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Remote, Virtual and Physical Labs in Engineering Education: What is the Best for What?

Abstract

Lab work plays an important role in engineering education to ensure that the students have familiarized themselves with and acquired the right practical and scientific competence in engineering, specifically procedural and practical knowledge and skills when leaving university. However, physical labs are costly, require specialized staff, are often underutilized, and in dynamic fields like manufacturing and logistics, they age fast. The rapid development of new educational technologies and the digitalization of both educational and industrial sectors offer new digital channels for delivering lab education to students, both with remote access and/or as fully virtual (online) labs. However, due to the lack of standardized assessments, there is an academic discussion going on about the extent to which these new forms of providing lab work to students can replace, improve, or complement physical labs work. This paper presents the results of a systematic literature review using the search terms: “remote labs”, “virtual labs”, and “physical labs” in the domain of teaching engineering. The main objective of this study is to develop an overview of what is identified as the advantages and disadvantages of each lab type in the scientific research literature. The secondary objective is to see if there was an explicit understanding of when to select a specific type of lab based on the learning achievements aimed at and learning activities for the students. Thirdly, its goal is to investigate if these types of labs are based on the same pedagogical foundation—like social or cognitive constructivism.

Keywords

Virtual Labs, Remote Labs, Physical Labs, Engineering Education, Cognitive Constructivism

1 Introduction

Due to the COVID-19 pandemic in the last two years, many higher education institutions had to offer their programs completely online [1, 2]. Most engineering and science schools offer a content-centered education with a focus on developing both 'critical-thinking' as well as 'problem-solving' skills, often through active-learning approaches, which are much more hands-on and project-based [3–6], and thus laboratories and internships play a vital role in educating future engineers [7, 8]. However, physical labs are costly, tend to have low utilization rates, and require specialized knowledge for their operation and maintenance [9, 10]. The DigiLab4U project was initialized before the COVID-19 pandemic hit the global education system and since then it has been focused on developing an international network of laboratories sharing their facilities in a virtual and/or remote operation way. This vision has come "just in time" to meet the upcoming challenges by providing future engineering students with the required hands-on skills to succeed in the Industry 4.0 era. The project is specifically focused on the Internet of Things (IoT) role in engineering education both at the undergraduate and postgraduate levels [11]. Moreover, online teaching is not new but many universities had only implemented it for lectures and not, for example, for situations that implied teaching subjects/courses within engineering education which required a high degree of lab work and physical interaction (e.g., with specialized equipment) [12]. In terms of online labs, their digital transformation from physical to digital has been described by [13] and [14]. These may be divided into software-driven labs (like simulations) and hardware-focused labs [7], while [15] have a slightly different understanding. The distinct understanding of what is meant by online, virtual, and remote labs might, however, increase the barrier to building a network of laboratories that offer education for each other's students [9, 16, 17]. The authors, therefore, carried out a "systematic literature" review to shed some light on the evolution and understanding of remote, virtual, and online labs in engineering education during the last five years. The reason for limiting the study to the past five years is rapid technological change, which directly impacts the possibility of creating suitable online, virtual, and remotely operated physical labs at lower costs.

2 Research Methodology

This paper aims to determine the research coverage in terms of the state of the art related to remote, virtual, and physical labs in STEM (Science, Technology, Engineering, and Mathematics) subjects. In this context, the study seeks an answer to two main research questions:

> RQ1: What is the current state of the art related to remote and virtual labs?
> RQ2: How does the digital transformation journey trend impact the way we serve education?

This work utilizes a systematic literature review (SLR) as its primary method. An SLR seeks to systematically search for, appraise, and synthesize research evidence on what type of lab (viz.: remote, virtual, or physical) is best for what learning achievements and learning activities for the students in engineering education. Therefore, it requires detailed work on the queries' definition and rigorous evaluation of the terms used (keywords) to ensure the search is widespread without being vague or general; given the context of the topic, it could quickly become overly broad, comprising all types of laboratory work provided to students.

An SLR aims to produce an objective protocol that is not compromised by the researchers' subjectivity. According to [18], this helps in defining what is known and what is unknown. In this review, we followed the SLR strategy proposed by [19], which implements a four-stage protocol. The reason for selecting this approach is that it has been utilized by several researchers [20–24] and we have good experience in carrying out its guidelines. The four stages reviewed and included in this SLR are:

1. Planning the review—Selecting the population or sample, i.e. the focus of the study.
2. Conducting the review—This stage involves four critical steps:
   i. Identifying keywords and search terms (from scoping study) from the literature review and discussion with a team.
   ii. Searching for published journals, bibliographic databases, unpublished studies, conference proceedings, industrial trials, the Internet, and even personal requests.
   iii. Providing a complete list of results (articles and papers) on which the review will be based.
   iv. Constructing data extraction forms, which reduce errors. These can be constructed on paper or by computer.
3. Reporting—Stating the findings in thematic analysis; identifying critical emerging terms/topics and research questions.
4. Disseminating.

A more detailed description of the SLR approach can be found in [24]

3 An SLR on Virtual, Remote and Online Labs

Basing our work on the method described in Section 2, we carried out an SLR according to the four-stage protocol. The progression of the four stages was: (i) plan the review, (ii) conduct the review, (iii) report, and (iv) disseminate—all of which are presented in the following sub-sections.

3.1 Stage 1: Planning the Review

Stage 1 comprises planning the SLR and determining the study sample, which is the focus of the study. This paper emphasizes various forms of online labs and their utilization in engineering education. The database we employed in the SLR is Scopus. This source is recognized for information on engineering education. The initial draft of the planning phase included the use of several databases. However, the authors removed them for two principal reasons: (a) low search results, and (b) limited space in this paper for dissemination of the results.

3.2 Stage 2: Conducting the Review

Setting inclusion and exclusion rules for a particular study are essential to conducting a review. In this case, the search was limited to fully available peer-reviewed academic journals. The period covered was from 2015 to 2021.

The search criteria were: “TITLE-ABS-KEY (remote AND labs ", " virtual AND labs ", and " physical AND labs) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016) OR LIMIT-TO (PUBYEAR , 2015)) AND (LIMIT-TO (DOCTYPE , "ar")”, which identified 22 results. However, since both authors teach engineering subjects/courses, and that is also the main field of the DigiLab4U project, we excluded articles not related to engineering education, which then yielded eight hits. In the first general screening, the search terms were title, keywords, and abstract. We discussed excluding one result since it was a conference paper. However, we decided to keep it. We did not, in this first step, establish alternative and associated terms to expand the search. The authors selected Scopus as the initial database to test the search terms with the completed list of terms, and this was considered sufficient for a first initial investigation.

3.3 Stage 3: Reporting

In the next step, we carried out the analysis on title, keywords, and abstracts, being accessible and in English.

From screening on coding criteria and duplicate elimination, only eight articles met all the requirements established. The complete list is presented in Table 3, which indicates each article's categorization, which is further explained in Stage 4. Following the search queries, the results obtained can be summarized as follows: Out of the seven articles identified in Scopus, five are reviews, surveys or bibliographies comprising the development of virtual and remote labs in recent decades. One specifically addresses the evolution of education in software engineering, while the conference paper focuses on how to facilitate the creation of labs. Only one article investigates the effects of remote labs on learning outcomes in higher education.

3.4 Stage 4: Dissemination

The relevant articles identified are limited in number but can be classified into the following groups: (a) Surveys and bibliographies proving an overall overview of the field from different perspectives (five articles), and (b) one is related to the effect on learning outcomes.

4 Findings

The search in Scopus with the keywords described in Section 3 with the limitation of being in the field of engineering education gave a quite small sample size. The complete list can be seen in Table 1.

Table 1 SLR Outcomes

Author(s)	Publication Date	Title–Description
Grodotzki, J; Ortelt, T.R, Erman Tekkaya, A.	2018	Remote and Virtual Labs for Engineering Education 4.0
Heradio, R., De La Torre, L., Dormido, S.	2015	Virtual and Remote Labs in Control Education: A Survey
Heradio, R. et al.	2016	Virtual and Remote Labs in Education: A Bibliometric Analysis

Author(s)	Publication Date	Title–Description
Potkonjak, V. et al.	2016	Virtual Laboratories for Education in Science, Technology and Engineering: A Review
Esquembre, F.	2015	Facilitating the Creation of Virtual and Remote Laboratories for Science and Engineering Education
Zalewski, J., Gonzalez, F.	2017	Evolution in the Education of Software Engineers: Online Course on Cyber-physical Systems with Remote Access to Robotic Devices
Post, L.S et al.	2019	Effects of Remote Labs on Cognitive, Behavioral, and Affective Learning Outcome in Higher Education
Bhute, V. J. et al.	2021	Transforming Traditional Teaching Laboratories for Effective Remote Delivery—A Review

The small number of relevant articles identified was surprising us. Therefore, we did a new search without restricting ourselves to the field of engineering education or only to articles. That result yielded 149 hits and excluding conference papers, but not limiting the search to engineering yielded 69 hits. A second interesting observation is that the majority of the journal articles' authors work in European organizations. The next section discusses in more detail the different findings and outlines the following steps.

5 Discussion and Conclusion

5.1 Contribution to the Research Questions.

RQ1: We aimed at investigating the current state of the art in remote and virtual labs. The articles identified, specifically the reviews, show that there are still several barriers to overcome before remote labs can be expected to deliver the same quality in terms of learning outcomes as traditional haptic labs. Furthermore, they also indicate that there are still several technical barriers to overcome on the one hand, but on the other hand, there is also a challenge for labs in keeping pace with technical developments. There have not been many thorough considerations of the cost factors, including maintaining and reducing the risk of lab aging in the articles we identified. Since we know that most of the authors are European and that there are publicly financed universities in large parts of the continent, this is a little surprising. There were also only a few considerations as to what a shift towards more remote labs would mean in terms of the technical and didactical qualification needs of the employees operating the lab.

In terms of virtual labs, the literature identified reports more mature and integrated concepts, which have been in daily operation longer and work as an integrated part of the education. Besides the challenge of facilitation, it seems that, to a large extent, these labs achieve the same quality as on-site labs.

RQ2: How does the digital transformation journey impact the way we serve education? Three of the eight articles specifically addressed how digital transformation impacts the way we deliver engineering education. However, while [30 and 32] describe in more detail the organizational and practical changes that the transformation has caused, article [31] investigates its influences on cognitive, behavioral, and affective learning outcomes based on an analysis of 23 articles reporting the effect in higher education. Even though the findings are very interesting, it is still too early to conclude under which circumstances we should offer students remote labs and when not, since there are so many unknown factors that need to be further investigated.

Furthermore, it is too early to conclude that the digital transformation of education that we have seen during the COVID-19 pandemic period will progress at an equal pace for remote and virtual labs since their setup is different and also the successful achievement of intended learning outcomes seems to be diverging. It can also be mentioned that hardly any of the articles address how remote and virtual labs influence different non-technical competence, which according to ABET (Accreditation Board for Engineering and Technology, Inc.), however, is of utmost importance.

5.2 Limitations in Our Study

We did only use one database to identify relevant articles. Searching more databases as well as carrying out a complementary snowballing approach would have given a more detailed picture of all lab developments. While the inclusion of more databases might provide a broader data set, the snowballing approach allows the researcher to identify relevant articles that may not necessarily appear in the database search using a search string [33] but can be identified in the articles in the search string. A quick look into the articles we analyzed showed, as expected since these are reviews, that this would provide us with a much larger data set. The starting point is the initial list of relevant articles selected as applicable in this area. The backward approach consists of scanning through the referenced articles in the initial list. Based on the defined inclusion and exclusion criteria, new articles are selected. The final inclusion decision is given after reading the full pre-selected papers. This might be an approach to consider in the next steps.

5.3 Future Work

The outcome of the SLR showed that even though the great focus has been put on the digital transformation of laboratories within engineering education during the last few (pandemic) years, there are not many journal contributions that systematically investigate all aspects of this transformation. We, therefore, intend to first complement this research by adding more databases like IEEE and Web of Science.

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