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VISITING RESTRICTED AREAS OF A NUCLEAR FACILITY VIA A VIRTUAL REALITY SIMULATOR

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ABSTRACT

The *Instituto de Engenharia Nuclear* (IEN) is a nuclear research facility whose main research lines comprehend non-destructive essays with thermal neutrons in biology, industry, environment and national public security. IEN is a restricted areas access composed by several laboratories, a particle accelerator and a nuclear research reactor known as the *Argonauta*. Viewing the accident in Fukushima has contributed to the reinforcement of the concern related to the nuclear applications, thus highlighting its negative aspects, it is important to provide information about what are the real purposes of a nuclear facility to avoiding misunderstandings created by sensational headlines. On the other hand, several researchers have proposed applications using virtual reality techniques to solve nuclear engineering related issues in recent years. Additionally, technical literature records a large number of uses of virtual reality concepts to develop simulated environments with a high degree of fidelity to their real counterparts. Therefore, this survey proposes a virtual environment that is able to simulate the visit procedure in a nuclear facility to provide information about the nature and purposes of the procedures, products and services developed in such technological centers without the access constraints found there. To do so, we used the *Argonauta* as case study. A group of 56 interviewees evaluated the proposed environment by means of a questionnaire composed by Likert-scale questions. Their feedback has shown that the proposed method can give a more reliable glance about the benefits of the nuclear energy thus contributing to avoid that only its negative aspects are known.

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INTRODUCTION

Research centers are responsible for generating new technologies and play an important role in scientific and technical developments. In Brazil, *Instituto de Engenharia Nuclear* (IEN), created in 1962, is a particular example of such facilities and deals with nuclear related research, generating technologies, products and services. Research laboratories at the facility include a particle accelerator and a research nuclear reactor, known as Argonauta. However, due to the nature of its activities, IEN and other nuclear facilities in several countries are restricted access areas. Viewing that the accident in Fukushima has contributed to the reinforcement of the concern related to the use of nuclear energy, its negative aspects were highlighting once more. In this sense, it would be interesting to provide information about which are the real purposes of a nuclear facility thus avoiding misunderstandings created by sensational headlines.

On the other hand, the use virtual reality (VR) techniques to address issues related to nuclear technologies, radioactive environments and ionizing radiation has become an important research field in the last few years. Examples of that are found in (Freitas *et al*., 2011), (Gatto, 2012), (Keller *et al*., 2013), (Kvalem *et al*., 2005), (Mól *et al*., 2011), (Passos *et al*. 2017), (Robins *et al*., 2009), (Ródenas *et al*., 2004), (Sanders *et al*., 2003), (Sanders *et al*., 2005), (Silva *et al*., 2015), (Xi *et al*., 2009) and (Zao *et al*., 2015). For this reason, this work proposes a virtual environment for visiting some of the installations of a nuclear facility without the need to expose the visitors to radiation or to interrupt the routine of its employees. Similar applications (Silva *et al*., 2015) and (Passos *et al*. 2017) has shown the possibility of using a game engine to develop virtual environments that reproduce their basic

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operational procedures with a high degree of fidelity to their real counterparts. Based on this possibility, we modeled a virtual simulator of the *Argonauta* reactor and used it as a particular case study. In this prototype, the user receives information about what kind of studies and technologies such facilities should manage. Therefore, the novelty of the present work is to propose an auxiliary tool that is able to simulate the visit procedure in a nuclear facility to provide information about the nature and purposes of the procedures, products and services developed in such technological centers without the access constraints found there by means of a virtual environment. Specialists that manage the regular visit procedure firstly evaluated the proposed environment. After receiving their positive feedback, we invited a group of 56 interviewees to fil out a questionnaire composed by Likert-scale questions, which intended to verify if they approved the method presented in this survey. The article is organized follows: chapter 2 presents Argonauta's basic characteristics; chapter 3 shows the methodology used to develop the simulator; chapter 4 describes the results and its analysis and finally, chapter 5 presents the conclusion and final considerations.

Argonauta Research Reactor

Basic Characteristics: Argonauta is a thermal nuclear reactor that uses 20% enrichment uranium, having 5kW as its maximum power. Its operational standard power ranges from 170 to 340W. Moreover, it was the first research reactor build in Brazil and presents characteristics for teaching, research and training for specialized personnel from science and technology fields. The use of Argonauta for the researching of neutronic fields started in 1965. The main research lines of the institute in which it is located comprehends non-destructive essays with thermal neutrons in biology, industry, environment and national public security (IEN – 2017). Moreover, several radioisotopes (Mn- 56, La-140, Se-75 and Br-82) produced at IEN are used as markers in environmental and industrial research. Argonauta was the first research reactor built in Brazil by a national company. It has excellent teaching, research and personnel training characteristics, specialized in nuclear science and technology. Table 1 shows the main characteristics of Argonauta while Fig 1 presents its physical structure.

Table 1. Argonauta's basic characteristics

First Criticality	20 February 1965 at 5:50 PM
Power	Maximum = 5kW Continuous operation = 500W
Fuel	Uranium 20% enriched in U-235
Fuel plate	The fuel plate cermet has a mixture of aluminum and U3O8, both in powder. The uranium is 19,91% enriched in U-235. After a proper treatment, the mixture is put in a 12-mm aluminum frame. This frame is first pressed and then welded between two 2-mm aluminum plates forming a set which is laminated to reach the following dimensions: 2,43 x73 x 610 (in mm).
Moderator	Deionized water, between the plates; and wedge-shaped graphite, between the fuel elements.
Reflector	Radial and azimuthal directions: Graphite Vertical direction: Water
Protection shield	Lateral: Blocks of concrete piled around the reflector Top: Blocks of concrete covered by steel panels Opposite side of the external thermal column: Water (shielding tank)
Control	The neutron population is controlled by six absorbing rods, made up of cadmium plates, which move inside channels in the external graphite reflector.

IEN(2017)

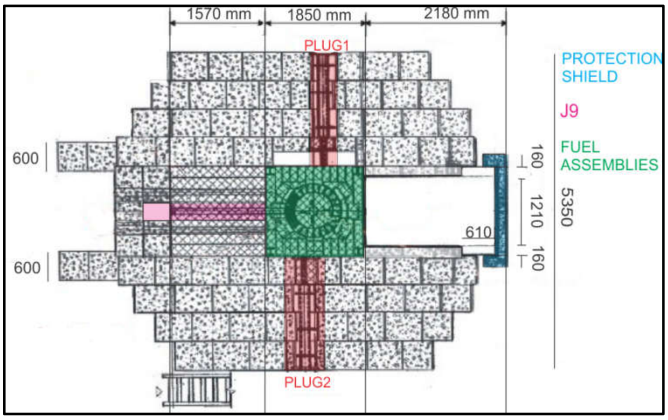

Fig. 1. Argonauta's physical structure

The facility in which Argonauta is located allows technical visiting but, as it stands in a restricted area, visitors must follow its security protocols. For more details related to the referred procedures, see section *IV* subsection *A*.

Applications Using Virtual Reality Developed by IEN Researchers

Virtual Reality (VR) is a set of techniques, technologies and interfaces designed to provide the user the feeling of integration with the computer system and enable its immersion in the virtual environment (Mól *et al*, 2013). Thus, VR uses human-computer interactions, three-dimensional environments, and input devices to allow the user the feeling of being inside the virtual environment. A system developed using VR allows interface options between the user and the virtual environment, which are able to provide visualization and interaction using multisensory devices in this process (Kirner and Siscoutto, 2007). There is a large range of VR concepts applications available in the technical literature in recent years. Some of them were developed at IEN, such as nuclear power plant (NPP) operators training, NPP control room ergonomic studies, estimation of radioactive dose levels, safety staff training, physical security management, development of virtual devices and nuclear waste management.

Methodology for the virtual environment development

General view: This work uses a methodology quite similar to the one employed in (Silva *et al*, 2015), using a two-phase method. The first phase, called "environment modeling", consists on building the virtual environment itself using the software Unity 3D, for ground plotting, and AutoDesk 3ds Max, for creating edifications. The second phase, called "functionalities implementation," consists on the addition of auxiliary devices for the Unity 3D nucleus, such as virtual cameras, aiming to allow it to fulfill the purpose intended in this work. The configuration of parameters using C# allows that Unity's nucleus uses such previously programmed functionalities.

Environment modeling: We modeled the simulator using photos to provide a more reliable proportionality between the environment itself and the objects designed with Google SketchUP and Autodesk 3ds Max. Thus, each dimension of every single virtual object used in this application corresponds exactly to its real counterpart. Fig 2 shows the interface in which the user can access basic settings as: start the simulation, set the graphical quality, view the credits or quit the simulation.

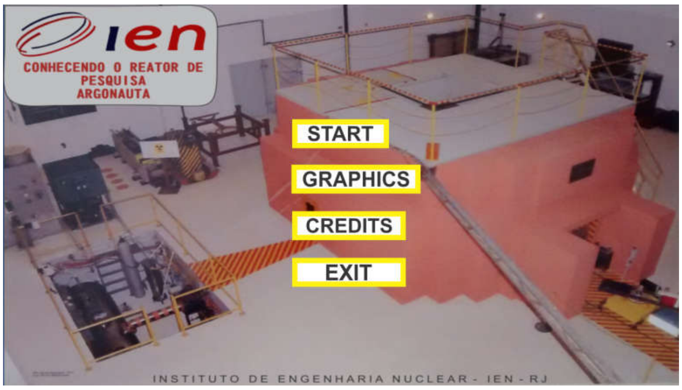

Fig. 2. Application's interface

Structures: *Argonauta*'s installations and its surroundings had their structures made using the previously mentioned modelling software. We based this procedure on photos, measurements and blueprint analysis. The interior of the building is in accordance to the real proportions concerning to format and measures. The development of secondary structures and objects as room details and furniture uses textures obtained with photos of the real objects. Some particular places inside the building needed to receive a more careful treatment because of the importance they have on providing a more realistic experience for the user. IEN specialists have defined such regions in primary tests.

Circulation Area: The simulator is a virtual environment that mirrors the building where the Argonauta reactor is located. We modeled each of the available areas with Unit 3D software based on blueprints and photos. Fig 3 shows initial studies of models made with Google SketchUP for Argonauta's outline and its neighborhoods, whereas Fig 4 presents the accessible areas (detached in blue). After completion, we import such models to the Unity 3D generated environment.

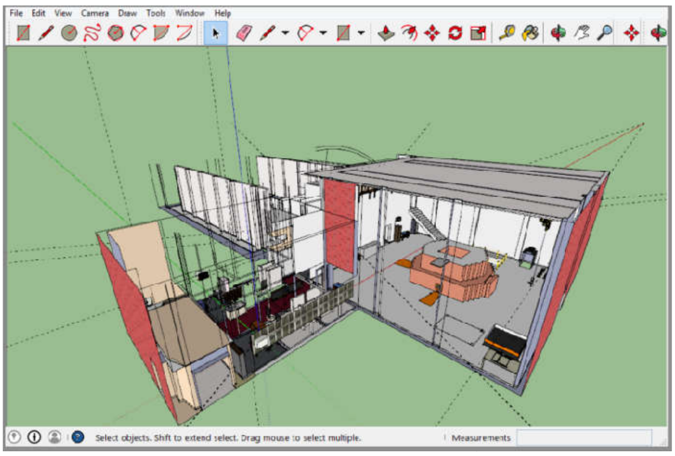

Fig. 3. Installation modeling

Interaction with Objects: According to the objective of this application, there was a need to insert interactive objects, like a radiation dosimeter. In addition, we placed non-controlled characters representing the facility's employees are positioned at key points of the facility giving descriptions and information related to nearby equipment, its way of operation and associated technical procedures. Fig 5 shows an example of a non-controlled character.

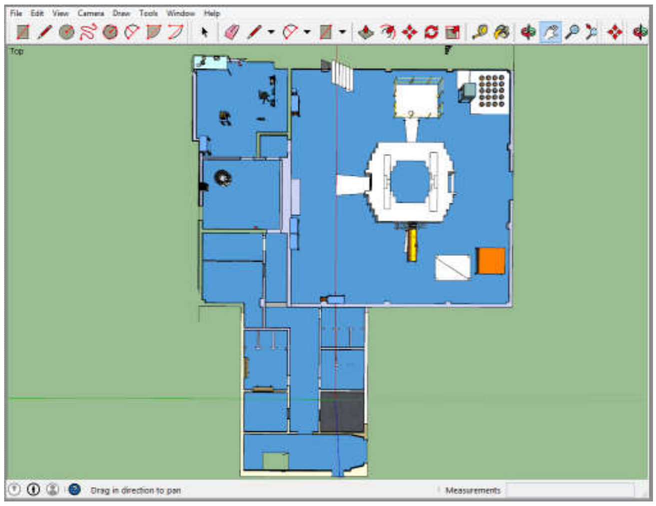

Fig. 4. Accessible areas (in blue)

Fig. 5. Non-controlled character

Specific actions of the controlled character: We implemented the actions associated to the characters (avatars) and objects to be in agreement with the requirements obtained from the facility's employees and specialists at nuclear related procedures by means of personal interviews. The next subsections show a brief description for each of the particular actions available in the virtual environment.

Interaction 1: using doors: The user can interact with any door of the scenery by accessing a particular position called "trigger area". Thus, we assume that the avatar is inside the interaction region of the object (in this case, the door). Consequently, the screen shows a message at the Guide user Interface (GUI) warning that an interaction with the referred object is available. Fig 6 and Fig7 show examples of that.

Fig. 6. Door trigger

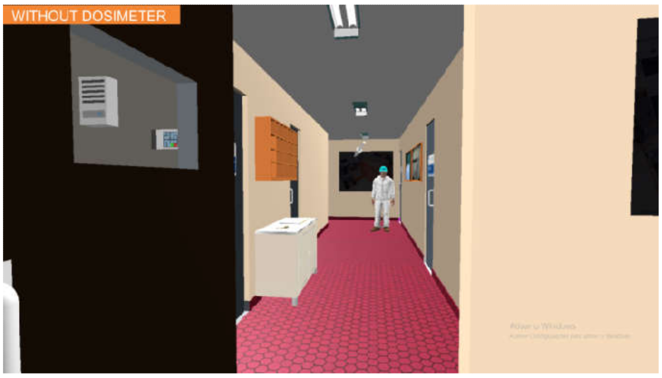

Fig. 7. Door opened

Interaction 2: Interacting with non-controlled avatars: The interaction with non-controlled avatars is available at 90% of the paths in the accessible area. By interacting with these avatars, the user receives information referred to the facility as well as the description of Argonauta's procedures and operational requirements. Instructional texts and audio files accompany all of this interaction. Fig 8 shows an example of "conversation" with a non-controlled avatar.

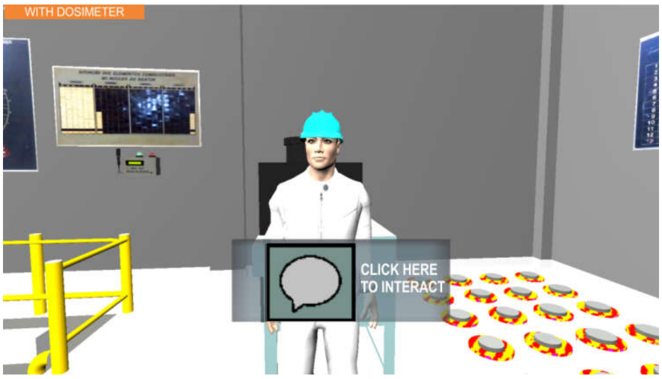

Fig. 8. Interaction with a non-controlled avatar

Interaction 3: Entrance procedures: By entering *Argonauta*'s installations, the visitor must fill out the Dosimetry Counter Register (DCR) following radioprotection norms established by *Comissão Nacional de Energia Nuclear* - CNEN, the governmental organization responsible for all nuclear related activities in Brazil. Moreover, it is required the use of an individual dosimeter, which will measure the virtual radiation dose "received" during the visitation (it is worth to mention that the virtual dosimeter does not make any measurement, being just a way to illustrate this stage of the procedure). As there is a need to record such value in the DCR at the end of the visit, if the user refuses to fulfill this requirement, the path is blocked and the simulation is interrupted , as it would observed in a real technical visit. Fig 9 shows the warning received by the user in this case.

Fig. 9. Non-controlled avatar blocking the way

The virtual dosimeter is designed to be in agreement with its real counterpart concerning to both scale and appearance. When shown at the screen, the dosimeter is animated with a rotating movement in order to make it easily identifiable. Fig 10 shows the dosimeter and the DCR. Fig 11 shows a comparison between the real *Argonauta*'s room (left side of the Figure) and its virtual counterpart.

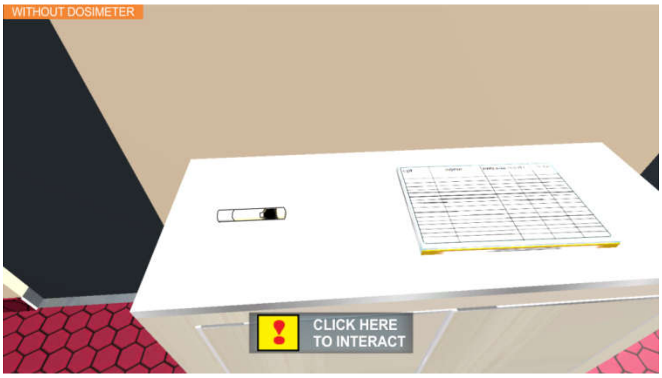

Fig. 10. Virtual dosimeter and DCR

Fig. 11. Comparison between real *Argonauta* chamber and its virtual counterpart

Steps for the technical visiting process: The technical visiting process comprehends by a set of basic safety related actions. Therefore, it must important to reproduce it as correctly as possible during the simulation, following the information obtained from the facility's employees at the interviews. Table 2 describes each step of the procedure.

Table 2. Steps for the technical visiting process

STEP 1	- The visitor must ask for permission to enter at the facility;
STEP 2	- The visitor must to fill out the DCR and receive the dosimeter to access the facility's interior. If one of these requirements is not fulfilled the access is denied;
STEP 3	- Access to the Argonauta's anteroom;
STEP 4	- Access to the control room, where basic information about its function and other components is provided;
STEP 5	- The visitor is guided to the reactor's room, where information related to the reactor and its components is provided;
STEP 6	- End of the visit.

RESULTS

The proposed application aimed to simulate the process of technical visiting in a nuclear facility using IEN as case study. Thus, we hope to provide a more reliable source of information concerning to the nature and purposes of the procedures, products and services developed in the Argonauta research reactor for students and general people, then avoiding a wrong understanding of that as observed in sensationalist headlines, for instance. The analysis of the developed virtual environment was done based on the comparison between the actual procedure and the simulated one. In a first moment, the simulator was tested by three of the facility's employees. They had contributed with the information used to guide the development of the virtual environment. Thus, we were able to evaluate if the given specifications, constraints and recommendations agreed to the ones considered in a real procedure. Questionnaires using Likert-style questions related to the current application guided the analysis. At this stage, the evaluation of the proposed method was performed to specify its agreement with the one used at the real facility concerning to scale, positioning and other technical characteristics. Furthermore, the volunteers had to analyze if the use of virtual reality concepts represents a suitable alternative to realize technical visiting at facilities like the one depicted here. Secondly, a group of 56 interviewees evaluated the virtual environment. To do so, they were invited to fill in a questionnaire, different from the one used by the facility's employees, which was also based in Likert-style questions. While the first questionnaire intended to analyze the visit procedure aspects, this one aimed to investigate in which form the interviewees had perceived the concepts related to the nuclear energy.

IEN is always available to realize such procedure: This stem aims to verify the specialist's opinion regarding to the periodicity of the visit procedure.

It is possible to overcome the restrictions related to the technical visit by using the proposed virtual environment: This stem aims to identify if the specialists have approved the proposed environment as an auxiliary method to proceed with the technical visit process if the regular way (i.e. using the facility installations) is not available.

I believe that this application is useful as an auxiliary way to realize the technical visit procedure: This stem aims to identify if the specialists have approved the proposed environment as an auxiliary method to proceed with the technical visit process if the regular way (i.e. using the facility installations) is not available.

Data analysis phase 2: After the tests with the three specialists, a cohort of 56 interviewees has tested the virtual *Argonauta*.

Table 3. Evaluation results phase 1

Likert stem	Interviewed 1					Interviewed 2					Interviewed 3				
	TA	A	N	D	TD	TA	A	N	D	TD	TA	A	N	D	TD
The virtual environment is in agreement with its real match regarding to the scale of objects and buildings.		x					x				x				
The regular technical visit procedure is easily realizable.				x				x						x	
IEN is always available to realize such procedure.				x					x					x	
It is possible to overcome the restrictions related to the technical visit by using the proposed virtual environment.		x					x					X			
I believe that this application could be used as an auxiliary way to realize the technical visit procedure		x					x					x			

TA Total agreement, A agree, N neither, D disagree, TD Total disagreement

Table 4. Evaluation results phase 2

Likert stem	Percentage response				
	TA	A	N	D	TD
The integration with the activities proposed in the Virtual Environment was satisfactory.	19,57	41,30	0,00	28,26	10,87
I have learnt about the nature and purposes of the procedures, products and services developed at Argonauta after using this virtual environment.	29,31	32,61	2,17	34,78	6,52
The concepts I have learnt using this application gave me a different point of view about the nuclear energy	17,39	47,83	4,35	19,57	10,87
It is important that IEN promote technical visits to students.	67,39	30,43	0,00	2,17	0,00
I believe that a virtual environment such this one could be helpful not only for the proposed application	65,22	30,43	2,17	2,17	0,00

TA Total agreement, A agreed, N neither, D disagreed, TD Total disagreement, NA not answered

Data analysis phase 1: A group of three professionals responsible to manage the technical visits in *Argonauta* used the proposed virtual environment. They filed in a questionnaire consisted by 5 Likert – style questions, other than that used to evaluate the students. Table 3 shows each of the obtained results.

Description of each statement of phase 1: The description of each statement used to obtain the evaluation of the professionals involved in phase 1 is showed next:

The virtual environment is in agreement with its real match regarding to the scale of objects and buildings: This stem aims to verify if the specialists observed some issue related to visual aspects among objects and structures depicted in the virtual environment and its real counterparts.

The regular technical visit procedure is easily realizable: This stem aims to verify how the specialists graduate the level of difficult associated to the visit procedure.

Description of each statement of phase 2: Next, we show the description of each statement used to obtain the evaluation of the high school students involved in phase 2:

The integration with the activities proposed in the virtual environment was satisfactory: This stem aims to verify the level of integration experienced by the interviewees concerning to the virtual environment limitations. Thus we intend to identify if the availability of some specific equipment (an oculus rift, for instance) could, in their opinion, have contributed to improve the feeling of immersion. Moreover, they could provide additional feedback concerning to any difficult faced in case of the lack of experience on using computers or games that could have compromised the use of the virtual environment.

I have learnt about the nature and purposes of the procedures, products and services developed at Argonauta after using this virtual environment: *This stem aims to analyze if the students were able to identify and understand the* *basic concepts related to the nature and purposes of the procedures, products and services developed at Argonauta presented during the virtual visit. In addition, we intended to verify which of the concepts involved were not correctly understood.*

The concepts I have learnt using this application gave me a different point of view about the nuclear energy: This stem aims to analyze if the students were able to identify and understand the differences between the correct concepts associated to the nuclear energy and the information that they receive by the media.

It's important that IEN promotes technical visits: This stem aims to analyze how important to them is such activity.

I believe that a virtual environment such this one could be helpful not only for the proposed application: This stem aims to verify if the students approved this kind of application.

DISCUSSION

The previous section results have two different meanings. Firstly, the analysis of table 3 data shows that the interviewees (the specialists responsible to manage the visits in the facility's installations) do not consider the visit process to be an easy procedure. Moreover, all of them agreed not only regarding to the feasibility of the proposed virtual environment for overcoming the restrictions related to it, but also to the belief, that such application can be used to emulate a visit without significant losses. Based on this information, we provided a link where people could proceed to the download of the environment. Then they were invited to fil in an anonymous survey that aimed to assess if it would be in agreement with our proposal to disseminate basic knowledge about the nature and purposes of the procedures, products and services developed at *Argonauta* to students and the general population by means of a virtual visiting. The results obtained at this stage of the research shows that there was a satisfactory receptivity of the method proposed here. Regarding to the integration it provided, there was 60,87% of positive answers. Talking about the nuclear concepts understanding, analyzed in statements 2 and 3 respectively, people have informed 61,92% of agreement for learning new concepts and 65,22% for a changing at the way they see the nuclear energy. The last two statements aimed to highlight the role of a nuclear facility on informing people about the benefits of nuclear energy instead of just detaching the risks associated to it, which are often poorly assessed. Concerning to that, the interviewees have pointed 97,82% of agreement for the importance of promoting technical visits. Also, 95,65% believe that a virtual environment as the one proposed in this survey could be helpful not only for this kind application, which grants a new branch of future works.

Conclusion

This work proposed the use of a virtual reality based simulator of the *Argonauta* research reactor and its surroundings to provide an alternative procedure for a technical visit in nuclear facilities. The information obtained with the facility's employees has guided the development of such virtual environment so that it agrees the specifications and requirements observed in a real visiting procedure. After its completion, the simulator was tested in two phases: by the specialists that manage the regular visit process in the former and for a cohort of 56 interviewees in the last. The analysis of the obtained results for the first phase tests shows that the facility's specialists have approved the simulator concerning to the following characteristics: similarity with its real counterpart (i.e. the facility's installations), interaction quality and capacity to reproduce the real procedure under study. Each of these topics received a positive evaluation, according to the collected answers. As specialists compose this particular audience, their opinion is sufficient to qualify the proposed application as suitable to reproduce the analyzed scenery and the simulated procedure without relevant losses. Furthermore, as the security protocols related to the technical visiting were successfully reproduced at this particular case study, there is a great chance that it could be also applied at other similar facilities like a nuclear power plant. The analysis of the obtained results for the second phase, shows that the majority of the interviewees have approved the simulator concerning to the following characteristics: level of integration experienced, understanding of the nature and purposes of the procedures, products and services developed at *Argonauta* and how it can change their point of view about the nuclear energy. Thus, we conclude based on the feedback of both, specialists and general people, that the virtual environment proposed in this survey can contribute as an auxiliary way to promote visits at a nuclear facility besides to provide a reliable source of scientific knowledge and avoid that the information biased by sensationalist headlines be accepted as an absolute true. As a result, we hope to develop new virtual environments using the method described in this survey to simulate technical visits in nuclear power plants.

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