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The proliferation of virtual laboratories in educational fields

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KEYWORD

Immersive virtual reality; virtual laboratory; virtual reality; technology enhanced learning; design; virtual didactic tool; learning environment

ABSTRACT

Since its emergence in the 1960s, the use of virtual reality (VR) has grown progressively. This wide dissemination of VR has allowed its application in an increasing number of disciplines, including education. It is well known that virtual laboratories (VLs), which base their use in VR technology, are very useful tools in both university and professional training. In this article, the main advantages and disadvantages of the use of modern VLs in teaching are analyzed. In addition, the design and development process that must be followed to appropriately create these VLs is described in detail, as well as a small-scale study of the perception that university teachers have about the use of VR in education. Lastly, the reasons why the implementation of VR is not currently as broad as it would be expected, given its proven potential in different fields, are discussed.

1. Introduction

The dissemination of information and communications technology (ICT) in most human activities is an obvious fact. Among the different applications of ICT is virtual reality (VR). The growth in the use of VR has taken place while the computing power has increased and the cost of hardware has been reduced. Evidence of this growth is shown in Table 1 and Figure 1 via the increasing number of articles published in recent years that contain the term "virtual reality" in its title, abstract or keywords (data indexed in Scopus and main collection of Web of Science) or only in its title (data indexed in Google Scholar), which suggests the great interest that this field of research stimulates in the scientific community. Table 1 shows the number of results indexed each year on each database, while Figure 1 represents graphically the data contained on Table 1.

The term VR appeared alongside computer graphics, and the first conceptual idea was presented by Ivan Sutherland in 1965: "make the (virtual) world on the screen looks real, sounds real, feels real and responds realistically to actions of the spectator" (Sutherland, 1965). Sutherland himself built in 1968 a device considered the first Head Mounted Display (HMD), already with stereo vision and precise head detection. The VR technology remained in the laboratories until the 1980s in which the company VPL sold its HDM "Eyephone" in 1988. Since then until now the use of VR has been steadily growing but it has been particularly in the last 5 years when VR has been imposed as technology and its use is becoming increasingly evident. In fact, Figure 1 shows that scientific articles in various disciplines have largely increased between 70% and 170% since 2015 depending on the database used, which is a clear indicator of the level of interest that this topic produces in the scientific community.

Table 1: Number of results obtained on each database (Scopus, Web of Science and Google Scholar) when searching the term "virtual reality", from year 2000 to 2018

Year	Scopus	Web of Science	Google Scholar
2000	2064	556	1110
2001	2406	636	1201
2002	2624	623	1350
2003	3339	684	1240
2004	4193	778	1340
2005	4818	880	1320
2006	5700	1056	1590
2007	5331	1239	1500
2008	5031	1267	1510
2009	5333	1599	1550
2010	5475	1406	1520
2011	6403	1451	1680
2012	5483	1417	1620
2013	6094	1578	1590
2014	6075	1732	1800
2015	6329	1974	1950
2016	7007	2434	2990
2017	8141	3267	4420
2018	9330	3441	5590

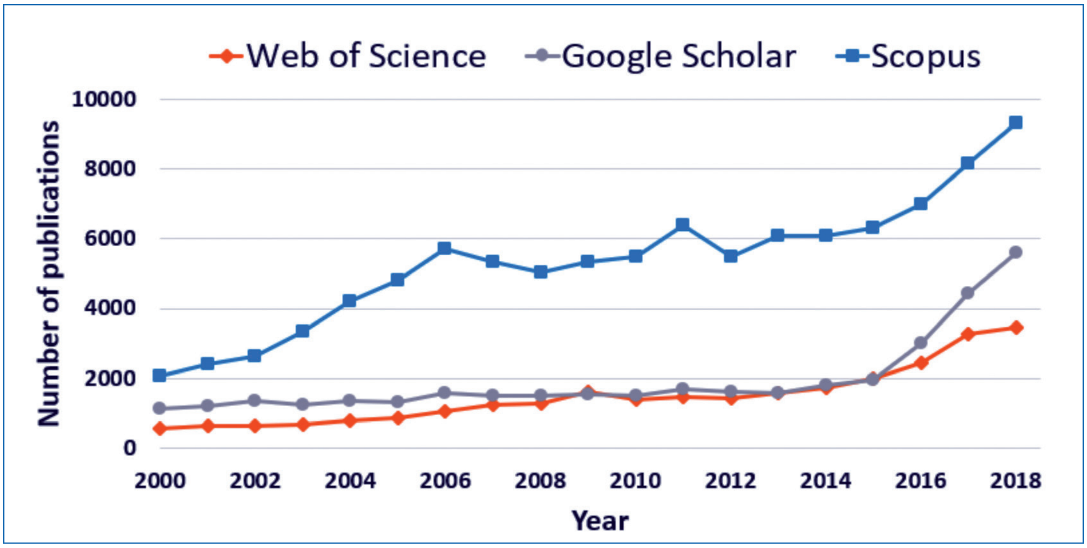

Figure 1: Number of articles published each year from 2000 to 2018 containing the term "virtual reality" in their title, abstract or keywords (Scopus and Web of Science) or in their title only (Google Scholar). Data collected on December 2, 2019 by Scopus, Web of Science and Google Scholar.

The field of education has similar trends to the growth of ICT, and in particular to the expansion of VR. More and more instructors use new educational methodologies based on VR, or augmented reality, to capture the attention of students and motivate them in the study of different subjects. In fact, there are numerous examples of the use of VR to improve the teaching-learning process in many disciplines such as: chemistry (Okamoto et al., 2017; Su and Cheng, 2019), archeology (Monna et al., 2019), robotics (Román-Ibáñez et al., 2018), materials science and engineering (Doblack et al., 2011, 2014; Flores et al., 2012; Meagher et al., 2014; Tarng et al., 2019; Vergara et al., 2017b, 2019), 3D animation (Ho et al., 2019), languages (Legault et al., 2019; Nobrega and Rozenfeld, 2019), photovoltaic installations (Miguel et al., 2019), history (Utami et al., 2019), gynecology (Chang et al., 2019), anatomy (Weyhe et al., 2018), architecture (Maghool et al., 2018), urban planning (Redondo et al., 2017), dentistry (Juan et al., 2016), surgery (Pan et al., 2015), physics (Daineko et al., 2018), electrical installations (Shao et al., 2018), hydraulics (Mirauda et al., 2019), biomedical engineering (Violante and Vezzetti, 2015), etc. These didactic tools are based on VR but there are different combinations of software and hardware to use them, so that it can be found VLs that, among others: (i) are visualized on a computer screen and handled by mouse and keyboard (Daineko et al., 2018); (ii) are based on augmented reality using a smartphone as a HMD and markers to position virtual elements in the real world (Okamoto et al., 2017); and (iii) are based on immersive virtual reality (IVR) displaying the virtual environment on a HMD and handling the VL with specific controllers (Tarng et al., 2019). It is also remarkable the use of other visualization systems, like cave automatic virtual environment (CAVE), which projects a virtual environment on walls, ceiling and floor that is visualized in 3D by means of stereoscopic googles, or Zspace, that allows a 3D visualization and the possibility of "pull out" virtual objects from the screen. Regarding the controlling methods, in addition to those mentioned before, it can be found, among others: VR gloves, joysticks, physical objects that simulate specific real tools, Leap Motion (which detect the movement of user's fingers in the space), etc.

A case in which the use of VR in university education stands out is that of virtual laboratories (VLs), which are computer applications that apply virtual reality (both immersive and non-immersive) to simulate real laboratory sessions – in many cases these environments are known as VRLEs (virtual reality learning environments) (Hahn, 2018; King et al., 2018; Rubio et al., 2019; Vergara et al., 2017b, 2020). VLs allow students to carry out experiments virtually without using a real laboratory consisting of specialized equipment and analysis tools (Figure 2). However, VLs are not limited to the simulation of experiments and in fact they represent effective tools to facilitate the teaching (and learning) of complex concepts.

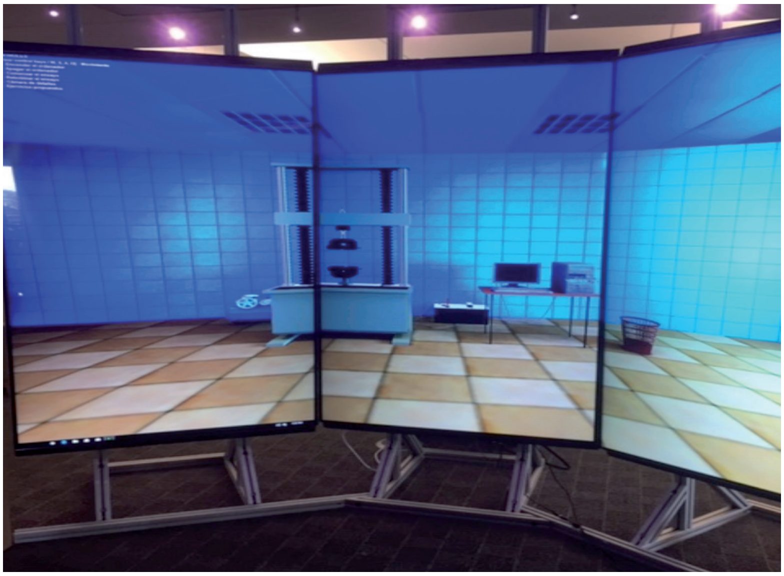

Figure 2: Screen capture of an example VRLE related to tensile testing available at UC Merced (USA).

In this article the authors analyze the spread of VLs, which have been increasingly used in university education and training and instruction at a professional level (Ni et al., 2013; Xu et al., 2013; Zhang, 2017), revealing (i) their advantages and disadvantages in the educational process, (ii) the design and development process, and (iii) the subsequent evaluation and update process after implementing a VL in the classroom. Furthermore, a brief analysis of data obtained from surveying 20 university teachers (who were asked about several topics concerning to VR) is exposed in this article. This study allows to create an image, at a small scale, of the perception that instructors have about the use of VR in education.

2. Advantages of virtual laboratories

Professional careers that are inherently experimental in nature (e.g. those related to science and engineering) often include in their academic programs subject areas that require students to carry out experiments in laboratories at universities or training centers. The realization of these practices in real laboratories entails in many cases varied disadvantages: (i) the number of groups of students are too large, which represents a poor use of such practices, (ii) the insufficient, outdated or poorly maintained equipment and instruments due to tight budgets, (iii) the possibility of accidents that could damage people or inferring valued materials or equipment or both, and (iv) the need for large physical spaces to install equipment. The use of VLs weakens or directly suppresses these inconveniences and offers additional possibilities not available to the real experiments. Thus, VLs offer the following advantages as they:

- Allow students to see in detail the instructors' explanation of concepts in the classroom (Vergara et al., 2017a).
- Require smaller investments of funds that real laboratories, since the budget for a VL is minimal compared to the cost of acquiring and maintaining a real laboratory (García and Entrialgo, 2015; Román-Ibáñez et al., 2018).
- Avoid the possibility of accidents, as they may occur during real experiments that could lead to serious consequences (e.g. industrial radiology practices (Vergara and Rubio, 2012) or chemical experiments (Xie and Tinker, 2006)).
- Reduce the need of physical space for large equipment as is common in real laboratories (Vergara et al., 2017a).
- Prevent damage to equipment or instruments due to improper usage (Vergara et al., 2016).
- Allow the use of equipment and virtual environments whose real homonyms are so expensive and sophisticated that they are not accessible to most universities (Berg and Vance, 2017).
- Facilitate the transformation of certain components into transparent mode to help visualize parts of an experiment that in a real equipment would be hidden. This feature is widely useful since some real equipment or tools have protective covers that prevent seeing certain parts involved in an experiment, making difficult to understand them (Potkonjak et al., 2016).
- Give the possibility of carrying out the experiments individually and as many times as the student needs, even after school hours (Hahn, 2018).
- Can include practical exercises that are solved in the VL itself, thus facilitating the knowledge acquisition (Hahn, 2018; Shao et al., 2018).
- Have different options that favor the teaching-learning process (Vergara et al., 2016; Vergara, Rubio, et al., 2018), some of which are: modify the speed of the experiments, enlarge areas to observe interesting details, and configure different possibilities of interactivity, among others.
- Favor the autonomy of students on one hand, and the personalization of the practice facilitating that the instructor designs it according to his/her criteria, on the other hand (Vergara et al., 2016).

Although the use of VR-based educational tools has been implemented for several years (Vergara et al., 2017b), the instructor who decides to use them as support for his/her classes should take into account that some problems may arise, including: (i) the user is often not aware of the danger associated with using certain equipment (Potkonjak et al., 2016), (ii) the user can acquire a poor and irresponsible attitude when conducting an experiment in a VL (Potkonjak et al., 2016), and (iii) the VL requires a constant evaluation and update work so as not to lose its effectiveness at the formative level (Vergara et al., 2017b, 2019).

3. Design and development of virtual laboratories

The procedure to design and develop a VL has been thoroughly studied and reported in the literature by Vergara et al. (Vergara et al., 2017b; Vergara, Rodríguez-Martín, et al., 2018). This body of work has highlighted the main stages necessary for the design and development process of a VL:

- Define the usefulness of a VL, establishing the specific objectives to be achieved, as suggested in the Pantelidi study (Pantelidis, 1997). At this stage, the needs to which it is intended to respond through the VL must be analyzed and whether the VL will be able to meet those needs.
- Set the general design criteria of the VL. In this stage, the levels of realism and interactivity that the VL should be defined by selecting the appropriate software and hardware, both for the development and the implementation of the VL.
- Develop the VL, which in turn consists of the 3D modeling process on one hand, and the interactivity programming process on the other hand.
- Use and evaluation of the VL in the classroom, using users' feedback to improve and update it.

It is important during the design stage to decide what experiment is going to be simulated or what concept is going to be taught, how the environment and the simulated equipment/instruments will be, how the user will interact with the virtual environment, and what specific exercises the students should solve when using the VL. In this stage, it is convenient to establish the level of interactivity that the VL must offer depending on the training objective that is sought, as described by Vergara et al. (2019). For instance, when a VL is intended to help students learn to perform an experiment, it is useful that the VL be provided with a low level of interactivity, implementing their interaction with the user on a step-by-step guidance system. On the other hand, when the objective of the VL is to help the student understand a theoretical concept, the designer must evaluate more thoroughly the practicality of implementing a level of interactivity that can range from very high (wide open world that allows the user to perform with a high level of freedom) to very low (more restricted world that requires a guided step-by-step). At the design stage, the software to be used to model the 3D environment (e.g. AutoCAD or 3DS Max) must also be chosen, as well as the game engine to be used to program the interactivity of the VL (e.g. Unreal Engine 4 or Unity) (Vergara et al., 2017b). In addition, the hardware that the end user must operate during the use of the VL (e.g. tablet, computer, virtual reality glasses, etc.) is determined accordingly.

When all the design criteria have been specified, the development of the overall application begins, which consists of modeling the 3D environment (Vergara et al., 2017b) and the required components that must be present when the application is executed (e.g. instruments, equipment, avatars, furniture, etc.). After modeling the 3D environment, the interactivity of the VL (Vergara et al., 2017b) is programmed, giving the end user the ability to handle objects, freely explore the whole virtual environment in the VL, solve exercises, and display information, among others. After the development process, the VL is used in the classroom by a group of students who subsequently provide feedback via surveys (Vergara et al., 2017b). The data from these surveys are collected and analyzed by instructors, after which they generate a list of actions that must be applied to the VL to improve further until the final VL version is obtained. For the sake of clarity, an illustration of the design and development process of a VL based on virtual reality is shown in Figure 3.

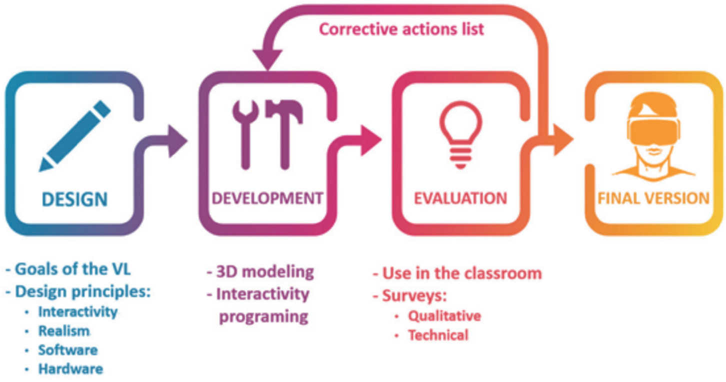

Figure 3: Schematic of the design and development process of a virtual laboratory based on VR.

The most common way to evaluate a VL has been through qualitative surveys that try to measure aspects related to the objectives pursued by its application and educational effectiveness, as well as some technical aspects (Leder et al., 2019; Miguel et al., 2019; Ouyang et al., 2018; Vergara et al., 2015, 2017a; Vergara, Rubio, et al., 2018; Zhu et al., 2018, Extremera et al, 2020). Thus, these types of surveys usually incorporate questions that ask the students, among others, about (Vergara et al., 2015; Vergara, Rodríguez-Martín, et al., 2018): (i) interactivity, (ii) motivation, (iii) ease of use, (iv) design traits, (v) formative effectiveness, and (vi) realism. However, it is interesting that students who use a VL, in addition to completing these types of qualitative surveys, they often fill in technical surveys. These surveys use the well-known SUMI (Software Usability Measurement Inventory) survey, which is adapted to each particular VL, and allows measuring users' perception of the usability of a program (Kirakowski and Corbett, 1993). These surveys consist of questions related to the operation of the VL, which once the data is collected and analyzed, instructors can learn valuable insights about what technical aspects of the application must be acted upon in order for it to work as expected and in this way the achievement of the objectives pursued in the use of the VL is not ruined or impaired.

4. Perception of teachers about VR in education

During December 2019, VR workshops were organized in Catholic University of Ávila and University of Salamanca, both in Spain. These workshops were aimed both at teachers and students, and during its realization attendees were instructed about practical applications of VR and could use an HMD for 10-15 minutes. Before using the HMD, attendees were asked about several aspects concerning to their previous experience with VR, habits playing 3D videogames, usefulness of the VR, etc. After using the HMD, attendees were asked again about several aspects concerning to VR and specially to those concerning to their perception and applications of VR in education. Since this study is aimed to know in a small-scale the perception that university teachers have about VR in education, the results exposed here refer exclusively to the surveys fulfilled by the 20 teachers that participated in the workshops as attendees. Furthermore, in this study are analysed only the main questions considered as more relevant for the purpose of this study. Thus, the questions asked to teachers are shown on Table 2:

Table 2: Main questions asked to teachers and possible answers (before and after using HMD in workshop)

Questions before using HMD	Questions after using HMD
Age: less than 18, 18-25, 26-50 or more than 50.	Do you know VR tools used in educative field?: yes or no
Previous experience with VR: none, little, quite or much.	Do you consider that VR helps to improve the teaching-learning process?: none, little, quite or much.

The results of the surveys performed before the use of HMD reveals that 80% of the teachers were aged within the range 26-50, while the rest (20%) were older than 50. To the question regarding to the previous experience with VR, 70% of the teachers answered to have no experience with VR, while 20% answered "little experience" and 10% "quite experience". The results obtained from the surveys performed after the use of the HMD show that 60% of the teachers knew at least an educative tool based on VR while 40% did not know any. Finally, 100% of the teachers answered that they consider that VR helps to improve the teaching-learning process (20% answered "quite" and 80% answered "much").

5. Discussion

From the point of view of VR technologies that can be used in teaching with a VL, there are two general categories depending on the visualization and interaction devices applied: (i) non-immersive VR, in which the user's vision of the world is through the flat screen of the computer (acting as a window), using conventional computer control devices (e.g. mice, keyboards, etc.) and (ii) immersive VR, which completely introduces the user to a virtual world through helmets with two small screens in front of his/her eyes and use various specific devices such as controllers, gloves or the user's own hands.

Each of the above VR categories has its most appropriate fields of study but the one that achieves better learning experiences in laboratory practices is the IVR. The term immersive is added to refer to the users being able to "dip" or "submerge" themselves in a virtual world, make movements and interact with virtual objects and people with an experience close to what they would live in the real world. It is very close to the original idea by Sutherland (Sutherland, 1965).

Hence if the IVR gives the best results in the learning process then why has its use not been widespread in the education field? The answers to this question can be obtained by analyzing the costs necessary for the design, commissioning and usage in the classes of the IVR application. These expenditures can be summarized as follows (Figure 4):

- Implementation costs: In this aspect, the number and benefits of the IVR systems must be taken into account, as well as the physical space where teaching is to be delivered. The quantity of equipment needed depends on the number of students designed to be in the practice group. For classes to be similar for each student, there should be a display and control device for each student. However, the price of such system is proportional to the realism of the virtual world generated. Thus, low-cost equipment often produces unrealistic experiences and high-end systems produce more realistic experiences but they are expensive (e.g. reaching values today of 2,000 euros per unit). Usually only one or two IVRs are available for a group.

- Cost of time: The actual practice in the VL requires a certain time of completion per student, so the total time of the practice would be very high for the entire group with a single IVR system. In addition, when a student is using the VL, the others should see on a screen what that student does to share his/her experiences and not lose interest or develop other parallel activities related to the practice.
- Cost of space: The required space depends on the selected IVR system, which can allow activities sitting (or standing without displacements) or activities with displacement in a more or less wide area. If several IVR systems of this second type are available, it will be necessary to have a large physical space to be able to use them simultaneously with a group of students.
- Development costs: The design, modeling and programming of a VL application with an IVR is a task that requires highly specialized multidisciplinary knowledge. In fact, the development involves great cost in staff working time, similar to that necessary to create a video game. In general, the VLs that are used today are the result of the efforts of groups of instructors and researchers who have developed them for specific needs in their classes or projects and are not shared with other groups. As these systems are still in their infancy, there are no specialized companies that develop commercial products for standard IVR use.

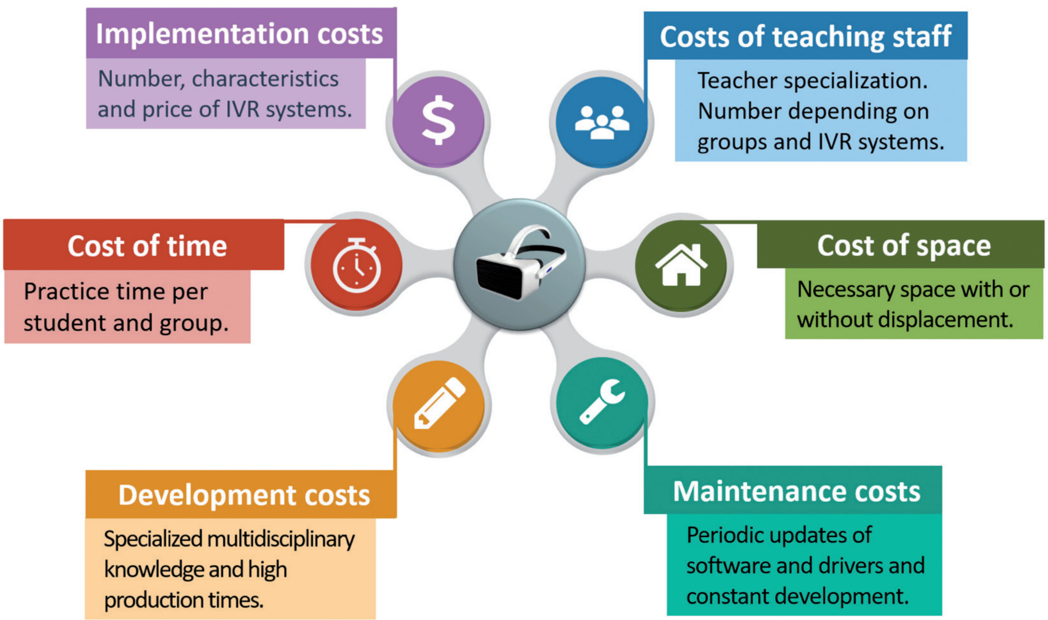

Figure 4: Costs associated with IVR technology currently curbing its development in the educational fields.

- Maintenance costs: IVR systems are constantly developing and require periodic updates of software, firmware and drivers. Additionally, the VL created with these technologies age rapidly (technological obsolescence) and it is necessary to constantly re-adapt them.
- Costs of teaching staff: It is necessary that the educational personnel who teach practical sessions be specialized in the use of IVR technology and in the concepts of the practice. If there is only one system available, two instructors will be needed, one who works with the student in the use of the VL and the other helping the rest of students in the group or class. If there are several systems available, several instructors will therefore be necessary.

Regarding possible solutions to the cost problem of the application of VLs based on IVR in teaching, the continuous development of IVR equipment and the generalization of its use will lead to improved performance and reduced prices as it has happened with other technologies such as in the field of computer science. Development costs can be reduced when the creators and marketers of digital content enter the marker of VL applications with IVR and educational centers setup specialized development departments of this type of applications just as they currently have creation departments of web pages. Maintenance and physical space costs will be further reduced with the implementation of specific classrooms and VR technicians.

The study presented in this article (section 4) has been carried out on a small scale and with a small number of respondents, therefore its results can only serve to intuit trends in the perception that teachers have about VR. However, the results obtained allow us to infer that there can still be a considerable number of university teachers who do not yet know any particular application of VR in education, although possibly most of them recognize the possibilities offered by this technology to improve the process of teaching-learning. In order to create a clearer picture of the perception that teachers currently have about VR applied in university education, the authors intend to expand this study by taking data in more universities and among a greater number of professors.

6. Conclusions

Virtual laboratories have a great potential in both the university teaching of science and technology and the technical training of qualified personnel, which is reflected in the tendency to be implemented as educational resources in the 21st century. In fact, given the vertiginous evolution of software and design environments of this type of laboratories, which are usually related to virtual reality and in turn directly related to videogame design software, the authors believe that in the near future virtual laboratories will be used widely in almost all areas of training and education. Although the best option for a VL to resemble a real laboratory would be to design it with immersive virtual reality technology, there are currently several aspects that hinder its development in the educational world including costs of implementation, time, space, development, maintenance, and teaching staff.

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