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ORIGINAL PAPER

Virtual reality laboratories: a review of experiences

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Abstract

Laboratory experiences are critical to the learning process across all domains of engineering, due to the fact that information technology has changed the educational laboratory landscape. Three general laboratory types are found in engineering education; namely, hands-on, virtual and remote; each of them with its own advantages and drawbacks. In this paper, various types of university laboratories around the world are described to present the updated state-of-the-art. Additionally, a discussion regarding the educational effectiveness of each laboratory format is discussed. Finally, a case study of the development and implementation of virtual reality laboratories and remote labs at *Tecnologico de Monterrey* is presented. Early results have demonstrated that the virtual labs are a viable option to complement and/or replace hands-on labs, mainly because of their low investment, low maintenance costs and ease of replication to meet user demand and, above all, because of their great impact on the new teaching paradigms, where it is necessary to encourage active learning and the development of skills based on challenges. In addition to reviewing the most characteristic learning outcomes of each type of laboratory, different elements that influence the success of teaching and learning processes, such as presence, belief, and collaboration, etc., are reviewed. We hope that this research will serve as a guide for designs of individual, blended or hybrid types of laboratories used for experimental teaching in engineering education.

Keywords Educational innovation · Engineering education · Hands-on labs · Remote labs · Virtual labs

1 Introduction

Laboratory experiences are critical to the learning processes across all domains of engineering. Some researchers think that "lab experiences are at the heart of learning science." Research has shown that students who engage in well-designed laboratory experiences develop important competencies and skills. Laboratory activities help inspire students to further their education and prepare them for high-technology careers by fostering skills sought by potential employers. This topic has implications for education, research and industry. Science professors see laboratories as a way of proving beliefs (laws & methods), while engineering professors see the laboratories as places for applications of scientific theories. Laboratories offer an interactive learning strategy. With their aid, students participate actively in the learning process, have real or almost vivid experiences, can work in group or independently, their attention can also be increased which improves their engagement [1].

A vast array of information technologies can be use within education [2]. They have changed the educational laboratory landscape. Virtual and remote labs used as research areas, growing in numbers during the last years, reduce the costs of hands-on labs (lowering costs of equipment, space, maintenance, updates and training, etc.) by taking advantage of the internet. Human remote control of vehicles, robot manipulators and tactile-feedback systems, etc. are likely to grow in their impact on remote labs, and computer simulated systems with high-fidelity are impacting virtual labs [3].

Virtual and remote labs have been increasing over the years because technology has progressed. "Virtual" is defined as, "imitations of real experiments. All the infrastructure required for virtual laboratories is not real; rather, it is simulated on computers." Remote labs are characterized by mediated reality. Similar to hands-on labs, they require space and devices. The difference between these and hands-on labs is "the distance between the experiment and the experimenter". In real labs, "the equipment might

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be mediated through computer control, but co-located." In remote labs, experimenters obtain data by controlling geographically-detached equipment [4].

Hands-on laboratories entail doing a physically-real investigation procedure (experiment), where all the equipment is set up and students are bodily present in the lab. Students get data from experiments that validate or disprove the theory. There is a need for the experimental area, expensive equipment and instrumentation that are high in investment and operating costs.

Virtual laboratories mimic the real experiments by simulating everything on computers. Simulations can reduce the amount of time for learning; students are allowed to review and understand the experiments in an active mode of learning that improves their performance. Data from virtual labs are not real, even with high performance simulators (which can be expensive), and students could be disconnected between virtual and real experiments.

Remote laboratories mediate reality. The distance between experiment and experimenter defines its main difference from hands-on labs. Real experimental data is obtained by controlling shared and geographically detached equipment. The educational effectiveness between a hands-on lab and its remote version is conditional and limited. However, the control of a remote lab is similar to the control of robots in remote manufacturing. Remote (and virtual) labs may provide ways to share skills and resources, thereby improving the educational experience. They also have additional advantages such as availability, observability, accessibility and safety.

An important concern has been assessing whether virtual and remote labs were able to provide learning outcomes similar to those of hands-on labs. The different viewpoints about educational objectives of hands-on, virtual and remote labs have not converged.

The rest of this paper is organized as follows: Sect. 2 is a discussion of the state of the art of laboratories in engineering education. Section 3 compares and contrasts the three types of laboratories. Section 4 presents a case study developed at *Tecnologico de Monterrey*. Section 5 concludes the paper.

2 State of the art of laboratories

Laboratories were initially conceived for scientists to perform research and to make discoveries. At that time, little effort was made so that students could learn by practice and participating in lab experiments. They were taught with lectures and textbooks, and, in rare cases, an apparatus was shown in class. In the United States, laboratories were introduced as part of students' curricula in the late 1800 s. They began to be used for both faculty research and students' learning. New laboratory formats have emerged in response to educational demands, [5] as science curricula have changed and become modernized. Within education, there are three main general formats of laboratory; namely, traditional, face-to-face- hands-on labs; virtual and simulated labs; and remote/tele-operated laboratories. Research and industrial laboratories are out of the scope of this article.

The educational ones are used in a variety of areas, including physics, chemistry, biology, medicine and engineering [6]. Hands-on labs can be further classified as on-site laboratories and mobile laboratories. The former are built in a fixed physical space, and the latter are hosted in boats, airplanes and cars (e.g., Chicago State University's "Chemistry Van" [7]). Virtual and remote laboratories are considered online laboratories; however, they have great differences regarding their functionalities, as previously mentioned. When the different lab formats are used conjointly or combined, these are classified as hybrid labs [6]. In this case, the idea is to complement the lab benefits of each type in order that students learn to use the different formats and improve their understanding of a given subject [8]. In general terms, virtual labs allow students to learn how a system works; hands-on labs let them analyze and understand the problems that arise due to the variations of parameters; and the remote labs provide ways to share skills and resources that improve the educational experience [9].

Researchers and students have different foci in their use of laboratories. Researchers have three main goals: a) gather and analyze data to design and develop products; b) determine if a given design performs as conceived; and c) generate new knowledge. In the case of students, the main objective is to learn the knowledge that has been already produced [10]. Regarding the pedagogical aspect, each lab format has its own advantages and disadvantages. Hands-on labs foster interactions and collaboration; they also let students learn by trial and error. However, students require supervision and the time for performing the experiment is limited. The main advantage of a virtual lab is the safety it offers when managing dangerous equipment and reagents. It also offers flexibility as students can perform experiments at any time. The main disadvantages are that mentoring is not possible and there is no palpable equipment. In regard to remote labs, they are useful for distant-learning programs and for development of conceptual understanding and professional skills. Their main back draw is that socialization is not possible [11].

There can be several debates about which lab format is best, but the main issue is to determine how these facilities and tools support student learning. Two important aspects to be considered are the perception and satisfaction that students have with the way they are learning. Student satisfaction, in particular, directly correlates to motivation and, thus, student retention [10].

2.1 Laboratory types in practice

This section covers examples of the different laboratory formats within engineering education. (This is not an exhaustive review). It includes brief descriptions of their functionalities and main goals.

2.1.1 Hands-on labs

2.1.1.1 University of Liverpool This university offers to students the *Central Teaching Hub*, a place in which research in the areas of chemistry, physics, environmental science and archaeology is performed [12]. The hub contains eight laboratories that are used by undergraduates to develop their final projects. The labs correspond to the fields of mechanics, radiation, optics and electronics, environmental sciences, computer training and general chemistry. The eighth lab is called the GFlex Teaching Space. It is a high-technology area with movable furniture, where students and professors work collaboratively. All the labs are physically separated; however, the equipment can be shared among subjects and programs. Regarding the available resources, the radiation lab has measurement apparatus, which include Canberra products (the leader in equipment for nuclear safety), germanium, sodium iodide and gas detectors. The optics-and-electronics lab has a dark room for performing optical experiments. It is sponsored by PHYWE, an international specialist in laboratory equipment. The hub was conceived to modernize the university after years of using traditional workrooms. The organization preferred to build a new facility instead of fixing the old spaces [13].

2.1.1.2 Nottingham Trent University (NTU) The Rosalind Franklin Building that contains the NTU lab was built to teach bioscience and chemistry students [12]. Undergraduate and master's degrees students are the main users of this space. They are immersed in lab activities from day one. Lab sessions are explained through radio receivers, and students use tablets to download instructions and to record experiment results for subsequent analysis outside the workroom. This lab has industry-standard equipment such as microscopes, visualizers, optical plate readers and DNA Gel Electrophoresis [14]. An X-ray research area is also available [12]. The lab aids students in learning and applying acquired knowledge, and it also helps them in undertaking innovative, challenging projects which are part of the final grade. The professors want students to make important and significant discoveries that generate new knowledge and contribute to society [14].

2.1.1.3 Cyril and Methodius University in Skopje This university is the largest in the Republic of Macedonia and offers programs in scientific fields [15]. The faculty of Computer Science and Engineering teach a Robotics course, which includes traditional lab sessions. Students have two theoretical classes, two theoretical-exercise classes and two laboratory-exercise classes per week. The robotics laboratory has different types of robots (e.g., manipulators, walking, wheeled and flying robots) serving as learning tools for study and skills practice. Students learn concepts and perform exercises both with the simulators and in the traditional lab. But for doing the course projects, they only use the hands-on lab. In this physical space, students use robots such as Lynx 5, Biped Scout, Nao, Robotics, BH3-R, Pioner3-DX, Arduino-based robots and Ar. Drone, but they also build their own machines (e.g., a color-detection machine robot). In the latter process, they must make a design, obtain necessary supplies build the apparatus and program it. The final project counts 20% of the total grade. It was determined that students performed better under this teaching methodology than in the other pedagogical activities [16].

2.1.1.4 Cardiff University The education of this university focuses on laboratory experience. The laboratory for the Electrical and Electronic Degree Programs was renovated to meet the educational objectives of the organization. Spaces were built to perform both research and teaching activities, so students could observe advanced research procedures and would be used to them when they had to develop their final project [12]. The lab machinery includes Agilent test equipment, which include an Arbitrary Signal Generator, an Oscilloscope, a Digital Multimeter and a Power Supply. Also, AMD processors and LG Electronic monitors are available. With these modern laboratories, students' activities have been developed in a more efficient manner. Their time for completion of the different lab tasks has been reduced, and the teaching practices have been standardized throughout the organization [17].

2.1.1.5 University of Bradford This university has the most vanguard research centers. The technology-driven-STEM Centre, a modern laboratory for developing research in science, technology, engineering and mathematics fields, has the goal to support effective interactions among students and professors. Some of their advanced facility and equipment include interactive touch screens and video walls and recorders [12]. The largest faculty, Life Science, has remarkable lab facilities that offer students, for example, digital autopsy tables in the anatomy and pathology lab and a vast collection of human anatomical specimens so that they can examine body parts in detail. In the School of Chemistry and Bioscience, there is an analytical lab with specialized equipment for students to learn. The Optometry and Vision Science facilities have clinics with the latest equipment for eye examination, e.g., apparatus for detection of disease, ocular measurement and photography, and electrophysiological investigation. They also have devices for use in specialized research in the areas of contact lenses, binocular vision, low vision and diabetes [18].

2.1.1.6 University of St Andrews In 2010, this organization in Scotland promoted the effective exchange of ideas by launching a renovated Chemistry Laboratory in which students of the first semesters can work in the same place. The lab has instrument and preparation rooms, as well as stores of chemicals and equipment, which enable better organization and dispersal of the resources to the students and professors in the time they are needed. Additionally, data processing equipment is offered, and a shared library is available at the center of the building. Two technicians are available to guide and answer student questions. The experiments are identified and organized by a color code for each semester level. The building uses open spaces to foster creativity and innovation. Its capacity accommodates up to 87 students. Users are highly satisfied with the lab environment and arrangement. In the feedback surveys, they state that the building is enjoyable and the lab work has become interesting [12].

2.1.2 Remote labs

2.1.2.1 Massachusetts Institute of Technology (MIT)—iLabs *MIT* remote labs were developed as part of the iCampus project, a research collaboration with Microsoft Research, the main goal of which is to "create and demonstrate technologies with the potential for revolutionary change throughout the university curriculum." [19] These remote labs consist of experimental facilities that can be accessed through the internet and permit faculty and students worldwide to perform experiments from anywhere. Diverse trials are available in iLabs, including those in areas such as electronics, control, physics, spectrometer, telecommunication, RF and Microwave Communications [20]. ILabs is distributed throughout the world—organizations such as the University of Queensland Australia, Makerere University and RMIT University are "subsidiaries" of this innovation. They have equipment and technology to develop, e.g., digital-controller-design-inverted pendulum, power flow control generators and frequency modulation experiments. With such remote labs, engineering students can learn concepts effectively. Depending on the activity design, collaboration skills can be developed [21].

2.1.2.2 Loughborough University The MSc program in Renewable Energy Systems Technology in Loughborough University in England changed its physical laboratories to a remote one in order to offer the lab experience to distance learners. This lab's main goal is to investigate the energy conversion properties of photovoltaic panels [12]; it specifically investigates the effects of temperature and irradiance on PV panels using a measurement called the IV curve [22]. In the remote system, students can observe the apparatus through a webcam, manipulate parameters and download data for analyses [12]. Advanced technology and great effort were required to transform the physical lab into this remote one. Hardware, various devices and LabVIEW software were used to achieve the project goal [22].

2.1.2.3 ReLOAD This is a remote laboratory developed by the University of Leeds (UK). Initially only used by its faculty and students, it now has been opened to other universities, such as the University of British Columbia [23] and the University of College London. Experiments that can be performed include those in vibration and control areas (e.g. vibration beam experiments). Students work via a webpage in which different parameters are available to be submitted, so that they can use the equipment to perform the experiment. At the end, graphs and videos of the results are submitted to the student [24]. The system takes advantage of the LabVIEW software and its architecture that enables easy, user-friendly handling and interactions [23].

2.1.2.4 NetLab This is an online remote laboratory in the area of electronics developed by researchers of the University of South Australia. Experiments include practices such as AC Circuit Phasor Analysis, RC Circuit Analysis and Series Resonant Circuit. The remote lab is highly realistic, and students manipulate it through a PC. The main distinctive characteristic of NetLab is that students are able to collaborate. The system supports multiple learners working at the same time and in the same experiment [25]. The lab has high accessibility, is easy to manipulate and is also fun for the students [26]. Students can perform experiments and practice in order to develop their abilities, "24/7." They only have to schedule their times in the lab through a booking tool in the system [25].

2.1.2.5 Blekinge Institute of Technology This Swedish institute offers to students around the world remote access to laboratories in the fields of circuit analysis and electronics [27]. Among the equipment that students can manipulate for building circuits are an oscilloscope, a multimeter, a function generator and a power supply [28]. Participants can work individually or in a synchronistical way, as up to eight computers can be connected to the remote network. They are supervised by a mentor who uses mainly Netmeeting to communicate and support the students. Professors and students can separate the lab sessions through a booking tool offered by the remote system. In the lab sessions, participants are connected by their computers to observe the different circuits. Using a mouse, they are able to manage the instruments, change parameters and receive the lab results [27].

2.1.2.6 University of Siena The Information Engineering Department of the University of Siena (Italy) developed the Automatic Control Telelab, a web-based platform in which students can perform experiments in the area of robotics remotely [29]. Students can interact with a robot manipulator, the 6-DoF KUKA KR3, to do basic and advanced experiments like inverse kinematics and visual servoing (VS) [30]. Also, experiments with a dc motor, a tank, a magnetic levitation system, and a 2-DoF helicopter are offered. Three forms of remote execution are available; namely, through a control experiment using a predefined controller; through a control experiment using a user-defined controller; and through a student competition experiment. The last option refers to an experimental process which is evaluated and ranked. The lab interface is simple, and all the necessary information, such as general information, the laboratory user guide and a list of experiments, is displayed in a user-friendly manner [29].

2.1.3 Virtual labs

2.1.3.1 TEALsim This is a web-based-simulation space developed through the Technology Enabled Active Learning (TEAL) Project at MIT. One of the main objectives of this tool is to offer to students knowledge in the area of electromagnetism. The distinctive aspect is that the experiments enable students to see phenomena not possible in real settings, for example, to visualize the invisible magnetic field lines [31]. Some of the system features include user-interface components, pluggable-application-"Look and Feel" templates, an HTML browser, simple audio support, visualization tools, real-time-3D rendering and a well-defined simulation model [32].

2.1.3.2 E-Space This is a web tool developed through the Virtual Community Collaborating Space for Science Education (VccSSe) project, the main objective of which is to promote the use of virtual instruments in science education. Several institutions from the UK, Romania, Spain, Greece, Poland and Finland participated in the development of this project [31]. E-space is comprised by a set of 55 virtual experiments arranged in categories such as Mathematics, Physics, Chemistry and Technology/Electronics. Some experiments include electrical resonance studies, Curie temperature investigation and parallel resistors for the creation of a simple circuit. The main features of this web tool include a browser, an uploader of experiments and a content translator [33].

2.1.3.3 ChemCollective This virtual lab project was developed by Dr. David Yaron, Associate Professor of Chemistry at Carnegie Mellon (Pennsylvania), with the support of software engineers, undergraduate programmers, educational consultants and technical writers [34]. It offers several virtual experiments in the chemistry field and includes tools such as scenario-based-learning activities, tutorials and tests. Users have a wide spectrum of reagents which can be manipulated as in real chemistry labs [35]. Students can work individually or in teams, and activities that can be performed range from preparation to laboratories and homework to in-class exercises [34].

2.1.3.4 Ironmaking This is a virtual laboratory developed by RWTH Aachen University (Germany) aimed at studying iron production [36]. As this is a complicated process, the main distinctive characteristic of this technological advance is the Visual Simulation Model (VSM) software it has, which enables an interactive interface [35] that monitors the activities done by students, evaluates quizzes and analyzes student performance [31]. Some features of this virtual lab are video streaming, online textbooks, interactive tests, videoconferences and specific simulations of the iron process [36].

2.1.3.5 Technical University of Madrid The virtual laboratories of this university were created in 2010 as a result of the GriblabUPM project. This is an educational innovation platform in which virtual labs of the colleges of the Technical University of Madrid are hosted. Students of biotechnology, biology, robotics, agroforestry, continuum mechanism, industrial [37], electronics, chemistry, physics and topography can develop practical abilities in an innovative and safe way. This platform is built on the open-source software, OpenSim [35], and almost 30 laboratories have been created.

For example, the chemical lab has three virtual buildings. The first one contains visual material, and, in it, some basic experiments can be performed with the aid of avatars. In the other two, Civil Engineering students can do experiments to determine metals in polluted soil. The electronics laboratory has experiments related to analog electronics. Students can use virtual instruments and change different parameters of virtual circuits [37].

2.1.3.6 EBiolabs This virtual lab from the University of Bristol (UK) was created in response to a need; namely, students were not well prepared for developing practices and did not learn what was expected. In EBiolabs, students develop different activities in the platform. Before doing the experiment, they take a quiz based on the experiment information. They receive the grade and feedback automatically. Then, they are ready to perform the virtual practical, which consists of an interface in which interactive animations and videos regarding the topic studied are presented. Finally, they complete post-lab assignments with the data gathered during the experiment. They have to enter the data into an electronic form and then analyze it and develop a report. The university states that this tool has aided them to increase student satisfaction in applied tasks [38].

3 Laboratories assessment

No consensus has emerged regarding the impact that these technological advancements might have on student learning.

In support of hands-on labs, some researchers argue there is much more information when working with real equipment. However, present evidence exists that supports virtual labs as potentially sufficient replacements, where students have multiple opportunities to access resources (including time) to complete specific activities that foster deeper learning. In addition to pedagogical considerations, the economic differences between these lab types are significant factors.

Findings in literature suggest that achievements in learning outcomes are different in virtual, remote and hands-on labs in all the learning outcome areas. However, outcomes and assessment tools were not consistent, so the KIPPAS framework was developed as a reference to assess and compare proposals of different type of labs [39] (see Table 1). KIPPAS is an acronym for Knowledge and understanding, Inquiry skills, Practical skills, Perception, Analytical skills and Social and scientific communication. In addition, the goals of laboratory experiences [5] and practices in science and engineering were considered in this proposal [40].

With respect to the practices of science and engineering, the NRC framework considers as essential for all the students to learn and describe in detail are: (1) Asking questions (for science) and defining problems (for engineering); (2) Developing and using models; (3) Planning and carrying out investigations; (4) Analyzing and interpreting data; (5) Using mathematics and computational thinking; (6) Constructing explanations (for science) and designing solutions (for engineering); (7) Engaging in argument from evidence and 8.-Obtaining evaluating, and communicating information.

A brief description of each learning outcome type will be included. It is important to think about the end purpose of the laboratory in engineering education [39].

“Knowledge and understanding” was the only outcome measured in every type of lab because the studies consider conceptual understanding, and most of the research shows evidence of higher or equal learning outcome achievement in virtual and remote labs compared with hand-on labs in this [4]. Five of eight of the practices of science and engineering are associated with this outcome [40]. Inquiry (skills) is at the core of scientific learning. Laboratory experiments must clarify and validate scientific principles and theories. Laboratories must direct students to explore the limitations of the equipment, the materials and the theory that students are trying to validate. Scientific research has its origin not only in objective facts alone but also in conceptions, a construction of the mind [41]. It is necessary to go beyond knowledge and, thus, beyond facts and results to know how new knowledge could be generated. Very few research projects of laboratories measure the inquiry skills as a learning outcome, even though there are four practices associated with this outcome [40]. And although the expectation is that hands-on labs would favor practical skills achievement, some results have indicated the opposite, that there are many high-performance-training simulators for developing these skills.

Perceptions of students about the laboratory experience may have more cognitive impact on them than actual content or psychomotor means associated with its completion. Students with great lab experience are likely to be lifelong science learners and informed scientific decision makers [42].

Analytical skills, regarded as an essential learning outcome, is associated with six of eight practices of science and engineering. Potential employers demand this in college graduates; however, very few studies have addressed this learning outcome.

Finally, social and scientific communication suggest that students must discuss their ideas, write reports, develop presentations and communicate with others [43]. Students should invest time in learning how to explain their projects clearly to the public. In many experimental laboratories courses, learning occurs in groups, and cooperative learning can improve content achievement and communication skills.

Learning outcomes can be achieved with equal or greater frequency with virtual and remote labs, regardless of the outcome category being measured under the KIPPAS framework. The degree of difference depends upon the outcome category. Studies supporting higher achievement in virtual and remote laboratories seem to place a lot of emphasis on content knowledge and understanding, whereas studies in favor of hands-on labs seem to rely heavily upon qualitative data related to student perception [39].

A few studies showed that virtual and remote labs are equally or more effective as hands-on labs at enabling use of the constructivist approach to teaching and learning. This approach emphasizes the importance of students taking an active role in their on learning. Physical manipulation, which can enhance learning as in hands-on labs, is not needed, according to constructivist or cognitive learning theory.

The effectiveness of any type of laboratory is related to the directness of its link to the real world [44]. Virtual and remote labs were questioned for their inability to provide authentic settings and interaction in the beginning.

Table 1 Categories of intended outcomes for labs learning

	Learning outcome		Description	NRC 2006 Lab goals	NRC 2012 Practices
K	Knowledge and understanding	The degree to which students…	…model theoretical concepts and confirm, apply, visualize and/or solve problems related to important lecture content	Enhancing mastery of subject matter	1, 2, 3, 6, 7
I	Inquiry skills		…make observations, create and test hypotheses, generate experimental designs and/or acquire an epistemology of science	Developing scientific reasoning; understanding the nature of science	1, 2, 3, 5
P_1	Practical skills		…can effectively use scientific equipment, technology, and instrumentation, follow technical and professional protocols, and/or demonstrate proficiency in physical lab techniques, procedures, and measurements	Developing practical skills.	2, 3
P_2	Perception		…engage in and express interest, appreciation and/or desire for science and science learning	Cultivating interest in science and interest in learning science	
A	Analytical skills		…critique, predict, infer, interpret, integrate, and recognize patterns in experimental data and use these to generate models of understanding	Developing scientific reasoning; understanding the complexity and ambiguity of empirical work	2, 4, 5, 6, 7, 8
S	Social and scientific communication		…are able to collaborate, summarize and present experimental findings, prepare scientific reports and graph and display data	Developing teamwork abilities	8

Engineering fidelity concentrates on the closeness of virtual environments to physical surroundings, while psychological fidelity is seen as the key factor for the effectiveness of a virtual device. A virtual approach with psychological fidelity can lead to a high transfer of learning and even low physical fidelity [45].

There are three types of presence: physical, remote, and virtual. Physical presence is associated with real labs. Remote is feeling like you are actually there at the remote site of operation. Virtual presence is feeling like you are present in the environment generated by the computer [3]. Beliefs are more important in order to justify the students' behavior when they work with computer-assisted learning [46].

Virtual and remote labs provide additional forms of presence that compete with physical presence. Perception of reality influences more than physical reality [47]. The sense of presence is related with the level of performance; it is one of the factors leading to higher task performance. However, different studies show the causal relationship between presence and performance is not clear.

The preferences of the students and their learning performances cannot be attributed to the type of laboratory. It is important to focus on how their mental activities are engaged in coping with the type of lab, their motivation, peer collaboration, feedback, media, etc. All of these factors generate the right interactive and immersive settings that lead to a space that students perceive as real. Students in a virtual/remote lab where the reality is faked/mediated by distance may experience psychological, but not physical, presence. However, students in hands-on labs could be exposed to a physically real process, but may not experience psychological presence, because they are bored (e.g., watching others interact with the real process) or distracted.

Another important factor related to learning performance is the students' collaboration. Even if remote labs are not as efficient as hands-on labs, the experience of working geographically with students and equipment/devices is educationally important to compensate for any problem in the technology. Also, there is value to well-constructed group activities used in virtual labs and in the feasibility of developing design skills [4]. New technologies allow new forms of coordination to compensate for possible isolation of students engaged in remote learning.

Based on the aforementioned research projects and the state-of-the-art, the general advantages and disadvantages of each type of laboratory are summarized in Table 2.

The educational objectives used to evaluate labs (hands-on, virtual and remote) differ. The competing technologies measure against different objectives. They all can indicate better performance, but each one is based on a different criterion. Based on the KIPPAS framework, the typical learning outcomes that each type of laboratory could generate are shown in Table 3. By "typical results", what are considered are the stated goals and implicit goals based on the discussions or the reported results and conclusions reported in the research articles.

Although the KIPPAS framework is a good approach for analyzing the different types of laboratories, there are different factors related to educational effectiveness, and sometimes successful results are mis-associated with the technology used or the type of laboratory. However, students' preferences and learning outcomes are the result of many coupled factors. Also, it is difficult to compare research projects which focus on different scientific domains; the effort should be focused on areas that looks the most promising. The effectiveness of laboratories may be affected by how much students believe in them; therefore, an understanding of presence, interaction and belief may lead to better interfaces.

The availability of any type of laboratory is not a sufficient condition to ensure success in the teaching/learning process. Any type of laboratory offered as a stand- alone setting, without connection to adequate learning material, usually leads students to the use of a trial and error strategy, which has a lower learning impact [48]. Learning Management Systems (*LMS*) could support in this task. *LMS* support the administration, documentation, tracking and reporting of training/educational programs; additionally, these systems enable rich contexts for social interactions of students (geographically distributed), even in virtual contexts exploiting collaboration tools.

A blended/hybrid approach (i.e. combination of hands-on, virtual and/or remote labs) could be a better proposal for the experimental engineering education instead of using only a single type of laboratory. A blended/hybrid approach can exploit the key features of each type of laboratory, based on the learning outcomes to be developed. Hands-on labs could be used in the first stage to build confidence in virtual and/or remote technology used in a second stage (based on the point of view of belief). This proposal must consider the suitability of the laboratory to accomplish the learning outcomes (taking the KIPPAS framework), the support of the laboratory for learning coordination and its capability to accommodate the individual differences of the students, e.g., grade level, cognitive style, psychological development, etc.

4 Implementation of virtual reality labs (VRL) and remote labs

Currently, automation courses for Mechatronics and Industrial Engineering demand that automation tasks be followed in real systems, because there is a constant need for industry-focused qualifications. However, the real systems that represent different type of industrial processes (e.g., a

Table 2 Advantages and disadvantages of each type of laboratory

Advantages	Disadvantages
Hands on lab	
There is nothing more real	They can only be used by a restricted number of students
There is a need to have physical objects at some point for learning	High investment and operating costs
Real data is generated	An improper handling of real equipment could lead to dangerous situations
Design skills are the distinctive learning outcome	Many times, hands-on interactions are only computer mediated
Facilitates the socio-constructivist theories that argue learning is a constructive and collaborative process	The presence of physical process is not always a requirement for understanding related concepts
Virtual lab	
They give a cost-effective solution and extra detail can be seen	Data from virtual labs are not real, even with high performance simulators
Several students can use the same virtual equipment at the same time	Students could be disconnected between virtual and real experiments
It is possible to simplify models to make phenomena more visible	Students could focus on the simulation procedures instead of the academic goals
Helps students visualize processes that normally are beyond perception	Fidelity is poor in some domains; students may show lack of seriousness, responsibility and carefulness
Damage is allowed in virtual labs; it is possible to learn from mistakes	It may be impossible to substitute real equipment to acquire fine skills in training
Simulations could reduce the amount of time for learning	Students rely on simplified models that do not correspond to real-life situations
Information technology is becoming more manipulative and interactive	The learning experience of identifying the differences between theoretical and real models may be missed
Experiments are easily replicable including expensive/dangerous simulations	
Students can speed up slow-dynamics systems for quick visualization	
Remote lab	
Real data is obtained by controlling/sharing distant equipment	They could be considered unrealistic and thought of as simulation labs
Similar to the control of robots in remote manufacturing	Their development and maintenance is usually expensive; however, its flexibility could justify the investment and operation costs
They may provide a way to share skills and resources	
Its flexibility increases the number of times and places a student can use it	
It allows collaboration from multidisciplinary professors/educators	
Costly/complex equipment and software can be used from different locations	
Students, in different locations, can take advantage of the same facility	
Learn about the existence of different types of measurement errors	

Table 3 Categories of intended outcomes for labs learning

	Learning outcome		Hands-on	Virtual	Remote
K	Knowledge and understanding	The degree to which students…	******	******	*****
I	Inquiry skills		****	***	*
P_1	Practical skills		****	****	***
P_2	Perception		******	***	****
A	Analytical skills		****	****	***
S	Social and scientific communication		***	**	**
Comments			Usually the 6 learning outcomes are well addressed. Special emphasis in K & I, P_1 & A are important goals	K, I, P_1 & A are key learning outcomes	Typically, they are focused on K & P_1

Stars indicate a relative level of achievement of the learning outcome storage warehouse, a transportation and sorting system, a manufacturing cell, etc.) are very expensive, and they are almost impossible to acquire and update for a university. Their investment and operating costs are very high. The design and implementation of remote labs and virtual labs represent an important option to resolve these challenges at universities and to open new opportunities. Remote and virtual labs could be an excellent option to consider instead of hands-on-labs.

4.1 Remote labs

Remote labs have tele-operated real equipment, and they are more complex and expensive than virtual reality labs. The main components of the remote labs are a scale model of the process, a Programming Logical Controller (*PLC*), two video cameras and a PC-server. Remote labs follow a Server-Client architecture. Figure 1 shows one of the implemented remote labs at *Tecnologico de Monterrey* with all the components [49].

4.1.1 Architecture

The remote lab of Fig. 1 simulates an automatically working high-level-storage system as used in many industrial companies. The model consists of a rack being divided up into 5×10 storage places, a warehouse operating device and two charge–discharge stations. A cage with a telescopic palette carrier is attached to the warehouse operating device.

The simulated process shows palettes being stored and withdrawn from the high-level storage. In case of one charge station being occupied by a palette, the telescopic palette carrier moves to the station and takes over the palette. This is recognized by a reflection light switch. Following this, the warehouse operating device brings the palette to the intended storage place in an optimized manner by moving in x-direction and z-direction at the same time. Occupying a storage place is recognized by software. In order to enable a quick movement to the storage place, on the one hand, and a safe lay-in movement on the other, the horizontal rack positions are equipped with advanced mechanical switches that allow retarding the warehouse operating device before reaching the intended position. Withdrawing palettes occurs in the same manner, done in inverse chronological order.

The access to the remote labs is controlled via a web page, where students can book separate 2 or 3 h for a specific day. Students use the remote labs to validate a specific practice that represents an automation sequence of the plant or process. Figure 2 shows the web page and the scheduling system where students schedule the day and the hours to use the remote labs.

When students need to access the remote labs, they use a web-based application that interacts with the server-side of the remote labs to tele-control the actual setup and to visualize information from the lab (e.g., video streaming, sensor data, etc.). Students have an App (application), which is running in their PC, and it allows them to connect to server-side via internet. The *HMI* launched is shown in Fig. 3, where the main window corresponds to the *PLC*, another window is used to visualize the front or lateral video camera of the warehouse storage, and the last window shows an *HMI* to manually manipulate the different actuators of the plant.

4.1.2 Objectives

The implementation of a remote lab with this kind of equipment reduces implementation and operational costs in a significant way, mainly because, instead of building a lot of stations for a traditional lab, only a few are set up, and they can be shared with all the campus. The costs of this proposal could mean a reduction of up to 80% of the costs of a hands-on lab [50]. The main objectives of remote labs are the following:

- The remote labs must be available 24 h per day and all days of the year. Students can access the remote labs

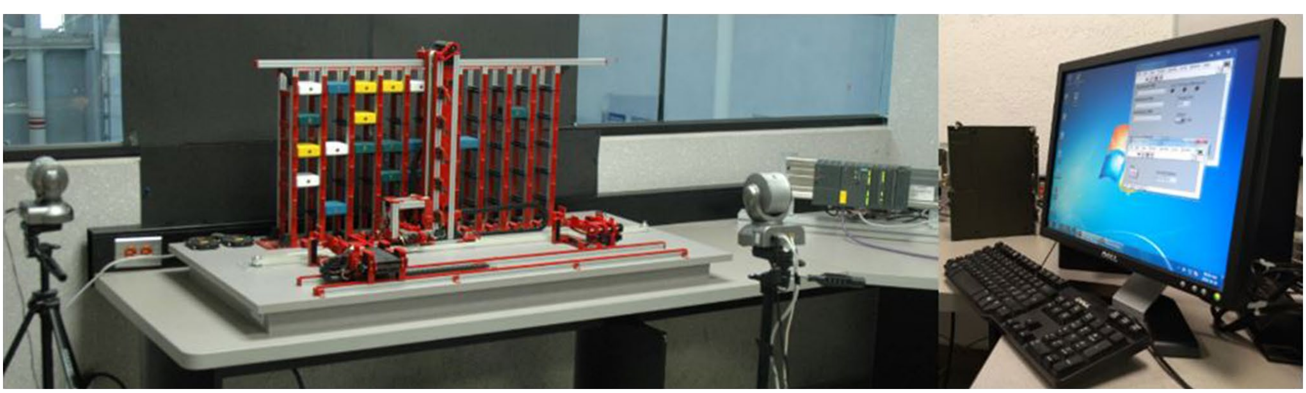


Fig. 1 Remote lab of the warehouse storage unit with two video cameras, PLC and PC-Server

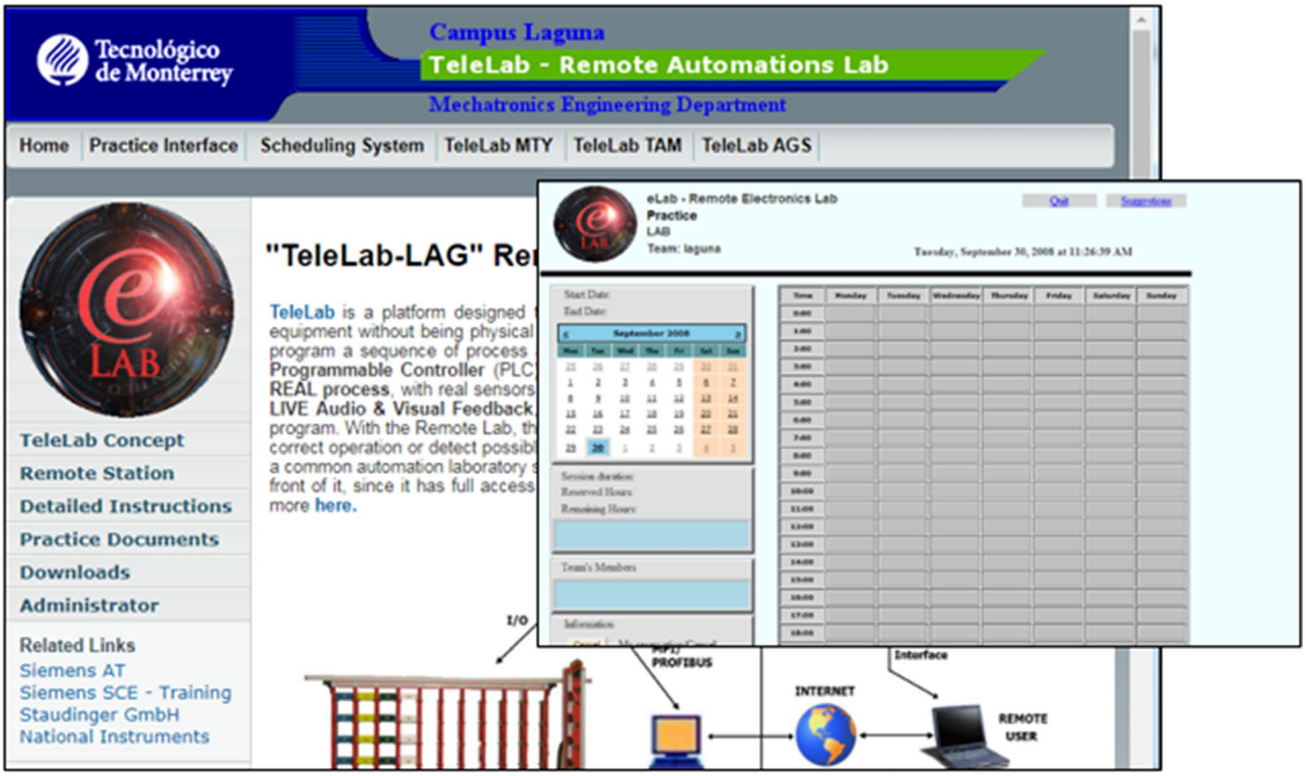


Fig. 2 Web page of the remote lab and the scheduling system

during the nights or weekends according to the availability of the lab.

- The remote labs can be used during the class. That is a huge advantage, because the teacher can demonstrate important automation concepts immediately with the remote labs projected in front of students.
- Students can validate and acquire skills to apply the automation concepts acquired during the class with the professor.
- The remote labs allow visualization and demonstrate the correct operation of the automation sequence implemented during the practices assigned by the professor.
- The remote labs must be available for all the students and professors.

4.2 Virtual reality labs (VRL)

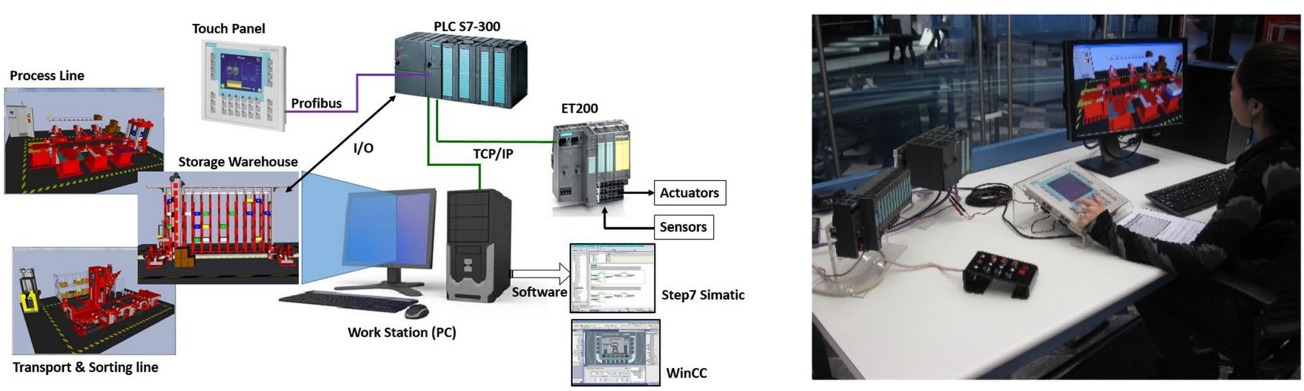
The *VRL* was implemented so that students perform a prior validation of the automation programs developed before testing them in the remote lab. This considerably reduces the damage that can be caused in the real system (remote labs) due to common and frequent errors in the programming of an automation sequence, when students do not have sufficient skills and knowledge in programming with *PLC*s.

4.2.1 Technological platform of the VRL

VRL is based on the use of the Virtual Reality Machines (*VRM*). The *VRM* represent 3D computer models that reproduce the operation of a real system (e.g., manufacturing cell, storage warehouse, transport and sorting line, etc.) with the integration of sensors and actuators that are connected directly to the *PLC*. The sensors send information to the *PLC* to identify a specific operating condition, and the actuators receive the permissive from a *PLC* to turn on/off a conveyor, *CNC* machine, and other plant equipment. Students can manipulate the *VRM* (rotate, zoom in, zoom out and move) to identify the main elements that are necessary in an automation process, and they can understand how the different components work in a specific process. Figure 3 shows some examples of *VRMs* that are connected with the *PLCs*. A complete description of the *VRM* is presented in [51].

The implementation of the *VRL* in Tecnologico de Monterrey included 4 workstations and a main station with one TV screen to project a complete virtual manufacturing plant. Figure 4 shows the different components of the workstation: personal computer, a *PLC*, touch panel, distribution system, and several *VRMs* that represent different manufacturing processes. The main components of the workstations are industrial equipment. Students work and practice with

Fig. 3 *HMI* used by students to interact with the remote lab. The main window represents the *PLC* to control the execution of the automation sequence. The other two windows define the video cameras installed in front and side of the warehouse storage. Finally, an *HMI* is shown to manually manipulate the actuators of the plant



System architecture

Workstation with all its components

Fig. 4 Workstation with all components and some examples of the virtual reality machines the *VRL* system as if they were working with a real system. Both exhibit equal interfaces.

The computer allows the student to write down a specific automation sequence, linked via ethernet or a fieldbus with the *PLC*, which controls the process system; also, the *PLC* is connected with an *HMI* via ethernet in which the user can control the process. Finally, *PLC* sends and receives digital signals to/from the *VRM*. In summary, the students have to learn how to program in different system languages a *PLC* and validate the automation sequence in several *VRMs* that represent a warehouse storage, an elevator, a transport and sorting line and manufacturing cell.

Figure 5 depicts the complete distribution of the laboratory, four workstations, the main station and different industrial networks used to link the different components and control the automation sequence of a manufacturing plant.

The equipment of the four workstations and the main station of the laboratory presents the versatility of communications through the use of different types of industrial networks (i.e., MPI, PROFIBUS, PROFINET and ETHERNET). This versatility allows students to know, analyze and evaluate different communication alternatives of the devices in order to control and monitor the manufacturing processes. The design, selection and implementation of all the equipment, programs, modelling and integration of VRMs was developed by the *Tecnologico de Monterrey* [52].

4.2.2 Objectives

The main objective of the *VRL* is to involve and provide an *Active Learning* environment that allows students to learn the new technologies involved in industrial networks and integrated manufacturing systems.

When students are coursing academic subjects in engineering, the best way to learn is by practicing. Some important advantages of using the *VRL* are the following:

- *Enhance Concepts*: Having a *VRL* enables the student to continue learning beyond the classroom.
- *Motivation:* A laboratory with instruments or machines with presence in industry is an extra motivation for the student to learn.

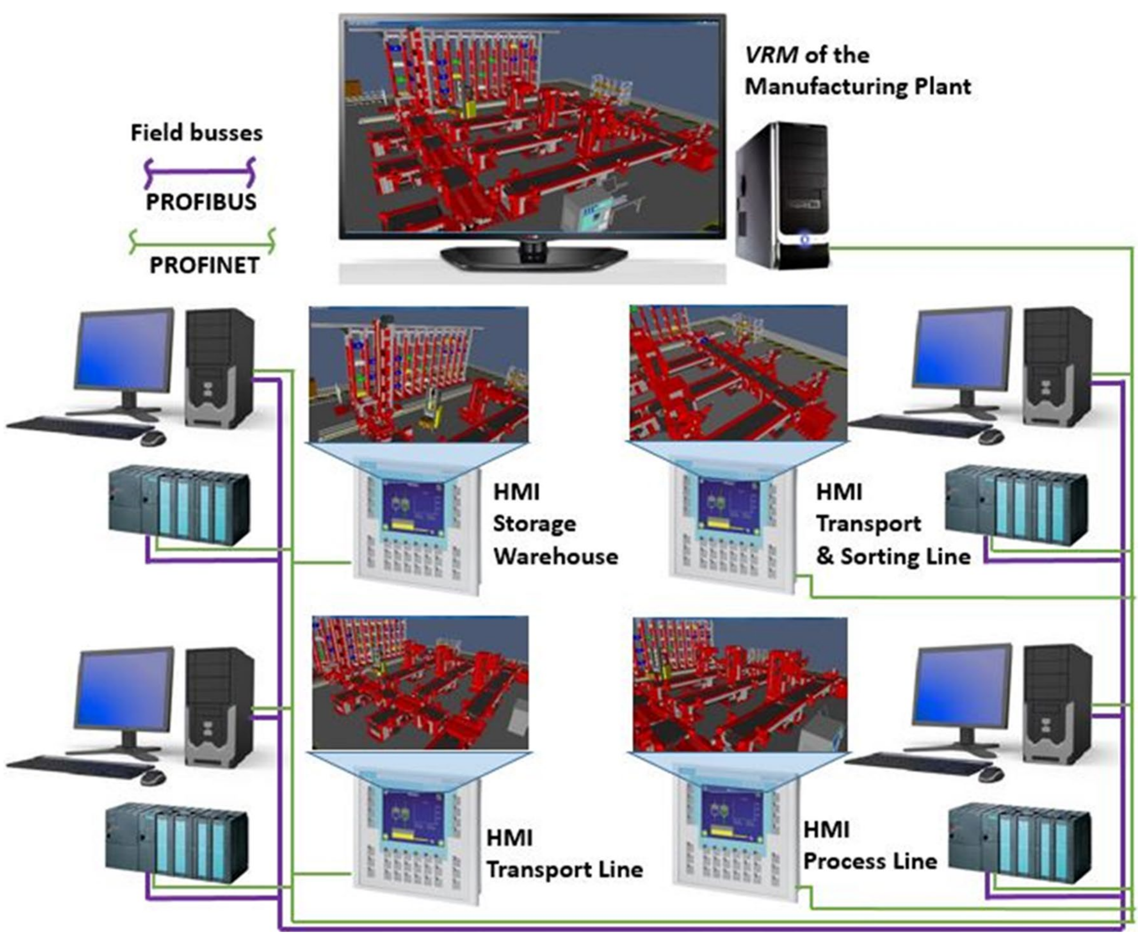


Fig. 5 Virtual laboratory of automation of processes used in industrial networks and integrated systems of manufacture courses

- *Diversity:* Using the virtual machines, *VRL* could easily possess an assortment of similar machines or processes, which will add diversity to each laboratory session and which will enable the student to program diverse processes.
- *Competencies:* The student acquires skills and strengths during the different practices and projects developed, allowing him/her to demonstrate the acquisition of the competencies that were established at the beginning of the course.

4.3 Academic objectives

Industrial Networks is a course that allows students to be able to propose efficient solutions related to the design and installation of industrial networks in process automation; to analyze, understand and learn about the most representative models, protocols, topologies, and devices involved in industrial communication networks; and to learn about automation for the total integration of plants and/or industrial processes by using *PLC*s and their transmission methods.

Integrated Manufacturing Systems is a course where students are able to recognize different technologies and equipment that can be found in an integrated manufacturing system. Some technologies that students must learn are related to *PLCs*, *HMI* and industrial communication buses.

During both courses, students must develop practices and produce a final project that allows them to satisfactorily fulfill the objectives of both courses.

The *VRL* allows the professor to teach the theoretical concepts of process automation as well as to explain the different topics related to the ladder and functional block programming languages used in a *PLC* and then put it into practice by using the industrial equipment and the *VRM*. Therefore, the objectives of the practices are to validate, demonstrate and solve the automation challenges of different processes by applying the theoretical concepts of *PLC* programming. A typical class with the *VRL* involves a minimum time to explain the theory. Then, students are involved with the *VRL*, where after programming an automation sequence, they can see, touch, analyze, and check the results of their learning and validate the theoretical concepts. In a traditional automation course, the students sometimes use the simulators to emulate the *PLC,* and they never have contact with a real *PLC,* so it is not possible to validate the programmed automation sequence in a real situation.

After validating the sequence of automation in laboratory practices in the *VRL*, some practices request the demonstration of programming by using remote labs. Therefore, the student proceeds to load the programs in the *PLC* of the real process (remote labs) to perform the corresponding demonstration.

Table 4 shows a typical sequence of laboratory practices developed for the use of the virtual and remote lab in a course of automation and industrial networks.

4.4 Competences and/or skills

VRL is an option of low-cost equipment used as a high-tech educational source that allows students to validate and demonstrate their results and skills based on theory and practice. The *VRL* allows students to develop the competencies that are demanded in their professional field. These competencies are the following:

- Ability to apply knowledge in practice. Students apply the knowledge acquired in a wide variety of automation practices, which allows understanding and reinforces the theoretical concepts seen in class.
- Knowledge of the area of study and profession. Being in contact with industrial *PLC*s, touch panels for the *HMI* and industrial networks, students are involved with the automation technologies that are currently used in their professional fields.
- Ability to identify and solve problems. The available *VRM* (storage warehouse, manufacturing cells, elevators, Cartesian robots, transport lines, etc.) allows developing practices that define very diverse situations of automation and control. This variety of equipment and processes allows teachers to pose different challenges that students must solve in the area of automation and process control.

The evaluation is made by considering four levels of competency development. The professor must apply the rubric shown in Table 5 during the evaluation of three specific practices during the semester. A feedback of the student's progress in the competencies is given individually to students.

4.5 Experiences

During the last 4 years, both the remote lab and the *VRL* have been used in the courses of *Industrial Networks*, *Project of Industrial Networks* and *Integrated Systems of Manufacturing* for students of mechatronic engineering and industrial and systems engineering. Previously, these courses were offered practically in a traditional-theoretical format due to the high costs of having industrial or didactic equipment for a hands-on-lab. The students did not show the same interest and enthusiasm to learn and know the current technologies for automation and integration of manufacturing systems. In the current courses, students can visualize and analyze the behavior of productive systems when using the *VRL* and remote lab and when developing the corresponding programming in the *PLC* to meet the diversity of challenges related to the operation of the plant or manufacturing processes. The

Table 4 Typical laboratory practices

Name	Objective	Application of VRL and remote lab
1. Project creation, *PLC* hardware configuration and interface configuration	The student will learn the process to configure the *PLC* hardware and create a MPI/Profibus/Ethernet interface between the *PLC* and the plant	The *VRL* allows the student to know the real parts of a *PLC*, as well as the use of industrial software (SIMATIC Manager) to configure an interface and know the diverse hardware components used in the industry
2. Logical functions AND, OR/SET-RESET operations in programming	The student will apply the concepts of programming in ladder language for the automation of an operative sequence of movement of Warehouse Storage	The *VRL* platform allows the student to understand the basic programming in ladder language as well as to execute the sequence of automation and visualize the results in the *VM* of the Warehouse
3. Logical functions AND, OR/SET-RESET and timers	The student will apply the logical functions AND, OR, Set-Reset and timers of the ladder language for the automation of an operational sequence in a processing line	The *VRL* platform allows the student to know and correctly understand the different options to program timers and visualize their effects in the virtual machine of the process line
4. Programming by blocks for the application of counters and comparators	The student will learn the concepts of programming by using function blocks to carry out a classification of pallets and then download them in the corresponding column in the warehouse storage	The *VRL* allows the student to validate the programming done to classify the pallets and then use the remote lab to load the program into the *PLC* and check the loading, sorting and unloading of pallets in the correct column of the pallet
5. HMI	The student will develop an *HMI* with the use of industrial software to supervise and monitor the operation of the warehouse	The student learns to use the industrial software to design and implement an *HMI* and thus be able to control and monitor a process in the *VRL*. Subsequently, the *HMI* is validated using the remote lab to remotely control the warehouse
6. Communication between two or more controllers (PLCs)	The student will learn to configure and communicate two or more *PLC*s, using MPI/PROFIBUS field buses and the Ethernet network	The student uses the *VRL* to configure and communicate two or more PLCs through the use of MPI, PROFIBUS or Ethernet networks. The student validates the transfer of information between the various controllers to manipulate the operation of different processes (*VM*s)

Table 5 Competency levels

Competence	Competency levels 1	2	3	4
Ability to apply knowledge in practice	The student has problems identifying the correct knowledge to solve an automation sequence for a specific *VRM*	The student resolves 80% of the automation sequence with the knowledge acquired for all *VRMs*	The student resolves 90% of the automation sequence with the knowledge acquired for all *VRMs*	The student has enough skill and knowledge to resolve any automation sequence defined for all *VRMs*
Knowledge of the area of study and profession	The student has problems understanding how to connect the *PLC* and *HMI* with the *VRM*	The student has some problems configuring the *PLC* and touch panel with the *VRM*. The student defines the correct industrial network to communicate devices with the *VRM*	The student understands very well how to configure the *PLC* and *HMI*,but he/she has some problems identifying the network to communicate all devices with the *VRM*	The student understands perfectly how to configure the *PLC*, touch panel, and the different industrial networks to communicate all devices with the *VRM*
Ability to identify and solve problems	The automation sequence is not complete because the problems identified in the programming are not resolved	The problems in the automation sequence are resolved with the help of the mentor and/or other students	The automation sequence is almost complete, but some errors are detected in the programming that do not allow restarting the automated process	The automation sequence is complete, and the automated process can be reinitialized once again without any problem

availability of various virtual reality machines allows different challenges to be offered each semester, enabling students to acquire and strengthen the skills demanded by the productive sectors in the corresponding engineering areas.

Additionally, in the current courses, the number of students with failing grades has been reduced. Students attend punctually and enthusiastically at the scheduled hours of practice in the *VRL*s. Likewise, students perceive an improvement in their automation-sequence-programming skills as the course progresses and when using the *VRL*. The verification of the sequences of automation with the remote lab increases the confidence and dexterity of the students to carry out the programming of any plant or process in the manufacturing industry. After checking in the *VRL,* the students really feel satisfied and amazed to see that the results observed in the operation of the remote lab correspond with what is specified in their practices. In a survey of 175 students about their perceptions of the use of the remote labs, the following results were obtained:

- 92.11% of students like to work with technology in their learning processes.
- 94.87% of the students perceived that the remote lab helps a better understanding of the topics seen in class.
- 92.31% think that they would like to use activities related to the remote lab in other engineering courses.
- 100% consider that the remote lab connects the theoretical concepts of the class with reality.

4.6 Discussion

The current advances in *IT*, computer systems, internet of things and the digitalization of systems have allowed the development of simulators of manufacturing plants and production systems with a high definition of image and realism in their animations that emulate almost perfectly the real systems. The integration of these virtual simulators with real automation equipment (augmented virtual reality) guarantees a process of visual, active and collaborative teaching for students.

*VRL*s currently implemented are a very attractive option because of their low cost, their ease of replication to meet the demand for use and their flexibility and versatility to increase the virtual models that emulate industrial processes. However, they have certain limitations in terms of their real-time response; the adequate dynamic response of their mechanical components; and the correct modeling of the hysteresis of activation and deactivation of inductive sensors and actuators.

Therefore, the combined use of the *VRL* and remote lab present a favorable option to compete with the hands-on-labs. They represent an innovative teaching process in this century, breaking paradigms and borders through the remote

Table 6 Learning outcomes for *VRL* and remote lab approaches

	Learning outcome	Results for *VRL*	Results for remote lab
K	Knowledge and understanding	Students learn and reinforce theoretical knowledge by developing laboratory practices. The practices allow the students to validate theory with practice, and even when there is a mistake in the development of the practices, this does not cause physical damage to the equipment	The professor can use the lab in class to demonstrate theory with practice and promote interactions among students to confirm the correct interpretation of the theory. It is not appropriate for students to use the remote lab to demonstrate some theoretical concepts for the physical damage they can cause
I	Inquiry skills	Students validate different options to program in ladder language to achieve the same result in the sequence of automation requested in the practices. Individually, the student feels motivated to investigate options to achieve a more efficient and structured programming	The remote lab does not allow improving research skills in terms of more structured and efficient programming. Programming errors can be very costly for the damages that can be caused to the equipment
P	Practical skills	As the different practices are developed during the course, considerable progress can be observed in the ability to program and solve more complex situations in the automation sequences of the processes	The correct validation of the practices in remote lab represents a great satisfaction for the students, allowing them to demonstrate the skills acquired in the language programming ladder or blocks
P	Perception	The student shows greater interest and enthusiasm in solving the different challenges that arise in the practices and projects and in being involved in an active learning environment and the visual and active parts of the *MRV* in the *VRL*	The interest and enthusiasm of the student to make use of the remote lab is of less impact with respect to the *VRL*. This is because all the practices are validated first with *VRL* and then in the remote lab
A	Analytical skills	The application of challenges of great complexity, such as the automation of a manufacturing plant, allows the development of competency in the ability to identify and solve problems. The work teams are more analytical, critical and predictive when dealing with this type of problem	The remote lab does not greatly encourage the development of skill proficiency to identify and solve problems; therefore, it does not allow the development of analytical and creative skills in students
S	Social and scientific communication	The participation of students in the challenges at the end of the course encourages collaborative work & results in the leadership of certain team members, as well as group participation for the demonstration and final presentation of the project	Students are strongly motivated to demonstrate that their collaborative work results in the automation of a manufacturing plant at the end of the course

use of these labs. Table 6 summarizes and compares the results for both *VRL* and remote labs.

5 Conclusions

Laboratory experiences are an essential part of engineering education. They help students to reinforce concepts, develop and practice skills and apply the acquired theory. Information technology has changed the laboratory-education landscape. Based on a state-of-the-art review, different types of laboratories in universities around the world were described. These included the labs in the University of Liverpool, Nottingham Trent University, MIT and Loughborough University.

It was determined that, regardless of the laboratory type, there is a great use of different types of technologies that have impact, such as technologies with specialized technical equipment, robots, computers, software and networks. Hands-on labs rely on technology, also, to facilitate student learning. Learners have tablets, radio receivers, interactive touch screens, video walls, recorders and data processing equipment in order to make the learning processes more efficient.

Regarding virtual and remote labs, some of them used for engineering education are iLabs, ReLOAD, NetLab, TEALsim, E-Space, ChemCollective and Ironmaking. It was determined that there is a sense of collaboration and sharing of technology among organizations; e.g., iLabs' remote labs from MIT can be used by students of universities around the world in diverse organizations such as the University of Queensland Australia and RMIT University. In fact, these are *subsidiaries* of this innovation.

The different lab formats are used by students to learn concepts, to practice skills and apply them during the development of projects. All the organizations have one goal when investing resources in the different type of laboratories, and that is to improve students' technical skills and help them to acquire knowledge better, so they can enter a competitive labor force.

A case study at *Tecnologico de Monterrey* showed that virtual remote and remote laboratories used in the courses of the engineering careers have demonstrated that these labs are a viable option to replace the hands-on laboratories, chiefly because of their low costs, the ease of replication to meet user demand and the great diversity of virtual reality machines that can be used. These have great impact on the new teaching paradigms that encourage active learning and the development of skills based on challenges. Among engineering students, these laboratories have had a great impact and acceptance as well. According to surveys given to students, more than 90% confirm their interest in working with the new technologies and having achieved greater learning with the use of the virtual remote labs and remote labs.

The availability of any type of laboratory is not a sufficient condition to ensure success in the teaching/learning process. Any type of laboratory offered as a stand- alone setting, without connection to adequate learning material, usually leads students to the use of a trial and error strategy, which has a lower learning impact.

A blended/hybrid approach (i.e. combination of hands-on, virtual and/or remote labs) could be a better proposal for the experimental engineering education instead of using only a single type of laboratory. A blended/hybrid approach can exploit the key features of each type of laboratory based on the learning outcomes to be developed. Hands-on labs could be used in the first stage to build confidence in the virtual and/or remote technology that would be used in the second stage (based on the point of view of belief). The proposal must consider the suitability of the laboratory to accomplish the learning outcomes (using the KIPPAS framework), the support of the laboratory for learning coordination and its capability to accommodate the individual differences of the students, e.g., grade level, cognitive style and psychological development, etc.

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References

1. Senthamarai, S.: Interactive teaching strategies. J. Appl. Adv. Res. **3**, 36–38 (2018)
2. Hernandez-de-Menendez, M., Morales-Menendez, R.: Technological innovations and practices in engineering education: a review. Int. J. Interact. Des. Manuf. (2019) (**in Press**)
3. Sheridan, T.B.: Musings on telepresence and virtual presence. Presence Teleoperators Virtual Environ. **1**(1), 120–126 (1992)
4. Ma, J., Nickerson, J.V.: Hands-on, simulated, and remote laboratories: a comparative literature review. ACM Comput. Surv. **38**(3), 1–24 (2006)
5. National Research Council: America's Lab Report: Investigations in High School Science. The National Academies Press, Washington (2006)
6. Zapata, L., Larrondo, M.: Models of collaborative remote laboratories and integration with learning environments. Int. J. Online Eng. **12**(9), 14–21 (2016)
7. Chicago State University.: What is the Chemistry Van. http://tyff.tripod.com/Outreach/chemvan.html. Accessed 30 Oct 2018
8. Viegas, C., Pavani, A., Lima, N., Marques, A., Pozzo, I., Dobboletta, E., Atencia, V., Barreto, D., Calliari, F., Fidalgo, A., Lima, D., Temporão, G., Alves, G.: Impact of a remote lab on teaching practices and student learning. Comput. Educ. **126**(July), 201–216 (2018)
9. Cotfas, P.A., Cotfas, D.T., Gerigan, C.: Simulated, hands-on and remote laboratories for studying the solar cells. In: Joint International Conference-ACEMP 2015: Aegean Conf on Electrical Machines and Power Electronics, OPTIM 2015: Optimization of Electrical and Electronic Equipment and 2015: International

Symposium on Advanced Electromechanical Moti, pp. 206–211 (2016)
10. Feisel, L., Rosa, A.: The role of the laboratory in undergraduate engineering education. J. Eng. Educ. **94**(1), 121–130 (2005)
11. Elawady, Y., Tolba, A.: Educational objectives of different laboratory types: a comparative study. Int. J. Comput. Sci. Inf. Secur. **6**(2), 8 (2009)
12. Gibbins, L., Perkin, G.: Laboratories for the 21st Century in STEM Higher Education. Centre for Eng and Design Education, p. 102 (2013)
13. University of Liverpool.: Central Teaching Hub. https://www.liverpool.ac.uk/central-teaching-hub/. Accessed 29 Oct 2018
14. Nottingham Trent University.: The Rosalind Franklin Building. https://www.ntu.ac.uk/study-and-courses/courses/our-facilities/the-rosalind-franklin-building. Accessed 29 Oct 2018
15. Ss. Cyril and Methodius University in Skopje.: University. http://www.ukim.edu.mk/en_content.php?meni=10&glavno=10. Accessed 29 Oct 2018
16. Ackovska, N., Kirandziska, V.: The importance of hands-on experiences in robotics courses. In: 17th IEEE International Conference on Smart Technologies—IEEE EuroCon 2017 Conference Proceedings, pp. 56–61 (2017)
17. Cardiff University.: Power electronic lab. http://www.cardiff.ac.uk/research-equipment/facilities/view/power-electronic-lab. Accessed 29 Oct 2018
18. University of Bradford.: Faculty of Life Sciences. https://www.bradford.ac.uk/life-sciences/. Accessed 30 Oct 2018
19. MIT ICampus.: iLabs. http://icampus.mit.edu/projects/ilabs/. Accessed 27 Oct 2018
20. MIT.: About iLabs (2011). https://wikis.mit.edu/confluence/display/ILAB2/about+iLabs. Accessed 27 Oct 2018
21. Corter, J.E., Esche, S.K., Chassapis, C., Ma, J., Nickerson, J.V.: Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories. Comput. Educ. **57**(3), 2054–2067 (2011)
22. Williams, S.R., Blanchard, R., Mohammed, A., Bliss, M., Pancholi, R., Clowes, M.: The development of a remote laboratory for distance learning at Loughborough University. In: Edulearn13: 5th International Conference on Education and New Learning Technologies, pp. 4342–4349 (2013)
23. Levesley, M.C., Culmer, P., Page, K., Gallagher, J., Weightman, A.P.H., Bhakta, B.B., Tennant, A., Cripton, P.: development and evaluation of personalised remote experiments in an engineering degree. In: WEBIST 2007: Proceedings of the 3rd International Conference on Web Information Systems and Technologies, Vol SeBeG/eL: Society, E-Business And E-Government, E-Learning, pp. 330–337 (2007)
24. Hanson, B., Stamp, A., Read, E.: The Use of Real Labs Operated at a Distance (Reload) as a Teaching Aid. The Higher Education Academy, New York (2008)
25. NetLab, "What is NetLab?," About NetLab. http://netlab.unisa.edu.au/about/whatIsNetLab.xhtml. Accessed 28 Oct 2018
26. Nafalski, A., Nedić, Z., Machotka, J.: Remote engineering laboratories for collaborative experiments. In: 2nd World Conference on Technology and Eng Education, pp. 101–103 (2011)
27. Gustavsson, I., Zackrisson, J., Olsson, T.: Traditional lab sessions in a remote laboratory for circuit analysis. In: Proceedings of the 15th EAEEIE Annual Conference on Innovation in Education for Electrical and Information Engineering (2014)
28. OpenLabs Electronics Laboratory.: Welcome. http://openlabs.bth.se/electronics/index.php/en?page=StartPage#. Accessed 30 Oct 2018
29. University of Siena.: Automatic Control Telelab. http://act.dii.unisi.it/home.php. Accessed 31 Oct 2018
30. Gomes, L., Bogosyan, S.: Current trends in remote laboratories. IEEE Trans. Ind. Electron. **56**(12), 4744–4756 (2009)
31. Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V.M., Jovanović, K.: Virtual laboratories for education in science, technology, and engineering: a review. Comput. Educ. **95**, 309–327 (2016)
32. Center for Educational Computing Initiatives.: About TEALsim. http://web.mit.edu/viz/soft/visualizations/tealsim/index.html. Accessed 27 Oct 2018
33. Gorghiu, G., Bîzoi, M., Gorghiu, L.M., Suduc, A.M.: Web tools and instruments created in the VccSSe European project with the view to support science teachers' experimental activities. Procedia Soc. Behav. Sci. **15**, 1231–1235 (2011)
34. ChemCollective.: Introduction, About. http://chemcollective.org/about_us/introduction. Accessed 27 Oct 2018
35. Lynch, T., Ghergulescu, I.: Review of virtual labs as the emerging technologies for teaching STEM subjects. In: 11th International Technology, Education and Development Conference, pp. 6082–6091 (2017)
36. Babich, A., Mavrommatis, K.: Virtual laboratory concept for engineering education. In: International Conference on Engineering Education and Research "Progress Through Partnership", pp. 1043–1050 (2004)
37. Fernández-Avilés, D., Dotor, D., Contreras, D., Salazar, J.C.: Virtual labs: a new tool in the education: Experience of Technical University of Madrid. In: Proceedings of 2016 13th International Conference on Remote Engineering and Virtual Instrumentation, REV 2016, pp. 271–272 (2016)
38. University of Bristol.: The eBiolabs story. http://www.bristol.ac.uk/ebiolabs/more/. Accessed 31 Oct 2018
39. Brinson, J.R.: Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: a review of the empirical research. Comput. Educ. **87**, 218–237 (2015)
40. National Research Council: A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. National Academy Press, Washington (2012)
41. Schwab, J.J., Brandwein, P.: The Teaching of Science. Harvard University Press, Cambridge (1962)
42. Koballa, T., Kemp, A., Evans, R.: The spectrum of scientific literacy. Sci. Teach. **64**(7), 27–31 (1997)
43. Michaels, S., Shouse, A.W.: Ready, Set, Science!. National Academies Press, Washington (2008)
44. Cooper, M., Donnelly, A., Ferreira, J.M.: Remote controlled experiments for teaching over the Internet: a comparison of approaches developed in the PEARL project. In: Proceedings of the ASCILITE Conference on Auckland New Zealand, p. M2D.1-M2D.9 (2002)
45. Patrick, J.: Training: Research and Practice. Academic Press, San Diego (1992)
46. Vuorela, M., Nummenmaa, L.: How undergraduate students meet a new learning environment? Comput. Hum. Behav. **20**(6), 763–777 (2004)
47. Biocca, F.: Inserting the presence of mind into a philosophy of presence: a response To Sheridan and Mantovani and Riva. Presence Teleoperators Virtual Environ. **10**(5), 546–556 (2001)
48. Pereira, C.E., Paladini, S., Schaf, F.M.: Control and automation engineering education: combining physical, remote and virtual labs. In: 9th International Multi-Conference on Systems, Signals and Devices, pp. 1–10 (2012)
49. Macias, M., Vallejo, A., Ramirez, D.: Remote and real time laboratories network for engineering education. In: 11th LACCEI Latin American and Caribbean Conference for Engineering and Technology, pp. 1–10 (2013)
50. Macías, M.E., Méndez, I.: TeleLab—Remote Automations Lab in Real Time. In: 38th ASEE/IEEE Frontiers in Education Conference SIB-15, pp. 15–20 (2008)

51. Salazar, E.A., Macías, M.E.: Virtual 3D controllable machine models for implementation of automations laboratories. In: 39th ASEE/IEEE Frontiers in Education Conference, pp. 1–5 (2009)
52. Macías, M.E., Guridi, E.D.: Emulation of real processes to improve training in automation. Int. J. Eng. Educ. **00**(0), 1–7 (2008)