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PAPER

Designing a Structured Repository of Remote Laboratories for Enhanced Online Education

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ABSTRACT

One of the key challenges for users of remote engineering is finding available remote laboratories worldwide and efficiently integrating them into teaching practice. The lack of practical skills and institutional support often limits their implementation, which contradicts the fundamental idea of expanding scientific and educational resources. To address this challenge, a digital repository of real remote laboratories was developed in this study. The search process was conducted according to a defined algorithm based on a strategy consisting of three sequential phases. First, relevant academic databases and general online sources were systematically searched using predefined keywords. Next, the identified laboratories were evaluated according to several criteria, including their geographical origin, field of application, and availability. Finally, a digital repository focused on Science, Technology, Engineering, and Mathematics (STEM) disciplines was developed. The repository was designed to enable fast and user-friendly access to practical knowledge. All included laboratories were thoroughly tested and individually evaluated. Based on the identified advantages and limitations, the main directions for the future development, sustainability, and improvement of remote laboratories were proposed.

KEYWORDS

mechatronics, science, technology, engineering, and mathematics (STEM) disciplines, online education, remote engineering, remote laboratories

1 INTRODUCTION

One of the fundamental premises of the systems approach is the continuity of changes. Changes in everyday life and work are particularly noticeable when observing the period since the beginning of the third millennium, marked by rapid technological development and significant technological achievements [1], [2]. These changes are characterized by unpredictability, as large-scale disruptions, such as the COVID-19 pandemic [3], occur more frequently today. The society needs to be able to cope with these challenges and adapt to the moment, which can be achieved by providing high-quality education and well-designed educational systems aligned with

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the needs of society and the current conditions [4], [5], [6], [7], [8]. For these reasons, countries create different strategies for education development [9], often for a long-term period, and revise their curricula across all levels, from primary and secondary education to higher education institutions. Courses related to the application of digital technologies are now taught from the early grades of primary school, while universities are creating entirely new educational profiles aimed at acquiring qualifications in modern fields such as artificial intelligence (AI) and machine learning [10], [11], and similar areas.

To improve the digital capacities of institutions, as well as the digital competence of students and employees, hybrid and online education is encouraged. A special form of education is asynchronous online teaching [12] in which learning materials are available at any time, offering a particularly high level of flexibility. This is especially convenient for students who are employed, which is often the case with master's and PhD students. Models of online teaching vary, and different meeting platforms and social networks are used, such as Microsoft Teams, Skype, Zoom, Viber, WhatsApp, Google Meet, Cisco Webex, YouTube, etc. [13] However, in fields within technical-technological, natural-mathematical, or medical sciences, the situation is somewhat more complex than in social sciences and humanities, primarily because traditional teaching modes rely on the use of all available equipment for conducting practical and laboratory exercises. One attempt to overcome this problem over the past two decades has been the development of remote and virtual laboratories [14], [15], [16], [17], [18], [19], [20].

In addition to adapting to continuous change and overcoming crises in society and education, such as those caused by the pandemic, the sociological aspect addressed by remote and virtual laboratories is also of great importance. Especially in rural areas, even in countries of the European Union [21], there is often insufficient laboratory equipment. Without the development of remote laboratories, this situation would likely result in a reduced interest in Science, Technology, Engineering, and Mathematics (STEM) disciplines and, consequently, a loss of valuable human capital. Furthermore, this would give rise to a societal condition that diverges from both the intended vision and the goals established in state education development strategies, resulting in a society incapable of keeping pace with change. Therefore, it can be asserted that remote laboratories offer multiple benefits. Among the most notable are improved understanding of experimental procedures, increased user safety, lower costs for educational institutions, wider dissemination of science in rural areas, greater flexibility in time management, and other related advantages [22]. With all this in mind, the Faculty of Technical Sciences in Novi Sad has, over an extended period beginning with the NeReLa project (Building Network of Remote Labs for strengthening university—secondary vocational schools collaboration) [23] and continuing thereafter, undertaken significant efforts in cooperation with partner faculties to develop remote laboratories [24]. Furthermore, for students of the undergraduate academic study program Information Systems Engineering, a course entitled "Remote Engineering" has been introduced [25].

One of the major challenges for potential users of remote engineering is identifying available remote laboratories worldwide and fully exploiting their capabilities. Even when instructors successfully identify an appropriate remote laboratory, they are often unsure how to integrate it into teaching activities and initiate experiment execution due to insufficient practical skills, which limits its effective use and contradicts the fundamental idea of disseminating scientific resources.

This paper presents a structured mapping study combined with the design and implementation of a digital repository of remote laboratories within STEM. Unlike purely descriptive overviews, the study applies a systematic multi-stage search strategy, functional verification of identified laboratories, and a multi-criteria evaluation framework. The main contributions are:

1. A structured identification and classification of remote laboratories worldwide;
2. A reproducible methodology for discovering and validating remote laboratories within and outside academic databases;
3. A multi-criteria evaluation framework addressing technical, pedagogical, and accessibility aspects;
4. The design and implementation of a validated digital repository to support integration into STEM education.

The paper is organized as follows: Section 2 defines the basic concepts related to remote laboratories and provides a brief overview of the state of the art in this field. Subsequently, Section 3 presents the research methodology in detail. In Section 4, the most important research results are presented, specifically the development of a digital repository of remote laboratories. Furthermore, Section 5 provides a discussion highlighting the impact, significance, and sustainability of remote laboratories. Directions for future research, as well as the methods for validating and maintaining the developed repository, are presented in Section 6. Finally, Section 7 presents the main conclusions.

2 RELATED WORK

The term "remote laboratory" refers to an experimental setup consisting of real, physical objects that can be accessed remotely via the Internet, with the experiment executed live and monitored via a webcam [26]. As such, remote laboratories represent a subset of online laboratories [27], [28], [29]. They are applied in various fields, including automatic control [30], electronics [31], [32], mechatronics [33], [34], robotics [35], [36], chemistry [37], physics [38], etc. The implementation of remote laboratories also results in:

- Increased operational safety, as users do not come into direct contact with specific tools, chemicals, etc.
- Reduced costs for educational institutions, since remote access enables the dissemination of science even in rural areas and eliminates limitations arising from the inability to procure expensive equipment,
- Significant flexibility in time management (laboratories are generally available 24/7),
- Improved understanding of the performed experiment, as it can be repeated multiple times, practically without limitation, etc.

The use of remote laboratories is often perceived positively by users. Participants in such learning processes express satisfaction with the given approach, appreciating its reliability, accessibility, real-time parameter control, and intuitive interface [39].

Although they have been in use for many years [22], remote laboratories face numerous challenges [40], [41]. The issue of sustainability [42], [43] is a pressing concern today, referring to maintaining laboratory functionality over a longer period of time. This particularly applies to periods following the completion of projects [24] within which certain laboratories were developed [44], [45], [46]. Therefore, ensuring the continuity of functionality and use of remote laboratories, given their many advantages, is crucial [47].

The issue of sustainability is significantly influenced by limitations related to equipment and quality assurance [48], a lack of practical experience among both instructors and pupils/students [49], limited interactivity [50], etc. Owing to continuous technological advancement, some of these shortcomings are being overcome through the integration of modern technologies, such as Augmented Reality (AR) and Virtual Reality (VR), into remote laboratories, leading to the emergence of Extended Reality Remote Laboratories (XRLs) [51]. In addition, remote laboratories based on technologies such as Digital Twin are also being developed [52], [53]. In general, the following are some key trends and advancements in remote laboratories: AR and VR remote laboratories [51], [54], [55], cloud computing [56], real-time data visualization [57], digital twin (simulations) [52], [53], remote access to specialized equipment [58], security and privacy measures [59], AI and Internet of Things (IoT) technologies [60], [61], [62], [63], [64], [65], etc.

3 METHODOLOGY

This study follows a structured mapping approach aimed at identifying, evaluating, and systematizing remote laboratories available worldwide. The methodology was designed to ensure transparency, reproducibility, and coverage of both academic and commercial platforms, which are often not fully represented in scientific databases. The objective of the study is not limited to reviewing academic literature but rather to identifying real, functional remote laboratories worldwide. Many operational platforms exist outside traditional academic publications (e.g., industry and institutional platforms). Therefore, inclusion of such sources is methodologically justified as part of a practice-oriented mapping study.

The research methodology applied in this paper consisted of three sequential phases, shown in Figure 1.

1. Identification of sources, screening, and eligibility assessment (search of academic scientific databases, general web search, as well as extended web search);
2. Data extraction and evaluation of the found references;
3. Repository design and validation (digital repository of remote laboratories within STEM fields).

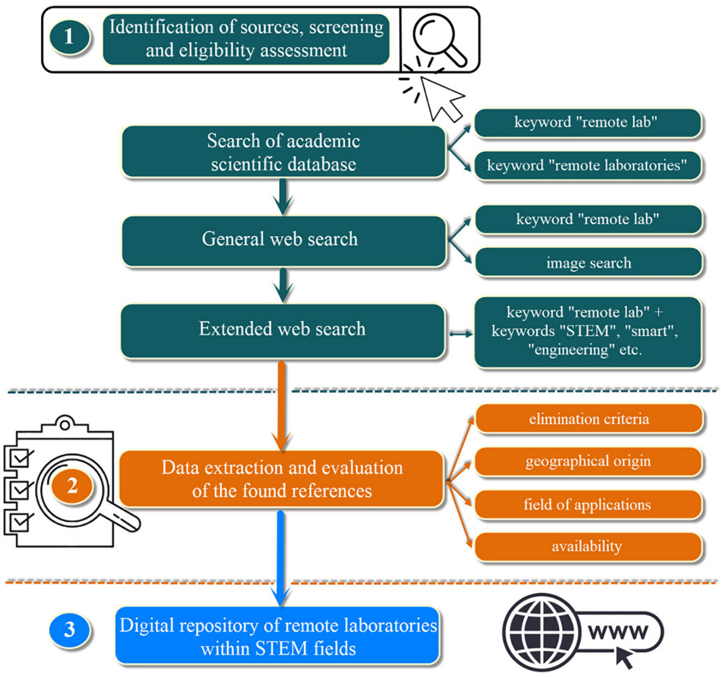

Fig. 1. Research methodology phases

A multi-stage search strategy was applied during the first phase (see Figure 1, Position 1): academic search, general web search, and extended web search of additional sources.

First, searches were conducted using the "Google Scholar" academic database. The search keywords were "remote lab" and "remote laboratories." The goal of this phase was to identify scientific publications, references to existing platforms, and implementation case studies, containing names and/or access paths enabling access to remote laboratories. Access was attempted either via direct links or by entering the name of the university and/or the remote laboratory into the standard "Google Search" engine using "Mozilla Firefox" and "Google Chrome" browsers, in accordance with the information provided in the publications. Through this process, it was established that some of the remote laboratories were not available and/or functional [35], [66], [67]. Some publications pointed to methods for developing laboratories using available open-source code [30], [68], [69].

A structured web search was conducted using Google Search to identify operational remote laboratories not documented in academic literature. The basic Google Search was performed from the Republic of Serbia using the keyword "remote lab." The search was conducted without the use of AI-generated suggestions. The resulting links were opened sequentially in new browser tabs. The results included blogs [70], [71], remote laboratories [72], [73], scientific papers [34], [74], [75], [76], [77] and books [27], [28], presentations [78], [79], brochures [80], [81], [82], as well as educational and/or scientific institutions [83], [84], [85], [86], [87] providing access paths to certain remote laboratories. Among the results, blogs and scientific papers were the most prevalent. All accessible results (links) were analyzed in detail in order to identify additional information that could lead to new keywords for searching, relevant publications, or direct access to remote laboratories.

As part of the general web search, a Google image search was also conducted. Although based on the user's subjective judgment and therefore potentially imprecise, this search method delivers results more quickly by minimizing the need for detailed reading (in line with the adage that a picture is worth a thousand words). The objective was to identify images containing elements characteristic of remote laboratories. Remote laboratories are typically distinguished by a specific user interface through which system parameters are set, as well as by real-time monitoring of system behavior via camera feeds. Along with symbols of remote access (such as globes, geographically distant computers, equipment located far from the user, cameras directed toward physical equipment, user interfaces—web applications with a dashboard, and specialized hardware equipment—microcontrollers, sensors, actuators, etc.), these elements served as key indicators of websites potentially leading to access to remote laboratories. Additionally, the website title displayed below the image aided in selecting which webpages to open.

Although blogs cannot be considered fully reliable sources due to their subjective nature, they were considered, as some authors may have actually developed and publicly shared certain remote laboratories.

One of the challenges encountered during the search was the unclear distinction on some websites between remote and virtual laboratories. Furthermore, the term remote access is often associated with various software solutions that may or may not be directly linked to an actual remote laboratory. In some cases, these were merely product advertisements provided by manufacturers [88], [89], [90]. For all identified remote laboratory results, attempts were made to access and verify their functionality.

Keywords and phrases identified in scientific papers served as inspiration for further searching. Finally, extended web searches were conducted following the same principles described above, with the addition of further keywords to the base phrase "remote lab." The following keywords were included in the searches: "embedded, STEM, programs, engineering, sustainable, available, overview, education, concepts, surveying, investigation, technologies, platforms, development, systems, presentation, teaching, training, implementation, novel, examples, framework, control, advancements, extended, continuity, accessibility, IoT-based, similarities, variations, resources, management, security, smart, developing, maintaining, consistency, evaluating, participation, cloud-based, testing, Internet, worldwide, connecting, instrumentation, trends, low-cost." It should be noted that these keywords were not combined all at once; instead, one or several keywords were added to the base phrase. As a result, the search queries consisted of two to six keywords, with conjunctions and prepositions such as "and, for, in, of, an," and "with" appearing between them (for example, "remote lab" and "STEM" and "available").

The second phase (see Figure 1, Position 2) included data extraction, and a detailed evaluation of all found references was performed. To establish a rigorous selection for this study, each identified laboratory was accessed via the provided links to verify its functionality and real-time interaction capabilities. This evaluation process directly informed the inclusion and exclusion criteria. References were deemed eligible for further research only if they featured real physical experiments rather than pure simulations, provided remote Internet access with real-time control, and were specifically designed for STEM applications. Additionally, the presence of observed system behavior, such as live data or video, was required to ensure authenticity. Consequently, any marketing and demo pages lacking authentic interaction and software tools unrelated to the physical experimental setup were excluded from the research as inappropriate. Further analysis focused on the attributes of the eligible remote laboratories, such as geographical origin, field of application, accessibility (free, restricted, paid), functionality status, etc.

The final phase of the study (see Figure 1, Position 3) involved the development of a digital repository based on a validated dataset. The validation of this system was ensured by verifying the functionality of each laboratory, the application of consistent classification criteria, and the implementation of an application-oriented evaluation scenario. This scenario was specifically designed to demonstrate how the repository could be effectively integrated into teaching activities. The result was realized as a web-based platform, where AI-assisted coding was employed to streamline the development of the site's infrastructure [91].

4 RESULTS

Based on the review of all identified references and the verification of those that are in fact related to remote laboratories, a tabular overview was created, as presented in Table 1. In addition to the name of each remote laboratory, the table provides information on its geographical origin (typically the university or company affiliated with it), the field of application, and its availability, including whether access to the laboratory is free of charge or requires payment, as well as whether the experiments are functional. Furthermore, a brief description of each identified laboratory is provided, including the most relevant information.

Table 1. An overview of identified available remote laboratories

No.	Remote Laboratory Name	Geographical Origin / Field of Application / Availability	Description
1.	LabsLand [72], [92], [93], [94]	Spin-off, University of Deusto, Bilbao, Spain STEM Available	LabsLand spaces are organized into groups, each of which includes laboratories and students granted access to them. The available experiments span Biology, Chemistry, Electronics, Engineering, Physics, Robotics, and Technology. A free trial option is available.
2.	Remote-LAB GymKT [95]	Jaroslav Vrchlický grammar school in Klatovy, Czech Republic Engineering; Robotics Available	The Remote Lab includes real physics experiments that can be controlled via a web browser. The remote experiments can be used by visitors free of charge and without registration.
3.	Stanford iLabs [96], [97]	Stanford University, California, USA Physics; Electronics Available	Stanford uses immersive technologies in remote laboratories, such as Digital Twin technology. A digital twin represents a digital version of the real laboratory hosted on an appropriate platform, which behaves in the same way as the physical laboratory. The key features of remote laboratories are preserved, and the system does not depend on other users.
4.	Laboratories Across Borders (LAB) [98]	Dnipro University of Technology, Ukraine; Reutlingen University, Germany Mechatronics; Robotics; Control Systems Available	LAB provides innovative and applied teaching methods aimed at preparing engineering students for their future work in the digital world. These laboratories were created as part of a joint project between the National Technical University "Dnipro Polytechnic" and Reutlingen University.
5.	iSES: e-LABORATORY PROJECT [99], [100]	Charles University in Prague, Czech Republic Electronics; Physics Available	This laboratory consists of a set of simple examples of remote experiments based on the iSES Remote Lab SDK. It is possible to obtain data in the form of diagrams as well as to save the data to a local computer.
6.	NetLab [101], [102], [103]	University of South Australia, Adelaide, Australia Engineering; Electronics Available	To access the NetLab remote laboratory system, users are required to register online for an account. This laboratory offers a booking system that allows users to reserve a time slot for performing experiments. If not already installed, users must download and install the Java Runtime Environment (JRE). Once the JRE is installed, NetLab can be downloaded and launched.
7.	RexLab [51], [104]	Federal University of Santa Catarina, Florianópolis, Brazil Physics; Robotics Available	The manipulation and management of remote experiments are enabled through the Remote Labs Learning Environment (RELLE). Access time is limited to 5 to 15 minutes, depending on the experiment.
8.	Renesas Lab on the Cloud [105]	Renesas Electronics' R&D centers, Tokyo, Japan Electronics; Embedded; IoT Available	Lab on the Cloud is a remote laboratory that supports the development and testing of skills related to embedded systems and IoT applications from anywhere, without the need for physical hardware. By providing an email address, users can access trial experiments.

(Continued)

Table 1. An overview of identified available remote laboratories *(Continued)*

No.	Remote Laboratory Name	Geographical Origin / Field of Application / Availability	Description
9.	LMU Munich [106], [107]	Ludwig-Maximilians-Universität München, Germany Physics Partially available	Remote experiments are available in the fields of magnetism, spectrometry, electrons in electric and magnetic fields, electric charge fields, waves, and related topics. For each individual experiment, an explanation of the physical experimental setup is provided, along with the defined hypotheses, the execution of the experiment, and the verification of the hypotheses.
10.	WebLab-Deusto [108], [109], [110]	University of Deusto, Bilbao, Spain Engineering; Robotics Partially available	WebLab-Deusto provides a management framework for remote laboratories. It was developed at the University of Deusto. This multidisciplinary research team aims to use and develop remote laboratories to enhance experiential learning.
11.	GOLDi [111], [112], [113], [114]	Ilmenau University of Technology, Germany Technical; Engineering Unavailable	The platform offers a wide range of experiments provided by various universities and colleges. In addition to live video streaming from a camera showing the state of the physical equipment, a virtual equivalent of the experiment is displayed alongside it.
12.	FARLabs [115], [116]	La Trobe University, Melbourne, Australia Physics; Environmental science Available	Upon launching the website, three categories for experiment selection are available: Nuclear, Structure, and Space and Environment. By selecting the Explore option, a list of available experiments is offered.
13.	Practable [117], [118]	University of Edinburgh, School of Engineering, UK Engineering; Physics Available/Paid	To obtain information on how to use the remote laboratories and access the corresponding links, it is necessary to contact the development team.
14.	UNILabs [119], [120]	University Network of Interactive Laboratories (UNILabs), Madrid, Spain Robotics, Mechatronics, Physics Partially available	It is necessary to download the .jar file of the selected experiment to the local computer. A prerequisite for running the .jar file is the installation of the JRE, as is also the case with the NetLab remote laboratory. An option is available to download the .jar files as a guest user. However, to access a wider range of experiments, it is necessary to create a user account.
15.	Go-Lab [121], [122], [123], [124]	University of Twente, Netherlands Physics; Engineering Partially available	The Go-Lab Portal is a platform that includes both remote and virtual laboratories from various scientific fields, including physics, astronomy, chemistry, biology, geography, and mathematics.
16.	EUBBC-Digital Project [125], [126], [127]	Universidad Privada Boliviana (UPB), La Paz, Bolivia Physics; Energy areas; Engineering; Robotics Partially available	From the total number of laboratories, it is possible to filter and display only those that are available. However, it is not possible to modify system behavior parameters for all experiments in real time. For certain experiments, only a finite set of predefined system parameter combinations is provided. In such cases, a video recording of the user interface demonstrating the behavior of the remote laboratory for the selected parameters is played.
17.	Virtual Labs at Amrita [128], [129], [130], [131]	Amrita Vishwa Vidyapeetham: Deemed University, Tamil Nadu, India Chemistry; Physics; Mechanical Engineering Partially available	The vast majority of experiments on this platform are virtual, with visual representations designed to closely resemble real equipment. In the list of available experiments, the “Remote trigger” next to the experiment name indicates that the experiment is remote rather than purely virtual.

(Continued)

Table 1. An overview of identified available remote laboratories *(Continued)*

No.	Remote Laboratory Name	Geographical Origin / Field of Application / Availability	Description
18.	The OpenSTEM Labs [132], [133], [134]	The Open University, Milton Keynes, UK STEM Available	Remote laboratories are offered as collections from various scientific fields. These collections include research based on interactive instruments, remote-access experiments, and digital twin virtual scenarios using real data. A specialized remote laboratory developed for Open University courses is the Virtual Microscope.
19.	VREL NextGen Laboratories [135], [136], [137]	Silesian University of Technology – Faculty of Automatic Control, Electronics, and Computer Science, Gliwice, Poland Embedded; Computer Science Available	Users can schedule an appointment for a duration of up to one and a half hours. It is necessary to select one of the available microcontrollers that controls a model with peripheral devices. The standard procedure involves writing the program code, compiling it, and uploading it to the selected microcontroller. The execution of the program can be monitored in real time through a live camera feed. If the display does not open automatically, it must be launched manually in a dedicated browser tab.
20.	Planet Debug [138]	MikroElektronika, Belgrade, Serbia Embedded; Computer Science Available	The program code is developed using the NECTO Studio programming environment. By selecting the appropriate project type and configuration settings (such as compiler, microcontroller, and display), users can write and deploy code to the chosen development board. The behavior of the executed program can then be observed in real time via the camera feed.
21.	EECS Remote Lab Services [139], [140]	York University, Toronto, Canada Embedded; Computer Science Available/Restricted	The commercial service EECS Remote Lab enables access to EECS laboratory workstations through a web browser, without the need for plugins or client-side software. Access is available to York University students and staff upon registration using their institutional login credentials.
22.	BMSTU Remote access computer-aided laboratory [141], [142], [143]	Bauman Moscow State Technical University, Russia Robotics; Mechatronics; Testing of Materials; Physics Available/Restricted	To begin working in the laboratory, users must contact the administrator via the provided email address. Following this, they receive registration confirmation and information regarding the scheduled date for performing the experiment. Without registration, users can access a demo version that provides an experiment description and an overview of the implementation methodology. For some experiments, simulation results can be generated using user-defined parameters.
23.	SoA Remote Labs [144]	University of Miami, USA Computer Science Available/Restricted	University of Miami students gain access to the service by logging in with their institutional credentials. After logging in, the client software is downloaded to establish a connection with the remote laboratory equipment.
24.	NIU Internet Accessible Remote Laboratories [145], [146]	Northern Illinois University, Illinois, USA STEM; Engineering Unavailable	Video demonstrations are available; however, direct access to the remote laboratory is currently not available.
25.	VXLab [147], [148], [149]	RMIT University, Melbourne, Australia STEM; Engineering Available/Restricted	This is not a public online platform offering a catalog of laboratories or independently bookable appointments through a web portal. Access is granted through the university system and according to the instructions provided by the study coordinators.

(Continued)

Table 1. An overview of identified available remote laboratories *(Continued)*

No.	Remote Laboratory Name	Geographical Origin	Field of Application	Availability	Description
26.	Fast Lane LIVE [150]	Fast Lane Group, Munich, Germany	Computer Science	Available/Paid	This is an interactive digital platform that offers paid access to remote laboratories. Prior to accessing the laboratories, users are required to install the Remote Lab Client on their computers.
27.	Armfield Engineering [151], [152], [153]	Armfield Limited, Hampshire, UK	Physics; Chemistry; Engineering	Available/Paid	This is a commercially available solution that enables remote control of equipment and the acquisition of experimental results. For further details, it is necessary to contact the manufacturer directly.
28.	The Construct Robotics Institute [154]	The Construct Robotics Institute, Barcelona, Spain	Robotics	Available/Paid	These are commercially available robotics courses that include distance learning with access to remote laboratory equipment.
29.	QiTASC [155]	QiTASC GmbH, Vienna, Austria	Telecommunication Engineering; IoT	Available/Paid	QiTASC has developed a comprehensive environment for automating the testing of user systems. Its portfolio includes software, hardware, and remote laboratory solutions. For pricing and access details, it is necessary to contact the manufacturer.
30.	Digiteq Automotive s.r.o. [156]	Digiteq Automotive s.r.o., Prague, Czech Republic	Engineering; Automotive	Available/Paid	This is a commercially available remote test laboratory intended for use in the automotive industry.
31.	Labwork PolyU [157], [158]	Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong	STEM	Available/Paid	Labwork was established as a spin-off project from the Hong Kong Polytechnic University (PolyU) and currently operates as an independent company offering commercial online laboratory services. Access requests must be submitted through the appropriate inquiry form on the company's website.
32.	Emerald Cloud Lab [159], [160], [161]	Emerald Cloud Lab, Austin, Texas, USA	Chemistry; Biology; Physical Chemistry; Biophysical Chemistry; Structural Biology	Available/Paid	Cloud laboratories are fully software-driven and highly automated platforms designed for various scientific disciplines, enabling researchers to design, execute, and analyze experiments remotely. For detailed information regarding accessibility and pricing, users should contact the service providers.
33.	Edutech Remote Lab [162]	Edutech India, Chennai, India	STEM; Engineering	Available/Paid	The platform offers commercial access to remote laboratories and provides multiple learning approaches and services throughout the learning process. For more detailed access information, it is necessary to contact the provider.
34.	Huawei Remote Labs [163]	Netcamp, Langenthal, Switzerland	STEM; Engineering; Computer Science	Available/Paid	An exclusively physical remote laboratory equipped with real Huawei hardware is available for rental and can be reserved for testing, exam preparation, or hands-on training.

(Continued)

Table 1. An overview of identified available remote laboratories *(Continued)*

No.	Remote Laboratory Name	Geographical Origin	Field of Application	Availability	Description
35.	Quanser Remote Lab [164], [165]	Quanser, Markham, Ontario, Canada	Robotics and Mechatronics; Autonomous Systems and Applied AI; Control Systems	Available/Paid	Quanser Inc. is a private company that designs, develops, and manufactures advanced solutions for engineering education and research, particularly in the fields of control systems, robotics, mechatronics, and digital laboratories. Its remote laboratory activities are implemented through digital twins and virtual laboratory environments.
36.	iLab: Remote Online Laboratories [166], [167]	Massachusetts Institute of Technology, Cambridge, Massachusetts, USA	Microelectronics; Chemistry, Structural engineering, Signal processing	Unavailable	The project has been discontinued, and access to the remote laboratories is no longer available.
37.	Remotely controlled laboratory Palacký University [168], [169]	Department of Experimental Physics, Faculty of Science, Palacký University Olomouc, Czech Republic	Physics	Unavailable	This was a web-based platform for accessing remote physical experiments. The experiments were accompanied by instructions for the experimental setup, including images of the equipment. Access to these experiments is no longer available.
38.	IIIT Remote Labs [170], [171]	International Institute of Information Technology – Hyderabad, India	Physics	Unavailable	RLabs at IIIT Hyderabad is an IoT-based remote laboratory architecture that enables hands-on access to real experiments (e.g., in physics and optics) through a web browser, integrating live video streaming and remote hardware control. It was developed within the IIIT research ecosystem as an affordable and scalable solution for remote experimentation; however, it currently does not offer a publicly accessible portal for unrestricted general use.
39.	NeReLa Library of Remote Experiments (LiReX) [23], [24]	University of Kragujevac, Faculty of Technical Sciences, Čačak	Engineering; Electrics; Mechanical Engineering; Mechatronics	Unavailable	LiReX is a web-based repository of remote experiments developed within the Tempus NeReLa project. The library contains remote experiments and exercises that were developed and deployed in the laboratories of four partner universities in Serbia: the University of Kragujevac, the University of Belgrade, the University of Niš, and the University of Novi Sad.
40.	VISIR [75], [172]	Blekinge Institute of Technology, Karlskrona, Sweden	Electrics; Electronics	Unavailable	VISIR is a remote laboratory for electric and electronic circuits. It is a 'real' laboratory with protoboards, sources, signal generators, meters, oscilloscopes, and components (resistors, capacitors, inductors, diodes, etc.).

After a detailed analysis of the identified remote laboratories, the third phase of this study was carried out—a digital repository of remote laboratories was created in the form of a website [91] (see Figure 2). The website sequentially presents all 40 remote laboratories listed in Table 1 in the following manner:

1. The website header displays three main elements. On the left side, the logos of the authors' faculty and the chair are displayed. The center of the header contains the repository name, together with the total number of laboratories included in the repository. On the right side, there is a legend explaining the symbols used to

denote the fields of application and the availability of the laboratories. In addition, when the mouse pointer hovers over any symbol, a short tooltip describing its meaning is shown.

2. All laboratories are presented in a standardized layout. In the upper-left corner of the image containing the laboratory name, a symbol of the university, company, or project of the laboratory's author is displayed. The lower-left corner contains a symbol indicating the availability of the laboratory. On the right side of the image, the laboratory's ordinal number is displayed in the upper corner, while the lower corner contains symbols indicating the corresponding fields of application. Below the image containing the laboratory name, a brief textual description of the laboratory is provided.
3. At the very bottom of the website, a discussion section (questions and answers) is displayed.

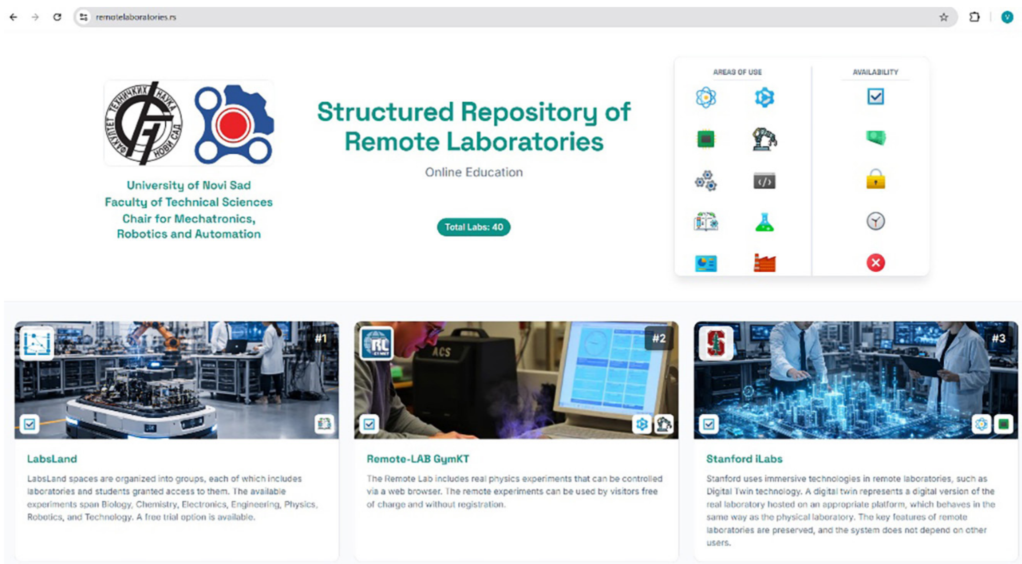

Fig. 2. The digital repository of remote laboratories

5 DISCUSSION

5.1 Availability

An analysis of the laboratories integrated into the digital repository reveals that a considerable share, approximately 15%, are no longer functional, although they were previously available. Examples include iLab: Remote Online Laboratories and NeReLa LiReX. This highlights long-term sustainability as one of the key challenges for remote laboratories. These laboratories were mainly developed and intensively used during project implementation and for a limited period after the projects had ended. Since they did not evolve into commercially viable services or secure follow-up funding, and because they require continuous financial support (software licenses, preventive and corrective hardware maintenance, operational expenses, etc.), they were either discontinued (as in the case of iLab: Remote Online Laboratories) or transformed into laboratory equipment accessible to students only on site (as in the case of certain remote experiments developed within the NeReLa project). To prolong the operational lifetime of remote laboratories, it is therefore necessary to ensure continuous equipment upgrades (for example, replacing outdated components with new ones or implementing modern IoT modules), uninterrupted access to up-to-date software solutions, and the implementation of contemporary concepts such as Digital Twin technology, including upgrades through virtual environments and similar enhancements.

5.2 Geographical origin

Further analysis of remote laboratories indicates that the majority have been developed within the EU (37.5%), with particularly significant contributions from authors in Spain (10% of the total), the Czech Republic (10% of the total), and Germany (7.5% of the total). In addition to the EU, major global countries such as the USA (12.5%), India (7.5%), the UK (7.5%), and Australia (7.5%) are also following trends in this field. The remaining remote laboratories were developed by authors from Canada (5%), Japan (2.5%), Russia (2.5%), Switzerland (2.5%), Brazil (2.5%), Bolivia (2.5%), Hong Kong (2.5%), Ukraine (2.5%), and Serbia (5%).

The results indicate that Europe is the leader in this field, followed by North America, Asia, Australia, and South America, respectively. During the research conducted within this study, no remote laboratories developed by authors based in Africa were identified. These findings suggest that authors from more industrially developed countries have recognized key challenges related to the global dissemination of scientific and engineering education, particularly in less developed countries, where access to appropriate laboratory equipment is limited. At the same time, the findings highlight the strong global potential for the further development and wider adoption of remote laboratories.

5.3 Field of application

With respect to the disciplines addressed by the remote experiments integrated into the analysis, the situation is quite diverse. In many laboratories, experiments from several different disciplines are available. Moreover, among 17.5% of the analyzed laboratories (such as LabsLand), a large number of experiments covering all STEM subfields are offered, making it difficult to identify any single dominant area.

Nevertheless, the results show that remote experiments are most frequently implemented in physics (35% of the analyzed laboratories), engineering (35%), robotics (22.5%), computer science (15%), mechatronics (12.5%), electronics (12.5%), chemistry (10%), embedded systems (10%), and other fields. These findings confirm the fact that remote laboratories are primarily developed in domains where physical equipment is either costly to procure in larger quantities (as in the case of robotics) or where the equipment must be handled with great care (as in the case of chemistry).

5.4 Classification

To accurately determine the current status of remote laboratories, a classification of all laboratories integrated into the developed digital repository (including those no longer active) was conducted according to two perspectives. The first involved analyzing disadvantages (difficulties and challenges), while the second focused on advantages related to technological progress. The results are presented in Tables 2 and 3, respectively.

In the analysis of disadvantages, the following parameters were considered:

1. Equipment Limitations – Limited number of setups, scheduling constraints, hardware dependency, etc.
2. Technical Issues – Browser compatibility, plugins, Java dependency, latency, etc.
3. Lack of Immersion – Limited physical presence, reduced hands-on feeling, etc.
4. Lack of Interactivity – The user cannot significantly influence the process.
5. Data Processing and Visualization – Graphical display of the process flow and the ability to save the obtained results.
6. Scalability and Access Constraints – Booking systems, user concurrency limits, etc.
7. Maintenance and Sustainability – Hardware wear, updates, institutional support, etc.
8. Security and Access Control – Login systems, authentication, restricted use, etc.

If a feature is marked, this indicates that certain limitations have been identified in the laboratory with respect to that specific criterion. It should also be noted that, due to limited or unavailable access, it was not always possible to determine the defined parameters with complete accuracy for some laboratories. In such cases, the reported characteristics were adopted as described by the laboratory authors (information available on official websites) or were excluded from the analysis.

Table 2. Classification according to implementation challenges in remote laboratories

No.	Remote Laboratory Name	Parameters							
		Equipment Limitations	Technical Issues	Lack of Immersion	Lack of Interactivity	Data Processing; Visualization	Scalability; Access Constraints	Maintenance; Sustainability	Security; Access Control
1.	LabsLand			☑		☑	☑		
2.	Remote-LAB GymKT			☑					
3.	Stanford iLabs					☑			
4.	LAB			☑	☑				
5.	iSES: e-LABORATORY PROJECT			☑	☑				
6.	NetLab		☑			☑	☑	☑	
7.	RExLab			☑		☑			
8.	Renesas Lab on the Cloud			☑					☑
9.	LMU Munich		☑					☑	
10.	WebLab-Deusto		☑			☑		☑	☑
11.	GOLDi					☑		☑	☑
12.	FARLabs	☑	☑		☑				☑
13.	Practable					☑	☑	☑	☑
14.	UNILabs		☑					☑	☑
15.	Go-Lab	☑						☑	
16.	EUBBC-Digital Project			☑	☑		☑	☑	

(Continued)

Table 2. Classification according to implementation challenges in remote laboratories *(Continued)*

No.	Remote Laboratory Name	Parameters							
		Equipment Limitations	Technical Issues	Lack of Immersion	Lack of Interactivity	Data Processing; Visualization	Scalability; Access Constraints	Maintenance; Sustainability	Security; Access Control
17.	Virtual Labs at Amrita		☑					☑	☑
18.	The Open Stem Labs						☑		☑
19.	VREL NextGen Laboratories			☑		☑			☑
20.	Planet-Debug		☑	☑				☑	
21.	EECS Remote Lab Services		☑				☑		☑
22.	BMSTU Remote access computer-aided laboratory	☑			☑	☑		☑	☑
23.	SoA Remote Labs		☑				☑		☑
24.	NIU Internet Accessible Remote Laboratories	☑		☑					☑
25.	VXLab						☑		☑
26.	Fast Lane LIVE						☑		☑
27.	Armfield Engineering	☑		☑					☑
28.	The Construct Robotics Institute	☑				☑	☑	☑	☑
29.	QiTASC	☑		☑					
30.	Digiteq Automotive s.r.o.	☑		☑			☑		☑
31.	Labwork PolyU	☑		☑			☑		
32.	Emerald Cloud Lab	☑		☑				☑	
33.	Edutech Remote Lab	☑	☑					☑	
34.	Huawei Remote Labs	☑		☑			☑		☑
35.	Quanser Remote Lab		☑					☑	☑
36.	iLab: Remote Online Laboratories	☑	☑	☑			☑	☑	☑

(Continued)

Table 2. Classification according to implementation challenges in remote laboratories *(Continued)*

No.	Remote Laboratory Name	Parameters							
		Equipment Limitations	Technical Issues	Lack of Immersion	Lack of Interactivity	Data Processing; Visualization	Scalability; Access Constraints	Maintenance; Sustainability	Security; Access Control
37.	Remotely controlled laboratory Palacký University	☑	☑	☑			☑	☑	☑
38.	IIIT Remote Labs	☑	☑			☑	☑	☑	☑
39.	NeReLa LiReX	☑	☑	☑			☑	☑	☑
40.	VISIR	☑	☑	☑			☑	☑	☑
Total		**17**	**16**	**20**	**5**	**11**	**18**	**20**	**25**

Based on this classification, it can be concluded that most challenges associated with the implementation of remote laboratories are primarily technical and infrastructural in nature. One of the most significant issues is security. Authentication systems and access restrictions play a crucial role in maintaining data confidentiality and preventing unauthorized access, which is particularly critical for experimental laboratories in educational and research institutions. As a result, significantly less than half of remote laboratories (up to 37.5%) provide unrestricted access. In all other cases, access is limited, and in many instances, payment is required (at least 27.5% of the analyzed laboratories).

Furthermore, significant limitations are related to sustainability (as previously discussed), technical difficulties (for example, university-level remote laboratories are often inaccessible from another university's network due to "closed network" policies), scalability (an increased number of users and system concurrency may significantly reduce the quality of laboratory work), immersion, equipment constraints (e.g., limited number of sessions, the need to manually power on/off systems limiting their availability, etc.), and software requirements.

Remote laboratories show the fewest difficulties in terms of interactivity (around 12.5%), leading to the conclusion that the hands-on experience can, to a certain extent, be effectively compensated for this approach.

Based on this analysis, it can be recommended that laboratories with high performance in scalability, security, and interactivity be considered the most suitable for implementation in educational systems and research activities, whereas laboratories with significant technical problems and equipment access limitations should focus on resolving these challenges to improve usability and system stability.

As previously stated, following the classification based on disadvantages, a classification according to technological advantages was also conducted. The following parameters were considered:

1. Integration of AR, VR, or Digital Twin technologies into remote experimentation, thus developing Extended Reality Remote Laboratories (XRLs);
2. Remote Access/User Interface and Experience to high-cost/specialized equipment;
3. Advanced/rich user Interface and Experience;
4. Support for global collaboration.

In laboratories where a specific characteristic is marked, this means that the feature has been implemented. As in the previous case, due to limited or unavailable access, it was not always possible to determine certain parameters with complete accuracy; therefore, the characteristics were adopted as described by the laboratory authors (information available on official websites) or excluded from the analysis.

Table 3. Classification according to technological advancements in remote laboratories

No.	Remote Laboratory Name	Parameters			
		XRL	High Priced/ Specialized Equipment	Advanced User Interface	Global Collaboration
1.	LabsLand	☑		☑	☑
2.	Remote-LAB GymKT			☑	☑
3.	Stanford iLabs	☑		☑	☑
4.	LAB		☑		☑
5.	iSES: e-LABORATORY PROJECT				☑
6.	NetLab	☑		☑	☑
7.	RExLab				☑
8.	Renesas Lab on the Cloud			☑	
9.	LMU Munich				
10.	WebLab-Deusto				☑
11.	GOLDi				
12.	FARLabs		☑		☑
13.	Practable				
14.	UNILabs		☑		☑
15.	Go-Lab		☑	☑	☑
16.	EUBBC-Digital Project		☑	☑	☑
17.	Virtual Labs at Amrita	☑	☑		
18.	The Open Stem Labs		☑	☑	
19.	VREL NextGen Laboratories				☑
20.	Planet-Debug		☑		
21.	EECS Remote Lab Services				☑
22.	BMSTU Remote access computer-aided laboratory		☑	☑	
23.	SoA Remote Labs				
24.	NIU Internet Accessible Remote Laboratories			☑	
25.	VXLab	☑	☑	☑	☑
26.	Fast Lane LIVE		☑		
27.	Armfield Engineering		☑	☑	

(Continued)

Table 3. Classification according to technological advancements in remote laboratories *(Continued)*

No.	Remote Laboratory Name	Parameters			
		XRL	High Priced/ Specialized Equipment	Advanced User Interface	Global Collaboration
28.	The Construct Robotics Institute	☑	☑	☑	☑
29.	QiTASC				
30.	Digiteq Automotive s.r.o.		☑	☑	
31.	Labwork PolyU		☑		☑
32.	Emerald Cloud Lab	☑	☑	☑	
33.	Edutech Remote Lab				
34.	Huawei Remote Labs				
35.	Quanser Remote Lab	☑	☑	☑	
36.	iLab: Remote Online Laboratories				☑
37.	Remotely controlled laboratory Palacký University		☑		☑
38.	IIIT Remote Labs				
39.	NeReLa LiReX		☑		☑
40.	VISIR	☑			☑
Total		**9**	**19**	**16**	**21**

The analysis of 40 remote laboratories integrated into the digital repository according to four criteria—XRL integration, remote access to specialized equipment, advanced user interface, and global collaboration—reveals clearly identifiable trends in modern distance education.

The integration of XRL technologies remains limited. A smaller number of laboratories (approximately 22.5%), such as VXLab and The Construct Robotics Institute, demonstrate a high level of immersive experience. In contrast, most platforms rely on standard web-based interfaces. This limitation may affect the acquisition of practical skills, particularly in engineering and experimental sciences.

Furthermore, laboratories that support remote access to specialized equipment and provide advanced user interfaces, such as OpenSTEM Labs, Emerald Cloud Lab, and Quanser Remote Lab, allow users to directly manipulate devices and observe results in real time, thereby significantly enhancing the educational experience.

Global collaboration is another key parameter that shows diversity in implementation. While platforms such as iLab: Remote Online Laboratories and LabsLand actively support international participants and collaborative experiments, many university-based or specialized projects restrict access to users outside their institutions, thereby reducing the potential for global cooperation and knowledge exchange.

Based on the analysis, it can be concluded that the most functional platforms combine remote access to real, specialized equipment with advanced user interfaces, whereas XRL elements are still experimental or less commonly implemented. This indicates a clear opportunity for further XRL development, as the integration of immersive technologies could further enhance the educational experience and increase interactivity, thereby reducing the gap between virtual and physical laboratory work. The implementation of such technologies could also significantly contribute to long-term sustainability.

6 FUTURE WORK

The practical applicability of the developed repository represents one of the key outcomes of this study. It is anticipated that its use will significantly facilitate the integration of remote laboratories into various teaching activities, supporting both instructors and students in the field of remote engineering.

More specifically, the repository is designed to support an intuitive integration scenario, enabling users to quickly access relevant information through a visual interface. By identifying images associated with specific fields such as robotics, users can efficiently locate appropriate remote laboratories, assess their availability, and evaluate their potential application in teaching.

To ensure long-term functionality and relevance, the developed digital repository requires continuous and systematic maintenance. This includes periodic verification of the availability and operational status of the listed remote laboratories at predefined time intervals. Such processes can be further enhanced through the use of AI-based tools for the automated monitoring of the corresponding web resources. Furthermore, an AI-driven framework will be extended to support automated searches based on the established research strategy to identify newly developed remote laboratories that may become available online over time.

User feedback is also expected to play a significant role in the further improvement of the repository. In this regard, the integrated discussion section provides a valuable mechanism for collecting user insights, suggestions, and experiences, thereby supporting the continuous refinement and practical relevance of the system.

7 CONCLUSION

Based on the findings of this study, it can be concluded that remote laboratories providing Internet-based access to real, physical experiments, with live monitoring via web cameras, began to emerge in the early 21st century, primarily in industrially developed countries, especially within the EU and the USA. One of the main motivations behind their development was to support the wider dissemination of scientific and engineering knowledge, especially in less developed regions facing limited access to laboratory infrastructure, expertise, and financial resources.

More than two decades of development and operation have led to a situation in which a portion of remote laboratories (approximately 15% of all identified laboratories) are currently unavailable for various reasons, such as the inability to maintain the system after the completion of project funding. At the same time, a number of remote laboratories have remained operational and have been substantially upgraded through the implementation of modern technologies such as XRL.

In order to provide a comprehensive overview of the state-of-the-art, with the aim of addressing the challenges related to identifying remote laboratories and effectively integrating them into the teaching process, the main contribution of this study lies in the design and development of a digital repository of remote laboratories. In total, 40 remote laboratories worldwide were analyzed in detail with respect to their geographical origin, fields of application, availability, key difficulties and challenges, as well as the implementation of technological advancements.

The results show that remote laboratories remain widely present today and that their future use is well justified, particularly due to their strong potential for integration with modern technologies, such as Digital Twins.

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