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SURVEY

Extended Remote Laboratories: A Systematic Review of the Literature From 2000 to 2022

ISABELA NARDI DA SILVA[1], JAVIER GARCÍA-ZUBÍA[1], (Senior Member, IEEE), UNAI HERNÁNDEZ-JAYO[1], (Member, IEEE), AND JOÃO BOSCO DA MOTA ALVES[2]
[1]Faculty of Engineering, University of Deusto, Bilbao, 48007 Biscay, Spain
[2]Federal University of Santa Catarina, Florianópolis, Santa Catarina 88040-900, Brazil

Corresponding author: Isabela Nardi da Silva (isabela.nardi@deusto.es)

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ABSTRACT Remote Laboratories (RLs) break barriers in education since they provide real experimentation anytime and anywhere. However, their greatest drawback is the lack of immersion. However, Extended Reality (XR) can overcome this shortcoming through the integration of AR, or VR techniques, into remote experimentation, thus developing Extended Reality Remote Laboratories (XRLs), which can be Augmented Reality Remote Laboratories (ARLs), or Virtual Reality Remote Laboratories (VRLs). Our study consists in a systematic review concerning the state-of-the-art of XRLs during the period 2000-2022. Findings from the systematic review generated two main results. First, a thorough analysis that reports: a timeline of publications, studies per country, most influential universities, most popular journals and conferences, most cited publications, description of ARLs, description of VRLs, and most notable publications. Secondly, a classification of the XRLs encountered during research, and a proposed architecture for creating XRLs, in order to guide developers wishing to integrate XR into their experiments.

INDEX TERMS Augmented reality, virtual reality, extended reality, remote laboratories.

I. INTRODUCTION

Quality education is the 4th sustainable development goal designated by the United Nations [1]. In 2020, as the COVID-19 pandemic spread across the globe, a majority of countries announced the temporary closure of schools, affecting more than 91 percent of students worldwide. Thus, the integration of online technology in education became even more necessary. Several educational tools were developed and applied in education during the pandemic to support remote learning [2], [3], [4]. In this new learning scenario, not all students and teachers were prepared for remote education, so it was necessary to identify and apply more effective educational resources to fill the gap produced by the pandemic and to prepare people for the new reality caused by the latter.

One of the targets established for the quality education goal is to "substantially increase the number of youth and adults who have relevant skills, including technical and vocational skills, for employment, decent jobs, and entrepreneurship". Throughout the world, there is a lack of STEM (Science, Technology, Engineering, and Mathematics) professionals [5]. Unfortunately, this derives from both a deficit of interest in these areas and the absence of opportunities for many people while seeking to pursue higher education [6]. For the Organization for Economic Co-operation and Development (OECD) [7], many students believe that STEM subjects are not enjoyable, and have difficulty trying to understand concepts introduced by teachers.

The OECD affirms that the lack of practical activities during STEM classes is one of the main reasons why students find it so difficult to understand concepts, and this deficiency is usually the consequence of not every school having functional science laboratories. South America and Africa suffer from a shortage of infrastructure and adequate equipment for classes [7]. In Brazil, for example, there is a total of 179, 533 schools, and only 22, 121 (12 percent) of these schools

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have science laboratories [8]. Without proper access to real equipment, students do not have the opportunity to practice science, and thus become uninterested in pursuing associated careers, since they believe those kinds of studies are not for them.

In this respect, the New Information and Communication Technologies (NICTs) bring many benefits to education. Learning technologies allow students to access information in several ways, for example, providing them with the opportunity remotely to practice concepts from their classes [7]. Resources such as simulations, Extended Reality (XR), and Remote Laboratories (RL) grant students the opportunity to benefit from a more practical understanding of their classes [9]. Therefore, they become more interested in these areas, since they transcend their difficulties through experimentation [10]. In this paper, we analyze the state-of-the-art of frameworks that integrate XR with RLs, to define a new general architecture that allows RL developers easily to design new educational platforms. There are two main concepts that exist within the context of XR: Augmented Reality (AR), and Virtual Reality (VR).

AR is the process of overlaying meaningful interactive information in a live video stream to create an enriched visual experience for users [11]. The integration of Augmented Reality into education provides a more interactive experience for students. Several publications evidence the successful use of AR during educational activities [12]. For Wen [13], AR is useful in many stages of students' careers, from kindergarten to higher education. Ibanez et al. [14] present an application of AR in secondary education for STEM subjects, in which the use of this technology was effective, and motivated students to pursue STEM areas in the future. VR refers to three-dimensional models and virtual environments with which a user interacts through a device [15]. VR is a promising educational technology with several learning benefits; the adoption of VR as a learning technology has challenged the conceptual definition of what constitutes a learning environment. Many authors present papers on the use of VR in STEM education [16], [17], [18], [19], the conclusion being that it is a digital resource that is becoming increasingly more accessible in education [10].

Finally, an RL is a physical laboratory that can be accessed remotely. Secure and low-risk access is enabled by a web system in order to teleoperate specialized equipment [20]. In an RL, this same interaction takes place at a distance with the assistance of the remote infrastructure. This interaction is usually conducted via a web interface, where the laboratory is video streamed in real-time using a webcam and presented in real-time on a website provided with controls for the user to observe or manipulate an experiment. Using an analogy to compare the RL and the conventional laboratory experience, the webcam is the student's eyes, and the mouse and keyboard are the hands. This is a new layer that occupies a space between the user and the laboratory equipment. It is responsible for conveying user actions and receiving sensory information from the equipment [21].

However, one of the main issues with RLs is the lack of immersion, since they usually provide no more than a video stream in real-time for the students to observe, and sometimes interact with. Thus, integration into XR can mitigate the lack of immersion by augmenting reality or bringing the experiment into a virtual reality with real data. In this paper, we introduce the term Extended Remote Laboratories (XRLs), which relates to AR and/or VR technologies integrated within RLs.

XR technologies are an emerging phenomenon. Analysis of the information provided by Gartner offers evidence of the main trends in technology. Gartner's Hype Cycle [20] illustrates the five phases that occur with each new technology or other innovation: the technology trigger, the peak of inflated expectations, the trough of disillusionment, the slope of enlightenment, and the plateau of productivity. Every year, the Gartner organization creates hype cycles for diverse technologies as a way for people to track technology maturity and future potential.

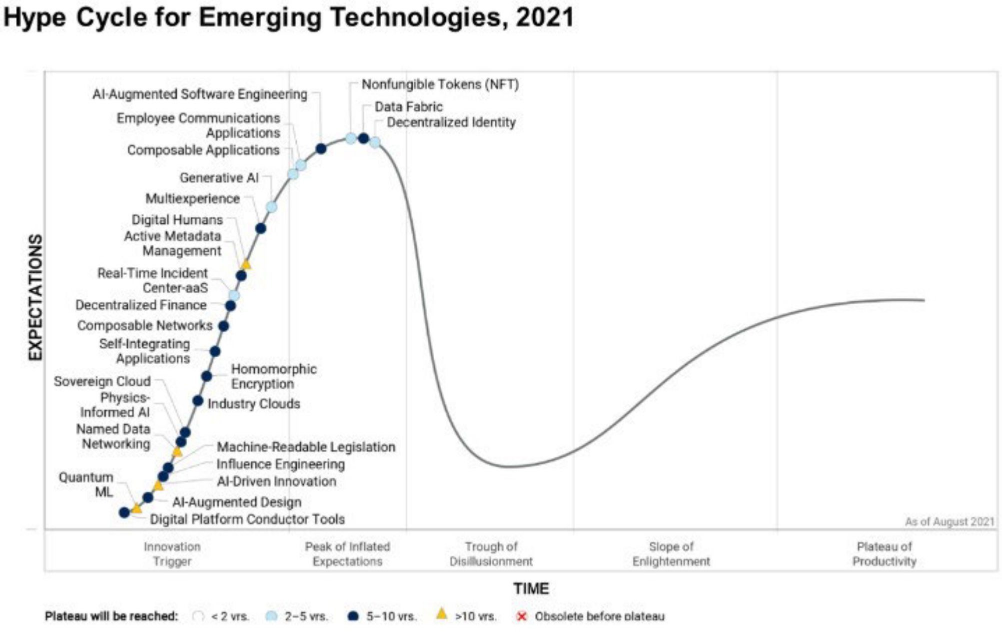
Fig. 1 presents the Hype Cycle for Emerging Technologies from 2021 when solutions linked to AR and VR are emerging. Concepts such as metaverse and digital citizens are also associated, related in particular to VR. AR is not presented in the 2021 Hype Cycle because, according to Gartner, it has matured so rapidly that it is no longer considered an ''emerging technology''.

In this context, in which there is a multitude of technologies such as AR, VR, and others, the complex combination of which improves user experience while accessing a RL, it becomes necessary to conduct a systematic review that will contribute to facilitating the work of RL developers. Therefore, this paper provides a systematic review of XRLs, to identify the state-of-the-art of combination of these technologies during the period 2000-2022.

After introducing the paper, we describe the AR, VR, and RL technologies that underpin this paper (section II). Then, the bibliographical resources, materials, and methods are explained (section III). The analysis of the results (section IV) consists of eight subsections focusing on different aspects of the results generated. Next, these results are discussed (section V), and based on the findings and discussion, we propose a new architecture for developing XRLs (section VI). Finally, we present our conclusions (Appendix).

II. ANALYSIS OF EXTENDED REALITY AND REMOTE LABORATORY TECHNOLOGIES

This section details the main technologies approached in the present document: Extended Reality, and RL, as well as the relationship between the two. Extended Reality (XR) is an umbrella term that encompasses an entire spectrum of realities assisted by immersive technology, such as AR and VR, among others [23]. XR engages users in a human-machine converged reality through integrated cyber-physical environments using computers and wearable technology [24]. Some authors, such as Xi et al. [24], believe that metaverse is another word for XR, because it enables



Source: Gartner (August 2021)
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FIGURE 1. Hype cycle for emerging technologies, 2021.

novel forms of engrossing telepresence, increasingly facilitating people's jobs, education, healthcare, consumption, and entertainment.

Thus, Mystakidis [25] presents the metaverse as an environment merging physical reality with digital virtuality. It enables multisensory interactions with virtual environments, digital objects, and people, using AR and VR. Mystakidis divides the metaverse's characteristics into four areas: principles, affordances, technologies, and challenges. Its main principles are that it is interoperable, open, hardware agnostic, and provides a network. Its affordances are immersion, embodiment, presence, and identity construction. Its technologies are AR, VR, and Mixed Reality (MR). Its challenges are physical well-being, psychology, ethics, and privacy. In Fig. 2, Xi et al. [24] present the metaverse technologies, principles, affordances, and challenges.

Given that the concept of metaverse has much to contribute to education, and that some of its main technologies are AR and VR, this paper focuses on both. As a starting point, in Fig. 3, Siewert et al. [26] present the main differences between AR and VR technologies:

Whilst AR is about augmenting the reality in which users already find themselves, VR brings a whole new dimension. AR presents introduces elements into natural reality. Examples of applications using AR are social media filters, tools such as Google Glass and HoloLens, and mobile games such as Pokémon Go, among others. People can use AR to add helpful information and better visualize natural reality. VR allows users to enter a whole new reality in which there are infinite possibilities. Using special gadgets such as VR glasses and haptic gloves, or even just a computer, users can emerge into a virtual dimension. Some examples include social media software such as Second Life, Meta, several videogames, and experimentation environments for students, people in training, and engineers.

Within the context of XR is the concept of Digital Twin (DT), which refers to the digital replica of a physical entity, with two-way communications between both [27]. DTs have been mainly used in the field of engineering [28]. A DT is not an exact copy: it can best be described as a container for models, data, and simulation [28]. With regard to its application in learning processes, Sepasgozar [27], Tagliabue et al. [29], and Liljaniemi and Paavilainen [30], present cases of successful integration of DT into education, mainly in engineering courses, whereas, Vikhman and Romm [31] introduce the potential of DT in education, pointing out that it enlarges user experience and enhances learning outcomes. In section six, we will present a proposed architecture for XRL, which will refer to the development of a DT.

The COVID-19 pandemic reinforced the use of such technologies since people were concerned about social distancing. Pillai and Guazzaroni [32] published a book about XR usage during the COVID-19 pandemic. The book presents different approaches to the use of XR, such as health, learning, industry, art, and others. In relation to learning, Mathew and Pillai [33] present pros and cons vis-Ã -vis the XR-based remote learning experience during the pandemic. For Mathew and Pillai, technologies have mitigated the negative impact that the lockdowns would otherwise have caused. For this reason, the challenges posed by remote learning could be

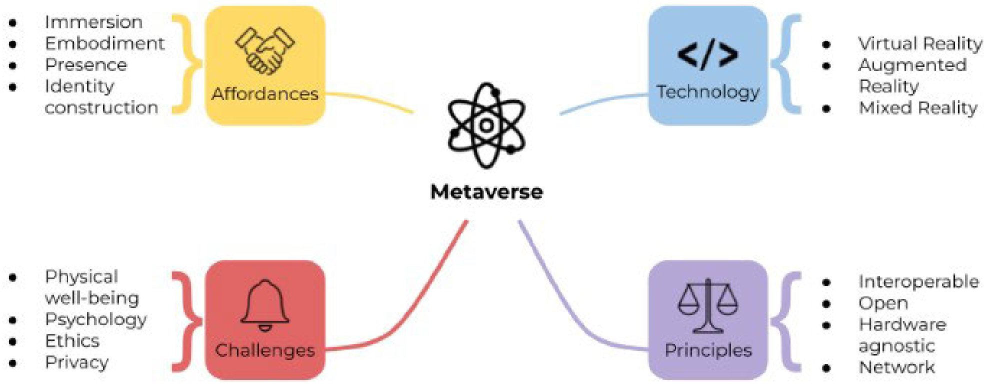

FIGURE 2. Metaverse technologies, principles, affordances, and challenges.

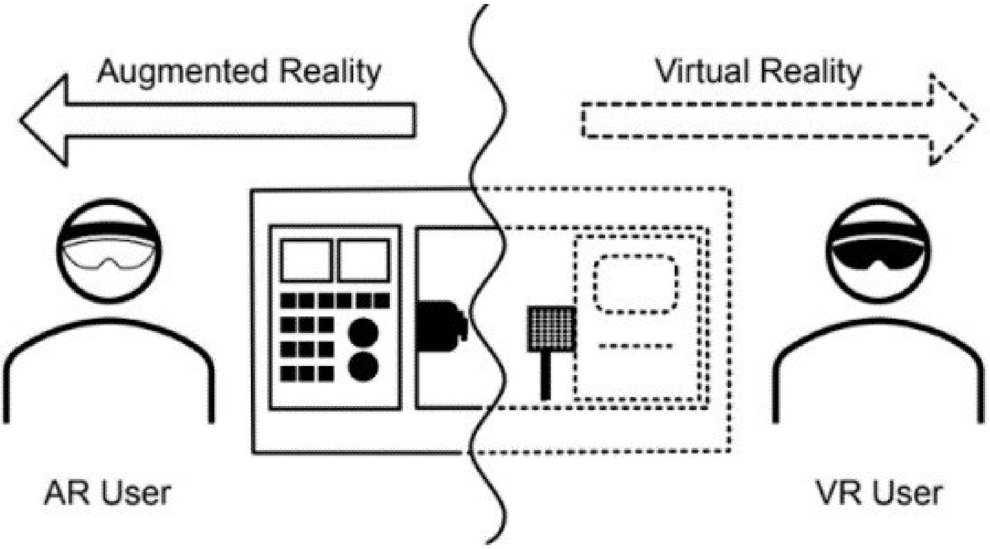

FIGURE 3. Comparison between AR and VR.

addressed by using XR to enhance the collaborative learning experience for remote learners.

Continuing in this context, MacCallum and Parsons [34] presented a paper on teaching perspectives on the potential of the metaverse in learning. For the authors, the variety of options within the AR space means that educators need guidance in order to understand how AR might be used in the classroom and impact student learning. MacCallum and Parsons allow the participants of the research to create mobile AR experiences using Metaverse Studio, an AR tool developed by GoMeta, an American software company with no relation to Meta, Meta Platforms' VR tool. Participants' responses showed that when integrating XR into educational settings, it is important to train the educators beforehand.

RLs allow students to access and interact with real science experiments even if they are far away from a physical classroom. Remote experimentation occurs when a real laboratory is mediated using the Internet. For example, a circuit board will be recorded through a webcam and the video will be transmitted live. Meanwhile, a user can control some parameters of the circuit board, and program the latter, while visualizing it in real time [35]. Thus, students can perform practical experiments at any time from anywhere. All they need is a device with a browser and access to the Internet [36]. Abumalloh et al. [37] presented the role of RLs during the coronavirus pandemic, from the students' perspective. According to the study, RLs motivated the students, who were able to perform their activities even during the quarantine.

In his book, García-Zubía [38] presents the advantages and disadvantages of RL, some of which are presented in Table 1.

Regarding the disadvantages, "Reality", refers to immersion, and how, even though users are interacting with real data, they can as if they are not when using a non-immersive environment. Aligned with this idea, Nickerson et al. [39] agree that the lack of immersion is one of the greatest dis-

TABLE 1. Advantages and disadvantages of RL.

Advantages	Disadvantages
Availability	Suitability for the student
Student safety	Suitability for the teacher
Safety of equipment	Safety of equipment
Time management and student autonomy	Freedom
Enhanced educational experience	Reality and sense of immersion

advantages of RLs, and can significantly affect a student's performance while experimenting. The drawback noted by Nickerson et al. can also be related to suitability for the student.

When pondering possible solutions for this problem, we can consider XR technologies, known to solve immersion problems by extending reality. Remote Laboratories in Extended Reality can overcome issues such as lack of immersion. In relation to the current context, we propose an umbrella definition that concerns Remote Laboratories in Extended Reality: Extended Remote Laboratories (XRLs). From now on, in this paper, Augmented Remote Laboratories will be referred to as ARLs, and Virtual Reality Remote Laboratories will be referred to as VRLs. For Maiti et al. [11], in this context, the integration of AR enriches the user experience and offers a more immersive user interface. For Palmer et al. [40], VR, when integrated into an RL, provides a realistic interaction between student and experiment, where the former will not only interact with a real device but also have a sensation of immersion. Several studies have illustrated the successful integration of these technologies [11], [40], [41].

Nevertheless, some platforms, such as Labster [42], should not be cited as examples of using XRLs, since Labster provides only virtual scenarios that work based on simulations. The difference is that simulations do not work with real data, and thus do not provide a real experience similar to an experiment conducted in a hands-on laboratory. In the present paper, we will research and analyze cases of integration of XRLs.

The main purpose of XR is to broaden experiences, and there is considerable potential for it to change how people work, collaborate, and create projects. In addition, XR allows students to feel immersed in an experimental environment, in a way in which they can improve their understanding of abstract concepts. Throughout this paper, a variety of publications regarding XRLs will be presented, proving it has the potential to increase learning opportunities.

III. MATERIALS AND METHODS

This section describes the materials and methods used for the development of this research. The paper concerns bibliographic research. Bibliographic research may be defined as any research requiring information to be gathered from published materials. There are several types of bibliographic research, but the most popular are narrative, integrative, and systematic. There are other types of bibliographic research that can be found in studies, such as bibliometric or rigorous, among others. As regards methodological choices to undertake this research, earlier publications were analyzed, in order to identify the best approach. Heradio et al. [10] and Raman et al. [43] chose the bibliometric analysis method for their state-of-the-art papers on remote and virtual laboratories in education. Meanwhile, other papers with similar objectives [44], [45], [46], [47] chose to perform a systematic review. The research method chosen for this paper is systematic review because it is based on a process that is transparent and easy to replicate. Systematic reviews are a firmly established method of ensuring that the proposed research is based on the best available evidence [48]. A review earns the adjective "systematic" if it is based on a formulated question, identifies relevant studies, appraises their quality, and summarizes the evidence by use of explicit methodology [49]. It is the explicit and systematic approach that distinguishes systematic reviews from traditional reviews and commentaries. A systematic review also identifies and minimizes partiality via transparent, explicit, and systematic methodology [48].

We will now indicate some papers that also used systematic review as their method of choice for developing their research. In view of the shortage of systematic reviews specifically addressing XRLs, so we decided to present examples related to research on RLs, since RLs constitute a more specific research field than XR technologies, because XR technologies are very wide-ranging. Nevertheless, we found a systematic review by Faulconer and Gruss [47], whose work is dedicated to integrating remote laboratories and games, which can be related to VR. Tulha et al. based their work on a protocol for systematic reviews developed by Kitchenham andCharters [48], and a systematic mapping review based on the methodology suggested by Bailey et al. [51]. Tho et al. [52] used the EPPI-Centre [53] methods for systematic reviews and research syntheses. Solis-Lastra et al. [54] employed a methodology proposed by Kitchenham et al.

Kitchenham et al. exemplify the PRISMA guidelines as a reliable method for conducting systematic reviews on engineering. We decided to use the PRISMA guidelines as the protocol for our research for two main reasons. Firstly, because they are widely used for engineering research, as evidenced in works by Arshad et al. [56], Anita et al. [57], and Pordanjani and Salehi [58], all of which were on the subject of education on engineering, or STEM education. The second reason is that the PRISMA guidelines provide a clear and validated path for developing the process, which facilitates the replication of the study.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [59] presents a flow diagram that depicts the flow of information through the different phases of a systematic review. Their flow diagram maps out the number of records identified, included, and excluded, and justifies the exclusions. Fig. 4 presents the PRISMA 2020 flow diagram for new systematic reviews of included searches of databases and registers only [60], which is the case for the present research.

There are three main steps: Identification, Screening, and Included. Identification refers to the location of databases and registers from where records (papers, communications, theses, among others) will be retrieved. Screening refers to the filtering of the results, and Included refers to the records included in the review. The identification step is divided into two actions. The first presents databases and registers from which the records are identified. Then, before the screening, some records are removed: records that are duplicated, ineligible, or removed for other reasons.

Subsequently, the screening first presents the number of records screened, followed by the records excluded, and then reports sought for retrieval. Next, presented unretrieved reports are presented, and the reports are assessed for eligibility. Then, the reports excluded and the reasons for exclusion. Finally, there is the section "Included", in which the studies included in the review are presented. The databases chosen for this research were IEEE Xplore, Scopus, Web of Science, ProQuest, and ScienceDirect. These databases were chosen based on our experience since they are the ones that return more results related to RLs, and also because some repositories, such as Springer, may provide fewer results, but these results are usually duplicated from other databases that return more results. Google Scholar was not used because it is a search engine, and not a database itself. For Gusenbauer and Haddaway [61], crawler-based search engines like Google Scholar or Microsoft Academic function differently from database providers such as ProQuest, or journal platforms such as SpringerLink, or Wiley.

Meanwhile, while defining which databases would be chosen, GRC2014 was considered. Zappatore et al. [62] created a bibliographical database specifically dedicated to VRLs, the GRC2014. However, according to Heradio et al. [10], GRC2014 has two drawbacks: it covers a short time span, including records on papers for the time span 2008-2013; and it does not provide information regarding paper citation. Thus, to obtain meaningful results in this survey, the preference was for databases that cover a longer time span, and provide citations. The citations are important because later in this paper analysis will be presented regarding citations from the literature found.

The keywords, or index terms, were chosen based on our experience of research on RLs; over the years, different definitions were used to describe RLs. Thus, as this research compiles publications since 2000, several terms were chosen in order to identify more studies, that, although did not use the term "Remote Laboratory", would specify research on remote experimentation.

The terms used for the research were "augmented reality", "virtual reality", "mixed reality", "remote lab*", "remote experiment*", "virtual world", "weblabs", "iLabs", "hybrid lab*", "internet-accessible lab*", "internet-accessible experiment*", "digital twin", "VR lab", and "virtual lab". The asterisk serves as the truncation (or wildcard) operator. Unlike the other operators, it should be appended to the word affected. Words match if they begin with the word preceding the * operator [63]. The operators chosen were mostly OR, except before "remote lab*", when it was AND. When keywords or index terms were not an option, the decision was taken to search for titles that included these words. The filters used were conference papers, articles, books, book chapters, abstracts, dissertations, and thesis. The time period chosen was from 2000 to 2022. The languages chosen were English, Spanish, and Portuguese.

Thus, in general, the string used for search would be:

("Index Terms":"“augmented reality") OR ("Index Terms":"virtual reality") OR ("Index Terms":"mixed reality") AND ("Index Terms":remote lab) OR ("Index Terms":remote experiment*) OR ("Index Terms":"virtual world") OR ("Index Terms":weblabs) OR ("Index Terms": iLabs) OR "Index Terms":"hybrid lab") OR ("Index Terms":internet-accessible lab*) OR ("Indexms":internet-accessible experiment*) OR ("Index Terms":"digital twin" OR ("Index Terms": "VR lab") OR ("Index Terms": "virtual lab").*

In the case of some databases, specific filters were also applied. For IEEE Xplore, Scopus, and ProQuest, journals related to medical and nursing research were excluded. Also, for Scopus, IEEE journals and conferences were excluded, since the search had already been conducted on IEEE Xplore. Furthermore, some databases would not support more than ten keywords. Therefore, we conducted tests with the order of the keywords and sorted the ones that would result in less relevant records, to be excluded when a database would not accept all the keywords. The keywords "internet-accessible experiment*", "digital twin", "VR lab", and "virtual lab" were omitted in these cases.

Even after the filters were applied to the databases, the results returned a large number of documents, which could not be read manually. Thus, we chose to use a systematic review automation tool. The systematic review automation tool SLR-Tool [64] was employed to assist research development. The SLR-Tool was developed by Kitchenham et al., who sought to develop a free tool to facilitate the process of developing systematic reviews in engineering. It provides functionalities such as refining searches within the documents by applying text mining techniques; defining a classification schema in order to facilitate data synthesis; exporting the results obtained to the format of tables and charts; and exporting the references from the primary studies to the formats used in bibliographic packages such as EndNote, BibTeX or Ris. The following section, Analysis of Results, will detail the findings of the systematic review.

IV. ANALYSIS OF RESULTS

This section consists of the analysis of the results obtained via the systematic review. It details results from the systematic review process, a timeline of studies, studies per country, most influential universities, most popular journals,

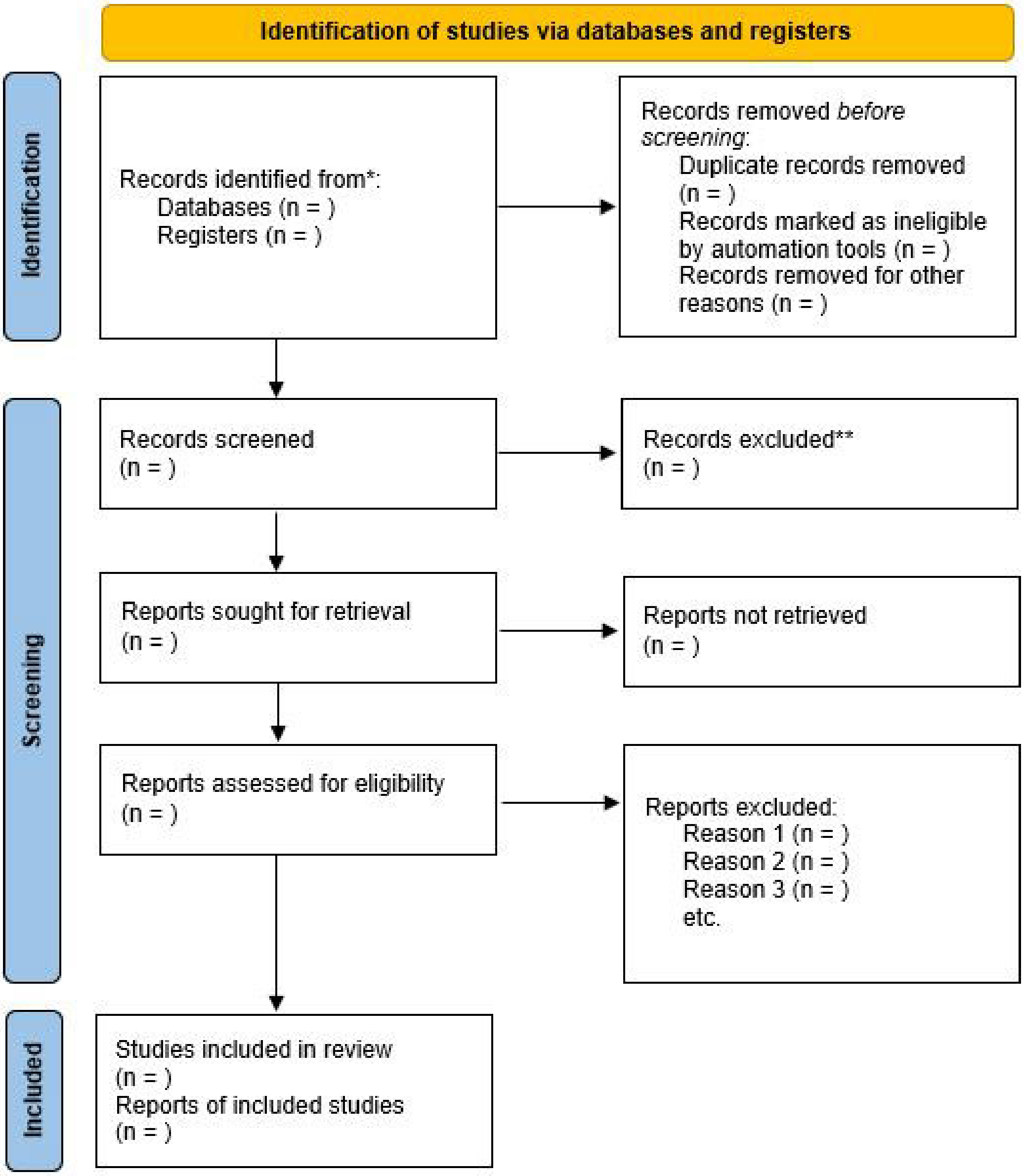

FIGURE 4. **PRISMA 2020 flow diagram for new systematic reviews with included searches of databases and registers only.**

and conferences, most cited publications, studies on ARLs, studies on VRLs, and most notable publications.

A. RESULTS FROM THE SYSTEMATIC REVIEW PROCESS

Fig. 5 presents the results from the systematic review process, according to the PRISMA protocol.

As presented in Fig. 6, in total 79 studies were included in the review. Fig. 6 summarizes the systematic review process:

In total, 7,742 records were identified from the databases, and before screening, 7,612 of these records were removed using the SLR-Tool. Thus, 130 records were screened. Of the records screened, 33 were excluded after reading the abstract, so 97 were sought for retrieval. Of these 97 records, 85 were assessed for eligibility, whilst six of these 85 were excluded because they were not related to remote experimentation, but simulations. Finally, 79 studies were included in the review.

The next sections detail these studies. To reduce the length of the article but provide the interested reader with more detailed information, Appendix presents the complete list of publications included in the research, listing authors, title, country, and year of each study, as well as specifying whether they were focused on AR or VR. Studies are classified in chronological order.

B. TIMELINE OF STUDIES ON XRLs

Fig. 7 shows the timeline of publications on XRLs. Note that the figure shows total XRL publications in blue, ARL-only publications in red, and VRL-only publications in yellow.

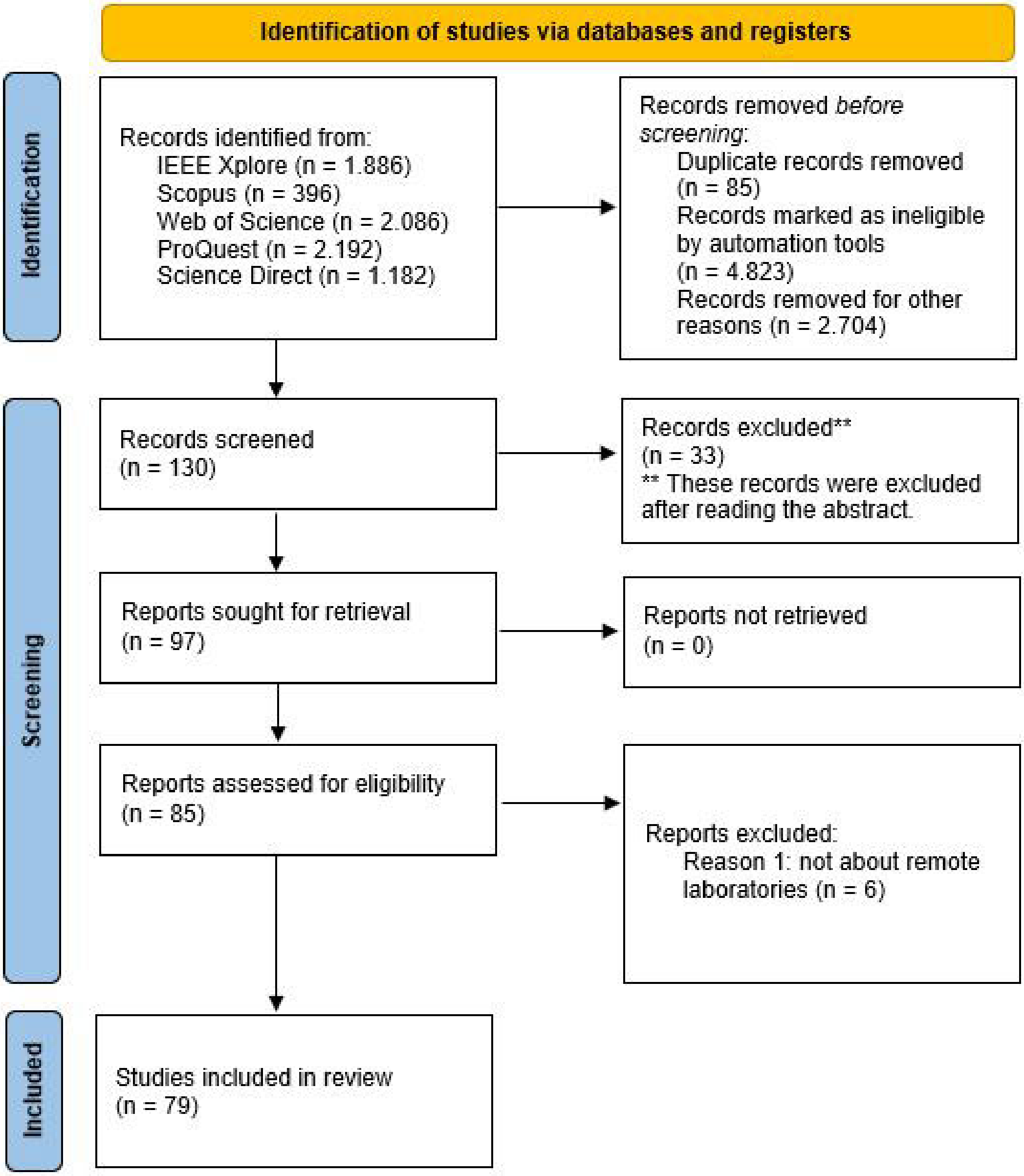

FIGURE 5. PRISMA 2020 flow diagram for new systematic reviews with included searches of databases and registers only.

Although this research was conducted during the period 2000-2022, the earliest study found was published in 2001.

The first publication on VRLs in the period 2000-2022 was published [93], and the first on ARLs was published [75]. The year with the most publications was 2012, with nine studies published: three on ARLs, and six on VRLs. The year with the most publications on ARLs was 2013, with four studies published. The years with the most publications on VRLs were 2004 and 2012, each with six studies published.

We can see that the number of VRLs increased over the years and that they were always the subject of more analysis than ARLs. Moreover, VRLs seem to become a tendency, because in spite of fluctuations, during the last years, they were the subject of a consistent number of publications, while ARLs were at a low.

C. STUDIES PER COUNTRY

Fig. 8 presents the number of publications per country. The color gray represents countries with no publications found. The closer the color is to green, the more publications the country has, and the closer to red, the fewer.

If the origin of the papers is analyzed, the country with the most publications is Germany, with 18 studies published. The top five countries are Germany (18), Spain (11), Brazil (10), Australia (9), and Portugal (5). The country with the most publications on VRLs is Germany, with 18 studies published,

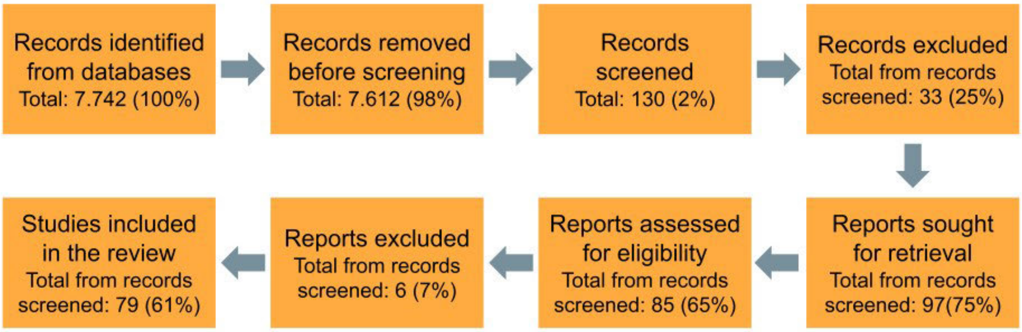

FIGURE 6. Summary of the systematic review process.

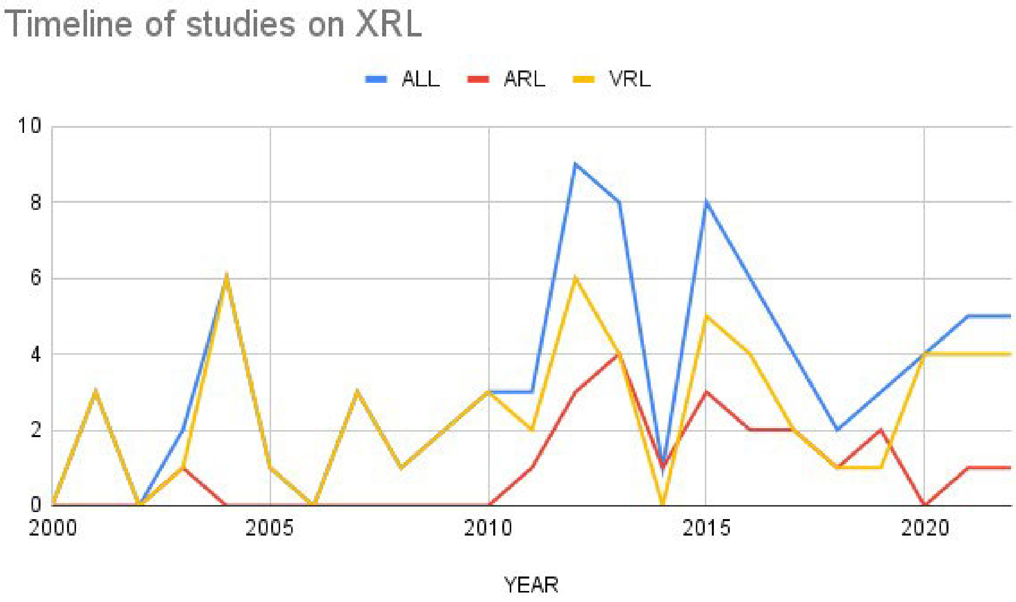

FIGURE 7. Timeline of studies on extended remote laboratories.

but the one with the most publications on ARLs is Australia, with eight studies published.

Some countries had studies produced by different universities. The studies from Germany come from several universities: the University of Hagen, Technical University Dortmund, University of Brethemen, and Ruhr-University Bochum. The studies from Spain also came from several universities: the Spanish University of Distance Education (UNED), the University of Huelva, the Polytechnic University of Madrid, and the University of Deusto. The studies from Brazil were mainly from the Federal University of Santa Catarina (UFSC), but also from the Federal University of Rio Grande do Sul (UFRGS).

D. MOST INFLUENTIAL UNIVERSITIES

From the analysis, it was also possible to identify that some universities had several publications on the subject, and would be publishing constantly, whereas others would not publish less frequently. Fig. 9 presents the five universities with the most publications on the subject.

It is noteworthy that 50.4 percent of the studies found were published by the same five universities. The University of Hagen published 13 studies in the period 2001-2007; the UNED published eight studies in the period 2011-2016; the Federal University of Santa Catarina published seven studies in the period 2010-2021; the University of Queensland published six studies in the period 2016-2019; and the Technical University Dortmund published five papers in the period 2020-2022. It is worth noting that the German universities of Hagen and Dortmund shared researchers and that some authors who published as associated with the University of Hagen in the period 2001-2004 are currently associated with Dortmund.

E. MOST POPULAR JOURNALS AND CONFERENCES

Fig. 10 presents the percentage of studies according to whether they were published in a journal, conference, thesis, or book chapter.

As the figure shows, most studies were conference papers (51.9 percent), although many were also published in journals

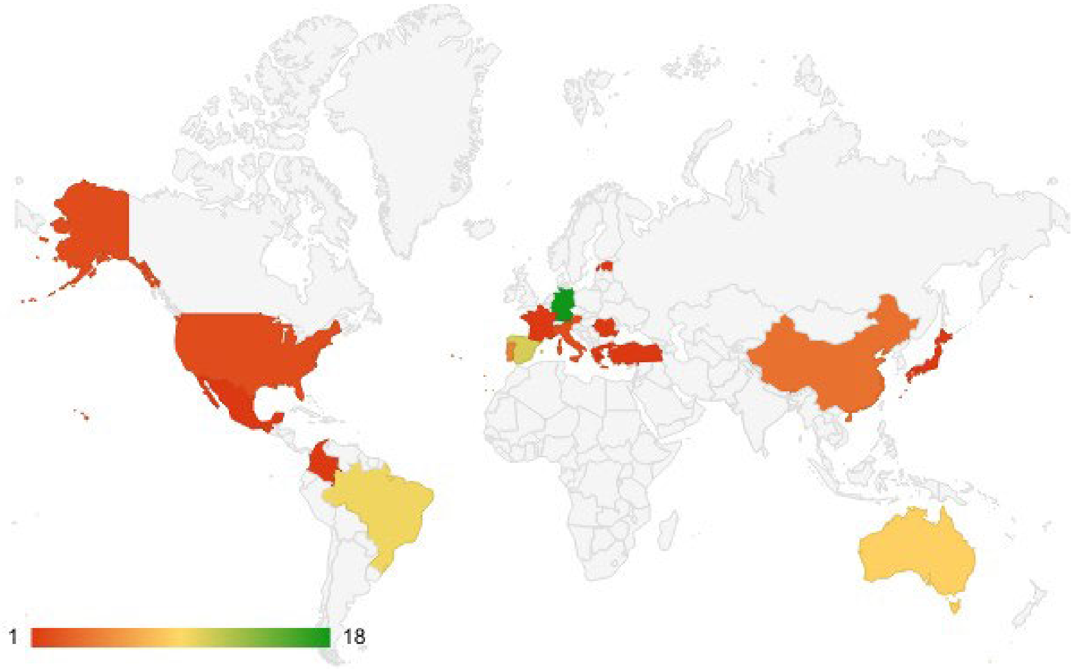

FIGURE 8. Studies per country.

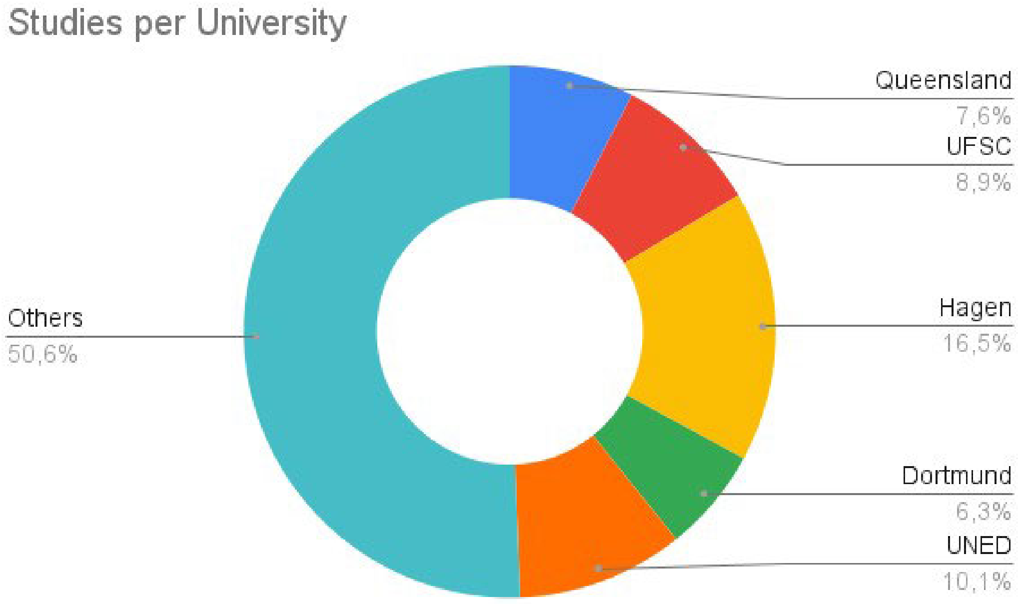

FIGURE 9. Studies per university.

(41.8 percent). For the studies presented in conferences, Fig. 11 presents the main conferences in question.

For the studies published in journals, Fig. 12 presents the main journals in question.

The figures show that the main conferences are: the International Federation of Automatic Control (IFAC) World Congress, International Conference on Remote Engineering and Virtual Instrumentation (REV), IEEE Global Engineering Education Conference (EDUCON), and Experiment@ International Conference (Expat).

The main journals are the International Journal of Online and Biomedical Engineering (iJOE), IEEE Transactions on Learning Technologies, IEEE Transactions on Education, and IEEE Access.

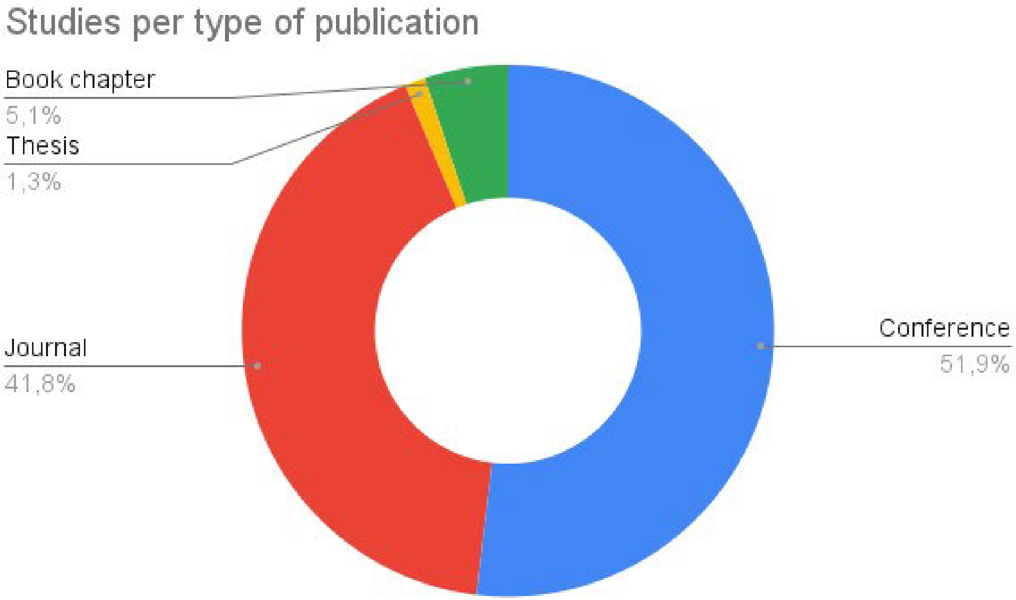

FIGURE 10. Studies per type of publication.

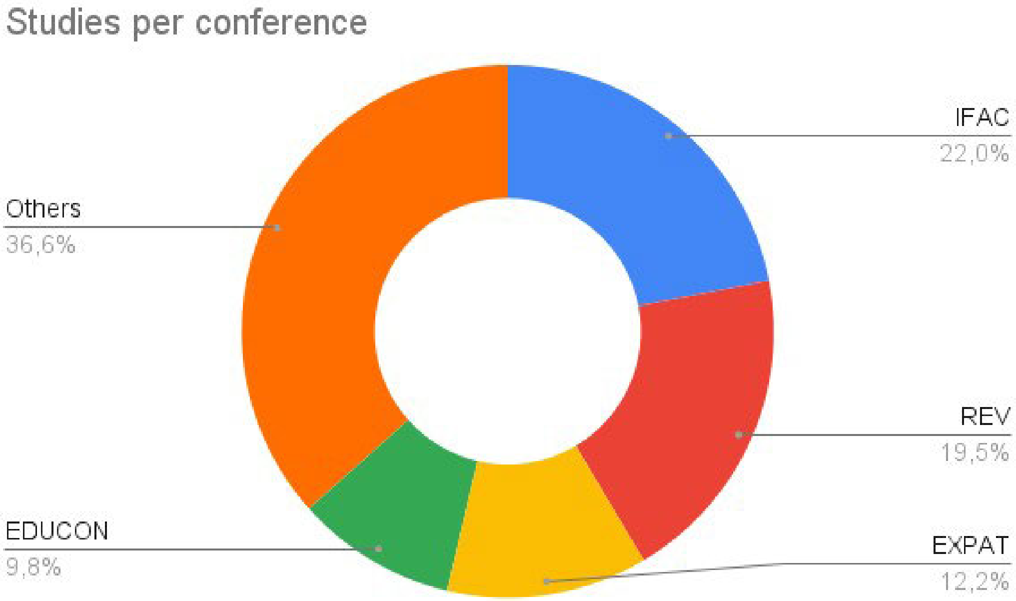

FIGURE 11. Studies per conference.

F. MOST CITED PUBLICATIONS

Of the studies included in the review, this section lists the most cited examples. Table 2 presents the ranking of the five most cited publications in all years from 2000 to 2022. The information was collected from Google Scholar since it indexes citations from other databases.

The table shows that the most cited papers are not the more recent ones. Furthermore, the influence of the papers from the University of Huelva is worthy of note, since these papers receive new citations at least once a month, despite being published over 10 years ago. This is because these papers define and employ an architecture for ARLs that has remained in use until today, and are therefore still very pertinent. On the other hand, the other papers presented as most cited do not define current architecture and technologies, and nowadays are usually cited to reference past practices in this area.

Table 3 presents the most cited publications in the period 2018-2022:

Table 3 shows that, of the most cited studies in the period 2018-2022, two were published by a research group from

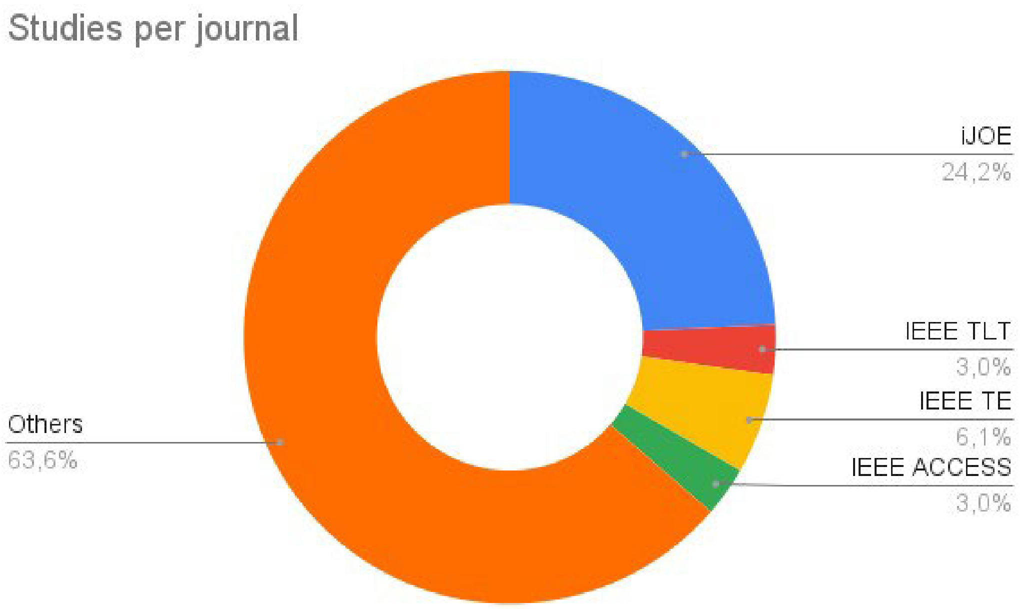

FIGURE 12. Studies per journal.

TABLE 2. Most cited studies in the topic of AR/VR applied to education.

Title	Authors	University	Year	Citations
Augmented Reality for the Improvement of Remote Laboratories: An Augmented Remote Laboratory	Marquez et al. [65]	University of Huelva	2010	300
A Pilot Study of the Effectiveness of Augmented Reality to Enhance the Use of Remote Labs in Electrical Engineering Education	Borrero et al. [66]	University of Huelva	2012	159
A Multiuser Virtual-Reality Environment for a Tele-Operated Laboratory	Hoyer et al. [67]	University of Hagen	2003	89
Collaborative Virtual 3D Environment for Internet-Accessible Physics Experiments	Scheucher et al. [68]	Graz University of Technology	2009	81
Web-Based 3-D Control Laboratory for Remote Real-Time Experimentation	Hu et al. [69]	University of Wuhan	2012	74

TABLE 3. Most cited studies in the period 2018-2022.

Title	Authors	University	Year	Citations
Remote Lab meets Virtual Reality – Enabling immersive access to high tech laboratories from afar	Trentsios et al. [70]	Ruhr-University Bochum	2020	25
Using Virtual Reality for Teaching the Derivation of Conservation Laws in Fluid Mechanics	Boettcher et al. [71]	TU Dortmund	2021	12
Virtual Reality for Remote Controlled Robotics in Engineering Education	Rukangu et al. [72]	University of Georgia	2021	10
Usage of a Virtual Environment to Improve the Teaching of Fluid Mechanics	Boettcher et al. [73]	TU Dortmund	2020	9
Virtual reality remote access laboratory for teaching programmable logic controller topics	Yerden et al. [74]	Marmara University	2020	8

the Technical University Dortmund, Germany. Meanwhile, the most cited study was published by Trentsios et al., from the Ruhr-University Bochum, Germany. The paper from Trentsios et al. has been accumulating citations, as have the papers from TU Dortmund. Therefore, we would recommend to keep up with their projects, since the increasing number of citations shows that these papers have been used as references in recent work. The frequency of citations has grown over the years, while the studies by Rukangu et al. and Yerden et al. have been cited as often.

TABLE 4. Studies on augmented remote laboratories.

Authors	Objective	Technologies used
NTT Microsystem Integration Laboratories [75]	Development of a system that allowed users to touch digital items and real-world movable objects visible through a display.	IR sensor tags, RF tags.
University of Huelva [65] [66] [76]	Development and validation of a water tank ARL. Validated with engineering students, who returned positive feedback. It also describes ARRL software, developed to create ARL.	AR markers.
UNED [77]	Development and validation of an ARL for programming. Validated with engineering students. 62.5% of the students considered it positive, while 12.5% had difficulties regarding usability.	AR markers.
Al-Quds University [78]-[81]	Development and validation of an ARL for teaching circuits. Validated with engineering students, who returned positive feedback.	AR markers.
UNED [82]	By the same research group as Cubillo et al. Development of an ARL for engineering students. The areas approached were thermal process, and robotics.	Easy Java Simulations, AR markers.
University of Oradea [83]	Development of a telerobotic ARL for engineering students.	AR markers.
University of Technology Sydney [84]	Adaptation of AR within overlay SmartGrid into RL for monitoring and selecting events.	AR SmartGrid System.
University of Porto [85]	Development of an ARL for teaching circuits in secondary schools and first years of higher education. The application had four laboratories: series and parallel circuit, XOR circuit, light bulb intensity regulator, and DC circuit puzzle.	AR markers.
University of Queensland [11] [86]	Development of a framework for ARL.	AR markers.
University of Porto [90]	Development of an Android mobile app proving three ARLs for secondary schools. The areas approached were mechanics, water level, and smart cities.	SolidWorks, JavaScript, AR markers.
RExLab/Federal University of Santa Catarina [91]	Development and validation of an ARL for teaching AC circuits in secondary school. Validated with secondary students, who returned positive feedback regarding the experience, but felt that the laboratory was insufficient to obtain satisfactory results in exams.	Unity
Swinburne University of Technology [92]	Presents a survey concerning the opinion of engineering students on the usage of AR glasses for RL. Students returned positive feedback and reported that they would like to use the resource with more frequency.	Hololens

G. STUDIES ON ARLs

This section presents the studies on ARLs, which are termed studies because they do not always involve direct implementation of a RL, but include discussion of the field, and proposals for frameworks and architectures. Table 4 lists the studies found, detailing the authors, objective, and technologies used. Studies are listed in chronological order. Some publications addressed the same study/project. In this case, they were paired by university/research group. If studies from the same university are listed separately, it is because they addressed different projects by the same group.

H. STUDIES ON VRLs

This section presents the cases of VRL. Table 5 lists the laboratories found, detailing the authors, objective, and technologies used. Studies are listed in chronological order. Some publications addressed the same study/project. In this case, they were paired by university/research group. If studies from the same university are listed separately, it is because they addressed different projects by the same group.

I. MOST NOTABLE PUBLICATIONS

Regarding the studies presented in the Tables 4 and 5, this section selects the most notable examples. Studies are listed in chronological order.

Although the technology used would not be relevant nowadays, the paper by Bischoff et al. [96] is notable because it showcases the development of an entire VRL environment when specific technologies were unavailable. Furthermore, Bischoff et al. affirm that RL could naturally be considered VR laboratories, since they are accessed through a virtual interface.

Andújar et al.'s paper on ARLs [65] is the most cited study found in the review, and although it was published in 2011, it is still relevant for literature on ARLss, because it describes a software made for creating ARL, ARRL software. The study conducted by Smith et al. [86], presenting the key aspects for developing ARLs, is also notable and relevant for people researching in this field.

Callaghan et al. [128] wrote about opportunities and challenges involved in the integration of RLs into VR, and this paper should be read by developers and researchers in this area, since it provides relevant information on issues such as usability, student satisfaction, technical approaches, and so on. In addition, Callaghan et al. not only worked with VR, but with integrating remote experimentation into videogames, exploring gamification applied to RLs while using VR.

As presented in the last two sections, several studies used Unity for the development of VRLs. Thus, Cosic's study [137] is recommended, since it showcases the development of a VISIR VRL using Unity, and details the use of Unity resources for VR.

V. DISCUSSION

This section is divided into two topics: ''Discussion of recent research'', and ''Recommendations for an XRL architecture''.

TABLE 5. **Cases of virtual reality remote laboratories.**

Authors	Objective	Technologies used
University of Hagen [93]-[103]	Development of a VR environment that integrated access to RL, videoconferences, chat, and screen sharing. Students and teachers could navigate the environment as avatars. Several RLs were provided, such as pendulum, gantry crane, and circuits.	Java
CERTH/ITI [104]	Development of four VRLs: Gas Laws, Inverse Law of Light Intensity, Magnetic Field of a Coil, and Digital Design simulation.	VRML
Universidade Federal do Rio Grande do Sul [105] [106]	Study was part of the RExNet project, in which Silva et al. [117] were also partners. Development of a VRL for teaching automation and control systems. They also tested four VR RLs with students: "Pilot Plant", "Thermal Plant", "Mechatronics Lab", and "Bottling Production".	MOODLE, Elipse, Java Applets
Graz University of Technology [107]	Presents the iLab Project, which integrates RLs combined with TEALsim 3D simulation toolkit in Open Wonderland, for creating collaborative 3D virtual worlds.	TEALsim 3D, Open Wonderland
RMIT University [108]	Development of a DC motor VR RL used for control engineering education.	VRML
RExLab/Federal University of Santa Catarina [109]-[115]	These studies were developed by the Remote Experimentation Laboratory (RExLab), coordinated by Silva et al. [117]. Addresses the development of a VR environment for RL aimed at secondary school students. Several RLs were developed, such as a microscope, and an AC circuit board.	OpenSimulator
University Jean Monnet [117]	Integration of VRL in the VR system Open Wonderland.	Open Wonderland
Polytechnical Institute of Porto [118]	Published in partnership with RExlab. Integration of RL into the VR system Open Wonderland.	Open Wonderland
Jiangxi Science and Technique Normal University [119]	Development of an architecture for developing VRL with 3Ds Max, and Virtools.	3Ds Max, Virtools
Engineering College Zhejiang Forestry University [120]	Development of an architecture for developing VRL with VRML, and JavaScript.	VRML, and JavaScript
University of Brethemen [121]	Development of a VR environment for RL using OpenSimulator. The paper presents a mechatronics VRL.	OpenSimulator
University of Siena [122]	Development of a robotics VRL developed with LEGO Mindstorms.	LEGO Mindstorms, Java Applets.
Harbin Institute of Technology [69] [123]	Development of the Networked Control System Laboratory (NCSLab), which provided a VR environment where students would interact as avatars, and control RL.	Flash 3D engine, AJAX Scripts.
Southern Polytechnic State University [124]	Development of mRLab, a framework for RL in VR.	Unity
University of Porto [125]	Development and evaluation of four VRLs for secondary school students: ideal lever, double-acting pneumatic cylinder, the elastic constant of a spring, and system of pulleys. In general, students returned positive feedback, although 26% found the experiments difficult to understand.	Oculus Rift, 1 DOF haptic.
Polytechnic University of Madrid [126]	Development of eLab3D, an electronics VRL provided in the VR environment OpenSimulator.	OpenSimulator
University of Deusto [127]	Development of SecondLab, a VR environment for RL developed with SecondLife.	SecondLab
Ulster University [128] [129]	Development of Digital Warz, a videogame that integrated a RL for teaching circuits, which is also available in VR. The authors also present opportunities and challenges of VR for remote and virtual laboratories.	Unity
Polytechnic University of Madrid [130]	Development of the iRIO-3DLab, a platform for VRL based on OpenSimulator. They showcase a VRL for teaching hardware configuration.	OpenSimulator
UNED [131]	Development of a Water Tank System VRL using EjsS.	EjsS
University of Deusto [132] [133]	Presents an architecture for developing RL in virtual environments, such as VR.	Unity
Militar University Nueva Granada [134]	Development of virtual and RL using Unity. It showcases a Beer Bottling VRL.	Unity
Monterrey Institute of Technology [135]	Development and validation of a VRL for teaching programming logic controllers. Students reported that the VRL motivated them in their studies.	PLCSIM

TABLE 5. ***(Continued.)*** **Cases of virtual reality remote laboratories.**

TU Dortmund [71] [73] [136]	Development of a VR RL for teaching fluid mechanics. They also present a methodology for immersive laboratories in VR.	Unreal
Ruhr-University Bochum [70]	Development of a VRL for teaching hydraulic.	Unity
Marmara University [74]	Development and validation of a VRL for teaching mechatronics. The study showed that students with access to the VR RL performed better academically than those without access.	Web-based
Carinthia University of Applied Sciences [137] [138]	Development of a VISIR VRL.	Unity
University of Derby [40] [139]	Development of a DC Motor VRL.	Unity
University of Georgia [72]	Development of a robot arm VRL.	Unity
Tallinn University of Technology [140]	Development of the ReImagineLab, a platform for creating digital twins of RL. They showcase the digital twin of a crane RL.	Unreal

A. DISCUSSION OF RECENT RESEARCH

This topic concerns discussion regarding the 79 papers, and focuses on studies published after 2018, in order to identify the challenges and opportunities involved in improvement in recent research.

The studies published by a research group from the University of Queensland [11], [86], [87], [88], [89] define a framework for developing ARLs. Although selected as some of the most notable studies included in this review, they affirm that not all RLs are suitable for integration with AR. An opportunity for improvement, or an open door for new research, would be to define whether or not some RLs would be suitable for AR, and requisites for integrating RLs within VR.

The studies published by a research group from the Technical University Dortmund [71], [73], [136] are recent and recommended for people developing VRLs. However, they are not so relevant for people researching aspects of VRL user experience, and student satisfaction or motivation. The study would be more complete if it not only focused on technical aspects, but also on pedagogical aspects. The same can be said of the studies conducted by the research group from the Carinthia University of Applied Sciences [137], [138], which developed a VISIR VRL using Unity.

Nicolete et al. [91] developed an ARL for teaching physics to secondary and high school students, using Unity. However, when evaluating the ARL with students, the feedback returned was that the ARL is easy to use, but that the didactic aspects were weak. Students said that they do not believe the ARL is sufficient for them to understand concepts and perform well in exams and tests. Therefore, an opportunity for improvement would be to work on the pedagogical aspects of the ARL.

Palmer et al. [40], [139] developed a VR DC motor using Unity. The studies published by this research group from the University of Derby are recommended for people developing VRL. Nevertheless, they lack information in relation to usability, user experience, and pedagogical issues regarding the system. The research would be more complete if they considered these factors in further development.

Alsaleh et al. [140] presented ReImagineLab, a platform for creating digital twins of RL using Unreal. This is one of the most recent studies in the review and is recommended because they not only focus on technical issues, but also on usability. No specific drawbacks are identified, although it would be interesting if further research on this project could focus on the pedagogical aspects of ReImagineLab.

Alvarez et al. [135] created a VRL for teaching programming logic controllers. According to a student survey, the VRL developed was satisfactory and motivated students. However, PLCSIM, the technology used for the development, is too specific, and the framework developed would not be so easily replicated for other RLs. The use of engines such as Unity and Unreal facilitates reuse in other RLs, projects, and institutions.

Mora et al. [134] present the development of virtual and RLs using Windows Server and Unity, and they showcase a virtual environment for a beer bottling VRL. However, it focuses on technical aspects and lacks information on usability, student satisfaction, and pedagogical aspects.

Racha et al. [92] conducted a survey of engineering students' perception vis-Ã -vis the use of AR glasses for RLs. They used the Hololens AR glasses, developed by Microsoft. Students enjoyed using Hololens and described the experience as satisfying and motivating, where improved by using the resource. Nevertheless, a drawback is that not everyone can afford Hololens, as they are not a low-cost resource, so this research could not be replicated so easily.

Trentsios et al. [70] developed a VRL for teaching about hydraulics, and used Unity to develop it. A drawback of this research would also be the lack of information about the pedagogical aspects of the RL, as well as usability.

Yerden et al. [74] developed VRRALAB, a VRL for teaching programming logic controllers. The study presented the validation of VRRALAB, confirming that students with access to the VRL had a better academic performance than those without access. However, a drawback in the research would be that the technology used is not so easy to reuse for other RL.

Rukangu et al. [72] used Unity to develop a digital twin of a robot arm RL. This study is recommended for people developing digital twins of RL. Although it would be more complete if also detailed pedagogical issues, and usability. Upon analysis of the studies considered, the main challenges

TABLE 6. Classification of the augmented reality remote laboratories found in research.

Year	RL name	University	Subject	Technology	Availability	Cost	Obsolete
2012	Water Tank [66]	University of Huelva	Mechanics	AR markers	Unavailable	Low	No
2012	Lab [77]	UNED	Computer Science	AR markers	Unavailable	Low	No
2012	Circuit Board [78]	University Al-Quds	Electronics	AR markers	Available	Low	No
2013	Heat Flow [82]	UNED and PUC Chile	Chemistry	Easy Java Simulations	Unavailable	Low	Yes
2014	Telerobot [83]	University of Oradea	Robotics	AR markers	Unavailable	Low	No
2014	Series and Parallel Circuits, XOR Circuit, Light Bulb, DC Circuit Puzzle [85]	University of Porto	Electronics	AR markers	Unavailable	Low	No
2017	Water Tank [90]	University of Porto	Mechanics	AR markers	Unavailable	Low	No
2021	AC Panel [91]	Federal University of Santa Catarina	Electronics	AR markers, Unity	Available	Low	No
2022	Lab [92]	Swinburne University of Technology	Not specified	Hololens	Available	High	No

identified while analyzing and discussing the research found were:

- Universality: most of the laboratories were based on architectures that specifically concern AR or VR, and that considered specific technologies that would eventually become obsolete, or that could not be so easily replicated in other RLs.
- Low-cost: some XRLs are hard to replicate because they used technologies with a paid license, or expensive gadgets.
- Up-to-date: several laboratories became, or risk becoming, obsolete, because they used technologies that would soon be out of date.
- Multilingual: some of the laboratories are only available in specific languages, rendering them hard for developers to replicate, and also unattainable for some users.
- Usability: most studies reported poor or negligible XRL usability
- Availability: this is related to universality and being up-to-date, because several XRLs are no longer available, because technology became obsolete, or the developers did not maintain the availability of RLs.

These challenges are approached in the next section, where we will present recommendations for the development of XRLs, and a proposed architecture.

B. RECOMMENDATIONS FOR AN XRL ARCHITECTURE

This topic presents recommendations regarding the development of XRLs based on the studies included in the systematic review, along with a proposed architecture to develop an XRL. Table 6 and Table 7 classify the XRLs encountered in the research, in similar fashion to the presentation in the sections ''Studies on ARLs'', and ''Studies on VRLs''. Each table defines the RL's name, the university where it was developed, the subject it addresses, the technology used, and whether it is available, obsolete, and high or low-cost. Positive characteristics are marked as green, and negative characteristics are marked as red. Some studies are not included in the table because they did not detail a specific RL, but defined an architecture or framework. When the RL's name is referred as simply ''Lab'', it means that the authors do not specify its denomination. When the subject is referred to as ''Several'', it means that more than two areas were approached with the RL. The table follows a chronological order.

Table 6 classifies the ARL:

The recommended technologies for developing ARLs are AR markers, and Unity. Although Unreal was only found in research on VRLs, it could be also recommended for AR because Unreal has a framework for AR. The most relevant ARLs found in the research are the ARL circuits developed by the research group from the University Al-Quds [78], [79], [80], [81], and by Nicolete et al. [91], because they are available, use current technology, and are low-cost.

Table 7 classifies the VRL:

The recommended technologies for the development of VRLs are game engines such as Unity, or Unreal. These engines provide resources for developing software in VR, and also for connection to remote devices, so they facilitate the development of VRLs. Moreover, although they have paid versions, they are low-cost because it is also possible to use them without payment, and there are plenty of tools for free downloading from their asset stores. Tools such as 3D models, libraries, projects, among others.

For VRs, there is also the possibility of integrating VR glasses, haptic gloves, and other devices. However, this increases the cost of the experience and this kind of project is not as easy to replicate. The recommendation therefore is to develop a project that can be employed in both ways: with or without gadgets.

TABLE 7. Classification of the virtual reality remote laboratories found in research.

Year	RL name	University	Subject	Technology	Availability	Cost	Obsolete
2001-2004	Circuit Board [93], Gantry Crane [101]	University of Hagen	Several	Java	Unavailable	Low	Yes
2005	VRLAB [104]	Informatics and Telematics Institute (Greece)	Several	VRML	Unavailable	Low	Yes
2007-2009	Pilot Plant, Thermal Plant, Mechatronics Lab, Bottling Production [106]	Federal University of Rio Grande do Sul	Automation	Java	Unavailable	Low	Yes
2009	iLabs [107]	Graz University of Technology	Several	TEALsim, Wonderland	Unavailable	Low	Yes
2010	DC motor [108]	RMIT University	Electronics/ Mechanics	VRML	Unavailable	Low	Yes
2011	Lab [119]	Jiangxi Science and Technique Normal University	Several	3Ds Max, Virtools	Unavailable	Low	Yes
2012	ACT Remote Lab [122]	University of Siena	Mechanics	LEGO Mindstorms, Java	Unavailable	High	Yes
2012	Lab [121]	University of Brethemen	Electronics	OpenSimulator	Unavailable	Low	Yes
2012-2016	Microcope, AC Panel [113]	Federal University of Santa Catarina	Biology, Electronics	OpenSimulator	Unavailable	Low	Yes
2015	Idea Lever, Double-acting Pneumatic Cylinder, Spring, Pulleys [125]	University of Porto	Mechanics	Haptic devices	Unavailable	High	No
2015	eLab3D [126]	Technical University of Madrid	Electronics	OpenSimulator	Unavailable	Low	Yes
2015	SecondLab [127]	University of Deusto	Robotics	SecondLife	Unavailable	High	Yes
2015	Circuit Warz [128]	Ulster University	Electronics	Unity	Available	Low	No
2016	Lab [130]	Technical University of Madrid	Computer Science	OpenSimulator	Unavailable	Low	Yes
2016	Water Tank [131]	UNED	Mechanics	EisS	Unavailable	Low	Yes
2018	Beer Bottling [134]	Militar University Nueva Granada	Mechanics	Unity	Available	Low	No
2019	Lab [135]	Technological of Monterrey	Mechanics	PLCSIM	Unavailable	Low	No
2020	VRRLAB [74]	Marmara University	Mechanics	Web-based	Unavailable	Low	No
2020	Hydraulic [70]	Ruhr-University Bochum	Mechanics	Unity	Available	Low	No
2021	VISIR [137]	Carinthia University of Applied Sciences	Electronics	Unity	Available	Low	No
2021	DC Motor [139]	University of Derby	Electronics/ Mechanics	Unity	Available	Low	No
2021	Robot Arm [72]	University of Georgia	Robotics	Unity	Available	Low	No
2021	Fluid Mechanics [71]	Technical University Dortmund	Mechanics	Unreal	Available	Low	No
2022	ReImagine Lab [140]	Tallinn University of Technology	Mechanics	Unreal	Available	Low	No

In addition, for VR, it is important to consider not only the technology that is going to be used, but also how the environment would be projected. Callaghan et al. [128] demonstrate in their study that immersion is not that easy' students also need to feel comfortable in the VR environment. Callaghan et al. explain that if the environment is not prepared properly, users can experience vertigo and nausea, which jeopardizes their experience in the virtual environment.

Based on the results found and discussed in this research, we developed an architecture for developing XRL. Fig. 13 presents the architecture.

While designing the architecture, we considered the main challenges found during research. One of the main challenges was to consider an architecture that would be easily replicated. Thus, we focused on proposing an architecture that would be universal, low-cost, up-to-date, and multilingual.

The architecture is divided into 3 main blocks: a yellow block, which refers to developing an ARL; a blue block, which refers to developing a VRL; and a green block, which shares elements of all kinds of XRLs. Currently, the software recommended for developing an XRL would be a game engine, such as Unity, or Unreal, since this kind of platform provides resources for connecting remote devices, and integrating XR features. They are also low-cost and provide most of resources for creating XRLs at no cost. The

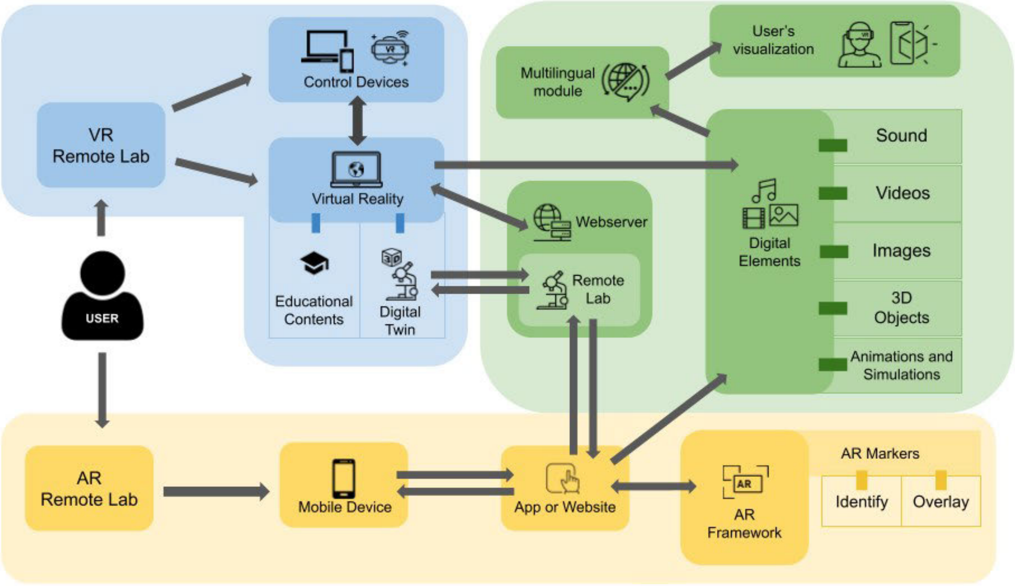

FIGURE 13. Architecture proposed.

communication between the application and the webserver where the RL is located could be achieved by several means, such as an API Rest, Web sockets, among others.

To explain how this architecture works, we are going to use an example of a developer that has a pendulum RL and wants to integrate it into XR.

In the case of development of an ARL, we recommend the development of an application for mobile devices. We recommend a mobile device as it allows the use of a camera, which is useful in most AR applications, in order to use AR markers. This application could be provided as an app or a website, and would be based on a framework that would involve identifying points, and overlaying them with information. The application would communicate with the RL, which is in the webserver, and overlay the RL's real-time video streaming with digital elements, such as sound, video, images, among others presented in Fig. 13. In the case of a pendulum ARL, these data could be, for example, the angle of the pendulum while it moves, the period in a chronometer, or its positions. These contents can be translated, and would then be presented to the user.

Concerning the development of a VRL, it could be an application for mobile devices, or PC, or a website. It is also possible to adapt it to VR gadgets, but as it is a low-cost architecture, we will focus on a downloadable application, or website, for mobile and PC. It would be a VR environment providing educational content and 3D replica, or a DT based on the RL. The application would enable the DT to receive information from the RL, so, when receiving certain commands, it would respond with the same behavior as the LR. Furthermore, the VR environment would also present other digital elements, such as animations, simulations, videos, and other content that can help immersion and user understanding of the experience. A pendulum VRL could be a 3D model of the real lab, but in a more immersive environment, where it is possible to rotate a room, zoom in, zoom out, and see the positions of the object change in real-time, as well as its angle. It could also be possible to provide simulations and ask the user about the differences between a simulation and the RL. Finally, before being presented to the user, the VRL is translated into their language of choice, after which they enjoy the experience.

Regarding innovation, this architecture is different from others found in literature because it is not exclusively for AR or VR. It concerns both possibilities, and is thus more general and can be used and adapted more easily. Moreover, it advises the use of a low-cost tool, and is therefore more replicable since more people have the possibility of re-using it. Furthermore, this architecture is not exclusive to certain types of devices, technologies, and configurations. Therefore, it is easy to adapt according to the developers' and user's scenario. In proposing this architecture, we hope to guide developers of RLs in their future work, providing a reference architecture for XRLs.

VI. CONCLUSION AND FUTURE WORK

This paper provided a systematic review of the state-of-the art of XRL in the period 2000-2022. Our study provides a thorough analysis of XRLs developed in the period 2000-2022, sharing information such as timeline of studies, studies per country, most influential universities, most popular journals and conferences, most cited publications, studies on ARLs, studies on VRLs, and most notable publications. We also classified the RLs found according to availability, cost, and

TABLE 8. List of studies found on the period 2000-2022.

Authors	Country	Year	Type	Title	Citations
Bischoff et al.	Germany	2001	VR	Remote Experimentation in a Collaborative Virtual Environment	18
Hoyer et al.	Germany	2001	VR	Multiuser environment for a teleoperated laboratory	4
Röhrig et al.	Germany	2001	VR	A multiuser environment for remote experimentation in control education	2
Hosoya et al.	Japan	2003	AR	A mirror metaphor interaction system: touching remote real objects in an augmented reality environment	27
Hoyer et al.	Germany	2003	VR	Virtual laboratory for Real-Time Control of Inverted Pendulum/Gantry Crane	20
Bischoff et al.	Germany	2004	VR	Streaming Audio/Video and Multiuser Virtual Reality based Environment for Collaborative Remote Experimentation	6
Bischoff et al.	Germany	2004	VR	Virtual Reality Environment with Shared PC and Live Video Streaming for Computer-Supported Collaborative Learning	1
Borgolte et al.	Germany	2004	VR	Distributed Collaborative Learning with Open Source Software	4
Bruns et al.	Germany	2004	VR	Mixed Reality with Hyper-Bonds - A Means for Remote Labs	28
Hoyer et al.	Germany	2004	VR	A Multiuser Virtual-Reality Environment for a Tele-Operated Laboratory	89
Masár et al.	Germany	2004	VR	A virtual laboratory for an inverted pendulum and crane control	15
Masár et al.	Germany	2004	VR	Remote Experimentation in Distance Education for Control Engineers	23
Tsakiris et al.	Greece	2005	VR	Remote experiment laboratories using virtual reality technologies: The VRLAB project	12
Gerke et al.	Germany	2007	VR	Practical Education of Control Systems Engineers in a Virtual University	1
Machado et al.	Portugal	2007	VR	Improving Interaction in Remote Laboratories Using Haptic Devices	12
Schaf and Pereira	Brazil	2007	VR	Virtual learning environment with flexible mixed reality remote experiments architecture	23
Berruti et al.	Italy	2008	VR	Remote Laboratory Experiments in a Virtual Immersive Learning Environment	15
Schaf and Pereira	Brazil	2009	VR	Integrating mixed-reality remote experiments into virtual learning environments using interchangeable components	34
Scheucher et al.	Germany	2009	VR	Collaborative Virtual 3D Environment for Internet-Accessible Physics Experiments	81
García-Zubía et al.	Spain	2010	VR	Secondlab: A remote laboratory under Second Life	38
Lee et al.	Australia	2010	VR	Development of a remote access control laboratory using xpc target and Virtual Reality Modeling Language	7
Marcelino et al.	Brazil	2010	VR	Extended immersive learning environment: a hybrid remote/virtual laboratory	13
Marquez et al.	Spain	2011	AR	Augmented Reality for the Improvement of Remote Laboratories: An Augmented Remote Laboratory	300
Costa et al.	Portugal	2011	VR	Remote Labs Accessible through 3D environments: A Case Study with Open Wonderland	7
Jailly et al.	France	2011	VR	Interactive Mixed Reality for Collaborative Remote Laboratories	13
Borrero et al.	Spain	2012	AR	A Pilot Study of the Effectiveness of Augmented Reality to Enhance the Use of Remote Labs in Electrical Engineering Education	159
Cubillo et al.	Spain	2012	AR	Control of a remote laboratory by augmented reality	17
Odeh et al.	Palestine	2012	AR	Remote augmented reality engineering labs	13
Casini et al.	Italy	2012	VR	A remote lab for multi-robot experiments with virtual obstacles	8
Hu (Ziaoqiang) et al.	China	2012	VR	The construction and development of Remote Virtual Laboratory Based on Virtools	1
Lei et al.	China	2012	VR	Research of the Remote Experiment System Based on Virtual Reality	9
Marcelino et al.	Brazil	2012	VR	3D virtual worlds using open source platform and integrated remote experimentation	12
Müller et al.	Germany	2012	VR	Integrating immersive 3D worlds and real lab equipment for teaching mechatronics	10
Tavares et a.	Brazil	2012	VR	The complementation of teaching using the remote experimentations integrated with the 3D virtual worlds Interaction of Real Robots with Virtual Scenarios	4

TABLE 8. ***(Continued.)*** **List of studies found on the period 2000-2022.**

Borrero et al.	Spain	2013	AR	through Augmented Reality: Application to Robotics Teaching/Learning by Means of Remote Labs	15
Odeh et al.	Palestine	2013	AR	A remote engineering lab based on augmented reality for teaching electronics	34
Shanab et al.	Palestine	2013	AR	Augmented reality internet labs versus hands-on and virtual labs: A comparative study	33
Vargas et al.	Spain	2013	AR	Using Augmented Reality in Remote Laboratories	28
Hu (Wenshan) et al.	China	2013	VR	Web-Based 3-D Control Laboratory for Remote Real-Time Experimentation	74
Liang et al.	China	2013	VR	Design of Remote 3D Virtual Laboratory for Education on Control System Experimentation	1
Lo et al.	USA	2013	VR	Work in progress: Enhance CS/CE student learning in computer architecture and organization through a remote instrument control lab with mixed reality	5
Marcelino et al.	Brazil	2013	VR	Immersive Learning Environment Using 3D Virtual Worlds and Integrated Remote Experimentation	5
Pasc et al.	Romania	2014	AR	Augmented Reality Used for Robot Remote Control in Educational Laboratories	1
Chaczko et al.	Australia	2015	AR	Augmented Reality based monitoring of the remote-lab	2
Odeh et al.	Palestine	2015	AR	Augmented Reality Internet Labs versus its Traditional and Virtual Equivalence	28
Restivo et al.	Portugal	2015	AR	Let's work with AR in DC circuits	11
Antonio et al.	Brazil	2015	VR	A remote experimentation and 3D virtual world for basic education	4
Antonio et al.	Brazil	2015	VR	Remote experiments and 3D virtual world in education	5
Callaghan et al.	UK	2015	VR	Opportunities and challenges in virtual reality for remote and virtual laboratories	23
López et al.	Spain	2015	VR	Remote Laboratory elab3d: A Complementary Resource in Engineering Education	22
Restivo et al.	Portugal	2015	VR	Hi kids: That's funny! Mechanics 3D Virtual lab	4
Maiti et al.	Australia	2016	AR	Key aspects of integrating augmented reality tools into peer-to-peer remote laboratory user interfaces	10
Smith et al.	Australia	2016	AR	Augmented and mixed reality features and tools for remote laboratory experiments	10
Antonio et al.	Brazil	2016	VR	Merging a Remote Microscope and Virtual Worlds: Teaching Kingdom Plantae on Basic Education	4
Carpeño et al.	Spain	2016	VR	3D virtual world remote laboratory to assist in designing advanced user defined DAQ systems based on flexrio and EPICS	8
Galan et al.	Spain	2016	VR	Virtual control labs experimentation: the water tank system	11
Rodriguez-Gil et al.	Spain	2016	VR	An architecture for new models of online laboratories: Educative multi-user gamified hybrid laboratories based on virtual environments	7
Maiti et al.	Australia	2017	AR	Using marker based augmented reality and natural user interface for interactive remote experiments	2
Rodrigues et al.	Portugal	2017	AR	Adding augmented reality to laboratory experimentation	7
Callaghan et al.	UK	2017	VR	Voice Driven Virtual Assistant Tutor in Virtual Reality for Electronic and Electrical Engineering Remote Laboratories	15
Rodriguez-Gil et al.	Spain	2017	VR	Towards new multiplatform hybrid online laboratory models	67
Maiti et al.	Australia	2018	AR	Augmented reality and natural user interface applications for remote laboratories	5
Mora et al.	Colombia	2018	VR	Virtual and Remote Labs Using Windows Server and Unity 3D	1
Smith et al.	Australia	2019	AR	Applying Augmented Reality to New or Existing Remote Access Laboratories	2
Smith et al.	Australia	2019	AR	Using Unity 3D as the Augmented Reality Framework for Remote Access Laboratories	6
Alvarez et al.	Mexico	2019	VR	Programming logical controllers using remote labs and virtual reality	6
Boettcher et al.	Germany	2020	VR	Usage of A Virtual Environment to Improve the Teaching of Fluid Mechanics	9
Trentsios et al.	Germany	2020	VR	Remote Lab meets Virtual Reality – Enabling immersive access to high tech laboratories from afar	25
Yerden et al.	Turkey	2020	VR	Virtual reality remote access laboratory for teaching programmable logic controller topics	8
Nicolete et al.	Brazil	2021	AR	Analysis of student motivation in the use of a Physics Augmented Remote Lab during the Covid-19 pandemic	5
Boettcher et al.	Germany	2021	VR	Using Virtual Reality for Teaching the Derivation of Conservation Laws in Fluid Mechanics	12
Cosic	Austria	2021	VR	VISIR Remote Lab Controlled via VR	2
Palmer et al.	UK	2021	VR	Virtual Reality based Digital Twin System for remote laboratories and online practical learning	3

TABLE 8. ***(Continued.)*** **List of studies found on the period 2000-2022.**

Rukangu et al.	USA	2021	VR	Virtual Reality for Remote Controlled Robotics in Engineering Education	10
Racha et al.	Australia	2022	AR	Work in Progress Augmented Reality Smart Tele-Assisting Technology for Enhancing Engineering Education	1
Alsaleh et al.	Estonia	2022	VR	Reimagine Lab: Bridging the Gap Between Hands-On, Virtual and Remote-Control Engineering Laboratories Using Digital Twins and Extended Reality	1
Boettcher et al.	Germany	2022	VR	Development Methodology for Immersive Home Laboratories in Virtual Reality	1
Kreiter et al.	Austria	2022	VR	A Virtual Reality Prototype for the VISIR Remote Lab	1
Palmer et al.	UK	2022	VR	Digital Twinning remote laboratories for online practical learning	2

technological relevance. Finally, we designed an architecture for creating XRLs, in order to guide developers.

This research provides helpful information for researchers and developers working with remote labs in extended reality, since it is a summary of developments in this research area since the beginning of the millennium. However, we cannot ignore the continuous technological evaluation of virtual and augmented reality. An example of this is the technological leap that they are expected to make, driven by social networks such as Meta. In this new context, immersive educational environments may have a dedicated virtual place, and developers, teachers and students will therefore play a fundamental role in the integration of education in the new Meta universe.

Regarding some of our future lines of research, in further work we will assess whether or not the architecture meets the challenges it was designed to tackle, by creating a prototype, and evaluating the prototype with students, addressing technical and pedagogical aspects. We will also explore opportunities for improvement, based on the feedback provided by students.

A field of future work can focus on analyzing the appropriateness of XR technologies in education. This study should not focus on the study of only quantitative results, such as learning outcomes, but on more holistic issues that address the learning of a learner by taking into account all his or her capabilities and not only some of them. Thus, the student's motivation or cognitive skills should be analyzed, and the impact that the use of technologies, XR being one of them, can have on these aspects.

APPENDIX

See Table 8.

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ISABELA NARDI DA SILVA received the bachelor's and master's degrees in information and communication technologies from the Federal University of Santa Catarina (UFSC), Santa Catarina, Brazil, in 2017 and 2019, respectively, and the dual degrees in pedagogy and English language, specializing in distance learning. She is currently pursuing the Ph.D. degree with the University of Deusto, Spain, where she studies engineering for the information society and sustainable development. She studies engineering and management of knowledge with UFSC.

JAVIER GARCÍA-ZUBÍA (Senior Member, IEEE) received the Ph.D. degree in computer science from the University of Deusto, Bilbao, Spain. He is currently a Full Professor with the Faculty of Engineering, University of Deusto. He is also the Leader of the WebLab-Deusto Research Group. His research interests include remote laboratory design, implementation, and evaluation.

UNAI HERNÁNDEZ-JAYO (Member, IEEE) received the M.S. and Ph.D. degrees in telecommunications engineering from the University of Deusto, Bilbao, Spain, in 2001 and 2012, respectively. In 2004, he joined the University of Deusto, where he is currently an Assistant Professor with the Faculty of Engineering, teaching classes in the area of electronics. His current research interests include the use of information and communication technologies in the educational process.

JOÃO BOSCO DA MOTA ALVES received the bachelor's degree in electrical engineering from the Federal University of Pará (UFPA), in 1971, the master's degree in electrical engineering from the Federal University of Santa Catarina (UFSC), in 1973, and the Ph.D. degree in electrical engineering from the Coordination of Postgraduate Courses in Engineering, Federal University of Rio de Janeiro (COPPE/UFRJ), in 1981. He was a Full Professor with the UFSC, from 1996 to August 2008, where he retired. He is currently with the Graduate Program in Engineering and Knowledge Management (PPGEGC) and the Graduate Program in Information and Communication Technologies (PPGTIC), Araranguá Campus, UFSC. He has experience in the areas of computer science, intelligent robots, remote experimentation, remote systems, distance education, accessibility, informatics in education, general theory of systems, interdisciplinary, and systemic view in organizations.

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