







# New Scenarios and Trends in Nontraditional Laboratories From 2000 to 2020

Ricardo Martin Fernandez , *Member, IEEE*, Felix Garcia-Loro , *Senior Member, IEEE*, Gustavo R. Alves , *Member, IEEE*, Africa López-Rey , *Senior Member, IEEE*, Russ Meier , *Fellow, IEEE*, and Manuel Castro , *Fellow, IEEE*

**Abstract**—For educational institutions in science, technology, engineering and mathematics (STEM) areas, the provision of practical learning scenarios is, traditionally, a major concern. In the 21st century, the explosion of information and communication technology (ICTs), as well as the universalization of low-cost hardware, has allowed the proliferation of technical solutions for any field, in the case of experimentation, encouraging the emergence and proliferation of nontraditional experimentation platforms. This movement has resulted in enriched practical environments, with wider adaptability for both students and teachers. In this article, the evolution of scholar production has been analyzed at the global level from 2000 to 2020. Current and emerging experimentation scenarios have been identified, specifying the scope and boundaries between them.

**Index Terms**—Education, federation, hybrid laboratories, nontraditional laboratories, remote laboratories, virtual laboratories.

## I. INTRODUCTION

LABWORK practices can be identified as educational activities carried out in a controlled environment, where there are controlled variables and observed ones. There is no doubt about the distinctive learning possibilities available in such environments. In a study carried out by the U.S. National Research Council, laboratory experiences were defined as “opportunities for students to interact directly with the material world (or with data drawn from the material world), using the tools, data collection techniques, models, and theories of science” [1, p. 31].

The goals and outcomes intended for laboratory activities may be diverse. Beyond the theoretical background, labwork

includes a variety of transversal competencies, such as teamwork; gathering, analyzing, and interpreting data; computational thinking; communication; practical skills; promoting mastery in the study area; skills development for advanced knowledge; scientific reasoning; and empirical capacities [1], [2], [3], [4], [5], [6]. Labwork also integrates easily into different approaches, such as project-based learning, problem-based learning, learning by doing, enquiry-based learning, and discovery-based learning, among others [3], [6], [7], [8], [9], [10]. Therefore, labwork is considered a key element for educational institutions when designing and constructing curricular content [1], [2], [3], [4], [11], [12], [13], [14], [15], [16].

Providing laboratory experiences does not guarantee that students achieve the potential benefits offered by transversal competencies. Teachers may provide laboratories according to their needs or importance but fail to justify their presence for meaningful learning [17]. Therefore, the integration of laboratories into curricular programs as well as the decision of making lab sessions mandatory or optional should be analyzed in the light of a global strategy to avoid a highly inefficient learning scenario [2], [11], [18].

In today’s educational landscape, the provision of labwork environments adapted to educational methodologies, as well as to the needs of institutions, teachers, and students, is a priority. This need has encouraged the creation of solutions based on the adaptation of laboratory experiences to emerging educational environments [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31]. The scientific community agrees on two main dimensions for distinguishing laboratory types: 1) “relative location between the experiment and the experimenter and 2) the physical nature of the experiment,” from which four main scenarios are well documented [19], [21], [22], [24], [25], [26], [27], [28], [32], [33], [34]. Based on the technological development of recent years, new alternatives have emerged, complementing and enriching laboratory solutions [29], [32], [33], [35], [36], [37], [38], [39], [40]. Comparison among these scenarios is a recurring concern [5], [20], [41], [42], [43], [44], [45]. However, each experimentation environment has advantages, as well as certain disadvantages over the others, for users, institutions, teachers, or learning objectives. A direct comparison among the different alternatives is not possible due to the lack of a uniform criterion to evaluate them [20], [43], [45]. We can conclude that they have become complementary tools: the best solution is a combination of them [5], [13], [43].

Manuscript received 27 June 2023; revised 4 January 2024 and 1 April 2024; accepted 1 April 2024. Date of publication 10 April 2024; date of current version 2 May 2024. This work was supported in part by Escuela de Doctorado de la UNED, Spain, in part by the project ECoVEM—European Centre of Vocational Excellence in Microelectronics, under Grant 620101-EPP-1-2020-1-BG-EPPKA3-VET-COVE, and in part by the UNED Research Group I4Labs, Industria Conectada y Tecnologías Educativas para la Ingeniería, and Innovative Educational Group (G-TEIC), and Tecnologías Educativas para la Industria Conectada. (Corresponding author: Ricardo Martin Fernandez.)

Ricardo Martin Fernandez, Felix Garcia-Loro, Africa López-Rey, and Manuel Castro are with the Department of Electrical, Electronics and Control Engineering, National University of Distance Education UNED, 28040 Madrid, Spain (e-mail: rmartin@ieec.uned.es; fgarcialoro@ieec.uned.es; alopez@ieec.uned.es; mcastro@ieec.uned.es).

Gustavo R. Alves is with the School of Engineering, CIETI, Polytechnic of Porto 4200-072, Portugal (e-mail: gca@isep.ipp.pt).

Russ Meier is with the Electrical Engineering and Computer Science, Milwaukee WI 53202-3109 USA (e-mail: russ.meier@ieee.org).

Digital Object Identifier 10.1109/TLT.2024.3387280

In this article, we address the evolution of these experimental learning environments. The research questions addressed are as follows.

*RQ1*: What are the lab scenarios used in education? And what are the scope delimitations of each scenario?

*RQ2*: What are the types of emerging labs scenarios?

*RQ3*: How have lab scenarios evolved in the 2011–2020 decade?

## II. METHODOLOGY

The first step of the methodological process was the collection of the core set of articles that address the topic. To obtain the corpus of scientific literature, scientific databases were consulted. The most important and widely used bibliographic scientific databases are Web of Science (WOS) and Scopus [46], [47], [48]. The Scopus database, produced by the ELSEVIER group, includes a larger catalog of scientific production from journals and international conference proceedings than the WOS. An initial analysis showed that three out of five papers documenting nontraditional laboratories were published as conference papers. Therefore, the Scopus database was the preferred database in this research.

For the construction of the database query used to establish the corpus, we first identified the existing laboratory scenarios. To identify the dimensions that make up the different experimentation scenarios, we started with the classification that gathers the greatest consensus in the scientific community. As previously mentioned, this classification uses two main dimensions and results in four basic types of scenarios [19], [21], [22], [24], [25], [26], [27], [28], [32], [33], [34]. From this basic classification with four possible scenarios, the emergence of new scenarios that propose an alternative approach in the laboratory architecture was analyzed, showing hybrid solutions that combine these basic scenarios [24], [25], [26], [27], [28], [29], [32], [33], [48], [49], [50], [51], [52], the proposal of completely alternative scenarios to the existing ones [16], [27], [38], [39], [40], [53], [54], or the application of different approaches that entail substantial changes in the main scenario [23], [29], [31], [32], [55], [56], [57], [58], [59]. We analyzed how each of these labels is used to define the adopted laboratory solution. In no case was the use of the same solution in different environments considered a different scenario or dimension; for example, the use of a remotely accessible system used by student in the classroom or outside the classroom. Although both the situations can provide different benefits, from the system point of view, the architecture is the same, and we cannot consider it a different scenario or dimension.

Once the spectrum of laboratory scenarios were identified, we proceeded to the construction of a taxonomy that encompasses all the scenarios and the labels used to delimit each environment. In this way, we built a common framework for the rest of this article.

To obtain the definitive query, an iterative process was carried out, adding new keywords to the ones included in each previous query.

Based on the framework labels, a query was built, and new keywords related to the topic emerged were analyzed and identified. These new keywords were processed, and if they seemed

to be relevant for the research, they were added into the query. Likewise, their scope and scenario have been analyzed in the research that used the term. In this way, not only were new terms or labels identified but also new scenarios. The goal was to identify unique scenarios for laboratories and which variables come into play. After the identification stage, the definition of these scenarios was done through a label or name, as well as their delimitation, so each laboratory subtype was defined and delimited without ambiguities. Subsequently, we proceeded to group the terms and keywords that turned out to be synonyms for the identified scenario under the same label.

Considering that the term “LAB” encompasses the terms “lab,” and “labs,” several iterations led to the debugged query shown below. The query does not use the “\*” wildcard in a term such as “lab\*” to avoid the appearance of terms, such as “label,” “labor,” or “labour.” Final query in which the terms related to “LABORATOR\*” and “EXPERIMENT\*” (replaced by ellipsis) have been removed as they imply replicated elements of the query of term “LAB”:

TITLE-ABS-KEY (“cloud LAB” or “computer aided LAB” or “computer assisted LAB” or “computer based virtual LAB” or “concurrent LAB” or “cyber enabled LAB” or “cyber LAB” or “dataset based LAB” or “deferred LAB” or “digital LAB” or “distance LAB” or “distant LAB” or “distant LAB” or “distributed learning LAB” or “distributed virtual LAB” or “electronic LAB” or “hands on distance LAB” or “home LAB” or “homeLAB” or “hybrid LAB” or “hybrid local LAB” or “hybrid online LAB” or “hybrid reality LAB” or “hybrid remote LAB” or “internet assisted hands on LAB” or “internet assisted LAB” or “internet based LAB” or “LAB at distance” or “LAB at home” or “LAB kit” or “massive open online LAB” or “mobile LAB” or “mobile open online LAB” or “mono user virtual LAB” or “mono user virtual LAB” or “multiuser virtual LAB” or “on line LAB” or “online LAB” or “pocket LAB” or “remote controlled LAB” or “remote hands on” or “remote LAB” or “simulated based LAB” or “simulated LAB” or “simulation based LAB” or “simulation LAB” or “smart LAB” or “software based LAB” or “software LAB” or “take home LAB” or “tele LAB” or “tele operated LAB” or “teleLAB” or “teleoperated LAB” or “ultra-concurrent LAB” or “ultraconcurrent LAB” or “virtual LAB” or “virtual manipulative LAB” or “web based LAB” or “web LAB” or “webLAB” or ..... or “web accessible simulat\*” or “vlab” or “virtual training software” or “virtual reality mock up” or “virtual instrument” or “rlab” or “remotelab” or “remote simulat\*” or “olab” or “o lab” or “mool” or “ilab” or “elab” or “e lab” or “dataset based simulat\*”) AND PUBYEAR > 2000 AND PUBYEAR < 2021 AND TITLE-ABS-KEY (education\* OR training OR learning OR teaching OR instruction OR tutoring OR pedagog\* OR tutoring) AND PUBYEAR > 2000 AND PUBYEAR < 2021.

The scientific literature corpus was collected using the query, and 13 321 documents were obtained. Out of those documents, preprocessing was carried out, searching for errors, as well as the standardization of terms and the identification of erroneous terms. To obtain the consistent number of eligible articles, the PRISMA flow diagram shown in Fig. 1 was used [60].

Finally, we proceeded to the homogenization and grouping of terms. As an example, the keyword “Hybrid lab” includes all the

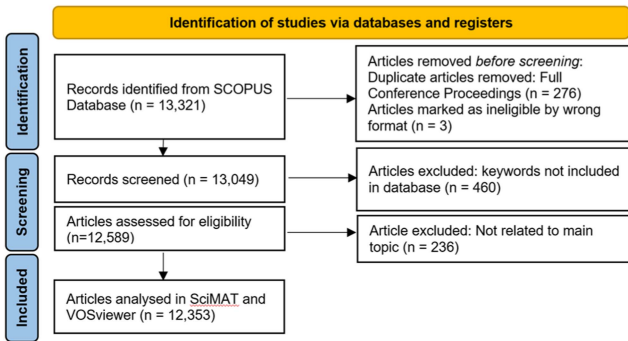


Fig. 1. PRISMA flow diagram (literature selection).

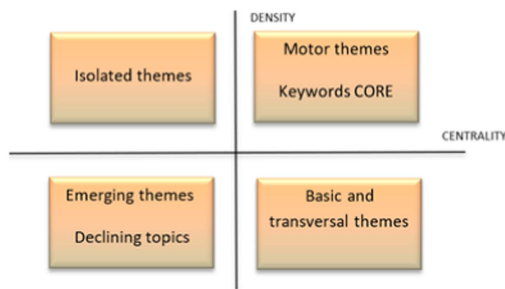


Fig. 2. Four-quadrant representation.

following keywords: “hybrid laboratory,” “hybrid laboratories,” “hybrid labs,” “hybrid laboratories in engineering,” and “hybrid remote laboratory.”

Once the data have been preprocessed, there are multiple software tools to carry out this task: Bibexcel, Biblioshiny, CiteSpace, CitNetExplorer, SciMAT, Sci2 Tool, VOSviewer [61], as well as those provided by SCOPUS. SciMAT software was used for the analysis. SciMAT is an open-source (GPLv3) software tool created by the SECABA research group at Granada University [62]. SciMAT software provides density and centrality graphs by periods, characterizing and classifying the clusters in four groups, mapping them into a 2-D space (see Fig. 2). In the representation, centrality indicates the importance of the subject under study within the field, and density represents the degree of development of the subject studied [47], where centrality is defined as:  $c = 10 \times \sum e_{kh}$ , with  $k$  an item linking to a topic and  $h$  an item linking to other topics. Density measures the internal degree of interrelations in the network and is calculated as follows:  $d = 100(\sum e_{ij}/n)$ , with  $i$  and  $j$  items belonging to the theme and  $n$  being the number of items in the topic. The coefficient  $e_{ab} = (c_{ab}^2)/(c_a \times c_b)$  is called equivalent index, where  $c_a$  is the number of words of  $a$ ,  $c_b$  is the number of words of  $b$ , and  $c_{ab}$  is the number of co-occurrence of words  $a$  and  $b$ .

Keywords in the upper right quadrant, with strong centrality and high density, include the core themes. These themes are externally related to concepts applicable to other themes, which are conceptually closely related. The themes in the upper left quadrant include isolated keywords; themes in the lower left quadrant consider disappearing themes or themes that may emerge in the future. Finally, the last quadrant (lower right) refers to transversal and basic themes that could become core themes in the future.

### III. IDENTIFICATION OF THE DIMENSIONS IN THE LABORATORY OPERATION SCENARIOS

Unfortunately, there is no classification unanimously supported by the specialized community, beyond those that leave out emerging and alternative scenarios. These discrepancies arise in the dimensions used to classify the different types of labs. A basic classification is the 1-D one used by Brinson [20], which divides laboratories into two large groups: 1) traditional labs to refer to those corresponding to on-site physical laboratories within an institution and 2) nontraditional labs to refer to those which are accessible remotely, usually through the Internet and whose nature may be based on real systems or simulated ones. The grouping of remotely accessible labs, regardless of their physical nature, is recurrent in numerous studies under different terminologies, such as online labs, digital labs, electronic labs (e-labs), web-based labs, distance labs, or virtual labs, as shown in Table I.

However, as aforementioned, there is a solid consensus of two core dimensions: relative location between the experimenter and the experiment—local or remote, and the nature of the experiment—real or virtual. The development of new technologies and the application of new methodologies have led to the emergence of new solutions that require a redesign of this model. The names given to these types of laboratories vary from author to author. These differences in typology will be detailed later to identify the terms to be used and define the scope of each laboratory.

Hybrid solutions emerge from core scenarios. Several authors contemplate hybrid solutions using the nature of the experiment “real/simulated” both locally and remotely [24], [25], [26], [27], [29], [32], [49], [50], [51], [52], while other authors have extended this approach and developed hybrid systems based on a real device locally manipulated together with a distant real laboratory or a simulated one [24], [25], [26], [28], [29]. The model proposed by Rivera and Larrondo-Petrie [29] includes all the hybrid approaches based on core dimensions found in the literature.

In a hands-on laboratory, the equipment can be manipulated directly, in a traditional way, or using a computer-based interface (e.g., a LabVIEW VI). Based on this idea, Gomes and Bogosyan [21] add a third dimension, based on the type of interaction mentioned earlier: controlling the devices and instrumentation equipment directly or through a computer-based interface. Strictly speaking, it cannot be considered a third dimension: in a lab based on a computer model, the interaction can only be carried out through a computer-based interface. Remotely accessible scenarios require interactive means. In other words, this third dimension exists only in experiments, whose nature is real and locally interacting.

Kammerlohr [53] consider a third dimension, analyzing if the lab environment is used by one or multiple institutions. However, in this research, we do not consider this characteristic, since it is a property of the laboratory administration system, either through an ad-hoc solution or through a remote laboratory management system, and, therefore, independent of the laboratory.

Some proposals only affect one type of laboratory scenario, leading to subtypes. A dimension that only makes sense within

TABLE I  
LABORATORY SCENARIOS

Scenario	Label	Terms Found in Scientific Literature
<b>Real Local— Centralized</b> Real lab Centralized lab Centralized user	Hands-on Lab	Classic lab [31] Computer aided/assisted experiment [155] [156] [208] Computer aided/assisted lab [153] [154] [207] Face-to-face lab [55] Hands-on lab [20], [21], [24], [30], [32], [33], [42], [44], [53], [96], [108], [116], [117], [131], [142], [149], [150], [152], [153], [208] In-person lab [55]
<b>Real Local— Distributed</b> Real lab Distributed lab Distributed user	Pocket Lab	At-home lab [168] Distance lab [36], [55], [56], [57], [165] Hands-on distance-lab [165] Home experimental/experiment kit [36], [59], [169] Homelab [23], [58], [161] Individual experimental kits [142]
<b>Hybrid (Remote &amp; Pocket)</b> Real Lab Centralized and distributed lab Distributed user	Hybrid	Hybrid lab [29], [32], [33] Remote haptic lab [98]
<b>Real remote</b> Real lab Centralised lab Distributed user	Remote Lab	Cyber-enabled lab [23] Distant lab [85], [182], [183] Distributed learning lab [181] Hands-on remote lab [210] Ilab [176] Internet-assisted hands-on lab [195] Internet-assisted lab [195] Lab at distance (lad) [189], [190], [191] Massive online lab (mool) [141] Massive open online lab (mool) [69], [70], [71], [72], [73], [142] Online lab (olab) [23], [174] Real virtual lab [127] Remote-controlled lab [67], [132] Remote hands-on lab [44], [176]
<b>Simulated Local – Distributed</b> Simulated lab Distributed lab Distributed user	Lab Simulator	Computer-based virtual lab [122] Computer-aided/assisted lab [154], [197], [198] Computer-simulated lab [86] Local simulation [21], [24], [25], [26], [32], [33], [109], [151] Multi-user virtual lab [19], [83], [22]
<b>Simulated Remote</b> Simulated lab Centralised lab Distributed user	Virtual Lab	Computer aided lab [203] Cyber lab [124] Digital lab [202] Distributed learning labs [181] Distributed virtual lab [149] Internet based lab [200] Mono-user virtual lab [19], [22], [83] Online virtual lab [206] Online lab (olab) [24], [56], [151] Remote simulation [21] Simulation-based lab [76]
<b>Deferred Labs</b> DDBB lab Centralized lab Distributed user	Deferred Lab	Dataset-based simulator [37] Deferred lab [38], [39], [40] Ultra-concurrent lab [16], [39], [55], [54], [136]
<b>Hybrid (Remote and Deferred)</b> Remote and deferred lab Centralized lab Distributed user	Hybrid	Hybrid Dataset and Reality Lab [37]
<b>Hybrid (Remote and Virtual)</b> Real and simulated Lab Centralized lab Distributed user	Hybrid	Hybrid lab [24], [29], [30], [32], [33], [51], [52], [109], [145], [146], [151] Hybrid online lab [25], [27], [49], [50], [151] Hybrid remote lab [26] Online hybrid lab [52], [53]
<b>Hybrid (Pocket and simulator)</b> Real and simulated lab Distributed lab Distributed user	Hybrid	Haptic Virtual Manipulative Lab [48] Hybrid Lab [25], [28], [29], [151] Hybrid Local Lab [26] Virtual Haptic Lab [98]

real systems, which are remotely accessible, is the one provided in [30]. Orduña [30] and Gomes and Costa [68] discriminate between two types of interaction: interactive laboratories and batch laboratories. Interactive laboratories refer to those whose connection and interaction are continuous during the experimentation, while in batch laboratories, the access is queue based. In the same scenario (remote and real), two types of laboratories are considered in [39]: 1) those whose interaction occurs in real time (or quasi-real time) and 2) those in which all possible interaction with the physical laboratory has been stored in a

way that is based on actual results recorded in a database. Based on this premise, Orduña et al. [37] go further and propose a scenario by combining both the laboratory subtypes in a hybrid way.

Within remotely accessible solutions, the terms massive open online labs (MOOLs) [69], [70], [71], [72], [73] and mobile massive open online laboratories (M-MOOLs) [74] have been mentioned. For the authors, the term MOOL only makes sense in remotely accessible physical systems since concurrent access is a representative characteristic of computer-modeled systems.

Langmann [75] identifies two types of laboratory operation depending on the interaction possibilities within the experiment (parameter tunability) and in the experimentation scenario (changeable experiment environment) for the experimenter: fixed/open laboratory. Maier and Niederstätter [24] add a third type of experiment or laboratory: observation laboratory. For their part, Terkowsky et al. [76] add a fourth scenario, with the possibility of guided semiopen laboratory. These types of operation modes are more likely to be provided in some types of laboratories. However, they are not exclusive to any of them and can even coexist allowing high flexibility in the laboratory at different learning levels.

An attempt to classify laboratories, providing them unambiguous names and their potential relations, is described in [29]. In it, the authors define a notation based on the unified modeling language. They consider laboratories divided into two main dimensions: physical and online ones, with hybrid combinations. However, their classification suffers from a space dedicated to local simulated labs.

A disruptive classification is the one offered by Terkowsky et al. [76]. In this research, the authors use three dimensions: pedagogical approach, degree of virtualization, and laboratory distribution. The degree of virtualization encompasses both the nature of the experiment and the distance between experiment and experimenter.

However, its dimension in terms of the “laboratory distribution” referred to the local/international access to the lab and is meaningless in face-to-face laboratories, as well as in remotely accessible laboratories since the location of the experimenter is not an influential variable for the laboratory. In short, we do not consider this dimension as valid to identify an exploitation scenario.

Laboratory classification is deeply analyzed in the next section; the different alternatives are contemplated, considering core dimensions, hybrid alternatives, and emerging scenarios, as follows.

- 1) *Labs based on real systems*: Experimentation in real environments whose occurrence is in real time. This dimension includes local and remote scenarios.
- 2) *Labs based in Software*: Experimentation based on modeled systems. This dimension includes local and remote scenarios.
- 3) *Deferred Labs*: Laboratories based on real environments, where events are deferred over time. The laboratory provides data previously stored in databases for this purpose.
- 4) *Hybrid Labs*: A fusion or combination of different scenarios.

#### IV. TYPE OF LABORATORIES

The first drawback that has been detected is the use of terms without a formal definition that establishes the physical framework in which the laboratory is deployed, and the limits in which the experimentation takes place [63], [64], [77], [78], [79], [80]. This ambiguity is further complicated by the diversity of terms used to identify the same experimentation environment or the use of the same term to define different environments, as already

highlighted in [13], [28], and [55]. Still, many authors establish a formal definition or description of the laboratory [13], [19], [37], [81], [82], [83], [84], [85], [86], [87], [88], [89], but in many cases, these are not consistent definitions with the real scenario [90], [91], partially not consistent [24], [25], [92], [93], [94], [95] or conflictive with the definitions provided in other studies. The classification of the terms found in the literature is collected in Table I, which includes most of the bibliography used for this article. The focus of the table is the classification of diverse designations used by researchers in the existing body of literature, according to the identified scenarios in this article, which is considered relevant and useful for further analysis on the subject.

##### A. Labs Based on Real Systems

Traditional laboratories are based on physical systems based on specific instrumentation, equipment, physical environments, and real components/elements. Real-scenario experiments give students unique experiences, such as facing errors, uncertainties, failures, and/or unexpected results in the real physical world [29], [31]. Within physical laboratories, they can be divided into two options, according to the relative location between experiment and experimenter: local laboratories and remote laboratories. Local laboratories are developed in scenarios, in which all the elements of the laboratory and the experimenter are in the same location, and in which the experimenter can observe and measure on the physical system, either directly or by means of instrumentation. Remote laboratories are physical systems for experimentation, in which the experimenter accesses and/or observes and/or remotely controls the experiment through a network, generally the Internet.

1) *Local Laboratory Interaction*: Traditional centralized physical labs are the classic laboratories in academic institutions. Scalability has been solved by replicating workbenches. In recent years, new educational resources have emerged that have led to the development of lower cost practical activities by using inexpensive components. In addition, they are also used in conjunction with open or low-cost software. The resulting laboratory allows students to perform simple laboratory experiments like those performed in a traditional and more expensive laboratory. In addition, users can experiment at home or elsewhere, without time restrictions. These physical distributed laboratories are commonly defined/named as mobile laboratories.

Saliah-Hassane et al. [32] argue that the mobile laboratory concept refers to having low-cost hardware so that students can create their laboratories. Klinger et al. [31] mention that “If electric or electronic components are used, a limitation will be for standard and cheap components, as any other solution will not be feasible due to financial reasons.” In the literature, there are different synonyms and definitions for these laboratories (see Table I).

From an educational point of view, pocket labs focus on self-study development, although they have also gained much ground in the academic environment of universities and colleges.

Pocket laboratories are a very useful tool in the first years of engineering careers, where there is a high component of

theoretical and abstract learning, bringing students closer to the practical activities that help cement the theoretical concepts they are acquiring [97]. In this approach, the role of the instructor as facilitator, besides guiding and motivating students, generates and designs contents for learning [98]. The elements and components used in the development kits must be easily accessible and reasonably priced [31]. It is intended that all the components are reused for new experiences, thus reducing waste of materials so that the activity is ecologically sustainable. While commercial products are one solution, there are also open-source hardware and software platforms that give instructors a powerful tool to arouse curiosity and learning in students. They have become widely used in the last years and allow students to create their laboratory at home with low-cost boards and sensors for the development of practical activities.

Pocket labs can be turned into a hybrid system if the mobile lab is an element of a complex system forming a symbiotic relationship between the local laboratory (mobile lab) and either local/remote software or remote hardware (see Table I). Several combinations are possible [98]; however, some of them have not been reported yet.

For some years now, the do-it-yourself (DIY) movement has gained relevance [99]. This approach seeks to promote lifelong learning by expanding digital skills, autonomy, and creativity of students through collaborative learning. Majstorovic and Jakovljevic [99, p. 7] highlight that “in recent times, it is not only attracting a significant number of science enthusiasts and talented lay people within and beyond the borders of universities and traditional research institutions but has also caught the public imagination as well as the attention of governments, policymakers and academics.”

Another philosophy based on DIY movements and open-source software is what is known as a fabrication laboratory (FabLab) [100]. FabLabs are a production space with physical hardware, equipment, and instruments, which incorporate electronic control and software. This philosophy promotes placing the experimenter at the center of the training experience, where they themselves produce the materials and learning activities. You et al. [101] define it as follows: “A DIY laboratory is a place, set up by interested person(s) or group, equipped for scientific experiments, research, or teaching in which numerous private and community-based initiatives use scientific methods alongside other forms of inquiry such as hacking and remixing to engage with techno-scientific concerns and societal challenges.” In this sense, Ferreti [101, p. 1] argues that “The locations of DIY science are various and range from small groups of tech enthusiasts to large online communities that share scientific objectives and outcomes, organized into local makerspaces, Fabrication Laboratory (Fablabs), classrooms, universities and museums, public libraries, and private enterprises.”

2) *Physical Remote Lab*: Complex experimentation with physical equipment in real environments is often costly in terms of time, money, and qualified staff as it requires the development and maintenance of learning infrastructures, kept in good condition [26], [34], [76]. In addition, it is frequent that, once these infrastructures are deployed, they remain underused

fundamentally due to the limitation in the available time to be used by students.

The rapid advancement of technology and the exponential use of the Internet in education have enabled practical scientific research to be performed in physical laboratories accessible through the Internet. Accessing and controlling physical laboratory devices through the Internet presents a solution to solving the learning needs of students, members of the workforce, and scientists by providing access to expensive and complex equipment remotely. In this regard, these labs are an appropriate tool to provide 24/7 availability to accessing a physical lab, in all educational levels and purposes, as well as in research and training in industry.

The term widely used to name this experimentation environment is “remote laboratory.” The authors use this term to describe a remote laboratory with physical equipment at some distance from the user who accesses the experimentation through the Internet [27], [80], [89], [103], [104], [105], [106], [107], [108], [109], [110], [111]. In this sense, Brinson [20] identifies remote labs as “(...) being characterized by mediated reality. Similar to hands-on labs, they require space and devices.” This same idea is highlighted in [21], [24], [25], and [37]. The difference from hands-on labs is the distance between the experiment and the experimenter [20].

Another relevant topic in remote labs is the elements from which it is made up. A remote laboratory is a tool composed of software and hardware layers that manage the access, validate the accessing request, and allow users to remotely access real equipment, located in the university through the Internet. Along the same lines, the authors in [88], [112], and [113] emphasize the existence of two large systems within laboratories based on remotely accessible physical systems: the software-based block and the laboratory-based block. The software-based block oversees the communications (human-machine and machine-machine) and interface between human and laboratory. It also manages several features, such as authentication, visualization in some cases, request management, and user management. The laboratory-based block consists of the equipment, instruments, elements, environment, and devices required for experimentation. de la Torre et al. [114] provide a comprehensive definition about the scope of remote laboratories where they say: “Remote Labs use real plants and physical devices which can be used at a distance, either by teleoperating and receiving measurements from them or by modifying some input parameters and allowing simple visual observation.” This definition is consistent with a broad scope of authors [12], [26], [29], [31], [50], [52], [53], [112], [115]. In this line, Hernandez-Jayo and Garcia-Zubia, [116] provide a similar definition; however, they emphasize remote labs as an educational resource.

3) *Real Remote and Local Hybrid Lab*: These hybrid laboratories are based on having local hardware that allows learners to control remote hardware through the Internet. This type of laboratory allows the user a physical manipulation of the experiment and a way to teleoperate a real piece of equipment at a distance [29], [32], [33], [98]. Through this approach, manual skills, the main drawback of online labs, are provided during laboratory experimentation. However, under this laboratory variant, the

existing bibliography is based on the development of theoretical models, without even the development of proofs of concept [29], [32], [33] when compared against real systems [98].

### B. Lab Based on Software

Laboratories based solely on software solutions have fields of application that laboratories based on real systems cannot reach. These are experiments whose implementation would require extraordinarily complex means, experimentation about unobservable phenomena, destructive tests, not be scalable, experimentation would involve living beings, be long in time and/or expensive [12], [117], [118]. Examples can be found in the building sector [119]; chemical processes [79]; botany [120]; agroforestry [121], biology [122], [123]; pharmaceutical [123]; and forming technology [80]. Pastor et al. [84] highlight the similarities between laboratories based on physical systems and those based on models, which have common features, view, and control but are separated attending to the nature of the experimentation environment, the “model” used.

For these laboratories whose existence is limited to software, there is an evident tendency to use the term “virtual,” especially to simulated laboratories that are remotely accessible. However, the term virtual lab is not used in a homogeneous way when identifying and defining the scope of the labs (see Table I). This lack of consistency in terminology and in its formal definition among studies was already pointed out long ago by Ma and Nickerson [13] and Harms et al. [124], and it continues to be a recurring problem [23], [28], [55].

1) *Simulated Local Lab*: Within laboratories based solely on software solutions, types can be clearly identified, where the software resides on the machine from which the user interacts, so their use can even occur offline. In the different studies, the terms most used for this type of laboratory involve the concept of simulation in some of its forms and with less weight that of virtual, although both the terms are used in a similar way to define an environment of laboratory that does not exist physically. At this point, the difference between the simulator and the simulated laboratory must be highlighted: while a simulated laboratory aims to model a real laboratory and the operations carried out in it, a simulator is not concerned with the experimentation environment and only with the results.

2) *Simulated Remote Lab*: The term used most often for simulated laboratories in different studies is, without a doubt, “virtual lab.” Mosterman et al. [86] establish the basis of the contemporary definition of virtual laboratory when they state that a “virtual laboratory is a simulation of a physical laboratory” and that “virtual laboratories are computer-simulated laboratories that look, operate, and produce results similar to real laboratories.” Therefore, they reserve the term “virtual laboratory” for referring to those laboratories whose environments are based on simulated processes regardless of the locations of experiment and experimenter. This definition is consistent with the ones used in [13], [81], [82], [83], [117], [119], and [125], where the authors discriminate two types of environments: simulated plants and real plants. Along the same lines, Scheckler

[92] establishes a definition based on simulations and computerized models that can be reached both locally (distributed virtual laboratories) and remotely (centralized virtual laboratories). However, they include in the concept of virtual laboratory supplementary activities to the laboratory or to experimentation such as forums, videos, and glossaries [93], [125], [126].

The authors in [85], [86], and [127] stress on a key aspect related to virtual labs: the similarity of the virtual experimental environment with the hands-on experimental environment. In this regard, Ferrero and Piuri [128] focus on similarity in controls and operations, while Cramer and De Meyer [129] highlight that the output data must be indistinguishable from data from a “real” experiment. For its part, the work in [82] in its definition emphasizes the interactivity of the simulation with [117] highlighting that a requirement for the virtual laboratories is that “student must feel like they are working with real authentic devices in a real authentic space.” From this requirement, they formulate four criteria that cover the aspects highlighted above in terms of the similarity of the environment, results, behavior, and control. However, they add one more component: “laboratory space must be created, which allows for communication and collaboration among students and with the lab supervisor.” Potkonjak et al. [117] reference the social and collaborative factor of traditional face-to-face labs.

On the other hand, many authors use the term virtual to refer to the way in which interaction with the laboratory is carried out [65], [66]. In this way, any laboratory in which the interaction is carried out through a software-based interface, even if the system on which the orders and/or control are executed is a real system, is defined as a virtual laboratory. Hatherly [67] provides a definition that encompasses the scenarios: “A virtual laboratory is one where the student interacts with an experiment or activity, which is intrinsically remote from the student, or which has no immediate physical reality” and highlights the interaction channel by saying: “via a computer interface.” This is the case of the system presented by Rohrig and Jochheim [64], in which the term virtual laboratory and remote experimentation are used indistinctly to refer to a real laboratory accessible and controllable through the Internet (remote laboratory). Similarly, Colace et al. [90] emphasize the concept of virtual through the use of software to cover the physical distance between the user and the real system. In this way, they define a virtual laboratory as a tool that allows “an emulation or simulation allowing distance interaction with the laboratory instruments.”

One confusing and recurring term in the different studies is that of “Virtual Instrument,” widely used in practice settings [128]. Virtual Instrument uses the term virtual to refer to the interface of an instrument built using software that can be made up of controls (knobs, buttons, etc.) and indicators (graphs, LEDs, screens, etc.) [130]. This Virtual Instrument can be connected to real instruments, for example, through communication standards (e.g., GPIB, PXI, VXI, RS232, or RS485) [131], [132], or be based in a modeled system [128], [131], [132]. Therefore, the term can be ambiguous to define a laboratory since a Virtual Instrument does not establish if there is a real physical system or if it is a simulated environment for

obtaining the results. Other contexts in which the term virtual has been used in the laboratory environment do not conform to the character used in this article. In 1967, MacLean [133] describes an experimental program for learning math, which transforms the traditional arrangement of the classroom. Authors labeled it as “virtual laboratory for learning.” However, students manipulate physical materials. Obviously, in 1967, the virtual term was used outside of the scope of the contemporary term, which is based on computerized processes. Also, Rapuano and Zoino [87] use the term synchronous virtual laboratory to describe a remote laboratory service: “to follow online a laboratory activity held by the teacher.” Although the authors consistently describe a distributed remote laboratory scenario, the term virtual does not respond to the described scenario; however, the term is intended to differentiate a series of services provided to students.

Despite the diversity, there is a high consensus in the establishment of the term “virtual laboratory” as those laboratories whose environment and results are based solely on software [12], [13], [20], [83]. It is considered a solid experimental model and an exclusively software-based environment. However, there are more characteristic aspects in virtual laboratories [13], [20], [86]. Therefore, in this article, we use the term virtual laboratory to refer to those laboratories whose environment is based on software, whose results are obtained through preestablished algorithms and whose control and behavior mimic a real system. Within virtual laboratories, regarding the relative locations between the virtual laboratory and the end user, Sáenz et al. [12] use the terms “virtual mono-user lab” to classify virtual laboratories whose interaction takes place locally with the “user interacting on the machine where the laboratory software is located,” and “multiuser virtual lab” to refer to those virtual laboratories whose interaction is carried out remotely where “the laboratory is located on a different machine from the user, so that it accesses the laboratory through some type of network.” In this study, we use the term virtual lab to refer to those software-based laboratories accessible through the Internet, while the term simulated lab is used for software-based laboratories locally accessible.

### C. Deferred Labs

The most recent technological addition to this pool of laboratories is based on considering the potential combinations of the actuators and sensors in a physical laboratory, recording in real time all the potential results, values, and videos, and storing all this information for later use [134], [135]. In this way, user–laboratory interaction reproduces the results of a real environment without the inconveniences of scalability, breakdowns, and maintenance of a real laboratory, although both the experiment measurements and viewing are not happening at the precise moment of the interaction.

A similar approach to this strategy has been traditionally used in virtual reality mock-ups for, among other objectives, training reasons [136], [137], [138], [139]. For these reasons, the authors consider deferred labs as a scenario included in scenarios with

remote access, and due to their characteristics, it cannot be classified as real, virtual, or hybrid.

The first record of this type of laboratory resource appears on Stanford’s online experimentation iLabs platform [140]. They do not provide a formal name for this laboratory paradigm. They describe it as digital versions of real-world science experiments, a virtual laboratory environment obtained from a physical experiment and based on images and data logged into a database, in which students interact with the same controls and video view as would be used during a real experiment session but observing prerecorded states. This description is consistent with the one provided by Labsland [39] as “a laboratory based on a set of prerecorded experiences carried out at a real lab” as well as with the ones found in [37], [38], [40], and [135]. However, Kammerlohr et al. [53] and Orduña et al. [135] highlight the recording of a certain number of copies, for example, for each possible state of the laboratory/experiment so that the end user does not always obtain the same results in the same state of the experiment, but, as in a real laboratory, there are small variations around the point equilibrium state of the experiment.

The process to store data of the potential experimental combinations and to obtain the consequent results and visualizations and test them may be automated [39], [55], [134] or not [39]. In fact, they can be developed from a hands-on traditional laboratory and a video camera, with later generation of the web interface adding controls for actuators and screens for sensors measurements or visualizations.

To identify this type of laboratory, Martin [38] highlights the way in which the experiment is carried out using the term “deferred laboratory,” a term that Labsland [39] also recognizes. However, the author in [39], as well as the authors in [16], [40], [53], [54], and [135], highlights the scalability aspect of the “ultra-concurrent lab.” Orduña et al. [37] highlight the storage aspect using the term dataset-based simulator. However, the term ultra-concurrent lab may not delimit well the technological field of this type of laboratory and may be confused with those laboratories used in massive environments and known as massive online laboratory [141] or MOOLs [142]. In addition, the limitation in the number of simultaneous users is not only hardware but also software, so the line between the present scenario and those laboratories that allow concurrent access through batch mode [30], [143], [144], through the federation of the same laboratory in different institutions [30], [39], [113], [145], or by providing a redundant laboratory [30], [39], [141], [142], can be very thin. For these reasons, in this article, the term deferred laboratory is used since it reflects faithfully the execution time of the experimental process.

Despite the limited bibliography on the matter and the different names used, there is a high consensus regarding the definition and coverage of this type of laboratory. In conclusion, we can define it as a web laboratory, in which all the possible interactions have been previously obtained from a physical laboratory and which visualization, results, and measurements have been prerecorded and stored in a database. In this article, we propose a name for this type of laboratory, deferred remote lab.

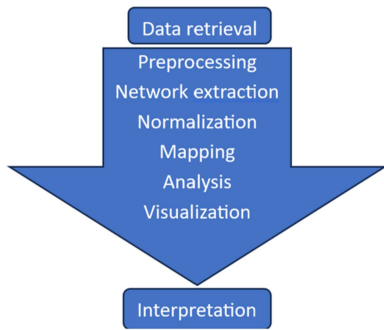


Fig. 3. Workflow of science mapping.

D. Hybrid Labs (Software and Hardware)

The combination of simulations and real systems, both accessed locally or remotely, is commonly accepted as hybrid laboratories by the research community [24], [25], [27], [49], [50]. This combination is intended to provide a more complete experience for users by taking advantage of the benefits and main characteristics of both the simulated and physical environments. Simulated and real environments allow users to quickly experience mathematical models based on software and experimentation in the real world, where disturbances and failures typical of physical experimentation are generated that are not reflected in a software program or a simulation algorithm. Hybrid laboratories allow learners to have the main advantages of real laboratories and virtual laboratories based on software, regardless of the user’s location. This allows complementary experiences through local simulation and then realization through the real experience. Or the user can access a hybrid remote laboratory, where they can first perform a software-based simulation in the same way and, for example, then remotely test this simulation on real hardware to contrast its operation [25], [52], [145], [146], [147]. Within hybrid laboratories where the benefits of both types of simulated and real laboratories are integrated, there are different possibilities according to the user’s location, if they access the experiment locally or remotely, presenting the options of local hybrid labs [24], [25], [26], [28], [29], remote hybrid labs [24], [25], [27], [49], [50], and the third option of hybrid labs with remote hardware and deferred laboratory [37]. We can conclude that any combination of a simulator, real and deferred system, accessible remote, local, and remote–local would be included in the hybrid laboratory term.

V. RESULTS

For the data analysis step of the research, the SciMAT software was used following the workflow shown in Fig. 3.

In co-word analysis, clusters of keywords and their interconnections are obtained. These clusters are considered as themes [47], [62]. Each research theme (cluster) is characterized by two parameters: density and centrality. These parameters are used to classify themes into four groups, as shown earlier in Fig. 2. Thus, a research field can be understood as a set of research themes, mapped onto a 2-D space [47]. Each cluster will consist

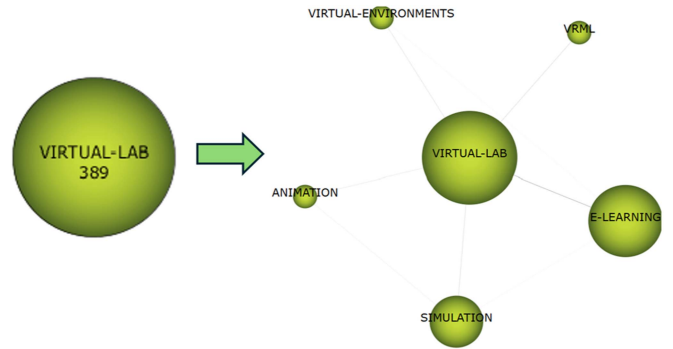


Fig. 4. Cluster network example.



Fig. 5. Keyword analysis 2001–2010.

of a minimum and maximum number of nodes or keywords. For example, in Fig. 4, the cluster consists of six nodes (the upper limit established in the study). Each cluster is represented by a sphere, a number (389 in Fig. 4), and a label in its corresponding period diagram (VIRTUAL-LAB in Fig. 4). The volume of the sphere is proportional to the number of documents belonging to the cluster, the number represents the number of documents, and the label is assigned by selecting the central node of the cluster. Similarly, each node within the cluster is depicted in the same manner, with its size being directly proportional to the frequency of the represented keyword. Within the cluster, the thickness of the links between keywords is proportional to the equivalence index and represents the degree of association between both the keywords. Regarding the value of a cluster, we can distinguish between “core documents” and “secondary documents.” Core documents are those documents that have at least two keywords within the cluster, while secondary documents refer to those documents that have only one keyword within the cluster. The union of core documents and secondary documents is shown in the results provided in Figs. 5–8.

Some parameters were set up, with the following criteria.

- 1) *type of analysis*: co-occurrence relations;



Fig. 6. Keyword analysis 2011–2020.

- 2) *minimum co-occurrence*: 2 for two-year periods; 3 for decade periods;
- 3) *clustering method*: to avoid irrelevant or weak associations simple center algorithm has been used;
- 4) *min frequency*: 3, only the item that appears in at least three documents in each period will be considered;
- 5) *cluster limits*: Max cluster size: 6; Min cluster size: 3;
- 6) *normalization*: equivalence index.

To begin the keyword analysis, a first study was generated covering the decade 2001–2010 (see Fig. 5) and then the decade 2011–2020 (see Fig. 6) to take a picture of the general situation and observe and compare the overall evolution of the core words. It is important to emphasize that over the analyzed years, the clusters’ networks, as well as the keywords of each cluster, evolve and may change.

In this first analysis by decade, the REMOTE LAB cluster is the main subject of the study in (2001–2010); in the second decade of the analysis, the number of appearances increases significantly to 1467, and it gains importance as a core theme.

The keyword VIRTUAL LAB with a strong presence in the decade (2001–2010) is in the SIMULATION cluster, in the second decade analyzed, and experiences a moderate movement between the two periods.

It should be noted that in the first period, VIRTUAL LAB is the keyword with the highest number of documents in the bibliography, which are strongly related to education and simulation topics. The use of software and simulation tools has fueled the growth of virtual labs. Among the most popular software tools used in the first decade were LABVIEW and MATLAB, which maintained moderate growth in the second decade of the study.

In the case of remote labs, they are associated with the development of learning management system (LMS) in the first decade, with advances in the topic of web services as a starting point for remote experimentation.

It is also observed that the growth of the field of knowledge in control engineering education encourages the use of nontraditional experimentation [83], as this is one of the most prolific areas in the studied period [115], [131].

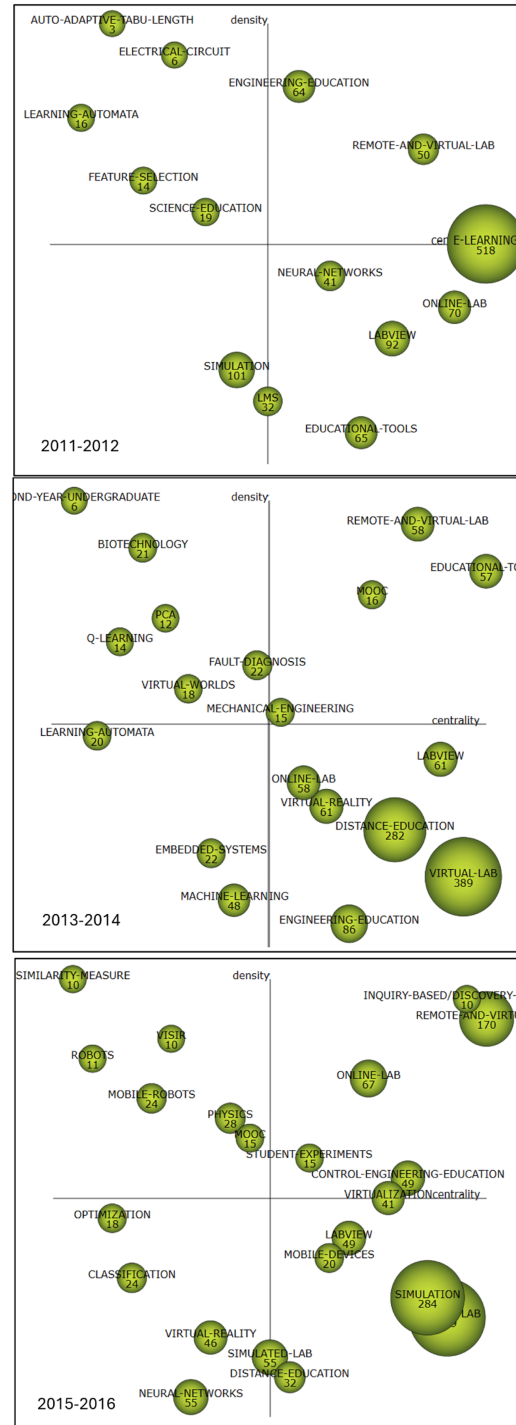


Fig. 7. (2011–2012), (2013–2014), and (2015–2016) analysis.

In the second decade, the sustained growth of open-source systems and the use of mobile devices for experimentation in learning environments should be noted.

After the first decade, a very strong growth in the term REMOTE LAB from 259 (first decade) to 952 (second decade) documents can be observed, while VIRTUAL LAB grows from 411 to 881 documents from the first decade to the second decade.

Since the goal is to observe and analyze trends, we will focus on the last decade (2011–2020) to deepen the analysis. In

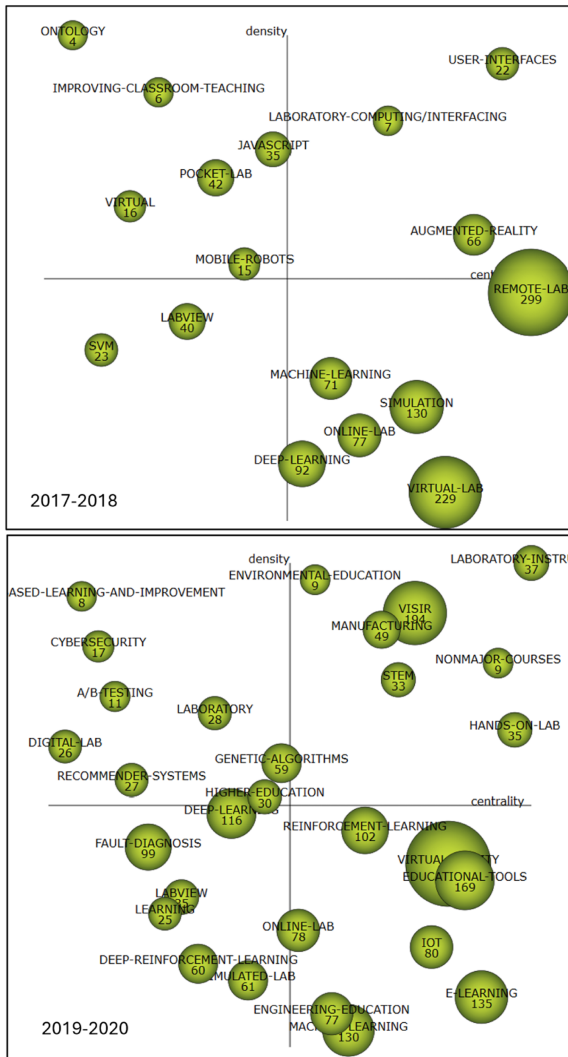


Fig. 8. (2017–2018) and (2019–2020) analysis.

this decade, two-year periods were considered, and the results analyzed to assess the evolution of the main topics related to remote laboratories, virtual laboratories, and topics that have become relevant in recent years. These are summarized in Figs. 7 and 8.

Table II provides a detailed list of the clusters belonging to each of the two-year periods studied, indicating that for each case, all the elements included in each cluster and the number of documents found with the software tool.

The table also contains the values for centrality and density as well as the number of core documents, i.e., documents with at least two keywords that are included in the thematic network. To obtain the total number of appearances, all the secondary documents, i.e., the documents with a single keyword included in the thematic network, are added [47].

Figs. 9 and 10 show the development of the keywords REMOTE LAB (clusters, C3, C11, C22, C33, and C44) and virtual lab (C3, C14, C23, C35, and C46) over the five biennia of the second decade studied, which evolve in different clusters.

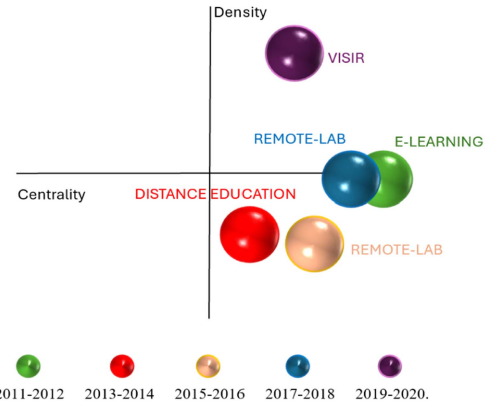


Fig. 9. Remote lab keyword evolution.

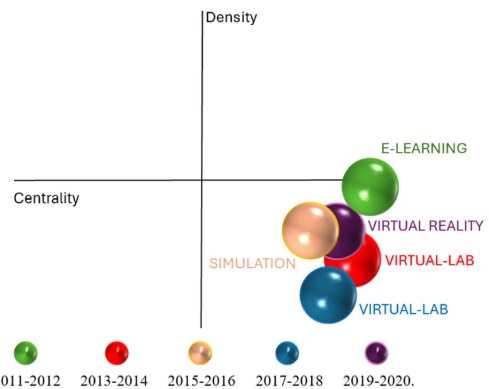


Fig. 10. Virtual lab keyword evolution.

Over the last analyzed biennia, there has been a strong push toward federation and consortium building, as well as a continuing trend toward the use of remote learning management system (RLMS) systems to remotely access and control physical lab equipment for experimentation.

The emergence of new technologies linked to the development of Industry 4.0 or Internet of Things (IoT), digitalization, as well as virtual and augmented reality is observed, which can provide resources to revolutionize science education by providing students with access to high quality, immersive, and interactive learning experiences.

In the next section of this article, the observed trends and avenues for future work will be detailed in greater depth.

## VI. ANALYSIS

The results of the systematic literature review show that virtual and remote laboratories have followed different evolutions during the decade 2001–2010 with both the alternatives presenting similar weights and presence in the literature. From the second decade, the studied biennia show a rapid acceleration of remote laboratories in becoming a driving theme, while virtual laboratories have also evolved, but at a slower pace.

In the case of virtual laboratories, in the different periods, they have belonged to different thematic clusters, going from VIRTUAL LAB to SIMULATION in the second decade, becoming

TABLE II  
CLUSTERS OF RELEVANT KEYWORDS, TWO-YEAR PERIODS

Nº	CLUSTER	C	D	CD	UD
2011-2012	<b>C1 remote-and-virtual-lab (24)</b> , haptic-devices (3), laboratory (16), web-based-design-tools (5), control-engineering-education (14), educational-laboratory (4)	7.87	8.79	11	50
	<b>C2 labview (51)</b> , virtual-instrument (53), power-electronics (3), monitoring (3), digital-signal-processing (3), robot-control (3)	5.1	3.13	22	92
	<b>C3 e-learning (156)</b> , virtual-lab (222), remote-lab (248), remote (8), distance-education (25), vocational-training (5)	17.67	4.55	127	518
	<b>C4 engineering-education (56)</b> , learning-assessment (3), learning-technology (3), telelab (7), weblab (9), e-portfolios (3)	2.51	13.36	12	64
	<b>C5 simulation (86)</b> , visualization (10), assessment (9), nursing-education (6), inquiry-learning (3), experiential-learning (5)	1.86	2.69	15	101
	<b>C6 educational-tools (40)</b> , mobile-devices (4), open-sources (47), learning (15), curriculum (5), ict (5)	4.3	1.57	8	65
	<b>C7 online-lab (40)</b> , online-course (8), web-services (13), computer-lab (7), rlms (16), university-education (3)	10.4	3.65	13	70
	<b>C8 lms (20)</b> , blended-learning (7), evaluation (9)	2.44	1.69	4	32
2013-2014	<b>C9 remote-and-virtual-lab (24)</b> , web-based-design-tools (6), laboratory (18), rapid-prototyping (3), physiological-systems (6), control-engineering-education (26)	9.63	31.59	11	58
	<b>C10 labview (36)</b> , virtual (3), sound-card (3), motion-control (4), virtual-instrument (32), distance-lab (3)	10.66	5.9	18	61
	<b>C11 distance-education (29)</b> , remote-lab (264), laas (6), lifelong-learning (9), online (4), vocational-education (3)	8.76	3.91	27	282
	<b>C12 online-lab (42)</b> , personalization (3), network (8), remote-control (11), laboratory-learning (4), inquiry-learning (6)	1.99	5.24	12	58
	<b>C13 virtual-reality(34)</b> , student-experiments (6) , augmented-reality (15), vrtools (3), web-based-lab (13), interactive-applications (3)	6.37	4.79	11	61
	<b>C14 virtual-lab (214)</b> , simulation (91), e-learning (152), vtml (5), virtual-environments (6), animation (5)	12.63	2.54	78	389
	<b>C15 engineering-education (54)</b> , hands-on-lab (6), educational-technology (11), m-learning (16), distributed-systems (5), evaluation (10)	6.78	1.6	15	86
	<b>C16 mooc (7)</b> , visir (9), mool (4), distributed-learning (4)	6.91	17.96	5	16
2015-2016	<b>C17 virtual-worlds (8)</b> , second-life (3), simulated-lab (11)	0.42	7.07	3	18
	<b>C18 remote-and-virtual-lab (32)</b> , e-learning (137), labicom (4), ejs (5), web-based-design-tools (10) , laboratory (20)	16.03	13.25	19	170
	<b>C19 online-lab (60)</b> , remote-sensing (3), inquiry-based-learning (8), undergraduate-education (3), biology (4), concept-maps (3)	4.8	8.31	12	67
	<b>C20 simulation (102)</b> , virtual-lab (172), educational-tools (48), nursing-education (4), control (11), resuscitation (3)	10.43	3.3	50	284
	<b>C21 labview (27)</b> , rlms (9), virtual-instrument (13), isa (4), sensors (7), pid-controllers (6)	3.52	4.33	14	49
	<b>C22 remote-lab (266)</b> , lms (17), engineering-education (54), electronics (5) ,raspberry-pi (12), learning-analytics (13)	15.19	3.18	62	299
	<b>C23 inquiry-based/discovery-learning (4)</b> , curriculum (5), laboratory-instruction (5), first-year-undergraduate/general (3), internet/web-based-learning (3)	15.82	38.42	5	10
	<b>C24 virtual-reality (28)</b> , visualization (5), augmented-reality (13), gamification (6), haptics (3)	0.77	2.49	9	46
2017-2018	<b>C25 control-engineering-education (26)</b> , educational-technology (9), web-based-lab (11), remote-control (7), educational-laboratory (4)	6.21	4.69	6	49
	<b>C26 simulated-lab (25)</b> , m-learning (14), hands-on-lab (19), interactive-simulations (3)	2.33	1.83	5	55
	<b>C27 visir (7)</b> , lab-federation (4), comparative-evaluations (3)	0.39	11.11	4	10
	<b>C28 mooc (11)</b> , oer (3), serious-games (5)	1.71	6.46	4	15
	<b>C29 distance-education (19)</b> , control-engineering (6), computer-aided-instruction (11)	2.34	1.81	4	32
	<b>C30 user-interfaces (3)</b> , data-analysis (3) , biology (6), cloud-lab (4), learning-analytics (10), inquiry-based-learning (7)	7.15	50.67	3	22
	<b>C31 augmented-reality (23)</b> , medical-education (3), virtual-reality (48), virtual-learning-environments (3), mixed-reality (5), computer-vision (3)	6.44	6.51	14	66
	<b>C32 javascript (9)</b> , lms (12), html5 (8), experimentation-language (4), experiments (11), java simulations (5)	2.45	29.79	7	35
2019-2020	<b>C33 remote-lab (209)</b> , mooc (29), e-learning (107), visir (22), embedded-systems (11) , engineering-education (30)	16.36	6.04	92	299
	<b>C34 simulation (100)</b> , nursing-student (3), standardized-patient (3), modeling (5), nursing (4), educational-tools (35)	4.9	1.72	18	130
	<b>C35 virtual-lab (214)</b> , ict (7), physics (10), inquiry-learning (7), conceptual-understanding (4), higher-education (7)	4.96	0.9	20	229
	<b>C36 online-lab (48)</b> , stem (13), a/b testing (3), oer (7), assessment (7), learning (10)	3.44	1.35	10	77
	<b>C37 pocket-lab (6)</b> , iot (27), teaching (7), raspberrry-pi (7), electrical-engineering (6)	2.09	14.23	6	42
	<b>C38 labview (24)</b> , ethernet (3), microcontrollers (3), measurements (3), virtual-instrument (18)	0.94	4.07	9	40
	<b>C39 laboratory-computing/interfaces (3)</b> , laboratory-instruction (4), general-public (3), computer-based-learning (4)	4.44	41.84	4	7
	<b>C40 virtual (5)</b> , online (3), laboratory (12)	0.35	11.11	3	16
2019-2020	<b>C41 laboratory-instruction (23)</b> , distance-learning (23) , second-year-undergraduate (10), upper-division-undergraduate (9), first-year-undergraduate (19), computer-based-learning (14)	52.37	48.37	29	37
	<b>C42 manufacturing (4)</b> , engineering (10), mooc (15), digital-learning (3), industry 4.0 (11), blended-learning (18)	5.64	16.2	6	49
	<b>C43 visir (18)</b> , remote-lab (187), lab-federation (9), rlms (8), electronics (5), electricity (3)	6.6	16.3	22	194
	<b>C44 hands-on-lab (25)</b> , thermodynamics (4), internet/web-based-learning (9), physical-chemistry (4), interdisciplinary/multidisciplinary (4), chemical-engineering (3)	21.18	8.56	8	35
	<b>C45 stem (22)</b> , inquiry-learning (6), xapi (5), personalization (3), inquiry-based-learning (8), technology-enhanced-learning (3)	6.14	13.01	11	33
	<b>C46 virtual-reality (68)</b> , virtual-lab (249), physics (9), experimental-platform (3), gamification (15), augmented-reality (21)	7.21	3.37	40	314
	<b>C47 iot (64)</b> , robotic-arms (5), distance-lab (4), embedded-systems (9), energy-efficiency (8), fog-computing (5)	6.9	2.12	14	80
	<b>C48 online-lab (54)</b> , lms (13), a/b tests (3), remote-control (5), design-of-experiments (3), control-engineering-education (13)	3.54	2.83	11	78
<b>C49 educational-tools (41)</b> , simulation (124), online-course (3) , simulation-training (5), curriculum (8), nursing (6)	7.62	3.37	15	169	
<b>C50 e-learning (118)</b> , laboratory-class (3), distance-education (15), smart-devices (4), laboratory-exercise, ict (7)	8.35	1.36	16	135	
<b>C51 simulated-lab (34)</b> , covid (18), system-dynamics (5), undergraduate (5), human-computer-interaction (7)	2.52	1.41	7	61	
<b>C52 labview (19)</b> , power-electronics (5), virtual-instrument (14), real-time (4)	0.73	3.21	7	35	
<b>C53 digital-lab (4)</b> , problem-based-learning (10), active-learning (16)	0.12	6.25	2	26	

C: Centrality

D: Density

CD: Core Documents

UD: Union Documents

a transversal tool with strong participation in simulated experimentation. In the case of remote laboratories, it forms a thematic cluster with great centrality and with strong participation in the formation of laboratory consortia and federations.

Analyzing the years 2019 and 2020, remote laboratories have positioned as a central tool when developing nontraditional remote experimentation, with the VISIR project standing out as the one with the largest presence at the European level, with some South American countries such as Brazil and Argentina

also installing their equipment with European funding within the VISIR and VISIR + projects. Other countries have also joined such as Costa Rica at the UNED University, the University of Georgia in the United States, and Morocco University Hassan.

The sustained advance of the IoT [75], [140] has also favored the growth and use of the Internet for the digitization of information, both in the academic and industrial world. With the emergence of this fourth industrial revolution, the trend to device diversity and connectivity for data collection and automation of

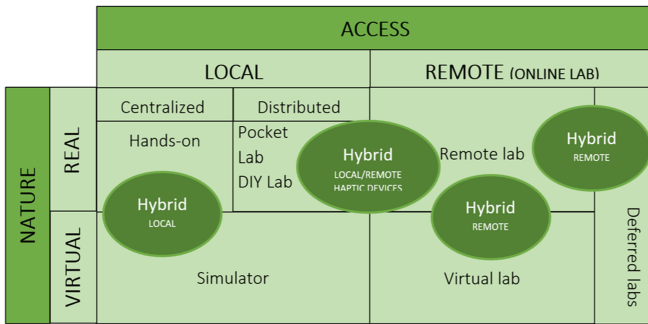


Fig. 11. Taxonomy of lab work.

low-complexity routine tasks helps enable advances in learning technologies.

Other highly important topics related to digitization are: big data, artificial intelligence, machine learning, neural networks, augmented reality, and among others related to Industry 4.0. They have emerged since 2012, with a strong growth and presence onward from the 2015–2016 biennium. These topics have a high content and value around the development of software tools, algorithms, and real-time processing of a large amount of global data to favor and inform decision making, topics that are driving forces in current research and surely in the next years.

Robotics is another area that, together with AUTOMATION, has allowed the optimization and improvement of both industrial production and academic training and training proposals when it comes to bringing the use, handling, and programming of high-cost and sophisticated equipment closer to users and students. Likewise, they are terms closely related to Industry 4.0.

The research questions introduced at the beginning of this research paper are now answered.

*RQ1: What are the laboratory scenarios used in education? And what are the scope delimitations of each scenario?*

In Section IV, we analyzed laboratory scenarios developed at educational institutions to provide practical competencies based on controlled scenarios. Derived from this analysis, together with the SciMAT results of Section V, scenario development has focused on real systems for distributed users, fostering anywhere and anytime scenarios. These laboratories can be either centralized or distributed. Analysis is reflected in our new taxonomy, shown in Fig. 11. This taxonomy makes concrete what 20 years of research work has produced.

In those laboratories, where access or interaction occurs locally, the nature of the experiment can be real or simulated. In a real system, scenarios can be defined where the laboratory can be centralized or distributed. In both the cases, the interaction between the user and the system can be computer mediated, for example, by means of Virtual Instruments. The characterization of the scenario is based on the relative location and nature of the laboratory, and not on the type of the laboratory interface. Within this scenario, one can identify centralized laboratories “hands-on labs” defined as traditional laboratories located in educational institutions, generally of high cost and with restrictive timetables, and distributed laboratories “pocket and DIY labs” defined

REMOTE LABS		TYPE OF INTERACTION		
		BATCH LAB	SYNCHRONOUS LAB	OBSERVATION LAB
TYPE OF SERVICE	CONCURRENT LAB	Visir [139]	Arduino Robot [41]	Meteolab [112]
	MONOUSER LAB	FPAA lab [174]	3-axis-Portal [147]	

Fig. 12. Remote labs scenarios.

as compact and portable systems, generally of low or moderate cost, formed by sensors and actuators, and designed for scientific and educational experimentation anywhere and anytime. The DIY, pocket, or FabLabs are lab scenarios adapted to the changes promoted in student-centered educational paradigms.

Distributed laboratories based on simulated systems are “lab simulators” that are software based, generally commercial, whose interface simulates, to some degree, a real system/laboratory, either in the modeled system or in the equipment and instrument panels. In other words, we can distinguish between simulators whose interface is a symbolic representation and simulators whose interface virtualizes a real system. Therefore, the authors of this article do not consider as lab simulators those which are based on symbolic representations, since their purpose is to work as a calculation instrument, and not as a tool to provide experimental or practical capabilities.

Remotely accessible labs based on real systems are “remote labs,” on which the scientific community has focused the greatest effort and development. These efforts for the provision of remotely accessible real scenarios to different learning environments have encouraged the application of different approaches in the system architecture to suit educational needs [7], [71], [110], [158]. Thus, different types of remote laboratories can be distinguished grounded on the type of user–laboratory interaction and the type of generated service. This classification, together with an example of each modality, is shown in Fig. 12, while more examples are given in Section IV.

Regarding the type of interaction between the user and the laboratory, we can distinguish three clearly different types: batch, synchronous laboratories, and observation laboratories.

*Batch laboratories* are based on communication protocols with experiment configuration request queues [30], [68]. Here, the user configures the experiment and sends this configuration to the remote laboratory for experimentation. This type of remote lab is typical of systems, where a program, routine, or algorithm needs to be loaded on a device [39], [145], [173]. The service type of batch labs can be either mono user or concurrent. As an example of a batch laboratory, we can mention the case of the VISIR laboratory architecture, which is based on a type of requests/responses interaction. It allows concurrent users, since the response of the electrical/electronic circuits is very fast, in the order of milliseconds, which gives the feeling of private control of the laboratory.

*Synchronous laboratories* are those in which the laboratory–user interaction is like that carried out in hands-on labs, responding in real time to the modifications made by the user. Obviously, this type of interaction in remote laboratories only

allows concurrent access through hardware replication or the federation of the laboratory.

*Observation laboratories* are those in which the user cannot change anything in system. They are laboratories dedicated mainly to monitor and obtain historical data [210].

The authors of this article do not consider the possibility of a mono user observation lab, since limiting its access to a single user would be an error of bad design (since the observation lab must be concurrent by nature).

Regarding hybrid laboratories, they are alternatives for very specific applications, where it is required to enrich a real environment with some kind of simulation.

*RQ2: What are the types of emerging labs scenarios?*

Great efforts have been made to provide real-world scenarios for distributed users. As shown in the results section, these efforts were particularly relevant to the increasing importance of remote labs in the field of experimentation. This has been aided by the development of technology, the emergence of open-source solutions, and the promotion of low-cost hardware. Another factor favoring growth is the plasticity and agility of nontraditional labs in incorporating new technologies adapted to the educational environment. This fact was demonstrated in the results section in examples, such as the emergence of Industry 4.0 [75], [53], [80]. In line with the DIY paradigm, this has also enabled the emergence of mobile laboratory alternatives that provide students with new experimentation scenarios. As a result, a variety of new and innovative ad hoc labs have emerged for the hands-on learning process (refer to Fig. 11). Alternative labs based on real-world systems, such as pocket labs, time-shifted labs, or hybrid options, have increased real-world experimentation for distributed users.

These new solutions allow adapting laboratory experiences to educational processes. In this way, the laboratory is integrated, developing from being an isolated activity to becoming a part of the whole learning process.

Deferred labs are an interesting alternative to provide real (prerecorded) experiences remotely, which can be easily accessed via the Internet. They make it possible to offer real or quasi-real experiences on a large scale. However, their potential based on ultra-concurrent access and stability, without maintenance or breakdown, makes them an ideal, if not the best, solution for massive environments such as MOOCs or courses with a high number of students or laboratory experiences with recurring access.

Regarding hybrid solutions, where characteristics of real and simulated laboratories are combined, there have emerged various alternatives that have complemented the academic offer, especially for types of laboratories with nonrepetitive tests and experiences.

Virtual laboratories have developed as a further, in many cases complementary, tool. These new systems are mainly focused on areas where another type of remote solution is not technologically possible, such as in health education, or where they are very expensive systems to implement in a remote laboratory, or in K-12 educational environments because they are reliable

systems where simple and attractive interfaces can be easily created [126].

In summary, there is a strong growth of real experimentation environments for distributed users. Emerging lab scenarios are adapted to the changes promoted in the student-centered educational paradigms. In this way, the student does not only consume what the teacher “puts on the table,” but the system encourages the student to be highly involved and motivated.

*RQ3: How have lab scenarios evolved in 2011–2020 decade?*

The emergence of the Internet, the advances in connectivity, and the appearance of low-cost hardware have allowed the creation of technological alternatives for the collection of information in real time through Internet-connected devices.

As regards the use of the LMS, in the period 2001–2010, there were 72 appearances in the study, presenting a high-impact transversal behavior. In the second decade, as shown in Fig. 6, encompassing the period 2011–2020, the appearance of RLMS gained strength with the growth and development of remote learning platforms.

The RLMS platforms made it possible to create systems, where the access and control of remote laboratories is centralized in terms of authentication, authorization, scheduling, and lab resources management, becoming a transversal tool for the operation of remote laboratories.

There is also a growing integration of laboratory networks to share resources, foster development in a specific area of expertise, and promote research.

This collaborative linkage has allowed enriching the academic and research offerings, where several educational institutions in different countries and regions participate to provide a high availability of academic learning resources.

One aspect that has gained relevance is the provision of laboratory experiences based on real systems in massive environments, MOOCs and MOOLS, where educational institutions have been able to cover a wide range of topics (not only in science) by offering content in a variety of formats, open to the community.

Another important trend is the creation of the laboratory exploitation scenarios, including immersive interaction (e.g., 3-D augmented reality) [117], [121], enriching the user’s experimentation process, which will be a strong trend in the coming years in laboratory development.

Another case to be mentioned is LabVIEW, a widely used tool since the emergence of remote laboratories as a hardware and software alternative. Nevertheless, in recent years, its use has decreased with the growth of low-cost hardware platforms.

The concept of collaborative laboratories [114], [142], [149], [210] is gaining prominence to make up for the shortcomings of online laboratories, in terms of teamwork capabilities. This is an important challenge for the evolution of remote laboratories in the future.

## VII. CONCLUSION

Although this highly specialized community does have a common framework in this area, this work shows that there is still a certain conceptual ambiguity of concepts, in terms of the

classification of laboratories found in its literature. This article contributes to the literature by providing a framework to delimit and define each term and scenario, offering a common language when talking about experimentation scenarios.

Over the last few years, new pedagogical tools have emerged, based on the strong impact of the Internet and the access to technology, where remote laboratories have become an important way to strengthen the development of practical activities, putting the student at the center of the learning process.

There is a strong trend toward laboratory federation through RLMSs. The creation of collaborative consortia between academic institutions links different regions and countries to unify learning criteria and methodologies and join efforts for better disruptive pedagogical alternatives in the age of knowledge and information. Therefore, federation protocols foster synergies between institutions and countries.

It is important to highlight the potential future contribution of the IEEE 1876 Standard [211], which establishes certain guidelines for the design, implementation, and general operation of remote laboratories, thus promoting collaboration and innovation. However, the use of the architecture proposed by this standard faces some resistance because the framework of many of the laboratories must be redesigned to comply with the standard, and for this reason, they are not currently being implemented.

One future direction for the standard would be a new version that covers the full range of scenarios outlined in Fig. 11.

The development of new pedagogical tools in the field of experimentation is oriented toward the implementation of solutions based on real systems, deferred laboratories, federations, and at least some degree of standardization either by the IEEE 1876 Standard or by RLMS.

As aforementioned, there have been discontinued efforts to provide collaborative online laboratory scenarios, which have not been successful due to an approach based on ad-hoc solutions. In this sense, an environment through an RLMS that universalizes this service is an interesting line of research to cover this gap in online scenarios. The possibility of alternating between collaborative and individual environments would make it possible to obtain the capabilities of both the scenarios.

There are alternatives through private companies, such as Labsland [39], that provide, among other alternatives, online laboratories for education. This service model promotes several aspects discussed in this article through the trends analyzed: federation, RLMS platforms with standardized communication protocols that allow easy integration into other platforms, promotion of deferred laboratories, and redundancy in remote laboratory services.

The challenge for the future of experimentation seems to be to increase the pedagogical offerings and the sustainability of parallel collaborative spaces that may promote inclusion and universal access to simple technological experiments that may enhance the learning experience of students worldwide. For now, laboratories based on real systems are positioned as the main tool for the acquisition of practical skills, focusing efforts on remote labs solutions, while virtual laboratories serve as additional

tools, especially in areas where other remote solutions are not feasible.

From an availability and reliability service point of view, Deferred Labs are a valid option when it comes to providing a reliable educational tool that minimizes the possibilities of failure, with the main advantage of being able to offer a real mass access experience, and low-cost maintenance. These labs have a potential application to shift specific lab experiences or complete remote labs and hands-on labs to deferred labs. In this way, maintaining the educational laboratory resource/tool indefinitely, so that no breakdown or failure would cause a discontinuity or even cancellation of service provision.

#### ACKNOWLEDGMENT

The authors would like to thank the Escuela de Doctorado de la UNED, Spain, for its support.

#### REFERENCES

- [1] National Research Council, *America's Lab Report: Investigations in High School Science. Committee on High School Science Education: Role and Vision*. Washington, DC, USA: National Academies Press, 2006.
- [2] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education," *J. Eng. Educ.*, vol. 94, no. 1, pp. 121–130, 2005.
- [3] A. Hofstein and V. Lunetta, "The role of the laboratory in science teaching: Neglected aspect of research," *Rev. Educ. Res.*, vol. 52, no. 2, pp. 201–217, 1982.
- [4] G. Kandamby, "Effectiveness of laboratory practical for students learning," *Int. J. Innov. Res.*, vol. 7, no. 3, pp. 222–236, 2019.
- [5] J. E. Corter, S. K. Esche, C. Chassapis, J. Ma, and J. Nickerson, "Process and learning outcomes from remotely-operated, simulated and hands-on student laboratories," *Comput. Educ.*, vol. 57, no. 3, pp. 2054–2067, 2011.
- [6] R. H. Chu, D. D.-C. Lu, and S. Sathiakumar, "Project-based lab teaching for power electronics and drives," *IEEE Trans. Educ.*, vol. 51, no. 1, pp. 108–113, Feb. 2008.
- [7] M. Stefanovic, V. Cvijetkovic, M. Matijevic, and V. Simic, "A LabVIEW-based remote laboratory experiments for control engineering education," *Comput. Appl. Eng. Educ.*, vol. 19, no. 3, pp. 538–549, 2011.
- [8] N. Pozzi and T. Rossi, "Experimenting 'learn by doing' and 'learn by falling'," *Eur. J. Eng. Educ.*, vol. 40, no. 1, pp. 68–80, 2014.
- [9] D. Domin, "A review of laboratory instruction styles," *J. Chem. Educ.*, vol. 76, no. 4, 1999, Art. no. 543.
- [10] A. Connor and W. C. Karmokar, "From STEM to STEAM: Strategies for enhancing engineering & technology education," *Int. J. Eng. Pedagogy*, vol. 5, no. 2, pp. 37–47, 2015.
- [11] P. Kirschner and M. Meester, "The laboratory in higher science education: Problems, premises and objectives," *Higher Educ.*, vol. 17, no. 1, pp. 81–98, 1988.
- [12] J. Sáenz, L. de la Torre, J. Chacón, and S. Dormido, "A study of strategies for developing online laboratories," *IEEE Trans. Learn. Technol.*, vol. 14, no. 6, pp. 777–787, Dec. 2021.
- [13] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, no. 3, pp. 1–24, 2006.
- [14] A. Hofstein and V. N. Lunetta, "The laboratory in science education: Foundations for the twenty-first century," *Sci. Educ.*, vol. 88, no. 1, pp. 28–54, 2004.
- [15] S. L. Bretz, "Evidence for the importance of laboratory courses," *J. Chem. Educ.*, vol. 96, no. 2, pp. 193–195, 2019.
- [16] AICTE, "Ultra-concurrent remote laboratory," 2020. Accessed: October 22, 2020. [Online]. Available: <http://free.aicte-india.org/Ultra-concurrent-Remote-laboratory.php>
- [17] J. W. Rice, S. M. Thomas, and K. O'Toole, *Tertiary Science Education in the 21st Century*. Sydney, NSW, Australia: Australian Learning and Teaching Council, 2009.

- [18] P. A. Kirschner, J. Sweller, and R. Clark, "Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching," *Educ. Psychol.*, vol. 41, no. 2, pp. 75–86, 2006.
- [19] R. Heradio, L. de la Torre, D. Galan, F. J. Cabreriizo, E. Herrera-Viedma, and S. Dormido, "Virtual and remote labs in education: A bibliometric analysis," *Comput. Educ.*, vol. 98, pp. 14–38, 2016.
- [20] J. E. Brinson, "Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research," *Comput. Educ.*, vol. 87, pp. 218–237, 2015.
- [21] L. Gomes and S. Bogosyan, "Current trends in remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4744–4756, Dec. 2009.
- [22] S. Dormido, "Control learning: Present and future," *Annu. Rev. Control.*, vol. 28, no. 1, pp. 115–136, 2004.
- [23] S. Seiler and R. Sell, "Comprehensive blended learning concept for teaching micro controller technology utilising HomeLab kits and remote labs in a virtual web environment," *Trans. Edutainment X*, vol. 7775, pp. 161–177, 2013.
- [24] C. Maier and M. Niederstätter, "Lab2go: A repository to locate online laboratories," *Int. J. Online Biomed. Eng.*, vol. 6, no. 1, pp. 12–17, 2010.
- [25] K. Henke, S. Ostendorff, H.-D. Wuttke, and S. Simon, "Fields of applications for hybrid online labs," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2013, pp. 1–8.
- [26] S. Mackay and D. Fisher, *Practical Online Learning and Laboratories for Engineering, Science and Technology*. West Perth, WA, Australia: IDC Technologies, 2014.
- [27] L. Rodríguez-Gil, J. García-Zubia, P. Orduña, and D. López-de-Ipiña, "Towards new multiplatform hybrid online laboratory models," *IEEE Trans. Learn. Technol.*, vol. 10, no. 3, pp. 318–330, Jul.–Sep. 2017.
- [28] I. Grout, "Remote laboratories as a means to widen participation in STEM education," *Educ. Sci.*, vol. 7, no. 4, pp. 85–102, 2017.
- [29] L. F. Z. Rivera and M. M. Larrondo-Petrie, "Models of remote laboratories and collaborative roles for learning environments," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 423–429.
- [30] P. Orduña, "Transitive and scalable federation model for remote laboratories," Ph.D. dissertation, Deusto Tech Res. Center, Univ. Deusto, Bilbao, Spain, 2013, vol. 86, pp. 78–91.
- [31] T. Klinger, D. Zutin, and C. Madritsch, "Parallel use of remote labs and pocket labs in engineering education," in *Online Engineering and Internet of Things* (ser. Lecture Notes in Networks and Systems), vol. 2, M. E. Auer and D. G. Zutin, Eds., New York, NY, USA: Springer, 2018, pp. 452–458.
- [32] H. Saliyah-Hassane et al., "Mobile laboratories as an alternative to conventional remote laboratories," in *Proc. 15th LACCEI Int. Multi-Conf. Eng., Educ. Technol.*, 2017, pp. 1–5.
- [33] L. Carlos, J. Simão, H. Saliyah-Hassane, J. Bento da Silva, and J. Bosco da Mota Alves, "Design and implementation of an architecture for hybrid labs," in *Cyber-Physical Systems and Digital Twins*. Cham, Switzerland: Springer, 2019, pp. 123–142.
- [34] E. Salmerón-Manzano and F. Manzano-Agugliaro, "The higher education sustainability through virtual laboratories: The Spanish University," *Sustainability*, vol. 10, no. 11, pp. 1–22, 2018.
- [35] A. Pester and T. Klinger, "Distributed experiments and distributed learning," *Int. J. Online Biomed. Eng.*, vol. 16, no. 6, pp. 19–33, 2020.
- [36] S. E. Brewer, B. Cinel, M. Harrison, and C. Mohr, "First year chemistry laboratory courses for distance learners," *Int. Rev. Res. Open Distrib. Learn.*, vol. 14, no. 3, pp. 488–507, 2013.
- [37] P. Orduña et al., "Classifying online laboratories: Reality, simulation, user perception and potential overlaps," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 224–230.
- [38] C. Clemente, V. Ottorino, and A. Dario, "A novel platform for the experimental training on Internet of Energy," in *Proc. IEEE Glob. Eng. Educ. Conf. (EDUCON)*, Tenerife, Spain, 2018.
- [39] Labsland, "Labsland," 2021. Accessed: March 24, 2024. [Online]. Available: <https://labsland.com/</bib>>
- [40] K. C. Narasimhamurthy, P. Orduña, L. Rodríguez-Gil, G. C. Bharath, C. N. S. Srivatsa, and K. Mulamuttal, "Analog electronic experiments in ultra-concurrent laboratory," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2020, pp. 37–45.
- [41] Z. Nedic, J. Machotka, and A. Nafalski, "Remote laboratories versus virtual and real laboratories," in *Proc. 33rd Annu. Front. Educ.*, 2003, Art. no. T3E.
- [42] P. Cofas, D. Cofas, and C. Gerigan, "Simulated, hands-on and remote laboratories for studying the solar cells," in *Proc. Int. Aegean Conf. Optim. Elect. Electron. Equip.*, 2015, pp. 206–211.
- [43] O. Naef, "Real laboratory, virtual laboratory or remote laboratory: What is the most effective way?," *Int. J. Online Eng.*, vol. 2, no. 3, pp. 1–8, 2006.
- [44] J. E. Corter, J. Nickerson, S. Esche, C. Chassapis, S. Im, and J. Ma, "Constructing reality: A study of remote hands-on and simulated laboratories," *ACM Trans. Comput.–Human Interact.*, vol. 14, no. 2, pp. 1–27, 2007.
- [45] E. D. Lindsay and M. C. Good, "Effects of laboratory access modes upon learning outcomes," *IEEE Trans. Educ.*, vol. 48, no. 4, pp. 619–631, Nov. 2005.
- [46] P. Mongeon and A. Paul-Hus, "The journal coverage of Web of Science and Scopus: A comparative analysis," *Scientometrics*, vol. 106, no. 1, pp. 213–228, 2016.
- [47] M. J. Cobo, A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera, "An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to Fuzzy Sets Theory field," *J. Informetrics*, vol. 5, no. 1, pp. 146–166, 2011.
- [48] C. Zacharia, "Examining whether touch sensory feedback is necessary for science learning through experimentation: A literature review of two different lines of research across K-16," *Educ. Res. Rev.*, vol. 16, pp. 116–137, 2015.
- [49] K. Henke, G. Tabunshchik, H.-D. Wuttke, and T. Vietzke, "Using interactive hybrid online labs for rapid prototyping of digital systems," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2014, pp. 61–66.
- [50] H.-D. Wuttke, K. Henke, and R. Hutschenreuter, "Digital twins in remote labs," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2019, pp. 289–297.
- [51] Z. Lei et al., "Modular web-based interactive hybrid laboratory framework for research and education," *IEEE Access*, vol. 6, pp. 20152–20163, 2018.
- [52] S. Guan, W. Hu, and H. Zhou, "Real-time data transmission method based on websocket protocol for networked control system laboratory," in *Proc. Chin. Control Conf.*, 2019, pp. 5339–5344.
- [53] V. Kammerlohr, A. Pfeiffer, and D. Uckelmann, "Digital laboratories for educating the IoT-generation heatmap for digital lab competences," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2020, pp. 3–20.
- [54] M. Apel, F. Odebrett, C. Paz, and N. Perozo, "Multi-phase flowloop remote laboratory," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2020, pp. 184–192.
- [55] E. K. Faulconer and A. B. Gruss, "A review to weigh the pros and cons of online, remote, and distance science laboratory experiences," *Int. Rev. Res. Open Distrib. Learn.*, vol. 19, no. 2, pp. 155–168, 2018.
- [56] T. M. Abdel-Salam, P. J. Kauffmann, and G. R. Crossman, "Are distance laboratories effective tools for technology education?," *Amer. J. Distance Educ.*, vol. 21, no. 2, pp. 77–97, 2007.
- [57] J. Reeves and D. Kimbrough, "Solving the laboratory dilemma in distance learning general chemistry," *J. Asynchronous Learn. Netw.*, vol. 8, no. 3, pp. 47–51, 2004.
- [58] S. Seiler, R. Sell, and D. Ptasiak, "Embedded system and robotic education in a blended learning environment utilizing remote and virtual labs in the cloud, accompanied by 'robotic homelab kit'," *Int. J. Emerg. Technol. Learn.*, vol. 7, no. 4, pp. 26–33, 2012.
- [59] D. Kennepohl, "Using home-laboratory kits to teach general chemistry," *Chem. Educ. Res. Pract.*, vol. 8, no. 3, pp. 337–346, 2007.
- [60] M. J. Page et al., "The PRISMA 2020 statement: An updated guideline for reporting systematic reviews," *BMJ*, vol. 371, no. 71, 2021, Art. no. n71.
- [61] J. A. Moral-Muñoz, E. Herrera-Viedma, A. Santisteban-Espejo, and M. J. Cobo, "Software tools for conducting bibliometric analysis in science: An up-to-date review," *Inf. Professional*, vol. 29, no. 1, pp. 1–20, 2020.
- [62] M. J. Cobo, A. G. López-Herrera, E. Herrera-Viedma, and F. Herrera, "SciMAT: A new science mapping analysis software tool," *J. Amer. Soc. Inf. Sci. Technol.*, vol. 63, no. 8, pp. 1609–1630, 2012.
- [63] N. Ertugrul, "Towards virtual laboratories: A survey of LabVIEW-based teaching/learning tools and future trends," *Int. J. Eng. Educ.*, vol. 16, no. 3, pp. 171–180, 2000.
- [64] C. Rohrig and A. Jochheim, "The virtual lab for controlling real experiments via internet," in *Proc. IEEE Int. Symp. Comput. Aided Control Syst. Des.*, 1999, pp. 279–284.
- [65] A. Jochheim and C. Rohrig, "The virtual lab for teleoperated control of real experiments," in *Proc. 38th IEEE Conf. Decis. Control*, 1999, vol. 1, pp. 819–824.
- [66] K. Achuthan et al., "The VALUE@ amrita virtual labs project: Using web technology to provide virtual laboratory access to students," in *Proc. IEEE Glob. Humanitarian Technol. Conf.*, 2011, pp. 117–121.
- [67] P. A. Hatherly, "The virtual laboratory and interactive screen experiments," *Connecting Res. Phys. Educ. Teacher Educ.*, pp. 1–7, 2016.

- [68] L. Gomes and A. Costa, "Embedded systems introductory course supported by remote experiments," in *Proc. Int. Workshop e-Learn. Virtual Remote Lab.*, 2004, pp. 89–98.
- [69] A. Longo and M. Zappatore, "A microservice-based MOOL in acoustics addressing the learning-at-scale scenario," *Annu. Comput. Softw. Appl. Conf.*, vol. 1, pp. 391–400, 2017.
- [70] F. Moghaddam et al., "Massive open online labs (MOOLS): An innovative solution to achieving SDGs in the global south," in *Proc. Exp. Int. Conf.*, 2019, pp. 394–398.
- [71] C. Salzmann and D. Gillet, "Smart device paradigm, standardization," in *Proc. Glob. Eng. Educ. Conf.*, 2013, pp. 1217–1221.
- [72] C. Salzmann, D. Gillet, and Y. Piguet, "MOOLS for MOOCS: A first eCX scalable implementation," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 246–251.
- [73] C. Salzmann, W. Halimi, D. Gillet, and S. Govaerts, "Deploying large-scale online labs with smart devices," in *Cyber-Physical Laboratories in Engineering and Science Education*. Berlin, Germany: Springer, 2018, pp. 43–78.
- [74] L. F. Zapata-Rivera et al., "Scalable. Ad hoc, low cost, mobile, online laboratories," in *Proc. Learn. MOOCS*, 2018, pp. 155–158.
- [75] R. Langmann, "A CPS integration platform as a framework for generic remote labs in automation engineering," in *Cyber-Physical Laboratories in Engineering and Science Education*. Cham, Switzerland: Springer, 2018, pp. 305–329.
- [76] C. Terkowsky, S. Frye, and D. May, "Online engineering education for manufacturing technology: Is a remote experiment a suitable tool to reach competences for 'working 4.0,'" *Eur. J. Educ.*, vol. 54, no. 4, pp. 577–590, 2019.
- [77] S. Sanz, M. Iskander, and L. Yu, "Development of an interactive multimedia module on antenna theory and design," *Comput. Appl. Eng. Educ.*, vol. 8, no. 1, pp. 11–17, 2000.
- [78] M. Cooper and J. M. M. Ferreira, "Remote laboratories extending access to science and engineering curricular," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 342–353, Oct.–Dec. 2009.
- [79] I. Hawkins and A. Phelps, "Virtual laboratory vs. traditional laboratory: Which is more effective for teaching electrochemistry?," *Chem. Educ. Res. Pract.*, vol. 14, no. 4, pp. 516–523, 2013.
- [80] J. Grodotzki, T. Ortelt, and A. Tekkaya, "Remote and virtual labs for Engineering Education 4.0: Achievements of the ELLI project at the TU Dortmund University," *Procedia Manuf.*, vol. 26, pp. 1349–1360, 2018.
- [81] S. Frerich, D. Kruse, M. Petermann, and A. Kilzer, "Virtual labs and remote labs: Practical experience for everyone," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2014, pp. 312–314.
- [82] Z. C. Zacharia, "Comparing and combining real and virtual experimentation: An effort to enhance students' conceptual understanding of electric circuits," *J. Comput. Assist. Learn.*, vol. 23, no. 2, pp. 120–132, 2007.
- [83] S. Dormido, "Control learning: Present and future," *IFAC Proc. Vol.*, vol. 35, no. 1, pp. 71–93, 2002.
- [84] R. Pastor, J. Sánchez, and S. Dormido, "Web-based virtual lab and remote experimentation using Easy Java Simulations," *IFAC Proc. Vol.*, vol. 38, no. 1, pp. 103–108, 2005.
- [85] H. Mostefaoui, A. Benachenhou, and A. A. Benattia, "Design of a low cost remote electronic laboratory suitable for bandwidth connection," *Comput. Appl. Eng. Educ.*, vol. 25, no. 3, pp. 480–488, 2017.
- [86] P. Mosterman et al., "Virtual engineering laboratories: Design and experiments," *J. Eng. Educ.*, vol. 83, no. 3, pp. 279–285, 1994.
- [87] S. Rapuano and F. Zoino. "A learning management system including laboratory experiments on measurement instrumentation," *IEEE Trans. Instrum. Meas.*, vol. 55, no. 5, pp. 1757–1766, Oct. 2006.
- [88] F. Garcia-Loro et al., "A federation of remote laboratory OERs: Grid of VISIR systems through PILAR project," *Int. J. Online Biomed. Eng.*, vol. 16, no. 4, pp. 72–81, 2020.
- [89] J. Chacon, H. Vargas, G. Farias, J. Sanchez, and S. Dormido, "EJS, JIL server, and LabVIEW: An architecture for rapid development of remote labs," *IEEE Trans. Learn. Technol.*, vol. 8, no. 4, pp. 393–401, Oct.–Dec. 2015.
- [90] F. Colace, M. De Santo, and A. Pietrosanto, "Work in progress: Virtual lab for electronic engineering curricula," in *Proc. 34th Annu. Front. Educ.*, 2004, vol. 1, pp. T3C/22–T3C/24.
- [91] D. M. Chiu, "Computer-aided laboratory in electronics," in *Proc. Int. Conf. Multi Media Eng. Educ.*, 1994, pp. 453–458.
- [92] R. K. Scheckler, "Virtual labs: A substitute for traditional labs?," *Int. J. Develop. Biol.*, vol. 47, no. 2-3, pp. 231–236, 2003.
- [93] D. Lane, "The rice virtual lab in statistics," *Behav. Res. Methods, Instrum., Comput.*, vol. 31, no. 1, pp. 24–33, 1999.
- [94] I. Ismail, A. Permanasari, and W. Setiawan, "Stem virtual lab: An alternative practical media to enhance student's scientific literacy," *Indonesian J. Sci. Educ.*, vol. 5, no. 2, pp. 239–246, 2016.
- [95] S. Sanchez-Gordon and S. Lujan-Mora, "MOOCs gone wild," in *Proc. Int. Technol., Educ. Develop. Conf.*, 2014, pp. 1449–1458.
- [96] A. Pester, C. Madritsch, and T. Klinger, "Collaborative learning with cyber-physical systems," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2015, pp. 184–188.
- [97] O. H. Graven and J. Bjork, "The use of Arduino pocket lab to increase motivation in electrical engineering students for programming," in *Proc. IEEE Int. Conf. Teaching, Assessment, Learn. Eng.*, 2016, pp. 239–243.
- [98] M. T. Restivo, A. M. Lopes, L. D. S. Machado, and R. M. de Moraes, "Adding tactile information to remote & virtual labs," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2011, pp. 1120–1124.
- [99] V. Majstorovic and Z. Jakovljevic, "Microfluidic chip fabrication for application in low cost DIY MicroPIV," in *Proc. Int. Conf. Adv. Manuf. Eng. Technol.*, 2017, pp. 451–459.
- [100] M. Aliazzo, *Lo sviluppo e il ruolo dei Fablab*. Milan, Italy: AICA, 2014.
- [101] W. You, W. Chen, M. Agyapong, and C. Mordi, "The business model of do-it-yourself (DIY) laboratories a triple layered perspective," *Technol. Forecasting Social Change*, vol. 159, pp. 1–14, 2020.
- [102] F. Ferretti, "Mapping do-it-yourself science," *Life Sci., Soc. Policy*, vol. 15, no. 1, pp. 1–23, 2019.
- [103] T. D. J. Mateo Sanguino, I. J. Fernández de Viana González, E. Ancos, and J. Fernández, "Exploring strengths and weaknesses. A case study after developing a remote network lab," *Comput. Appl. Eng. Educ.*, vol. 26, no. 5, pp. 1422–1434, 2018.
- [104] M. Bauer et al., "An extensible platform for building remote experiment control," *J. Comput. Methods Sci. Eng.*, vol. 17, no. S1, pp. s35–s46, 2017.
- [105] N. Lima, C. Viegas, and F. Garcia-Penalvo, "Different didactical approaches using a remote lab: Identification of impact factors," *IEEE Revista Iberoamericana de Tecnol. Aprendizaje*, vol. 14, no. 3, pp. 76–86, Aug. 2019.
- [106] C. Viegas et al., "Impact of a remote lab on teaching practices and student learning," *Comput. Educ.*, vol. 126, pp. 201–216, 2018.
- [107] P. Nedungadi, M. V. Ramesh, P. Pradeep, and R. Raman, "Pedagogical support for collaborative development of virtual and remote labs," in *Proc. Cyber-Phys. Lab. Eng. Sci. Educ.*, 2018, pp. 219–240.
- [108] J. R. Brinson, "A further characterization of empirical research related to learning outcome achievement in remote and virtual science labs," *J. Sci. Educ. Technol.*, vol. 26, no. 5, pp. 546–560, 2017.
- [109] L. F. Zapata Rivera and M. M. Larrondo Petrie, "Models of collaborative remote laboratories and integration with learning environments," *Int. J. Online Eng.*, vol. 12, no. 9, pp. 1–8, 2016.
- [110] Z. C. Zacharia et al., "Identifying potential types of guidance for supporting student inquiry when using virtual and remote labs in science: A literature review," *Educ. Technol. Res. Develop.*, vol. 63, no. 2, pp. 257–302, 2015.
- [111] S. Ferrari, M. Lazzaroni, V. Piuri, L. Cristaldi, and M. Faifer, "Statistical models approach for solar radiation prediction," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, 2013, pp. 1734–1739.
- [112] F. Garcia-Loro et al., "Spreading remote laboratory scope through a federation of nodes: VISIR case," *IEEE Revista Iberoamericana de Tecnologías del Aprendizaje*, vol. 14, no. 4, pp. 107–116, Nov. 2019.
- [113] F. Garcia-Loro et al., "Electronics remote lab integration into MOOC-achieving practical competences into MOOCs," in *Proc. Online, Open Flexible Higher Educ. Conf.*, 2016, pp. 367–379.
- [114] L. de la Torre, M. Guinaldo, R. Heradio, and S. Dormido, "The ball and beam system: A case study of virtual and remote lab enhancement with moodle," *IEEE Trans. Ind. Informat.*, vol. 11, no. 4, pp. 934–945, Aug. 2015.
- [115] M. E. Rabek and K. Žáková, "Development of control experiments for an online laboratory system," *Information*, vol. 11, no. 3, pp. 1–10, 2020.
- [116] U. Hernandez-Jayo and J. Garcia-Zubia, "Remote measurement and instrumentation laboratory for training in real analog electronic experiment," *J. Int. Meas. Confederation*, vol. 82, pp. 123–134, 2016.
- [117] V. Potkonjak et al., "Virtual laboratories for education in science, technology, and engineering," *Comput. Educ.*, vol. 95, pp. 309–327, 2016.
- [118] T. Alkhalidi, I. Pranata, and R. I. Athauda, "A review of contemporary virtual and remote laboratory implementations: Observations and findings," *J. Comput. Educ.*, vol. 3, no. 3, pp. 329–351, 2016.

- [119] A. Campioli and C. Talamo, "Studies and experiments for a laboratory of virtual construction elements," *Trans. Inf. Commun. Technol.*, vol. 5, pp. 489–504, 1993.
- [120] T. Fourcaud, X. Zhang, A. Stokes, H. Lambers, and C. Körner, "Plant growth modelling and applications: The increasing importance of plant architecture in growth models," *Ann. Botany*, vol. 101, no. 8, pp. 1053–1063, 2008.
- [121] D. Fernández-Avilés, D. Dotor, D. Contreras, and J. Salazar, "Virtual labs: A new tool in the education: Experience of technical University of Madrid," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 271–272.
- [122] N. J. Gibbons, C. Evans, and D. K. Griffin, "Learning to karyotype in the university environment: A computer-based virtual laboratory class," *Cytogenetic Genome Res.*, vol. 101, no. 1, pp. 1–4, 2003.
- [123] S. C. Huang et al., "An internet-based 'kinectic imaging system' (KIS) for MicroPET," *Mol. Imag. Biol.*, vol. 7, no. 5, pp. 330–341, 2005.
- [124] U. Harms, "Virtual and remote labs in physics education," in *Proc. 2nd Eur. Conf. Phys. Teach. Eng. Educ.*, 2000, pp. 140–146.
- [125] L. Mercer and J. Ranan, "The concept and design of a virtual laboratory," in *Proc. Graph. Interface Conf.*, 1990, pp. 149–155.
- [126] I. Ghergulescu, T. Lynch, M. Bratu, and A.-N. Moldovan, "STEM education with atomic structure virtual lab for learners with special education needs," in *Proc. Int. Conf. Educ. New Learn. Technol.*, 2018, pp. 8747–8752.
- [127] H. E. Keller and E. E. Keller, "Making real virtual labs," *Sci. Educ. Rev.*, vol. 4, no. 1, pp. 2–11, 2005.
- [128] A. Ferrero and V. Piuri, "A simulation tool for virtual laboratory experiments in a WWW environment," *IEEE Trans. Instrum. Meas.*, vol. 48, no. 3, pp. 741–746, Jun. 1999.
- [129] P. G. Cramer and G. De Meyer, *The Philosophy of the Virtual Laboratory*. Tübingen, Germany: German Inst. Res. Distance Educ., Univ. Tuebingen, 1997.
- [130] National Instruments, "What is a virtual instrument in LabVIEW?," Accessed: Sep. 9, 2020. [Online]. Available: [ftp://ftp.ni.com/pub/gdc/LV\\_Online\\_Eval/daq\\_ic/getting\\_started\\_with\\_LV.pdf](ftp://ftp.ni.com/pub/gdc/LV_Online_Eval/daq_ic/getting_started_with_LV.pdf)
- [131] M. Abdulwahed and Z. K. Nagy, "Developing the TriLab, a triple access mode (hands-on, virtual, remote) laboratory, of a process control rig using LabVIEW and Joomla!," *Comput. Appl. Eng. Educ.*, vol. 21, no. 4, pp. 614–626, 2010.
- [132] M. Stefanovic, "The objectives, architectures and effects of distance learning laboratories for industrial engineering education," *Comput. Educ.*, vol. 69, pp. 250–262, 2013.
- [133] J. MacLean, "The quest for an improved curriculum. The arithmetic teacher," *Arithmetic Teacher*, vol. 14, no. 2, pp. 136–140, 1967.
- [134] B. Carey, "'iLabs' offer a new way to add science experiments to online education," Stanford—News Service, 2013. Accessed: Mar. 24, 2024. [Online]. Available: <https://engineering.stanford.edu/news/ilabs-offer-new-way-add-science-experiments-online-education>
- [135] P. Orduña et al., "Addressing technical and organizational pitfalls of using remote laboratories in a commercial environment," in *Proc. IEEE Front. Educ. Conf.*, 2018, pp. 1–7.
- [136] V. Whisker, A. J. Baratta, S. Yerrapathruni, and J. Messner, "Using immersive virtual environments to develop and visualize construction schedules for advanced nuclear power plants," in *Proc. 2nd Int. Congr. Adv. Nucl. Power Plants*, 2003, vol. 3, pp. 4–7.
- [137] T. Shaw and V. Whisker, "Generation IV nuclear energy systems construction cost reductions through the use of virtual environments," No. DOE/SF/22327. Pennsylvania State University (US), 2004.
- [138] K. Jeong et al., "The scenario-based system of workers training to prevent accidents during decommissioning of nuclear facilities," *Ann. Nucl. Energy*, vol. 71, pp. 475–479, 2014.
- [139] S.-K. Kim, H.-S. Park, K.-W. Lee, and C.-H. Jung, "Development of a digital mock-up system for selecting a decommissioning scenario," *Ann. Nucl. Energy*, vol. 33, pp. 1227–1235, 2006.
- [140] L. Hesselink, "Digital lab twins-diffraction experiment," 2014. Accessed: Mar. 24, 2024. [Online]. Available: [https://ilabs.education/showExperiment?exp\\_id=5187247892594688](https://ilabs.education/showExperiment?exp_id=5187247892594688)
- [141] M. E. Macías García and E. G. Rincón Flores, "MOOC lab, a massive online laboratory with real time access," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2019, pp. 646–652.
- [142] D. Lowe, "MOOLS: Massive open online laboratories: An analysis of scale and feasibility," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2014, pp. 1–6.
- [143] F. García, G. Díaz, M. Tawfik, S. Martín, E. Sancristobal, and M. Castro, "A practice-based MOOC for learning electronics," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2014, pp. 969–974.
- [144] F. Garcia-Loro et al., "PILAR: A federation of VISIR remote laboratory systems for educational open activities," in *Proc. IEEE Int. Conf. Teach., Assessment, Learn. Eng.*, 2018, pp. 134–141.
- [145] J. García-Zubía et al., "Boole-Weblab-FPGA: Creating an integrated digital electronics learning workflow," *Int. J. Online Biomed. Eng.*, vol. 9, no. 8, pp. 19–22, 2013.
- [146] K. Henke, T. Vietzke, R. Hutschenreuter, and H.-D. Wuttke, "The remote lab cloud 'GOLDi-labs.Net'," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 37–42.
- [147] A. Maiti, D. G. Zutin, H.-D. Wuttke, K. Henke, A. D. Maxwell, and A. A. Kist, "A framework for analyzing and evaluating architectures and control strategies in distributed remote laboratories," *IEEE Trans. Learn. Technol.*, vol. 11, no. 4, pp. 441–455, Oct.–Dec. 2018.
- [148] L. Breslow et al., "Studying learning in the worldwide classroom research into edX's first MOOC," *Res. Pract. Assessment*, vol. 8, no. 1, pp. 13–25, 2013.
- [149] D. Müller and H. H. Erbe, "Collaborative remote laboratories in engineering education: Challenges and visions," *Adv. Remote Lab. E-Learn. Exp.*, pp. 35–59, 2007.
- [150] J. J. Chini, A. Madsen, E. Gire, N. Sanjay Rebello, and S. Puntambekar, "Exploration of factors that affect the comparative effectiveness of physical and virtual manipulatives in an undergraduate laboratory," *Phys. Rev. Special Topics. Phys. Educ. Res.*, vol. 8, no. 1, 2012, Art. no. 010113.
- [151] D. G. Zutin, M. E. Auer, C. Maier, and M. Niederstatter, "Lab2go A repository to locate educational online laboratories," in *Proc. IEEE Glob. Eng. Educ. Conf.*, 2010, pp. 1741–1746.
- [152] L. V. Alexeychik, M. P. Zhokhova, D. V. Mikheev, and M. V. Karpunina, "Electrotechnical laboratory: From physical experiment to virtual scenario," in *Proc. Int. Conf. Inf. Technol. Eng. Educ.*, 2018, pp. 1–4.
- [153] P. Ali-Zade, K. Buruncuk, K. Radjabli, and H. Mamadov, "Motor's expense repaid in savings," *IEEE Ind. Appl. Mag.*, vol. 12, no. 6, pp. 21–28, Nov/Dec. 2006.
- [154] T. Vinay, "Computer aided laboratory in digital control," in *Proc. IEEE Int. Conf. Multi Media Eng. Educ.*, 1996, pp. 253–259.
- [155] I. Hahn and I. Scheuring, "The effect of measurement scales on estimating vegetation cover: A computer-assisted experiment," *Community Ecol.*, vol. 4, no. 1, pp. 29–33, 2003.
- [156] S. Achouch, L. Masmoudi, M. Gharbi, and P. Nonnon, "Design and development of a sensor for distance and velocity measurement using an Infrared camera for studying kinematic movements," in *Proc. Int. Conf. Wireless Technol., Embedded Intell. Syst.*, 2019, pp. 1–6.
- [157] Z. C. Zacharia and G. Olympiou, "Physical versus virtual manipulative experimentation in physics learning," *Learn. Instruct.*, vol. 21, no. 3, pp. 317–331, 2011.
- [158] Z. C. Zacharia and C. P. Constantinou, "Comparing the influence of physical and virtual manipulatives in the context of the Physics by Inquiry curriculum: The case of undergraduate students' conceptual understanding of heat and temperature," *Amer. J. Phys.*, vol. 76, no. 4, pp. 425–430, 2008.
- [159] T. Klinger and C. Madritsch, "Use of virtual and pocket in education," in *Proc. Int. Conf. Remote Eng. Virtual Instrum.*, 2016, pp. 267–268.
- [160] A. Pester and T. Klinger, "Analog computing with pocket labs: An approach for multidisciplinary first year student projects," in *Proc. IEEE 4th Exp. Int. Conf.*, 2017, pp. 313–317.
- [161] J. Chevrier, L. Madani, and A. Bsiesy, "Can a smartphone be a Home-lab?," *Learn X Des.*, pp. 1072–1083, 2015.
- [162] J. P. Oliver and F. Haim, "Lab at home: Hardware kits for a digital design lab," *IEEE Trans. Educ.*, vol. 52, no. 1, pp. 46–51, Feb. 2009.
- [163] J. P. Oliver, F. Haim, S. Fernandez, J. Rodriguez, and P. Rolando, "Hardware at home possible with ultra low cost boards," in *Proc. IEEE Int. Conf. Microelectronic Syst. Educ.*, 2005, pp. 19–20.
- [164] P. Gutruf, U. Utzinger, and V. Subbian, "Moving from pedagogy to andragogy in biomedical engineering design: Strategies for lab-at-home and distance learning," *Biomed. Eng. Educ.*, vol. 1, pp. 301–305, 2021.
- [165] J. E. Mickle and P. M. Aune, "Development of a laboratory course in nonmajors general biology for distance education," *J. College Sci. Teach.*, vol. 37, no. 5, pp. 35–39, 2008.
- [166] M. D. Jackson, "A distance-education chemistry course for nonmajors," *J. Sci. Educ. Technol.*, vol. 7, no. 2, pp. 163–170, 1998.
- [167] M. J. Patterson, "Developing and internet-based chemistry class," *J. Chem. Educ.*, vol. 77, no. 5, pp. 554–555, 2000.
- [168] R. S. Casanova and J. L. Civelli, "Distance learning: A viable alternative to the conventional lecture-lab format in general chemistry," *J. Chem. Educ.*, vol. 83, no. 3, pp. 501–507, 2006.
- [169] R. Lyall and A. F. Patti, "Taking the chemistry experience home—home experiments or 'kitchen chemistry,'" in *Accessible Elements*. Athabasca, AB, Canada: Athabasca Univ. Press, 2010, pp. 83–107.

- [170] M. Jawad et al., "Remote laboratory exercise to develop micropipetting skills," *J. Microbiol. Biol. Educ.*, vol. 22, no. 1, pp. 1–4, 2021.
- [171] B. Balamuralithara and P. Woods, "Virtual laboratories in engineering education: The simulation lab and remote lab," *Comput. Appl. Eng. Educ.*, vol. 17, no. 1, pp. 108–118, 2009.
- [172] F. Esquembre, "Facilitating the creation of virtual and remote laboratories for science and engineering education," *IFAC Papers Online*, vol. 48, no. 29, pp. 49–58, 2015.
- [173] A. Macho et al., "Dynamic reconfiguration in FPAA for technical and nontechnical education in a global environment," *Comput. Appl. Eng. Educ.*, vol. 29, no. 4, pp. 911–930, 2020.
- [174] M. Alliet-Gaubert et al., "Cooperative WebLab in chemical engineering between France and Brazil: Validation of the methodology," *Educ. Chem. Eng.*, vol. 7, no. 1, pp. 7–13, 2012.
- [175] C. C. Ko et al., "A largescale web-based virtual oscilloscope laboratory experiment," *Eng. Sci. Educ. J.*, vol. 9, no. 2, pp. 69–76, 2000.
- [176] M. Waldrop, "Education online: The virtual lab," *Nature*, vol. 499, pp. 268–270, 2013.
- [177] C. C. Ko, B. M. Chen, J. Chen, Y. Zhuang, and K. Chen Tan, "Development of a web-based laboratory for control experiments on a coupled tank apparatus," *IEEE Trans. Educ.*, vol. 44, no. 1, pp. 76–86, Feb. 2001.
- [178] Z. Aydogmus and O. Aydogmus, "A web-based remote access laboratory using SCADA," *IEEE Trans. Educ.*, vol. 52, no. 1, pp. 126–132, Feb. 2009.
- [179] A. Yazidi, H. Henao, G.-A. Capolino, F. Betin, and F. Filippetti, "A web-based remote laboratory for monitoring and diagnosis of ac electrical machines," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4950–4959, Oct. 2011.
- [180] A. Selmer and M. Kraft, "Weblabs in chemical engineering education," *Educ. Chem. Eng.*, vol. 2, no. 1, pp. 38–45, 2007.
- [181] L. R. Winer, M. Chomienne, and J. Vazquez-Abad, "A distributed collaborative science learning laboratory on the internet," *Amer. J. Distance Educ.*, vol. 14, no. 1, pp. 47–62, 2000.
- [182] K. K. Tan, T. H. Lee, and F. M. Leu, "Development of a distant laboratory using LabVIEW," *Int. J. Eng. Educ.*, vol. 16, no. 3, pp. 273–282, 2000.
- [183] V. Mengov, "Remote access to computer aided lab experiment for students in electronics engineering courses," in *Proc. XXIX Int. Sci. Conf. Electron.*, 2020, pp. 1–4.
- [184] D. Zamarrón, N. Arana de las Casas, E. Grajeda, J. Ávila, and N. Uday, "Educational robot arm platform," *Comput. Syst.*, vol. 24, no. 4, pp. 1387–1401, 2020.
- [185] A. Balestrino et al., "From tele-laboratory to e-learning in automation curricula at the University of Pisa," *IFAC Proc.*, vol. 38, no. 1, pp. 133–138, 2005.
- [186] H. Hoyer, A. Jochheim, C. Rohrig, and A. Bischoff, "A multiuser virtual-reality environment for a tele-operated laboratory," *IEEE Trans. Educ.*, vol. 47, no. 1, pp. 121–126, Feb. 2004.
- [187] C. Terkowsky, D. May, T. Haertel, and C. Pleul, "Experiential remote lab learning with e-portfolios: Integrating tele-operated experiments into environments for reflective learning," in *Proc. Int. Conf. Interact. Collab. Learn.*, 2012, pp. 1–7.
- [188] B. Dolle, F.-K. Benra, D. Brillert, and H. J. Dohmen, "An educational laboratory with a remote-controlled centrifugal pump test rig," in *Proc. Int. Conf. Nanochannels, Microchannels, Minichannels*, 2016, Art. no. FEDSM2016-7557.
- [189] R. Mhiri, M. Besbes, M. Saad, V. Nerguizian, and H. Ben Attia, "Implementation of laboratory at distance (LAD): Specific considerations and recommendations," in *Proc. IEEE Int. Conf. e-Learn. Ind. Electron.*, 2013, pp. 52–56.
- [190] M. Saad et al., "Enhanced remote laboratory work for engineering training," in *Proc. Can. Eng. Educ. Assoc.*, 2013, pp. 1–4.
- [191] S. Maarouf et al., "Collaborative activities in the remote laboratory work," in *Proc. Int. Conf. Interact. Collab. Learn.*, 2012, pp. 1–6.
- [192] J. Schwarz, A. Polze, K. Wehner, and L. Sha, "Remote lab: A reliable tele-laboratory environment," in *Proc. Int. Conf. Internet Comput.*, 2000, pp. 55–62.
- [193] S. H. Choy, K. L. Jim, C. L. Mak, and C. W. Leung, "Remote-controlled optics experiment for supporting senior high school and undergraduate teaching," in *Proc. Educ. Training Opt. Photon.*, 2017, Art. no. 1045241.
- [194] A. Chevalier, M. Bura, C. Copot, C. Ionescu, and R. De Keyser, "Development and student evaluation of an internet-based control engineering laboratory," *IFAC Papers Online*, vol. 48, no. 29, pp. 1–6, 2015.
- [195] E. Palou et al., "Remote experiments for food engineering," *J. Food Eng.*, vol. 67, no. 1/2, pp. 129–133, 2005.
- [196] V. Potkonjak, M. Vukobratović, K. Jovanović, and M. Medenica, "Virtual mechatronic/robotic laboratory—A step further in distance learning," *Comput. Educ.*, vol. 55, no. 2, pp. 465–475, 2010.
- [197] C. Chang, "Enhancing tenth graders' earth-science learning through computer-assisted instruction," *J. Geosci. Educ.*, vol. 48, no. 5, pp. 636–640, 2000.
- [198] P. D. Boger and J. L. Boger, "Interactive computer applications for the improvement of introductory-geology laboratory exercises," *J. Geol. Educ.*, vol. 42, no. 5, pp. 461–466, 1994.
- [199] K. Sankaranarayanan, P. Mirza-Babaei, and F. D. R. Tome Filho, "Video games to the rescue: Can game design make software based lab experiments engaging?," in *Proc. IEEE Games Entertainment Media Conf.*, 2015, pp. 1–4.
- [200] Z. He, Z. Shen, and S. Zhu, "Design and implementation of an internet-based electrical engineering laboratory," *ISA Trans.*, vol. 53, no. 5, pp. 1377–1382, 2014.
- [201] Z. Zacharia and G. Olympiou, "Effects of experimenting with physical and virtual manipulatives on students' conceptual understanding in heat and temperature," *J. Res. Sci. Teach.*, vol. 45, no. 8, pp. 1021–1035, 2008.
- [202] P. Viitaharju, K. Yliniemi, M. Nieminen, and A. J. Karttunen, "Learning experiences from digital laboratory safety training," *Educ. Chem. Eng.*, vol. 34, pp. 87–93, 2021.
- [203] P. Doulai, "Engineering and science laboratory courseware delivery using world wide web technology," in *Proc. IEEE Int. Conf. Multi Media Eng. Educ.*, 1996, pp. 339–344.
- [204] S. Chatterjee, M. Parmasivam, and W. J. Yakowenko, "Architecture for a web-accessible simulation environment," *Computer*, vol. 30, no. 6, pp. 88–91, 1997.
- [205] F. Bianconi, S. A. Saetta, and L. Tiacci, "A web-based simulation game as a learning tool for the design process of complex systems," *J. Des. Res.*, vol. 5, no. 2, pp. 253–272, 2006.
- [206] K. T. Sun, Y. C. Lin, and C. J. Yu, "A study on learning effect among different learning styles in web-based lab of science for elementary school students," *Comput. Educ.*, vol. 50, no. 4, pp. 1411–1422, 2008.
- [207] S. Arnous, A. Leleve, K. Kouiss, and P. Prevot, "Configuration and management tool for laboratory training," in *Proc. 6th IEEE Int. Conf. E-Learn. Ind. Electron.*, 2012, pp. 104–109.
- [208] C. Uyanik, M. Ozkan, and O. Parlaktuna, "Design of an experimental platform for process control systems," in *Proc. Int. Conf. Elect. Electron. Eng.*, 2015, pp. 812–816.
- [209] R. J. Ross, C. M. Boroni, F. W. Goosey, M. Grinder, and P. Wissenbach, "Weblab! A universal and interactive teaching, learning, and laboratory environment for World Wide Web," *ACM SIGCSE Bull.*, vol. 29, no. 1, pp. 199–203, 1997.
- [210] M. A. Bochicchio and A. Longo, "Hands-on remote labs: Collaborative web laboratories as a case study for IT engineering classes," *IEEE Trans. Learn. Technol.*, vol. 2, no. 4, pp. 320–330, Oct.–Dec. 2009.
- [211] IEEE Standard for Networked Smart Learning Objects for Online Laboratories, Section 5.2, Accessed: Apr. 23, 2023. [Online]. Available: <https://standards.ieee.org/ieee/1876/5482/>



**Ricardo Martin Fernandez** (Member, IEEE) received the B.Sc. degree in electronic engineering from National Technological University, San Nicolás, Argentina, in 2000. He is currently working toward the Ph.D. degree with the National University of Distance Education, Madrid, Spain.

He is also a Professor in Electronics and Control Systems with the National Technological University, where he is the Head of the Robotics and Intelligent Vision Research Group.

Dr. Fernandez is a Member of the Excellence Student Society of the IEEE Eta Kappa Nu.



**Felix Garcia-Loro** (Senior Member, IEEE) received the B.Sc. degree in industrial electronics and control engineering and the Ph.D. degree in engineering from the School of Industrial Engineering, National University of Distance Education (UNED), Madrid, Spain, in 2008 and 2018, respectively.

He is currently a Researcher and Assistant Professor with the Department of Electrical, Electronics and Control Engineering, UNED.

Dr. Garcia-Loro is a Member of the Excellence Student Society of IEEE Eta Kappa Nu.



**Gustavo R. Alves** (Member, IEEE) received the Ph.D. and Habilitation degrees in computer and electrical engineering from the University of Porto, Porto, Portugal, in 1999 and 2023, respectively.

Since 1994, he has been with the School of Engineering, Polytechnic Institute of Porto, Porto, where he is currently an Associate Professor and the Head of the Innovation Centre for Engineering and Industrial Technology.



**Russ Meier** (Fellow, IEEE) received the B.S., M.S., and Ph.D. degrees in computer engineering from Iowa State University, Ames, IA, USA, in 1992, 1994, and 1998, respectively.

He is currently the Program Director of the undergraduate Computer Engineering Program and a Professor with the Department of Electrical Engineering and Computer Science, Milwaukee School of Engineering, Milwaukee, WI, USA.

Dr. Meier is a Member of the IEEE Eta Kappa Nu, the IEEE Computer Society, the IEEE Education Society, and the IEEE Professional Communication Society.



**Africa López-Rey** (Senior Member, IEEE) received the bachelor's degree in industrial engineering (specializing in electrical, electronic and control engineering) and the Ph.D. degree in industrial technologies from the School of Industrial Engineering, National University of Distance Education, Madrid, Spain, in 1997 and 2017, respectively.



**Manuel Castro** (Fellow, IEEE) received the doctoral degree in industrial engineering from the Higher Technical School of Industrial Engineers, Technical University of Madrid, Madrid, Spain, in 1988.

He is currently a Professor with the Department of Electrical and Computer Engineering, National University of Distance Education, Madrid, where he is also the Vice Rector and the Director of the Department.

Dr. Castro is a President Emeritus of the IEEE Education Society and the Director of the IEEE Division VI.