual and accurate reconstruction of the environment, it emerges the possibility of using the system to carry out trainings. Consequently, the operators can explore and acknowledge the physical details of the objects, besides simulating different operation possibilities for the circuit without compromising the system's safety and performance. Figure 2 shows the system during an operation to consult the status of one of the substation's components.

The proposed system needs to correctly represent the status of the referred operation, showing exact machinery's information. In this sense, it becomes feasible the elaboration of an internal architecture that adapts itself to the engine. This engine was conceived using the object orientation paradigm. The equipment's data are collected and transmitted through WebService, which in turn, is provided by the electric power operator.

Through a data collecting and controlling system, the real equipment's status which compose the electric power substation are collected, processed, and made available. Afterwards, the virtual environment consumes these data and updates the system, accurately corresponding itself to the actual substation. For it being a two-way architecture, it is possible to alter the machinery's state through the virtual environment, thus modifying the actual components' status.

As for the construction of the 3D models, the software Studio Max was used, therefore a modeling convention was elaborated so that all three-dimensional objects were developed within the same standards, for instance high level of realism, low quantity of polygons and full-scale dimensions. For this purpose, catalogs of equipment, plants and images were used. After modeling the components, 3D Studio Max was also responsible for the objects exportation through its plugin FBX. It made possible to export objects or even entire settings in formats perfectly recognize by the engine in which SRV was developed.

The whole three-dimensional setting, acquisition architecture, data delivery, and interactions mechanisms that compose the application were built utilizing Engine Unity 3D,

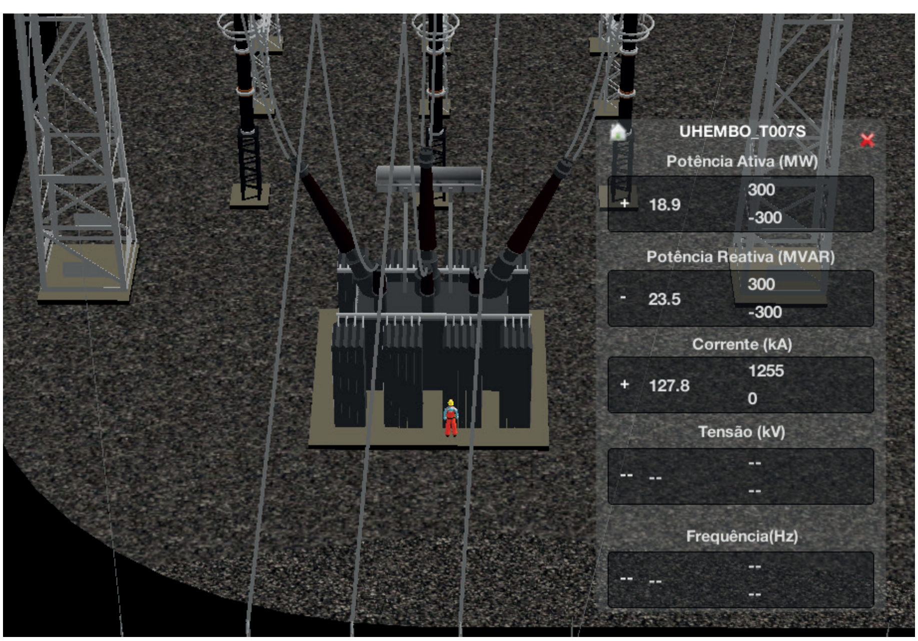

Figure 2. Status information consult of a transformer through WebService.

for script development (programming code) the programming language C# in Visual Studio environment was used.

It is important to consider that some animations were also made in Unity 3D, as the camera transition, for instance, working collaboratively with animations developed in the modeling software.

The system has two application architectures. The first is based on desktop platform using conventional input and output devices (mouse, keyboard and monitor). The Figure 3 presents the desktop platform use in the system's operation center.

The second architecture has the option using the HMD (Head-Mounted Display) for Virtual Reality as a display device, as well as a proper joystick for mechanisms regarding data input. Figure 4 depicts the use in this format.

It is worth mentioning that the user has freedom to choose which utilization architecture is more appropriate and convenient in certain situations.

ELABORATION OF INTERFACE STYLES AND METHODS THAT REUSE THE OPERATOR'S MENTAL MODEL REGARDING THE TRADITIONAL OPERATION PROCESS

For it being a complementary strategy to the electrical substations' operation context, it is important to elaborate screens to control the VR system that reuse the mental operation model acquired by the operators throughout the time by using the traditional operation interface based on a single-line diagram.

To elaborate these Virtual Reality system's control screens, which have the purpose to operate the electrical components of the substation, some requirements related to the usability, design, and layout aspects were defined. These are traditional in two-dimensional systems (2D widgets). They are: a) Every control screen must be integrated to the virtual environment. b) The control screens must provide mechanisms that allow a fast activation. c) The control components have to be shown only when it is necessary to the interaction context or when it is activated by the user.

Selection taskbar – menu

The elaborated strategy contains a single taskbar to select the control options, situated to the left side of the environment. The space occupied by it, related to the vertical axis of the screen, is 100%. Regarding the horizontal axis, in inactivity moments, only 1.2% (just enough space to see its existence) of the area is occupied and there are no items referring to the selection options in them. However, in moments of activity, its space is enlarged to 15% and the referred items are shown. Figure 5 shows the item with the active selection taskbar.

This activation is made by hovering the mouse over the taskbar. It is observed that the control interface is inserted in the 3D application context, with a 50% transparency.

Actions' control panels

Each item that composes the side taskbar has a panel ith the options referring to specific actions. To show this panel, it is only necessary to hover the mouse over the unfolding icon (arrow). Thereby, the panel is only shown when the involved action is being solicited. When the pointer is outside the control interface, the panel is hidden. Hence, the side taskbar returns to its inactive state. Figure 6 shows a part of the lateral taskbar and the panel regarding a control action contained in the virtual environment.

Figure 3. Virtual Reality System for substation operation shown on the left side of the display.

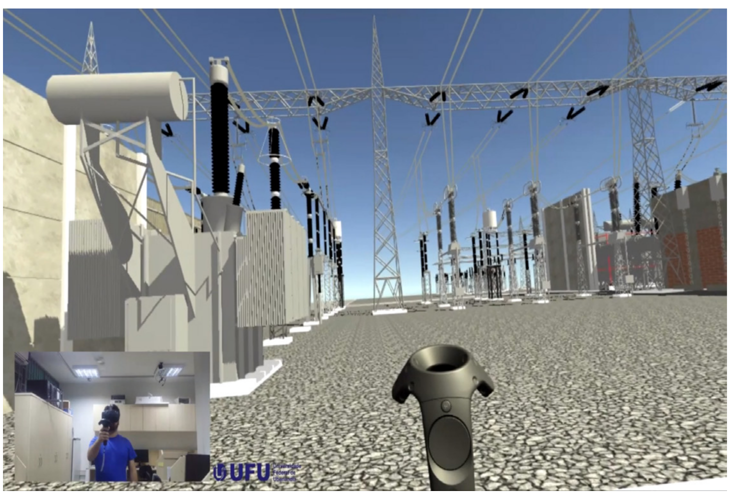

Figure 4. The lower-left corner of the picture shows the user interacting in the entirely immersive utilizing HMD HTC *Vive*.

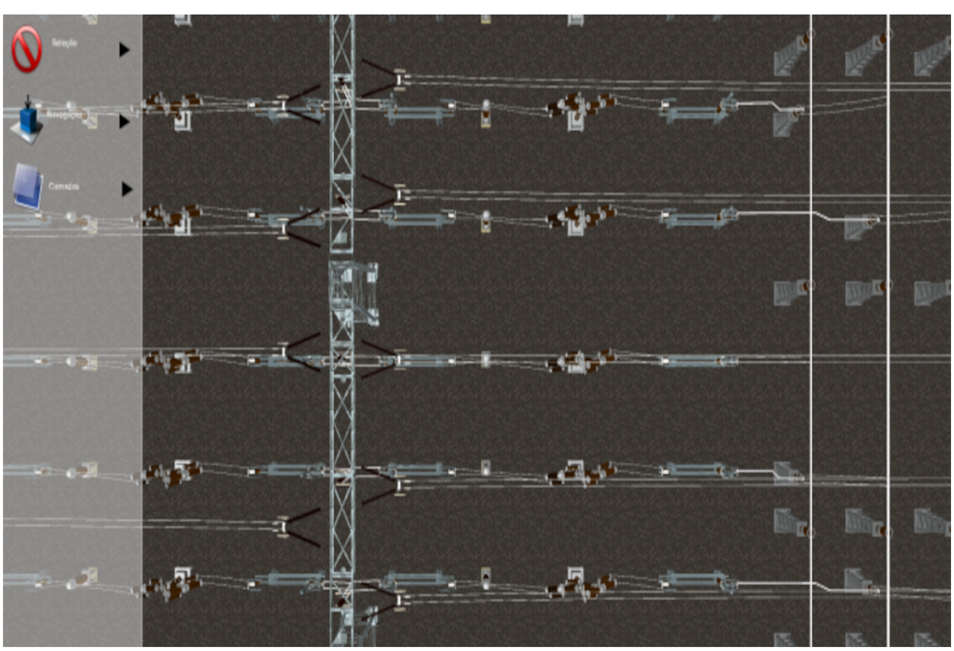

Figure 5. Active Selection Taskbar. (Selection; Navigation; Layers).

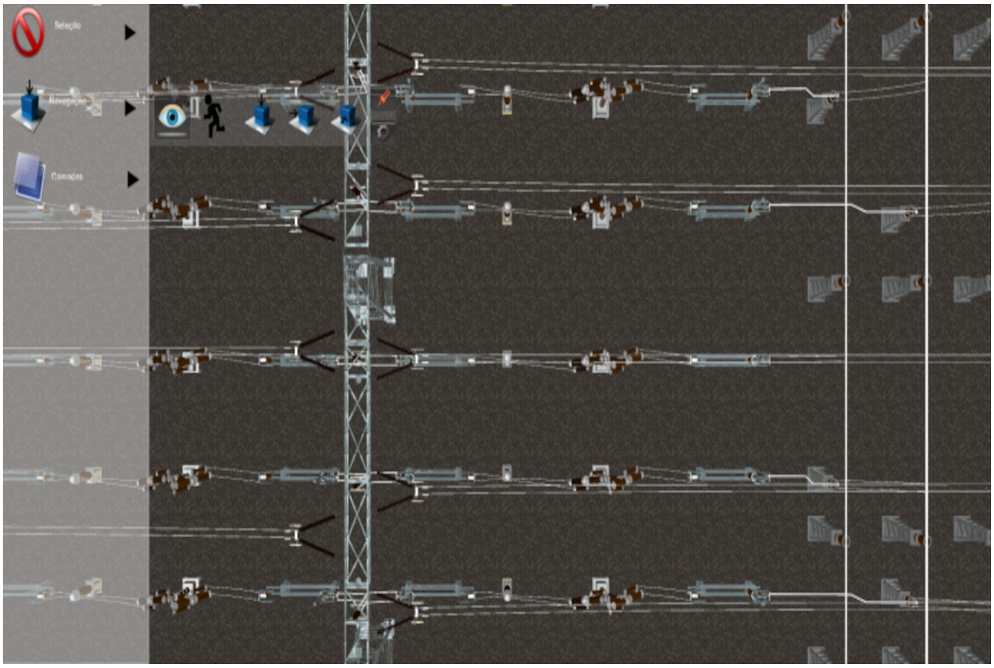

Figure 6. Selection Panel of the Control Action. (Selection; Navigation; Layers).

Control Windows and content presentation

When the user needs to manipulate a virtual environment, windows and control elements are shown after their selection. These windowa are also integrated into the virtual environment and ther exhibition area automatically finished after executing of canceling the action, thus making the virtual enviroment less overloaded and more intuitive. Figure 7 shows these windows:

Wrapper layer

This function allows controlling of the content view in an independet way, enabling the activation or deactivation during the usage of the VR system. The user is free to manipulate this resource according to necessity at any time in the application, adding complementary information to the virtual environment.

An example of controlled content is the layer called "warpper". Its aggregation value to he virtual enviroment is given by applying a contour over the virtual equipment. If the equipment' s status is "closed", the contour will be red, inf otherwise, it will be green. By activating this layer, the user will obtain a faster intepretation of the machinery's status. Figure 8 shows this content layer in an active state.

The use of these colors relates to the mental model utilized by the substation's operator in the traditional interface (single-line), using such attributions to represent the states (open and closed).

When the user requires only to navigate through the virtual substation, the wrapper layer can be turned off, avoiding a visual overload in the virtual environment.

RESULTS

During all the development period and implementation of this strategy, the potential users were involved, besides having a 6-hour training regarding the system's usability and functionality.

To analyze the strategy, various methods were applied, such as moments to observe and monitor the usage of the Virtual Reality system, evaluation questionnaires, and application

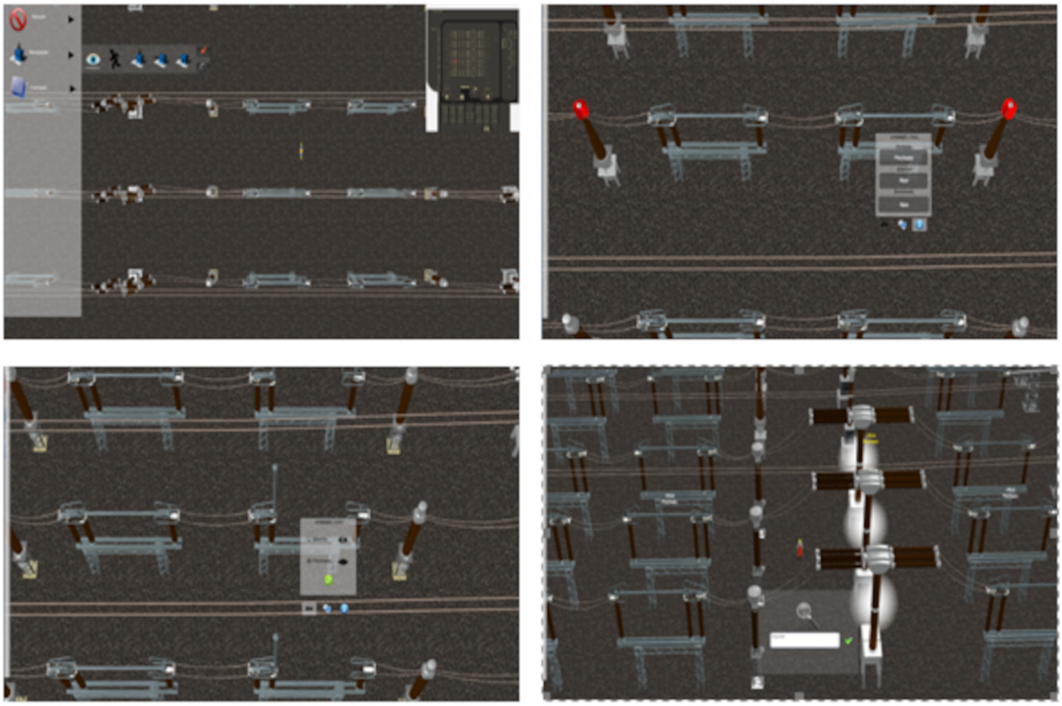

Figure 7. Content Presentation and Control Windows.

forms to analyze the system's performance. These tests were carried to 12 operators from System Operation Center and they correspond to 65% of its population.

The questionnaire's development was based on the QUIS (Questionnaire for User Interaction Satisfaction) methodology. The QUIS was projected to evaluate the overall satisfaction of the users with specific aspects of the human-machine interface (QUIS 2018).

Therefore, the users were able to properly talk about what is working and what is not. However, an efficient way to perceive users' necessities is by observing them directly (Lowdermilk 2013).

To develop the application forms related to the operators' performance analysis, common failure recurring situations associated with substations operations were utilized.

Reaction to the VR system usage

This criterion analyzes the user's satisfaction regarding the system's proposal: monitoring and controlling the substations. The aspects addressed were: the degree of interest towards the application, utilization ease, suitability with the proposal, and its overall pleasantness. Figure 9 shows the results obtained in these attributes.

By making a total average between the number of operators that utilized the system and the adopted criteria to analyze the proposal, it was assessed that 76.5% of the users partially or totally agree that the VR techniques-based system has the necessary adherence to be used in the substations operation context.

Usage control screens – 2D Widgets

This criterion analyzes the menu, submenu, alternative interface, control, and data presentation screens. Aspects analyzed: visualization, adequacy to the proposal, aesthetics, usage ease and the feeling of integration to the 3D environment. In Figure 10, it is possible to see the obtained results.

According to Figure 10, ample satisfaction regarding the control mechanisms used in the

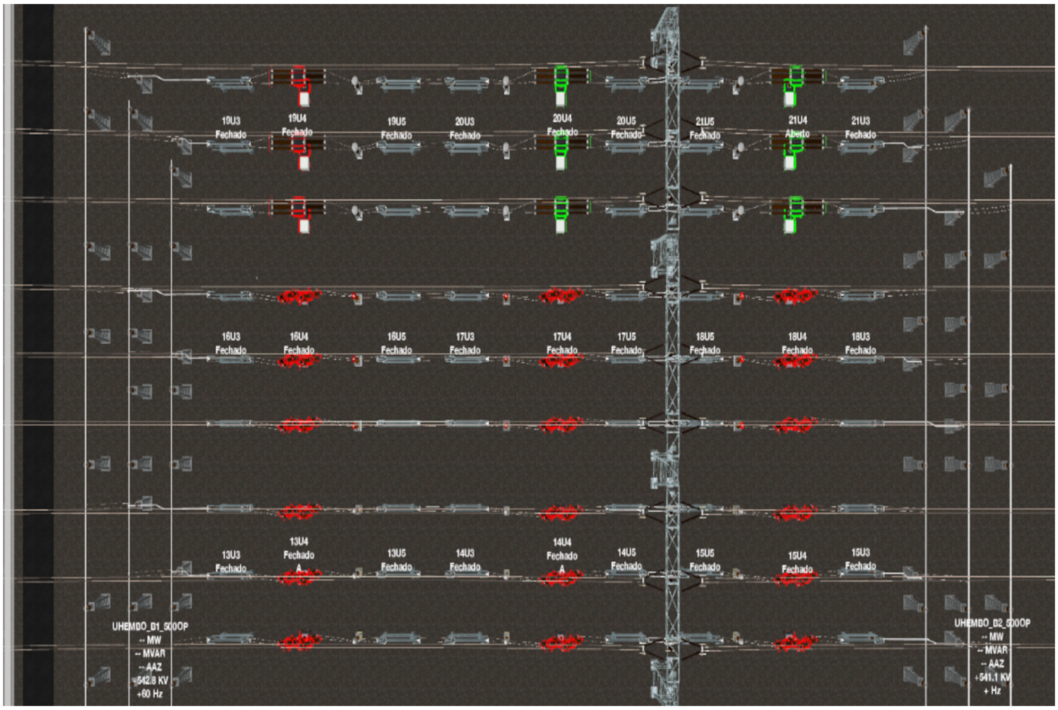

Figure 8. Active "wrapper" layer.

VR system can be noticed. They were elaborated with the intention to reuse the previous knowledge acquired through the conventional model, thus making the training and adaptability processes easier to the operator. This is one of the specific objectives of the research. Figure 10 shows the results obtained.

It is important to point out that in the criterion of "legible visualization", 41% of the operators did not positively evaluate the attribute. Consequently, a specific analysis of the situation was necessary and it was perceived that, in some moments, small visual confusions tended to happen. Figure 11 contextualizes the failure scenario.

After identifying the failure, the presentation mechanism of control interfaces was fixed, eliminating the occurrence of such kind of failures.

Navigation mode and spatial visualization

This criterion analyzes the usability of the distinct navigation modes that the VR system has, highlighting the user's presence sensation, considering the control interfaces integration in the virtual environment and the paradigms confrontation (between 2D widgets and 3D vitural environment).

The evaluated parameters were efficiency, interest, ease of learning how to execute the commands, and the overall sensation of presence during the system's usage. Figure 12 shows the results collected in this criterion.

Based on the obtained data, it can be noticed that the available navigation modes and the way to fulfill this procedure were well received by part of the operators, easily allowing the access to their points of interest.

It is relevant to report that all the operators who took part in this research partially or totally agreed that the developed system transmits a strong feeling of presence with the approached context. This feeling is an important attribute to reduce the absence of a method to transmit spatial and functional information to the operator in a way that it can be readily assimilated.

Afterwards, a second stage was made to test the system, this stage being constituted of task executions and procedures associated to the operation domain of electric power substations.

To this end, the operators carried out two determined and simulated activities relevant to the operation process in the new proposed interface, with the objective to measure their success during the execution.

Activity 1: Locating the equipment and approaching the field of view to it

In this activity, the operator needed to locate a designated transformer situated in a substation and, afterwards, approach the field of visualization through the “zoom in” resource, having a 30-second time limit. Figure 13 shows this activity’s results.

In this concern, it is possible to infer that most of the operators successfully accomplished the proposed task without facing any difficulties, finding it easy to spatially locate the substation’s components. On the other hand, 17% of them needed help to accomplish the task and 8% were not successful, considering the 30-second time threshold. Since it is a critical engineering system, stipulating a time limit to execute a task is crucial.

Activity 2: Consulting information from equipment and altering its operation state afterwards

In order to accomplish this task, the operator needed to consult the information about a designated circuit breaker (status, alarm, simulated mode) and afterwards to alter its state (from open to closed and vice-versa), having a 45-second time threshold. Figure 14 shows the results regarding this activity.

This performed task is considered routine in the substations’ operation context, and as presented result, most of the operators managed to accomplish it with total success, while only 16.5% needed help to accomplish and the same percentage of operators couldn’t succeed in the given time.

Lastly, it is important to point out that approximately 83.3% of the operators that took part in these processes stated that they have already had previous experience with a kind of three-dimensional virtual interactive environment.

Overall, based on the tests and reports of the participating operators, it was possible to observe that most of these who obtained mistakes in the activities’ execution or needed help during the test declared in the form that they possessed little or no experience with virtual 3D environments. Accordingly, one of this research’s future works is associated with providing a time increase in adjustment and training stages of this system for the operators under this profile and subsequently reapplying the test in order to obtain new results.

Part of the operators reported the possibility of using this system in maintenance planning and intervention domain regarding electrical substations due to its ability to convey spatial and functional information, an important and yet rarely available resource in such actions.

Another suggestion from the operators collected in training and test stages is related to making available resources that allow them to edit the virtual setting that compose the substations, since there is the possibility of changing the layout in real substations due to its expansion, thus being accuracy between virtual and real important for the substations’ operation. This observation configured as another future work in this research.

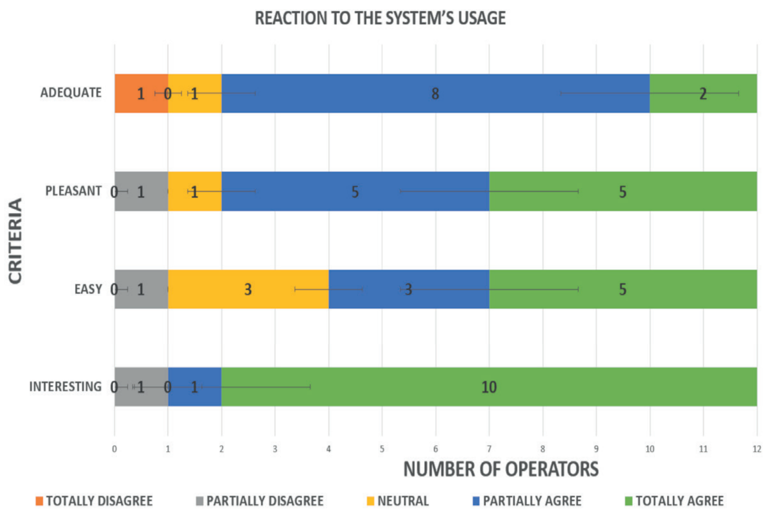

Figure 9. Graph showing the analysis criteria about the system's usage.

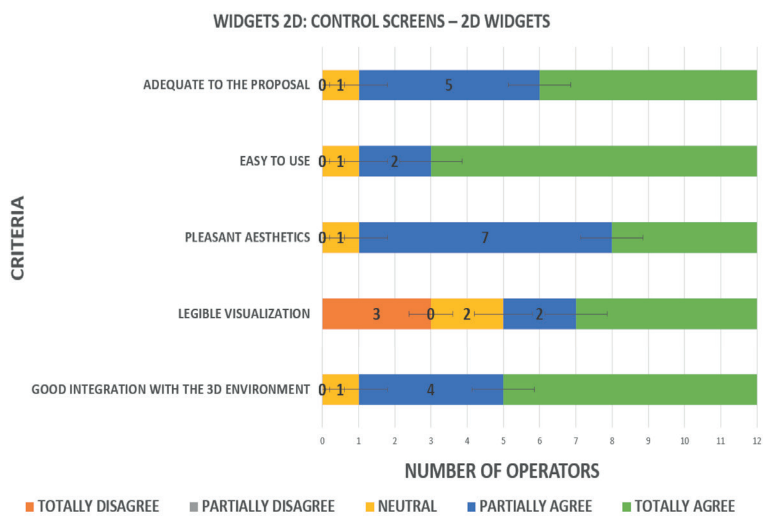

Figure 10. Graph regarding the analysis criteria about the control screens.

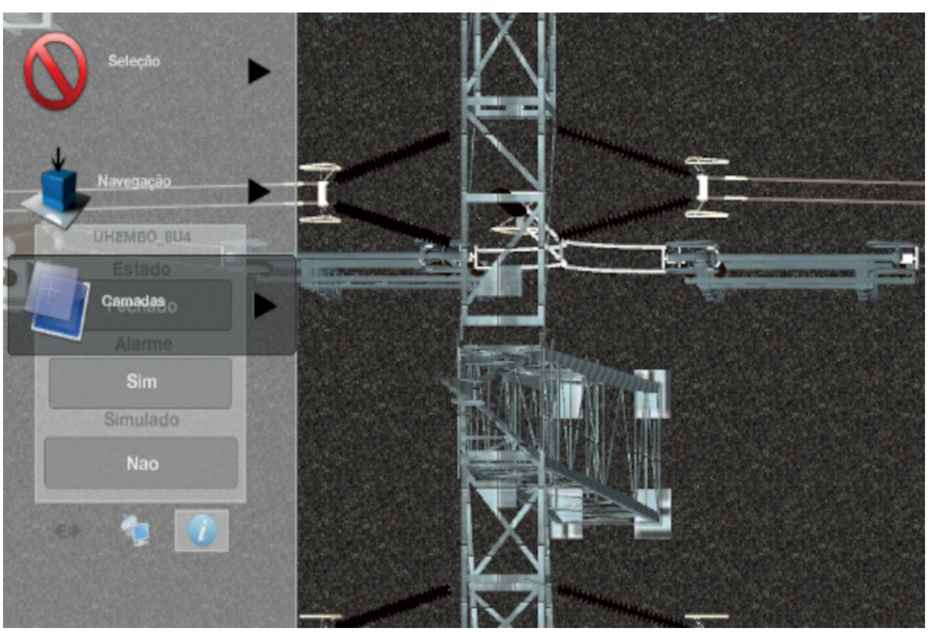

Figure 11. Visual confusion between the menu and the data presentation window.

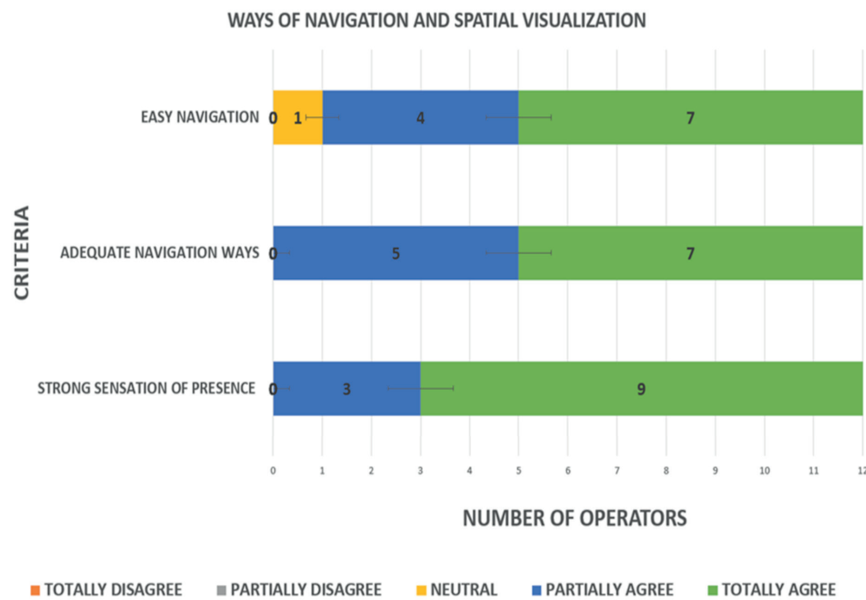

Figure 12. Graph regarding the analysis criteria about the navigation in the 3D environment.

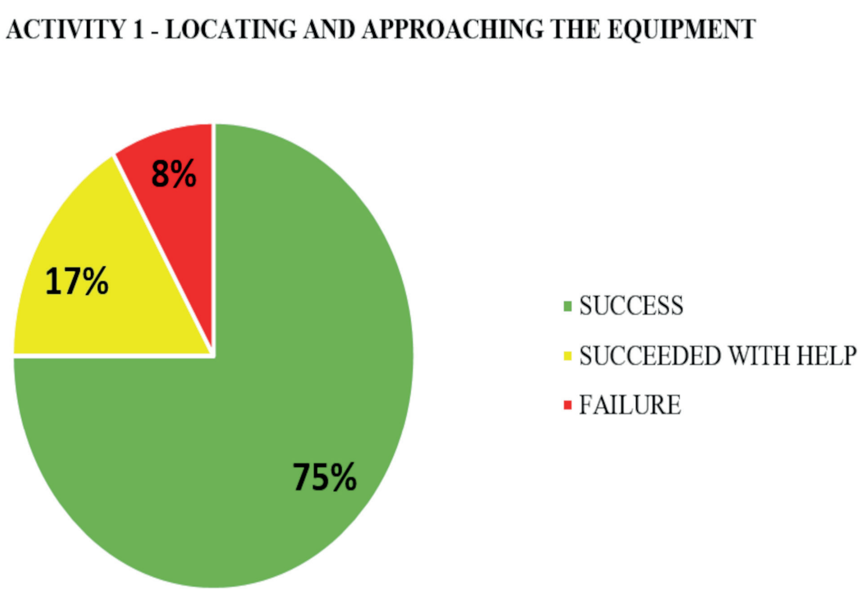

Figure 13. Graph regarding the activity "Locating and Approaching the Equipment".

DISCUSSION

As mentioned before, it is crucial that the operator can assimilate the operation interface in a way that there is no difference between it and the real field, and for this purpose, it is important to develop strategies that transmit spatial and functional information.

Interaction concepts and techniques in Virtual Reality can favor the intuitive and natural operational notion, which is strongly requested in engineering systems operation contexts. Thus, this project presented a new strategy and examples of representation and interaction of the user interface, which in turn can act as a complementary method to the current operation ones.

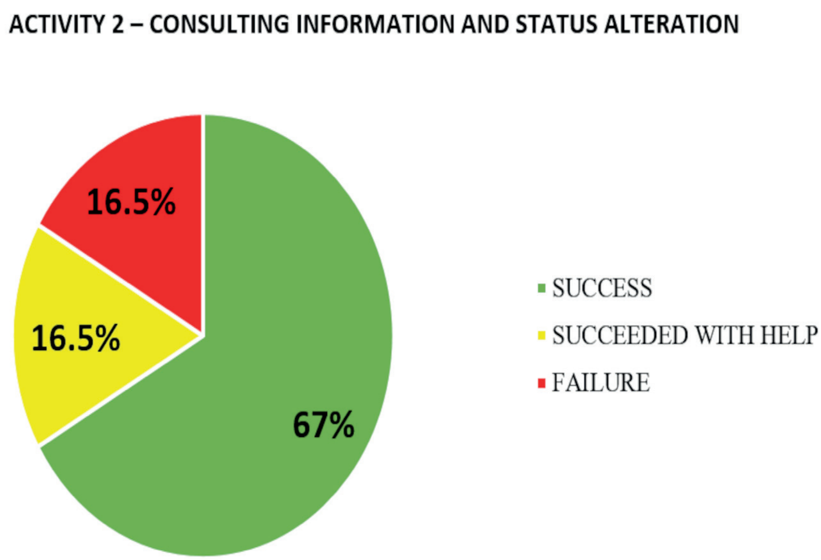

Figure 14. Graph regarding the activity "Consulting Information and Status Alteration".

It is also believed that the system proposed here contributes to a positive and more natural aspect in the substations operation process, consequently, an ally in the search to improve the quality and continuity of the electric power supply.

In this context, all operators will need to be exhaustively trained to use the VR system. An uncontested advantage is that this training will be optimized since it can be conducted remotely, saving time and accelerating the results. As it can be seen in the applied tests, the proposed system is satisfying and easy to use.

Nonetheless, it is necessary to raise awareness to the fact that Virtual Reality systems allow virtualization of real and specific environments. Consequently, the visualization and interaction mechanisms are different from traditional interfaces contained in electrical power substations' operation centers. Presenting and inserting a new interface in a high criticality environment like the one shown require a thorough implementation study, being important to consider in which operating situations the new interface can be employed, besides the importance of embodying and adapting the pre-existing mental models and operation command concepts.

Therefore, it is essential to present, highlight, and debate with all people involved in the process the limitations and potential of the current traditional interface. Emphasizing the limitations it presents, such as not providing spatial and functional information to the operators in a way that they can readily understand during the decision-making process, as well as showing the difference between the traditional interface and the reality in field, in order to later delimit situations in which the use of a Virtual Reality system can yield benefits in an operational context. This being a fundamental action for the acceptance of a new interface in a critic operation system that does not tolerate failure.

This system has been deployed and remains active at the operation's center of an electrical supplier in Minas Gerais, and as future project in this research, it is intended to analyze other error-promoting conditions faced in engineering systems and build new strategies to minimize their impacts in the electric power substations operation context.

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