Educational trends post COVID-19 in engineering: Virtual laboratories

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ABSTRACT

The rapid advance of Information and Communication Technology (ICT) in recent times and the current pandemic caused by COVID-19 have profoundly transformed society and the economy in most of the world. The education sector has benefited from this ICT-driven revolution, which has provided and expanded multiple new tools and teaching methods that did not exist just a few decades ago. In light of this technological change, virtual laboratories (VLs) based on the use of virtual reality (VR) have emerged, which are increasingly used to facilitate the teaching–learning process in a wide range of training activities, both academic and professional types. The set of advantages offered by this type of VL, the main of which are listed in this article, has made its use increasingly common as support for engineering classes at universities. This paper presents a study involving 420 engineering students from Spanish and Portuguese universities and associated analyses on the assessment of different parameters in various VLs designed by the authors. The results obtained indicate that, in general, VR-based VLs are widely accepted and demanded by students, who likewise consider real laboratories (RLs) necessary in face-to-face teaching. In the current post-COVID-19 educational scenario, VLs and RLs will coexist within the new hybrid models that combine face-to-face and online teaching and learning.

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1. Introduction

New technologies have transformed the world since the end of the 20th century, accelerating the radical change in society and the economy, which these first two decades of the 21st century have identified. An example of this change is the many tasks that were performed manually in the past that have been automated in recent years. And as a result, the labor landscape of today's society has been profoundly altered. Another example of how new technologies have differentiated today's society from that of the 20th century is in the scenario that originated from the COVID-19 pandemic. Indeed, since the pandemic was declared, the use of new technologies has allowed a large part of the economic sectors to continue their activity in a relatively normal and safe way, thanks to remote work. That is, teleworking has been promoted. Currently, most of society uses information and communication technologies (ICT) daily, making a new way of life and social behavior.

Thus, most remote personal communications are carried out through instant messaging services, which is a change from what happened just 30 years ago when the most common communication method was phone calls. In the same way, electronic mail has almost completely replaced postal mail (both in the personal sphere and between institutions or companies); the creation and sharing of images and videos have displaced much of the information that was once shared through text; social networks have created a new concept of the relationship between people from all over the world; etc. Such is the influence of ICTs on society that two new adjectives emerge to define people [1]: (i) digital natives, who are those individuals who were born with the ICT revolution already consolidated; and (ii) digital immigrants, who are those who were born before the ICT revolution began, and from a certain point in their life have had to update their knowledge and adapt their habits to this new reality. Even the first group of digital natives differentiates those who were born without the internet that we know today (millennials or generation Y) and those who were born with the current network of networks (internet generation or generation Z).

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The education sector is no stranger to this ICT revolution, being today a sector in which digital transformation is an unstoppable event. In this way, instructors often implement new ICT-based methodologies in the classroom to capture the attention of the students and motivate them to study different subjects, regardless of educational level. In this sense, practical classes traditionally developed in laboratories (e.g., in which experiments are carried out) are moving to virtual worlds [2]. Two of the most promising technologies with the best results when developing virtual laboratories (VLs) are: (i) virtual reality (VR); and (ii) augmented reality (AR). Both technologies (VR and AR) have revolutionized both the education sector and the professional sector [3]. This statement is reinforced by the data illustrated in Fig. 1, which shows the number of works indexed in Scopus that contain the expression "virtual reality" in their title, abstract, or keywords, and that have been published annually between the period of 2000 and 2019.

Fig. 1 distinctly points out 4 periods, which are described as follows:

- 2000–2006 (period "i" in Figure 1): The year 2000 saw the release of the first VR-based video game called ARQuake, where players had to use a head-mounted display and carry a backpack containing gyroscopes and a computer [4]. Since this launch, the interest on the part of the industry and the scientific community for immersive technologies increased, even though the equipment was expensive, with unrealistic graphics, inaccurate positioning systems and great difficulty in programming the VR applications.
- 2006–2012 (period "ii" in Figure 1): After the first years of growth in the VR industry, the global economic crisis of 2007 and the high cost of equipment, as in other industries, held back its growth expectations, research and practical application, giving rise to a phase of stagnation until the appearance in 2012 of the Oculus Rift device [5].
- 2012–2016 (period "iii" in Figure 1): The launch of Oculus Rift sparked Facebook's acquisition of the company responsible for its creation and led a race for VR development and commercialization. As a result of this race, in 2014 Google launched Google Cardboard, a cardboard viewer that allows a user to insert a smartphone with an Android operating system to enjoy immersive content – mainly panoramic or spherical videos, encompassed within 360° video technology – at a low cost.
- 2016-present (period "iv" in Figure 1): In 2016, a milestone in the VR industry took place: the launch of the HTC Vive device, this being the first VR device with a certain degree of physical movement and real sensorization and tracking of hands and feet [6], which favors a high sensation of immersion. The announcement by HTC of the launch of this device triggered the launch of different immersive devices in the 2016–2019 period, among
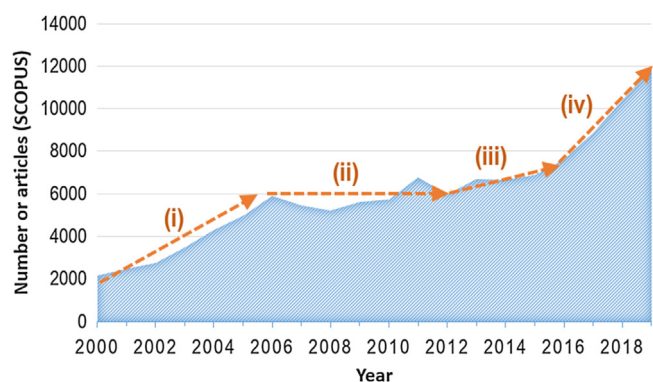
which Samsun Gear, Play Station VR, and HTC Vive Pro stand out. Also, the progressive cheapening of these devices has had an impact at a more affordable price for the public and this, in turn, in an expansion of the use of VR devices in different sectors.

The growing trend in the number of publications related to VR (Fig. 1), which shows that there is a vigorous scientific interest in this topic, also marks a paradigm shift in university teaching since the use of VR is increasingly relevant at this educational level of teaching. Thus, this article focuses on the authors' experience using VLs in the practical teaching of Mechanical and Civil Engineering courses (Fig. 2).

The article has been organized into the following sections: a section dedicated to the analysis of the advantages of VLs in engineering education; another section addresses the design and development of this type of didactic tools, pointing out which are the most used software tools to carry it out; later, the results of the assessment that the students of various engineering disciplines (Mechanical Engineering and Civil Engineering) give to the application of VLs are described; and the last section exposes the conclusions of the current work.

2. The virtual laboratories

The use of VR-based resources in the teaching–learning process has been implemented for several decades [7] and, although some studies highlight the lack of use of the potential that this type of technology presents, the advantages that VLs present from an educational point of view have been analyzed by different authors in countless articles, some of them are:

- They represent a minimal expense when compared with the investment involved in installing a real laboratory and, besides, they do not require a maintenance cost [8] to keep them running (although they do have a cost of periodic updating [9]).
- Avoid or prevent potential damage that can arise from misuse with a real machine [10].
- Reduce the space occupied by large equipment installed in real laboratories [11].
- Avoid problems or accidents that may arise in training carried out in real settings, for example during chemical reactions [12], during training in industrial radiology [10], during firefighter training [13], during firefighter training technicians working in critical facilities, such as nuclear power plants [14], during training in industrial processes, such as welding [15], etc.
- Allow access to expensive and sophisticated facilities that would otherwise be virtually impossible to access [16,17].
- Allow you to apply transparency options to see hidden parts of a real machine (some machines or tools have protective covers that cannot be removed during a test and, therefore, do not allow you to understand the execution of the test in more details) [18].
- Facilitate the instructor's work in large groups of learners since they allow each student to see at his/her own pace the instructor's explanation with the highest level of detail [11].
- They offer different possibilities that favor the teaching–learning process [19]: interactivity options, zone transparency, zooming in to see interesting details, modifying the execution speed of a task to check certain details or obtain related insights, and so on.
- They favor the autonomy of the student [20] and the personalization of educational practice by facilitating the design desired by the instructor [21].
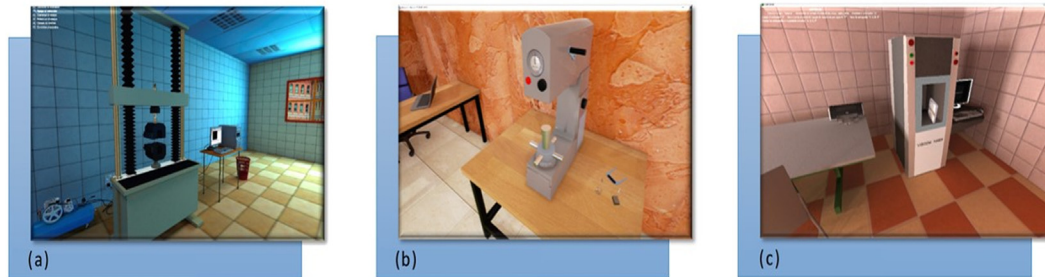

Fig. 1. Number of articles indexed in SCOPUS that include the expression "virtual reality" in the title, abstract, or keywords, published between 2000 and 2019.

Fig. 2. Different practical VLs used in Mechanical Engineering courses showing the following machines: a) traction machine, b) Rockwell hardness tester, and c) industrial radiology equipment.

- Admit to repeating the task as many times as the student wishes [22].
- They include – in many cases – practical exercises that are solved interactively from the virtual laboratory itself, thus completing the process of training the corresponding topic [10,23].
- They promote research opportunities for students who work individually or in a team, guided by an instructor who will need to design pedagogical materials that are effective in terms of content and engagement [24–27].

On the other hand, some drawbacks should be discussed in this article:

- VL programming, although in general, it does not require the participation of expert programmers, it does need to be carried out by people who have dedicated a considerable amount of time to training in this activity. The same occurs with the creation of virtual environments, which can be modeled by almost anyone who has previously invested some time in learning to handle 3D modeling tools. For these reasons, it is necessary to form a multidisciplinary team to deal with the design of a virtual laboratory [7] or to hire a specialized company for this purpose.
- Technological obsolescence affects VLs in a relatively quick time, thereby reducing student motivation to use the obsolete tool [28]. Therefore, every few years the instructor must redesign the virtual laboratory so that it continues to be relevant and interesting among the student community.
- Design is essential to achieve optimal results in different educational aspects such as meaningful learning, motivation, etc. [29,30], and for this, an essential factor is the instructor's experience [31], which must be broad for the design to be truly effective at the educational level.

The steps to follow to design a virtual laboratory are divided into three levels (Fig. 3): (i) determine the usefulness of the virtual laboratory, defining specific objectives – in this case educational – and specific objectives for interactive use; (ii) define the technical design of the virtual laboratory, taking into account the desired levels of realism and interactivity, and (iii) develop and evaluate the virtual laboratory, modifying it as many times as necessary to ensure that the final version of the virtual laboratory meets the objectives desired. It should be noted that the development of a virtual laboratory consists of two different stages: (i) the creation of the 3D virtual environment; and (ii) the programming of the virtual laboratory.

Generally, during the creation of the virtual environment, the rooms, machines, instruments, and other virtual elements are modeled in three-dimensions, materials are applied, and lighting is defined. Although there are different programs that allow these activities to be carried out, some of the most widely used currently

are: 3DS Max®, Maya®, and Blender®. Moreover, the programming stage consists of making interactive the virtual environment to allow the students to interact with the virtual laboratory (that is, they can move through the virtual environment, pick up objects, manipulate machines and instruments, receive messages, etc.). Two of the programs most used today at this stage are the Unity 3D® and Unreal Engine 4® game engines.

3. Implementation of virtual laboratories in the classroom

The implementation procedure in the classroom of the VL is outlined in Fig. 4 and consists of the following stages [28]:

- The instructor of a given subject gives master classes in which he/she explains to the students the concepts related to the laboratory practices that will be carried out. Depending on the subject taught, this stage can last between 2 and 10 h.
- Each student individually uses a VL under the supervision of the instructor. This stage can last from 30 min to 1 h.
- Students solve practical exercises in groups made up of 2–4 students, which are later commented on and corrected by the instructor. In some subjects this stage, which last approximately 2 h, can be omitted.
- Once outside the classroom, students have the possibility of using the VL individually (self-study) as many times as they wish.
- Depending on the subject matter under study, the students attend a real laboratory (RL) in which they repeat the experiment that they carried out virtually through the VL.
- Students fill out surveys from which data is obtained that is subsequently analyzed to improve the teaching–learning process.

4. Results and discussion

According to the educational experiences lived in recent years with different virtual learning environments, the authors have been able to verify that VLs are especially useful for explaining concepts that may be difficult to explain by the instructor, such as situations related to the capacity for spatial vision of the students, in which the instructor is limited to make the students understand something that they are not able to visualize or abstract concepts (e.g. crystallography). In addition, throughout different teaching experiences, the authors have been able to obtain the assessment of 420 students on the use of VLs and real laboratories to carry out the teaching–learning process. These students, as it was described in the methodology of implementation of the VL in the classroom, answered a survey (Table 1) after having used several VLs in the classroom and also after having practiced in RLs.
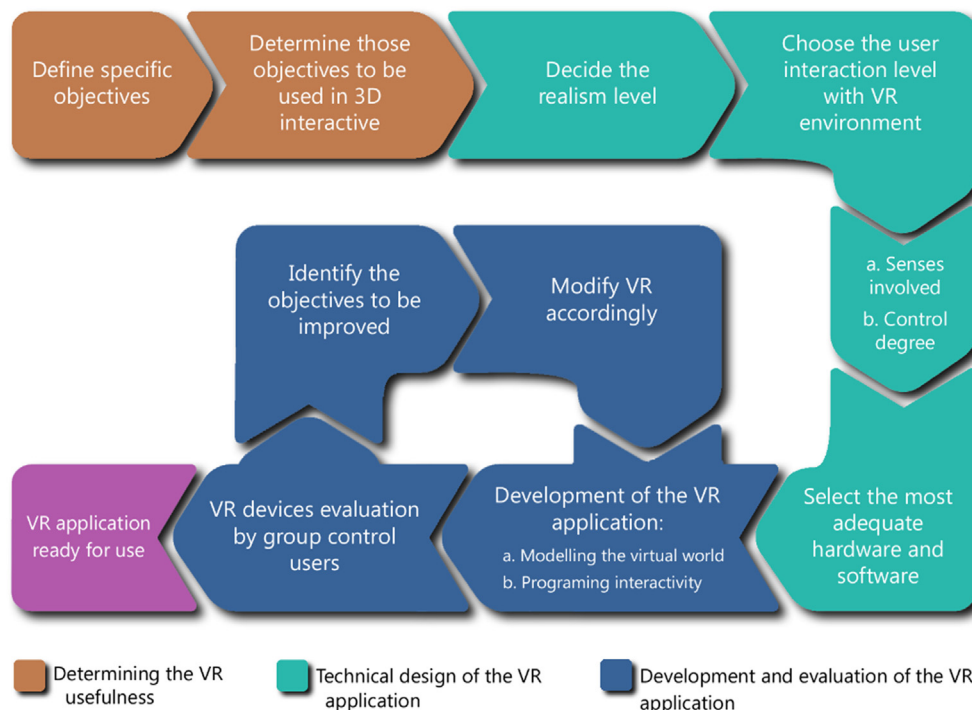
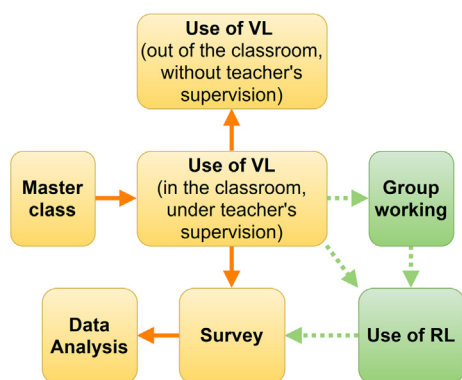**Fig. 3.** Flowchart of the VR application design process. Source: [7]

Fig. 4. Implementation scheme in the classroom of the VLs (adapted from [28]).

All students were studying Mechanical or Civil Engineering at one of the following universities:

- Spanish universities: (i) Universidad Católica Santa Teresa de Jesús de Ávila and (ii) University of Salamanca (Spain) - Escuela Politécnica Superior de Zamora, Escuela Técnica Superior de Ingenieros Industriales de Béjar, and Escuela Politécnica Superior de Ávila-.
- Portuguese universities, during several LLP Erasmus Programmes: (i) Polytechnic Institute of Bragança and (ii) Polytechnic Institute of Viseu

From the results of the surveys carried out in these universities, the IBM SPSS Statistics 25® software was used for information processing and as a statistical calculation tool. As shown in Table 1, the survey used to collect the information had questions related to the effectiveness of the application of the VLs (question 1, Table 1); others were related to the possible methodological changes that the implementation of a virtual laboratory implies (questions 2–

Table 1
Questions asked in the survey (adapted from [32]).

Number	Question	Answer Options
1	In relation to the usefulness of the teaching, you consider that the VL:	a) VLs are a useful complement to reinforce and/or clarify the explanations of the instructor. b) VLs are self-sufficient in explaining the subject matter.
2	In your personal opinion, the practical part of the subject should be taught:	a) Using just VLs. b) Using just the RLs. c) Mixing VLs and RLs, using VLs in the first place. d) Mixing VLs and RLs, using RLs in the first place.
3	If you chose option (c) or (d) in the previous question, what do you consider to be the most appropriate percentage distribution of practical classes?	a) RL: _____% b) VL:_____%
4	In your opinion, what is the most appropriate percentage distribution to be applied in the classroom?	a) Master Classes: ____% b) Problem Solving Classes: ____% c) RL: ____% d) VL: ____% e) Other virtual resources:____%
5	Rate from 1 to 10 the following characteristics of VLs (a) interactivity, (b) motivation, (c) ease of use and (d) educational usefulness.	a) _____ b) _____ c)_____ d)_____

4, Table 1); and, finally, a question centered on the design of the VLs (question 5, Table 1).

In the first place, when asked about the effectiveness of the VLs as methodological resources (question 1, Table 1), the students answered mostly (89%) that the VLs are a useful complement to reinforce and/or clarify the explanations of the instructors (Table 2).

Table 2
Students' evaluation of VL teaching is useful (Question 1, Table 1).

Answer option	Results	
	Number of students (n)	Percentage (%)
a) VLs are a useful complement to reinforce and/or clarify the explanations of the instructor.	373	89%
b) VLs are self-sufficient in explaining the subject matter	47	11%

With regard to question 2 (Table 1), students clearly preferred the distribution of practical classes (Table 3). In this case, 89% of the students prefer the combined use of VLs + RLs (option c, question 2 in Table 1), and only 6% prefer the practical classes taught exclusively in the RLs. Among the students who choose this option (89%) - mixed option of VLs + RLs-, all of them decided that most of the hours of the practical classes should take place in real environments (RLs), thus suggesting that virtual environments (VLs) can actually be a complement to the teaching–learning process.. The distribution preferred by students (question 3, Table 1) were 71% of practical classes held in a RL and the 29% in the VL (Table 4).

Regarding the preferred distribution of the methodological organization of subject teaching, including practical classes in laboratories (question 4, Table 1), it was found (Table 5) that the master class (MC) is recognized as the most valuable methodology (42%). The problem-solving class (PSC) is valued in second place (28%) as a methodological resource to include when it comes to solving technical concepts, followed by the RLs (14%), VLs (7%), and finally, other virtual resources (9%).

Finally, students were also asked about the basic characteristics of VLs (question 5, Table 1). The results (Table 6) reflect the following ranking in terms of technical aspects of VLs: (i) interactivity: students ranked highest; (ii) ease of use: was ranked second; (iii) motivation: was ranked third; and (iv) educational usefulness: was the least valued. The engineering students valued the interactivity and ease of use with 9.8 mean (μ) out of 10, with a 0.80 standard deviation (σ) and 9.14% of coefficient of variation (C_V). Ease of use resulted 9.3 mean and 7.90% of coefficient of variation. Motivation resulted in a mean of 8.5 with a standard deviation of 0.64 and 7.54% coefficient of variation. and, finally, in the case of educational usefulness, the evaluation obtained was 8 out of 10, with 0.59 standard deviation and 9.14% coefficient of variation.

Given the above results, it is possible to affirm that there are evident advantages of using LVs in the classroom compared to traditional RLs. In the same way, it is convenient to point out some aspects in which the RLs stand out:

- RLs are widely demanded by students, since from the students' point of view, the experience lived in a virtual world – no matter how sophisticated and detailed it has been designed – is not

Table 3
Students' evaluation of VL teaching is useful (Question 2, Table 1).

Answer option	Results	
	Number of students (n)	Percentage (%)
a) Using just VLs.	8	2%
b) Using just the RLs.	26	6%
c) Mixing VLs and RLs, using VLs in the first place.	373	89%
d) Mixing VLs and RLs, using RLs in the first place.	13	3%

Table 4
Students' assessment of the methodology followed in the practical classes (Question 3, Table 1).

Answer option	Results	
	Number of students (n)	Percentage (%)
a) RL	298	71%
b) VL	122	29%

Table 5
Students' evaluation of methodological organization (Question 4, Table 1).

Answer option	Results	
	Number of students (n)	Percentage (%)
a) Master Classes	176	42%
b) Problem Solving Classes	118	28%
c) RL	59	14%
d) VL	29	7%
e) Other virtual resources	38	9%

Table 6
Students' evaluation of different features of VLs (Question 5, Table 1).

Answer option	Results			
	Mean (μ)	Variance (σ^2)	Standard deviation (σ)	Coefficient of variation (C_V)
(a) interactivity	9.8	0.64	0.80	8.14%
(b) motivation	8.5	0.41	0.64	7.54%
(c) ease of use	9.3	0.54	0.73	7.90%
(d) educational usefulness	8	0.34	0.59	7.34%

the same as in the real world. In this sense, new design trends include immersive VR [7], by bringing the user closer to the real world.

- The interest generated by laboratory practices in students – at least in engineering students – is especially high in the case of RLs (compared with VLs). In the practices developed in RLs, students perceive a simulation of their future professional development.

For this reason, it can be ensured that currently, students demand the joint use of VLs and RLs for the delivery of practical teaching. This confirms what previous articles [33] reflect, where it is indicated that VLs are a useful resource to complete the training process, but not a substitute for the traditional. In this sense, although VLs are clearly imposing themselves in the teaching of the 21st century, in the future it is very likely that RLs will be present in university facilities – at least in those of a classroom nature.

5. Conclusions

Taking into account the technological advances that have occurred in the last part of the 20th century until today, and the positive experiences that are being lived in practical teaching when using virtual laboratories – which reflect a series of clear advantages compared to traditional practical classes in real laboratories – the implementation of VLs in the educational sector is an unstoppable fact. The current situation due to the pandemic caused by COVID-19 has only accelerated a process of virtualization of education that had already begun previously. Despite this, university students emphasize the importance for them to be able to use real laboratories in practical teaching. Depending on the current situation and the opinion of students, it is possible to affirm that both types of laboratories (virtual and real) will coexist in the new

post-COVID-19 hybrid educational models, which combine face-to-face and online teaching and learning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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