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RESEARCH ARTICLE

A Flexible Framework for the Deployment of STEM Real Remote Laboratories in Digital Electronics and Control Systems

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ABSTRACT The present work proposes a flexible framework for the deployment of real remote laboratories (RRLs). These kinds of laboratory allow students to access hands-on experiences and experiments through an online platform, eliminating the geographical and time constraints associated with traditional on-site laboratories. This innovative approach has proven especially valuable in STEM disciplines (Science, Technology, Engineering, and Mathematics), where hands-on practice and interaction with specialised equipment are critical to learning. In our approach, RRL has been developed for practices in digital electronics and control systems considering multiple practical situations related to distant learning using RRLs accessible through an online booking system. This is an essential tool that allows students to make reservations accessing the practical platform and due to that, it has been integrated into a particular learning management system (LMS) using a separate database online server for greater flexibility and usability. To perform laboratory activities remotely, each RRL instance has local ad hoc hardware that enables the generation and control of different signals letting users to test different practices with the same hardware. The proposed framework can be applied in many knowledge fields and different educational levels for laboratory resource sharing allowing students to receive new teaching technologies online that allow them to use real laboratory equipment avoiding the use of simulations and related constraints to on-site laboratories.

INDEX TERMS Control systems, digital electronics, laboratory resource sharing, real remote laboratory, real-time remote experiments, remote laboratory management, STEM distance learning.

ABBREVIATIONS AND ACRONYMS

RRL: Real remote laboratory.
LMS: Learning management system.
STEM: Science, Technology, Engineering and Mathematics.
HEI: Higher education institution.
DECS: Digital Electronics and Control Systems.
VPN: Virtual private network.
AD2: Digilent Analog Discovery 2.
VM: Virtual Machine.
DUT: Device under test.
OS: Operating system.
PWM: Pulse-width modulation.
DAC: Digital-analogue converter.
RDP: Remote desktop protocol.
AR: Augmented reality.
VR: Virtual reality.

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I. INTRODUCTION

Distance learning and real remote laboratories have emerged as a transformative technologies solution to enhance practical learning experiences in various educational domains, including the fields of science, technology, engineering and mathematics (STEM) [1], [2]. The rapid advancements in information and communication technologies have paved the way for these innovative approaches, offering unprecedented opportunities for students and educators alike.

The integration of RRLs in STEM education offers several advantages [3]. Distance learning allows learners to access educational content and interact with instructors remotely, transcending geographical barriers. It enables flexible scheduling and self-paced learning, accommodating the needs of a diverse student population. Additionally, it provides access to high-quality educational resources and facilitates collaborative learning through online platforms. RRLs allow students to remotely access and control real scientific instruments and conduct experiments, providing them with a hands-on learning experience that bridges the gap between theoretical knowledge and practical applications, eliminating the limitations imposed by physical distance and resource availability, comparable to traditional on-site laboratories. The integration of distance learning and remote laboratories has opened up new avenues for Higher Education institutions (HEIs) to enhance the educational experience in STEM fields.

But also, RRL systems presents important disadvantages in comparison with on-site laboratories solution [4], [5]. While distance learning undoubtedly provides numerous advantages, the challenges stemming from the lack of reliable internet quality outside major cities, and sometimes its complete unavailability, significantly hinder the organisation of such learning option. Moreover, It is essential to acknowledge that RRLs demand significant self-discipline and the ability to independently delve into specific subjects. Unlike traditional on-site laboratories, where students are physically present in a structured classroom setting with direct supervision from the teacher, remote learning provides a more independent and flexible space. Students engaged in RRLs often need to manage their own time, set priorities, and maintain focus without the immediate supervision of a teacher. The absence of physical resources and face-to-face interactions requires students to take greater responsibility for their learning journey, including adhering to schedules, completing assignments, and staying motivated. Furthermore, spending a substantial amount of time in front of a computer screen can cause issues such as physical inactivity and potential health concerns, like eyes tiredness or back pain. Furthermore, the absence of direct contact with the teacher and the lack of access to computer equipment further amplify the limitations of this learning mode, which can make the learning experience more difficult and not very friendly in some cases.

Although RRLs offer unparalleled advantages such as time efficiency and access to an extensive amount of resources and hardware, their successful implementation requires a greater commitment from educators to motivate students and foster knowledge expansion. The following subsection will illustrate different RRL proposals, providing an overview of the current state of the art in RRLs.

A. STATE-OF-THE-ART OF RRLs

Real remote laboratories have a particular difference from virtual laboratories, as RRLs typically consist of a physical setup of scientific apparatus, sensors, and measurement devices that are remotely connected to a web-based interface accessible by students. Virtual laboratories can be set up on a local machine owned by the student and try to mimic real conditions. Real and simulated practices can be used both in the learning path. The RRL interface should be equivalent to the physical place, therefore students can manipulate the equipment, collect data, perform experiments, and analyze results, but remotely [6].

Between real remote laboratories and virtual laboratories, there are other approaches that use web-based frameworks. In this regard, it is worth mentioning the LabLands approach based on open-source WebLab-Deusto API software [7], which makes available an experiment or practise with an explicit web interface built for it. One well-known example in the field of electronics is VISIR; however, users complain that the interface is outdated and requires specific technical support [8], [9].

Another important aspect to consider is whether there is a substantial distinction between these remote controlled laboratory web interfaces compared to other virtual simulators [10]. For example, the circuit simulator applet Faldstad is ready to use and at no additional cost. Another initiative that uses the HTML5 interface is the Networked Control System Laboratory (NCSLab) [11]. In the NCSLab, multiple users and virtual/remote experiments can be performed on top of the platform, but the interface is not the real one, but a composition offered remotely to the user and particularly adapted to the practice. In these approaches, remote equipment is used and mixed with a virtual web interface possibly enriching the features of the system.

By engaging in hands-on experiments, students can develop practical skills such as problem-solving, data analysis, and decision-making [12]. In addition to virtual laboratories based on simulations, with RRLs students observe real phenomena, leading to a deeper understanding of theoretical principles. The interactive nature of these laboratories fosters student engagement and encourages independent exploration, enhancing the overall learning experience.

The emergence of the COVID-19 pandemic precipitated an unprecedented shift in educational paradigms, forcing institutions around the world to move rapidly from traditional on-site laboratory learning to distance learning solutions. Faced with the imperative to ensure the safety of students and educators while maintaining educational continuity, the sudden closure of physical campuses led to the rapid adoption of virtual platforms. This unexpected transition required the development and implementation of distance learning solutions, challenging educational institutions to adapt their curricula, teaching methodologies, and laboratory practices to the digital realm.

For example, engineering students at Oulu University of Applied Sciences, underwent a significant transformation with the closure of the campus, necessitating a complete switch to remote learning. Teaching was facilitated through digital learning environments and assessments were administered through electronic exams [13]. For some parts the students perceived that transformation was successful, but in many parts, there were clear challenges in the digital remote learning. They remarked that they had some connectivity problems and expressed a desire for a more defined division of labour among themselves. These kinf of issues, highlighted above as the main disadvantages of RRLs, constitute one of the primary drawbacks of distance learning systems and should be considered diligently during the development of such platforms.

Article [14] presents a solution for a junior-level undergraduate microelectronics course during pandemic COVID-19. The remote laboratory developed rapidly by the institution used five Digilent Analog Discovery 2 (AD2) modules, each linked to a dedicated Virtual Machine (VM) accessible to students through a Remote Desktop connection. Students were allocated specific time slots on designated VMs. Through this interface, the students gained the ability to manipulate a physical circuit and successfully conduct experiments comparable to those performed in on-site laboratories. This RRL approach has some similarities with the one we are proposing and will be described as of section II. The main difference between this solution and ours is that we created an application letting students to independently manage their reservations for the RRL; time slots are not assigned directly but can be selected by the students. Additionally, we designed a web-based application to generate various signals for assessing diverse responses to users' programs. This differs from the alternative approach, where users merely load the code without the capability to modify the program's response behavior. In any case, the approach presented by the author demonstrated cost-effectiveness, scalability and all while preserving the essential pedagogical objectives.

In [15] an Open-Hardware-Based solution for a FPGA remote laboratory was developed that supports diverse FPGA hardware and a range of HDL experiments focused on interfacing with various peripheral components. Additionally, it facilitates remote access to essential software packages, enabling the execution of exercises not only on PCs but also on tablets or smartphones. This solution presents a cross-platform, allowing users to conduct tests without relying on a PC. This flexibility provides users with the freedom to perform their tests in spaces where they feel most comfortable. However, a key drawback of this approach is that students are provided with pre-developed programs, limiting their involvement to loading the code and checking results. In contrast, our approach involves users in the complete process, starting from the development of the code, its compilation, loading onto the board, and subsequently checking the response to various input signals. This approach allows users to explore different scenarios using the same program, enhancing their engagement and understanding. Although this, most of the students who tested this Open-Hardware-Based solution RRL offered positive feedback, believing that it offered hands-on experience with real hardware during the pandemic, an opportunity that would otherwise have been unavailable for testing on real hardware.

As can be shown, the pandemic acted as a catalyst for innovative approaches, pushing the boundaries of distance learning and reshaping the landscape of face-to-face laboratory teaching.

Article [16] discusses the integral role of teaching laboratories in engineering education, emphasising their contribution to experiential learning. Acknowledging the challenges posed by social distancing measures, the text proposes alternative modes of delivery, exploring insights from distance learning and virtual laboratories. Moreover, it aims to identify evidence-based approaches for transforming hands-on laboratories into virtual or remote operations in the post-COVID-19 era.

Article [16] states that remote delivery of laboratory experiences can effectively bridge the gap between theoretical knowledge and practical application, especially in circumstances where physical access to laboratories is limited. Although this approach requires careful planning and design of remote laboratory environments to ensure effective learning outcomes with the correct instructor support to guide and engage students to do the RRL practices.

In addition to their pedagogical benefits, RRLs also contribute to cost-effectiveness and sustainability. Real hands-on laboratories require significant investments in infrastructure, equipment maintenance, and consumables. The RRL approach makes the physical laboratory available 24/7, allows resource sharing with other HEIs. In this sense, the LabsLand RRL Federation [7] proposes the implementation of an open-sharing platform for RRLs. This platform aims to facilitate the sharing and exchange of remote laboratory resources among educational institutions, enabling access to a wider range of experiments and equipment.

RRL enables learning on demand, facilitating the shift from traditional structured learning environments to more flexible and personalized learning experiences that are driven by learners' immediate needs and interests [17]. They extend the usage time for students while reducing travel costs and time away.

There are precedents of university institutions that have worked on the development and implementation of remote laboratories applied to the study of technological engineering. Some significant ones are cited below.

At the Karlsruhe Institute of Technology (Germany), they have developed the "Robot Learning Lab", a remote-accessible robotics laboratory that allows students to access the laboratory's robots remotely and run their own projects on them [18]. The laboratory consists of ten robots, each equipped with a manipulator arm with force/torque sensing capabilities and machine vision, a 3D sensor, and a webcam for remote viewing of the experiment. Students also obtain logs and data collected during the experiments.

The Swiss Federal Institute of Technology Lausanne provides students, through its "Remote Lab of the Automatic Control Laboratory", equipment for remote teaching of control systems that consists of twenty-two stations for online practices including servo-drivers, temperature control systems, and a inverted pendulum [19].

The University of New South Wales (Sydney) offers students from the School of Electrical Engineering and Telecommunications the possibility of working remotely in the laboratory from their homes. They do this through a remote access software interface to generate and measure time-varying voltage and current waveform, and working with software and re-configurable hardware to build circuits. Additionally, a webcam and Microsoft Teams are used for increased feedback and interaction with the system [20].

At the MIT Lincoln Laboratory, the Mobile Devices Laboratory offers remote assessment methods of mobile device technology before its deployment in the field. Researchers can test location-based service applications, model protocols for packet loss, and practice mobile malware triage without interfering with public wireless networks [21].

The University of Edinburgh, through its "Remote Labs", facilitates the connection from the student's own computer to a laboratory computer to be able to use certain applications. Not all applications are available to all users; the student's course enrolment determines which applications they have access to [22].

The University of Missouri-Kansas City also offers remote access to a variety of specialized software commonly used by University students, faculty and staff. The selected software has been specifically optimized for remote access [23].

University of Alcalá has a long trajectory working on the development of system that ease the reservations and enable access to remote resources [24]. The goal is that the equipment could be managed both on-site or online, using the corresponding booking system and increasing the operational hours of the equipment, thus reducing the amortization time.

The RRL hybrid use opens a new type of collaborative learning approach, including internationalization skills as multicultural exchanges are possible. Remote collaboration can enhance the student's skills with internationalization-at-home activities. The authors of [25] emphasize the benefits of collaboration among educational institutions across borders, such as the sharing of resources, expertise, and best practices in the development and implementation of remote laboratories. New challenges and opportunities emerge together with the remote laboratories to expand international cooperation for education on a global scale.

To reduce costs, typically a smaller area of the laboratory, even a cabinet, can be used for the RRL equipment, controlling its illumination and air-conditioning requirements [26]. Yet another potential benefit of the RRL approach is to increase the safety of end-users as they are performing the experiment or practice at a distance. The setup is properly prepared by a qualified laboratory technician or teacher.

From the state-of-the-art review related to remote laboratories, it can be observed that there are multiple areas that are in need of improvement:

1) **Enhancing User Experience**: it is required to improve the user interface and usability of remote laboratories platforms to enhance the overall user experience. This may involve designing intuitive interfaces, incorporating interactive elements and implementing features that promote user engagement and ease of use.
   In our developed system, our aim is to grant access to an identical set of tools and computers, striving to replicate the configuration of a traditional on-site laboratory setup. The visual component will be facilitated through a webcam capturing the platform (development board, sensors, and actuators). Additionally, a web-based interface will be employed to deliver input signals and control the visualization of the generated signals from a multiplexer, ensuring the seamless execution of experiments. This integrated approach is designed to offer a remote experience that closely mirrors that of a on-site laboratory environment.
2) **Security and Privacy**: given the sensitive nature of data and equipment in remote laboratories, it is necessary to address security and privacy concerns. A robust authentication mechanism, data encryption techniques, and privacy-preserving protocols must ensure the integrity and confidentiality of student information.
   In our approach, we have used the HEI VPN (Virtual private network), to reduce the number of attacks and propose a changing password mechanism for each student session on a STEM RRL instance that only let the user to access and use the RRL instance the time slot they booked, expelling the user when the time out of the reservation is reached. Only students that are enrolled in the course and have a VPN account can access the RRL, preventing from security problems that other remote laboratories may have.
3) **Scalability**: as the demand for remote laboratories grows, the capacity for expansion becomes crucial. Therefore, it is imperative to implement a system that is easily scaleable, with minimal integration costs for accommodating different technologies.
   Our contribution to this field is to develop a framework that facilitates a scaleable architecture, contingent upon sufficient network bandwidth and minimized latency within the laboratory premises. This enables the seamless integration of additional hardware com-

ponents such as actuators and sensors. Moreover, the framework supports the flexibility to transition to different development boards or integrate various instances of RRL on a single remote computer.

The overarching objective of this project is to design and implement a comprehensive system that serves as a catalyst for improvement across STEM areas, namely enhancing user experience, fortifying security and privacy, and fostering scalability. The system will be intricately crafted to ensure user-friendly interfaces, intuitive navigation, and seamless interaction, contributing to an overall positive and efficient experience for all students that will be working with the RRL developed. Simultaneously, robust security and privacy mechanisms will be incorporated, with a particular focus on implementing access controls. This proactive approach aims to safeguard user data and system integrity, mitigating potential risks associated to external attacks to the system by protecting it with the HEI VPN. Additionally, scalability will be a pivotal aspect, with the system designed to adapt and accommodate evolving needs, whether in terms of expanding user capacity or integrating new technologies. By addressing these key areas comprehensively, the developed system seeks not only to meet but to exceed the expectations of users, laying the foundation for an user-friendly, secure, and scalable STEM remote laboratory environment.

The paper is organized as follows. Next section presents our proposed RRL framework with an overview of the methodology employed. Section III presents briefly the main features of the online booking system that RRL requires. Section IV shows the development of a RRL platform focused on Teaching Digital Electronics and Control Systems and presents the web-based application developed to generate and control different signals useful for testing the user's programs. In section V some of the practices that were carried out on the developed RRL and the feedback given by those students it is shown. Discussion is carried out in Section VI. Finally, conclusions and future work are drawn in Section VII.

II. RRL FRAMEWORK

In our proposal, see Fig. 1, the remote laboratory system schema consists of the following parts:

1) **LMS environment**. We consider that HEIs have any LMS (Moodle, Blackboard, etc.) to store online courses information and interaction among students and teachers. Let us assume that a particular authentication system is in place and remote students can gain access through a VPN mechanism to different online services offered by the HEI.
2) **Booking system**. An online booking system that assigns different roles based on the LMS registration, with the ability to provide a mechanism to gain access and control specific remote online resources during a time slot previously booked.
3) **RRL instances**. Multiple laboratory equipment instances will be available for remote operation by both professors and students. These instances can serve both online and onsite users, with differentiation for maintenance and laboratory area organization. Each remote instance typically comprises two different types of physical elements:
   a) Practice elements, the very same modules that should be used for the same hands-on experiment in the standard on-site laboratory.
   b) Management modules that makes possible the remote control of the practice. In the electronic area, all the signal generators, digital inputs, etc. should be controlled remotely.

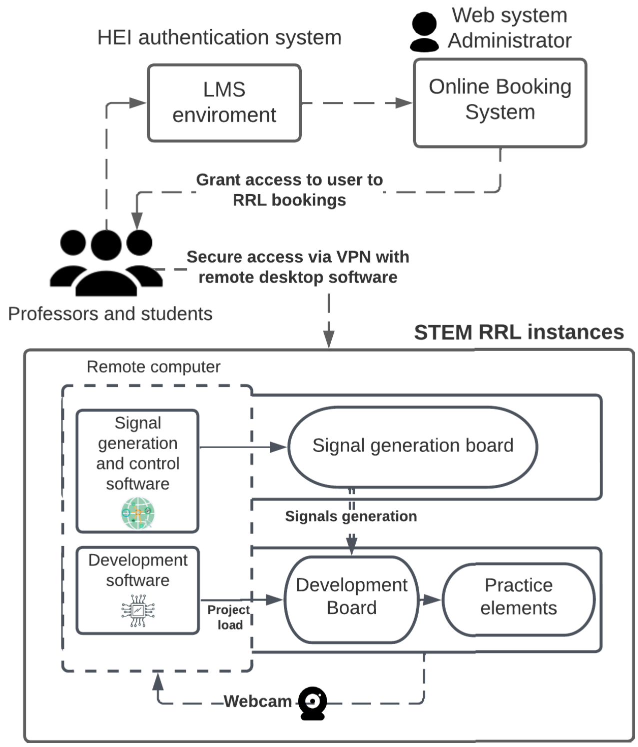


FIGURE 1. Proposed RRL framework.

Only registered users, authenticated via the mechanisms established by the HEI and VPN access are considered. For ease operation, the online booking service obtains and reuse the registered user data from the LMS. Therefore, the RRL instance can be made available directly in the selected LMS courses. Clicking on the configured link (See Fig. 2) the registered users access seamlessly the online booking system with those credentials.

To ensure flexibility and broad usability across institutions, our integration of the booking system with the LMS is not reliant on specific LMS add-ons or plugins. Instead, we have developed a standalone online booking system that can operate on the institution's premises or in the cloud. This approach offers greater adaptability and re-usability among different educational institutions.

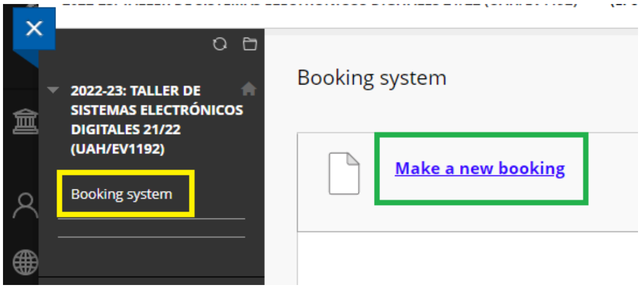


FIGURE 2. LMS course example: link to booking system on BlackBoard.

Through the booking system, users can make advance bookings for available RRL instances, schedule periodic bookings (feature exclusive to professors), and gain access to the RRL instance. It's important to note that user registration and authentication within HEIs are beyond the scope of our work. However, initiatives like "myacademic-id" aim to simplify user identification and authentication for electronic student services across multiple HEIs, for example, *myacademic-id* [27] will allow students to easily identify and authenticate to access electronic student services through a single sign-on for HEIs belonging to the eduGAIN federation.

III. ONLINE BOOKING SYSTEM

The online booking system provided by our RRL framework is a fundamental part of the system. It is the key cornerstone from where to manage the relationships among users and RRL instances. There are two different profiles, one for students and one with more possibilities and management options for professors.

Once the user has accessed the booking system using the same credentials with which the user registered in the LMS will be able to make new bookings by accessing the booking system timetable or view and access previously made bookings.

The flowchart in Fig. 3 shows the procedure followed by the booking system when a user accesses the system. First of all, it checks if the user belongs to the list of users of the course and if it is already registered in the system, otherwise, the user will be registered in the database. Likewise, if the user is already registered, they will be able to manage all the bookings made or make new bookings.

The different access profiles of the booking system, as well as the management of the system database and access to RRL instance reservations, are described below.

A. BOOKING PROFILES

Depending on the type of user registered in the LMS, different roles have been defined in the booking system:

1) System Administrator: An IT technician responsible for the proper functioning of the online booking software and the management of the booking system database.

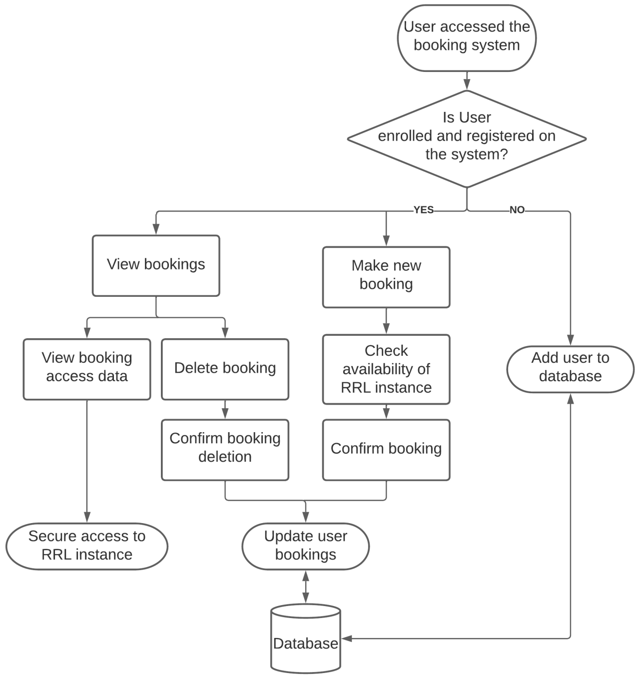


FIGURE 3. Booking system flowchart.

2) Remote Laboratory Admin: They, professors or technicians, have the ability to create new laboratories spaces, add equipment, configure the number of students per equipment, define available schedules, schedule maintenance, and many more capabilities related to the administration of the RRL.
3) Professors: They have expanded reservation capabilities, without time restrictions, and can modify reservations made by enroled students.
4) Students: They have limited reservation capabilities, allowing them to request certain resources within specific time limits.

The next subsection describes the relational database that stores the required data for a proper operation of the RRL booking system.

B. BOOKING DATABASE

The main actor in the creation of RRL instances is the professor with the role of "Laboratory Admin Professor". Several professors or technicians can have this role to facilitate the creation and maintenance of the RRL. In addition, they are responsible for maintaining the database as well as adding and keeping up to date the list of users allowed to access the RRL. The database is composed of the following tables that store information about users and courses:

1) **Courses Table**: Store information related to LMS courses. Each course has an identifier that is designated automatically when the course is added to the Booking System.
2) **User Table**: Stores information related to any user accessing to the booking system from the LMS,

whether student or teacher. Every user has an unique identifier designated automatically by the booking system and an attribute that distinguishes users with the student role from those with the professor role.

3) **Student list Table**: List of students enroled in the course and who will have access to the booking system. Any user who attempts to access without belonging to the list will be rejected by the system. Once the student is registered on the course, its data is stored on the User Table.
4) **Resource Table**: Store information related to any RRL instance that belongs to a course. Each RRL instance has a unique identifier designated automatically by the booking system, an IP address, RRL instance name, and description.
5) **Reserve Table**: Stores information related to any booking made for RRL instances. Each booking has an unique identifier linked to the user who made the booking and a password that is created when the user makes a new reservation. This password is used to securely access the RRL for the duration of the reservation.

There are multiple relations and options that must be well processed and fully understood for a proper operation of the booking system. For example, the RRL group has an enabled feature, but there is also an enable parameter for each RRL instance. In addition, RRL instances have an availability period frame, with start and end time frames, to better allocate RRL instances in different courses.

For the sake of conciseness, it is out of the scope of the paper to review all those data and how they are interconnected to provide a flexible and better operation of the RRL equipment.

C. INTERFACE FOR BOOKING RESOURCES

Two interfaces of the booking system have been developed depending on the role of the user who is accessing.

In case the user is a professor, the developed interface is the one shown in Fig. 4. This interface allows teachers to create new RRL instances, add students to workgroups, make new bookings and view the bookings made by both the user itself and the students in the course. Once the RRL group and instances are created, any user can book the resource created by the professors.

If the user is a student, they will be able to make new bookings and manage the ones previously made. In addition, from the interface students get the credentials to access the RRL instance, which are only available for the duration of the booking.

Bookings are made using the timetable interface shown in Fig. 5. Once the user has selected the day and the RRL they wish to book, they can choose the time slot for the booking. Only the RRLs and days enabled by the professors of the course are shown to the user. Finally, the user should select the time slots that best suit, within the time constraints for the user account type.

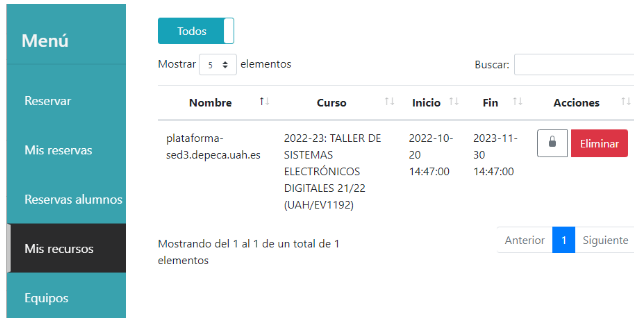


FIGURE 4. Professor booking system interface.

When a time slot is selected it changes to green, and only time slots adjacent to the selected time slot shown in white can be selected. The selection must have contiguous time slots available. The system does not allow to select more than the maximum number of time slots configured for students. Time slots shown in red indicate that they have been booked by other users of the course and in orange those that are not adjacent to the chosen booking duration selected. Finally, the grey time slots indicate hours already passed. Additionally, the booking system informs the user if he/she has reached the maximum allotted time for booking resources on a given course.

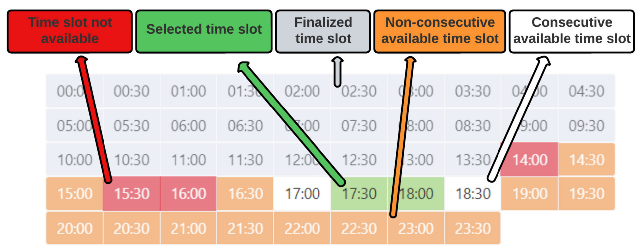


FIGURE 5. Booking system timetable.

The next section shows typical usage examples to verify that the booking system is correct.

D. EXAMPLES OF USE

Let us describe two examples of use to assess the true potential of the booking system.

1) RRL CREATION

Professors has the capability to create an RRL group (laboratory), name, and description, not enabled now to not allow reservations. Next, RRL instances should be configured, names, IP address, remote connection, assignment to RRL group, etc. Once the RRL group is enabled, and also the RRL instances assigned to it are enabled, the user can make bookings on these RRL instances.

2) BOOKING AN RRL INSTANCE

Two cases will be discussed. Let us consider that the RRL instance data is correct and enabled for use. A student can book a time slot once entered the Booking system through the LMS. The time slots shown to the student are limited, both as a maximum allowable booked time and maximum time ahead. For professors, there are no limitations on the number of times or when to book.

In addition, the website provides scripts to manage RRL bookings, deleting all bookings for several RRL instances (selected names using wildcard characters) at particular time slots or days.

Once the RRL framework is described, the next section is devoted to the development of a Digital Electronic and Control Systems RRL instance.

IV. RRL FOCUSED ON DIGITAL ELECTRONIC AND CONTROL SYSTEMS

As mentioned in the state-of-the-art in section I, there are various virtual laboratories and simulators available that facilitate learning about different aspects related to digital electronic and control systems (DECS). Debuggers like Keil μVision provide a high degree of signal control, step by step debugging, etc., enabling a quick and straightforward simulation of the operation of fairly complex systems. Also Matlab and other programming and development tools can be used in the control field. These are great tools to gain basic competencies, coding programs, checking configurations, etc. However, there is a crucial aspect of the learning process for DECS related to real-world applications. An example of this is the interaction among multiple temporal real signals. Generating such scenarios in a simulator tool proves to be highly challenging and often disconnected from reality.

For this reason, the academic community considers favourably the inclusion of a practical component, at least in the last part of the courses syllabus dedicated to DECS, where students can practice and observe the operation of a real system. Henceforth, we will assume the hypothesis of the necessity of having a real system based on development boards that are connected to input signals, push-buttons, potentiometers, etc., and output signals that can be connected to actuators, motors, LED diodes, displays, oscilloscope probes, etc.

A. PROPOSED MODULES FOR THE DECS-RRL

The proposed DECS-RRL instance has been divided in two separate modules:

1. The development board to be programmed (the device under test - DUT)
2. Web-application to control and observe the DUT.

The design is crafted in a manner that allows for the execution of multiple practices without requiring frequent adjustments, provided the appropriate connections and necessary instrumentation are in place. While changes are necessary when transitioning between practices of different subjects, or connecting to those of another laboratory subject, the involvement of technical laboratory staff and teaching personnel is required, although not within a short timeframe. For instance, the interface developed enables remote management of certain scales and parameters of the oscilloscope. Fig. 6 shows the DECS-RRL instance developed, with the following components:

- Remote computer, with the SO and required tools installed similarly to physical places. No screen is needed if the instance is only used remotely.
- Signal generation board to provide real input signals and input sequences via local web-application.
- Development Board, connected to the computer with a JTAG probe to download the code of practices and debug the correct operation.
- Protoboard, connected to the development board with the required output components such as displays, LEDs, etc.
- DC motor and H-bridge connected to the development board used in the control practices.
- A servomotor and ultrasound sensor, for a mixed electronic and control practice, to capture the surrounding environment.
- A configurable low-cost oscilloscope capable show different signals selected via an analog multiplexer.
- Cameras connected to the computer to see the operation in real-time.

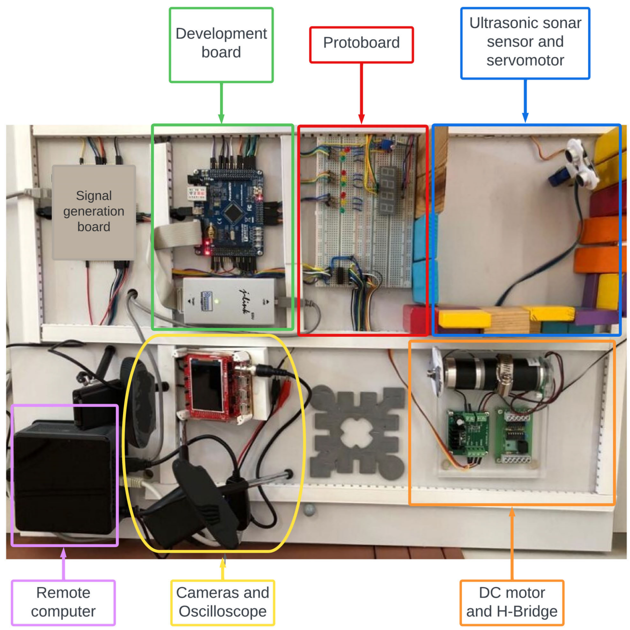


FIGURE 6. Main components for the DECS-RRL instance.

B. INPUT SIGNAL GENERATION: BOARD AND WEB-APPLICATION

The DECS-RRL instance gives the user multiple possibilities to generate input signals to the development board. The aim

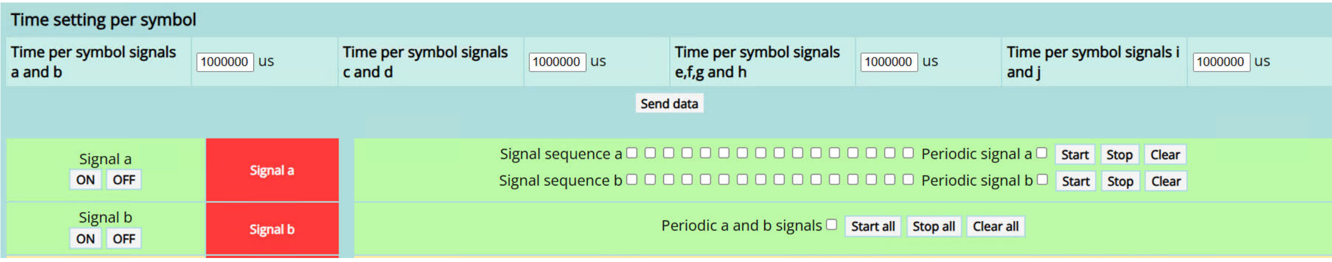


FIGURE 7. **Digital signal generation and control interface.**

is to reuse the STEM RRL system in different practices, electronic and control fields, considering a diversity of learning levels. It is based on the same development board but already programmed.

By using the hardware integrated in the platform and through the use of this interface, it is possible to generate and control analogue and digital signals that are connected to the development board and the results can be visualised by means of visual feedback from cameras. An Ethernet connection is used to provide the user with a local web-application to control the different elements, input signals, and additionally, to observe the response from the DUT.

1) DIGITAL SIGNAL GENERATION

Fig. 7 shows part of the the web-based interface through which the user can generate remotely various digital signals and sequences (has not been shown in its entirety for clarity of the figure, but consists of ten signals and sequences similar to the ones shown). The user can directly control its digital value from the buttons ON/OFF on the interface changing the signal level to high or low, respectively. In addition, 16-bit sequences can be generated and the time of emission of each symbol can be settled. The generation of the sequences can be periodic or not, this can be selected from the interface.

2) ANALOGUE AND PWM SIGNAL GENERATION

Within the same environment the user can configure analogue signals, PWM (Pulse-width modulation) and select the channel to capture from the oscilloscope. The interface for the generation and control of all these signals is shown in Fig. 8. This interface allows, on the one hand, to configure the analogue signal generation values (frequency and amplitude) and, on the other hand, to start/stop the generation of the signal, which can be sinusoidal, sawtooth or triangular. The analogue signals that can be generated are limited so that the user cannot generate any signal whose voltage exceeds the Vref of the development board, so the ADC of the development board is protected. Other solutions are being considered to protect the inputs of the development board in case of incorrect input/output assignment by the user by means of optocouplers.

In addition, the system can generate up to four PWM signals to be set, all of them sharing the same frequency reference.

There are two PWM signals of type *single edge* and two of type *double edge*, being able to configure in which the signal changes value in the rising and falling edge. Each instant of signal change must be configured as a percentage of the PWM signal duty cycle. The interface has two buttons *Start* and *Stop* that allow to start or stop the emission of the PWM signals.

Finally, the remote platform has an oscilloscope and an 16-channel analogue multiplexer that allows the selection of the channel to be displayed on the oscilloscope of the user's choice controlled via the web-based interface.

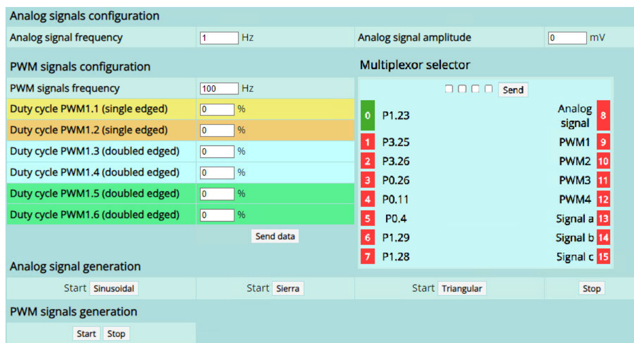


FIGURE 8. **Analog and PWM signal generation and control interface.**

V. RESULTS

Let us describe three examples of practices that can be carried out in our STEM RRL. In the first one, students will be required to generate a digital signal varying its duty cycle according to the digital code entered through the web-based interface, the second one consists of generating an analog signal whose frequency will depend on the digital code entered in four of the interface signals, and in the last one, students will obtain the distance from a sonar sensor placed on a servomotor to an object by controlling the movement of the servomotor using two signals from the web-based interface. Moreover, to obtain some feedback about the tests and a comparison of their on-site experience with the DECS-RRL experience, ten students that are enrolled in the Digital Electronics Systems course were asked to collaborate developing each one the three practices. Figure 9 represents the programming flow for the subject Digital Electronics Systems, although for each subject the porgramming flow may vary.

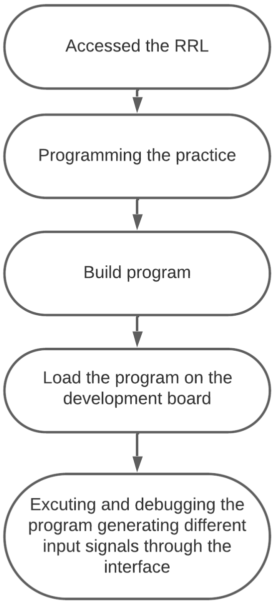


FIGURE 9. Programming flow.

A. PRACTICE 1: CONTROL AND GENERATION OF A DIGITAL SIGNAL USING GENERAL PURPOSE PORTS

The first practice to be developed by the students shall generate a digital signal of 1 Hz with a duty cycle that changes according to the binary value set on signals "a" and "b". The block diagram of this practice is shown in Fig. 10. In addition, signal "m" will be used to capture the values introduced via signals "a" and "b", and update the duty cycle of the output signal.

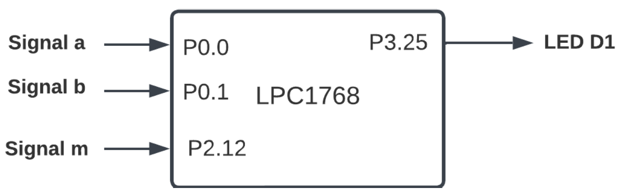


FIGURE 10. Practice 1 diagram.

The duty cycle of the generated output signal should change as shown in Table 1. The expected response according to the value of the digital code entered via signals "b" and "a" is shown in Fig. 10. For example, if the digital code entered is "00", the output signal generated has a duty cycle of 20% (see Fig. 11a), and the same is applicable for the other digital codes. Furthermore, as no timer was used to generate the digital signal, the frequency obtained is not 1 Hz, but 0.83 Hz (a period of 1.2 seconds).

B. PRACTICE 2: HANDLING THE DIGITAL-TO-ANALOGUE CONVERTER

The objective of this practice is to generate at the analog output of the LPC1768 board a sinusoidal signal whose frequency varies between 1 kHz and 15 kHz that takes maximum advantage of the output voltage range.

TABLE 1. Digital code and duty cycle of the output signal.

Signal "b"	Signal "a"	Duty cycle
0	0	20%
0	1	40%
1	0	60%
1	1	80%

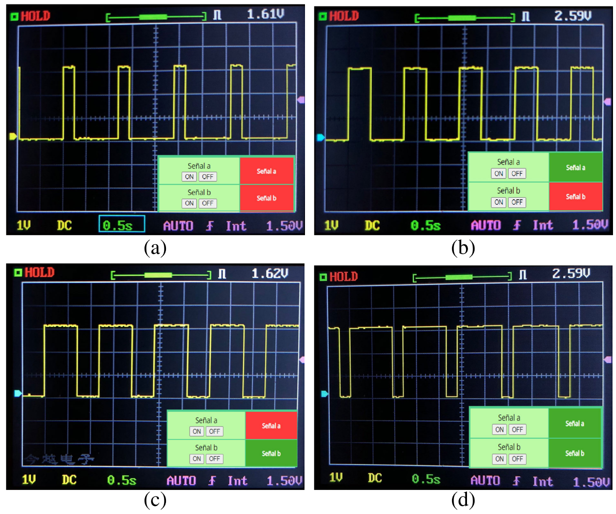


FIGURE 11. Control and generation of a digital signal practice example. (a) Output signal with 20% duty cycle. (b) Output signal with 40% duty cycle. (c) Output signal with 60% duty cycle. (d) Output signal with 80% duty cycle.

The signal frequency can be modified via the digital signals interface by means of the "m" signal. This pulse shall trigger one of the external interruption of the board, and the frequency shall be proportional to the digital value of the 4 bits of the signals "f" to "i". For example, for the value "i"…"f" = "0001" the frequency must be 1 kHz and for the value "i"…"f" = "1111" it must be 15 kHz. For the value "i"…"f" = "0000’ the frequency shall be 100 Hz. Fig. 12 shows the diagram of the application.

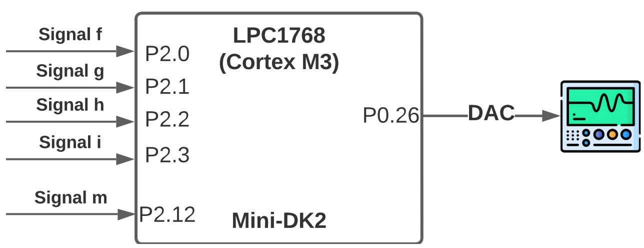
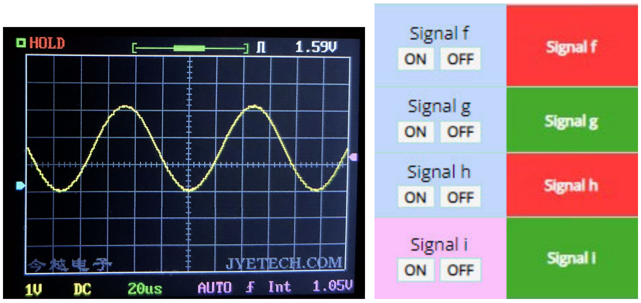


FIGURE 12. Practice 2 diagram.

The waveform shall be stored in an array of 50 elements and for the calculation of the sine will be calculated using the *sin()* function included on the math library of Keil μVision. Therefore, in one cycle there will be 50 samples with values between 0 and 1023 as it is a 10-bit DAC. For the signal generation through the DAC port, a timer on the board is used to output samples according to the frequency specified by the user.

Fig. 13a shows an example of generation for a signal of 10 kHz frequency as the value introduced using the web interface via the signals "i"…"f" ="1010" as shown in Fig. 13b.



(a) (b)

FIGURE 13. Handling the digital-to-analogue converter practice example. (a) Generated signal with frequency of 10 kHz. (b) Introduced value via signals "i"…"f"="1010".

C. PRACTICE 3: DESIGN OF AN ULTRASONIC SONAR SYSTEM

The first practice involves the design of an embedded system based on the laboratory board (LPC1768 microcontroller) that implements an ultrasonic sonar capable of extracting the distance measurements to the nearest objects, in a plane and over a 180° environment, with the possibility of being controlled through the external interrupts inputs using the web interface. The system shall also have the possibility of detecting obstacles, allowing the configuration of a detection threshold so that, in the presence of an obstacle, it generates a sinusoidal signal whose frequency is proportional to the measured distance in kHz.

Fig. 14 shows the diagram for the pins connected to the development board and ultrasound sensor signals. As shown in the diagram, a PWM signal is needed to control the servomotor in charge of performing the angle sweeps and two signals to control the ultrasound sensor, the trigger one to start measuring, and the echo to capture the pulse width to determine the distance to the obstacle.

Fig. 15a shows the servomotor positioned 3 cm from the obstacle after pressing the signal "m" from the digital generation signal interface. The measured distance can be visualized at the Watch Window of Keil μVision shown on Fig. 15b. Fig. 15c shows the sinusoidal signal generated by the digital-analog converter (DAC) displayed on the oscilloscope being the signal frequency 3 kHz.

D. FEEDBACK GIVEN BY THE USERS

Our research aims to provide information about the benefits or disadvantages about STEM remote laboratories offering a real remote platform. To do so, twenty-eight students from three different laboratory groups from the Digital Electronics Systems subject from our institution were required to test the STEM RRL developed.

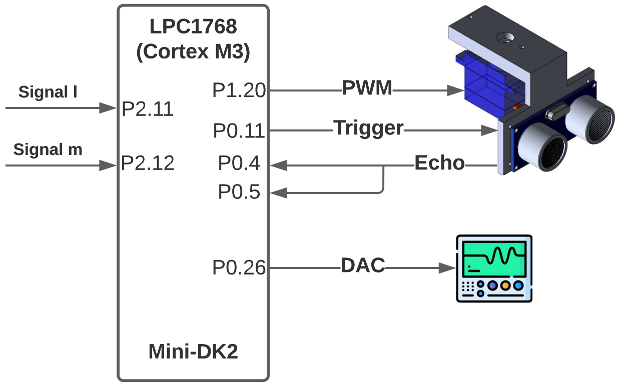
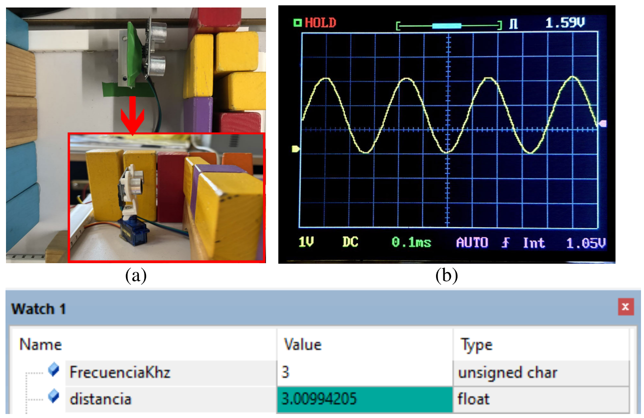


FIGURE 14. Practice 3 diagram.



(a) (b) (c)

FIGURE 15. Distance sensing application practice example. (a) Servo positioned 3 cm of obstacle. (b) 3 kHz sine wave signal generated. (c) Distance measured by ultrasound sensor and proportional frequency calculated. Figure courtesy of Keil μVision.

Participants were asked a few questions after testing the system with the practices previously explained and which they already had to program in the on-site laboratory, so that they could compare the differences between working remotely or in the on-site laboratory. Evaluations between -5 to -1 means results are better in on-site situation, 0 is the neutral answer and between 1 to 5 means results were better in the STEM RRL system. The feedback given by these students is shown in Table 2, 3 and 4, one per practice, where results are represented with the percentage of the number of student's degree of agreement to each question.

First question asked how easy they found to manage the different signals to generate and visualize the results of the tests. For the first practice, more than half of the students that participated thought that it was a bit complex to control the different signals and obtain the results via the webcam and preferred, in this first contact with the STEM RRL, the on-site laboratory option. However, perceptions shifted after the second practice, with a notable improvement in responses.

TABLE 2. Student evaluations of results (%) obtained after testing the STEM RRL with practice 1.

Questions	-5	-4	-3	-2	-1	0	1	2	3	4	5
Signal handling and visualization of results	10,71	17,86	25,00	28,57	7,14	7,14	3,57	0,00	0,00	0,00	0,00
Practice development time	14,29	7,14	17,86	14,29	17,86	21,43	7,14	0,00	0,00	0,00	0,00
Percentage of reached results	25,00	0,00	3,57	21,43	28,57	14,29	7,14	0,00	0,00	0,00	0,00
Access to the practice elements	0,00	0,00	0,00	0,00	7,14	17,86	50,00	21,43	3,57	0,00	0,00
Assessment of learning by doing	0,00	32,14	3,57	10,71	39,29	14,29	0,00	0,00	0,00	0,00	0,00
Booking system and platform access	-	-	-	-	-	0,00	28,57	39,29	10,71	21,43	0,00
Overall satisfaction	-	-	-	-	-	3,57	10,71	25,00	42,86	17,86	0,00

TABLE 3. Student evaluations of results (%) obtained after testing the STEM RRL with practice 2.

Questions	-5	-4	-3	-2	-1	0	1	2	3	4	5
Signal handling and visualization of results	0,00	0,00	0,00	0,00	14,29	0,00	25,00	0,00	28,57	21,43	10,71
Practice development time	0,00	0,00	0,00	0,00	0,00	0,00	3,57	3,57	21,43	46,43	25,00
Percentage of reached results	0,00	0,00	0,00	0,00	10,71	7,14	3,57	28,57	25,00	17,86	7,14
Access to the practice elements	0,00	0,00	0,00	0,00	0,00	10,71	21,43	10,71	25,00	28,57	3,57
Assessment of learning by doing	0,00	0,00	0,00	0,00	7,14	3,57	7,14	10,71	32,14	39,29	0,00
Booking system and platform access	-	-	-	-	-	0,00	10,71	14,29	21,43	28,57	25,00
Overall satisfaction	-	-	-	-	-	0,00	0,00	10,71	28,57	53,57	7,14

TABLE 4. Student evaluations of results (%) obtained after testing the STEM RRL with practice 3.

Questions	-5	-4	-3	-2	-1	0	1	2	3	4	5
Signal handling and visualization of results	0,00	0,00	0,00	0,00	0,00	0,00	10,71	7,14	10,71	21,43	50,00
Practice development time	0,00	0,00	0,00	0,00	0,00	3,57	17,86	7,14	28,57	25,00	17,86
Percentage of reached results	0,00	0,00	0,00	0,00	14,29	3,57	7,14	0,00	35,71	10,71	28,57
Access to the practice elements	0,00	0,00	0,00	0,00	0,00	0,00	3,57	17,86	14,29	42,86	21,43
Assessment of learning by doing	0,00	0,00	0,00	0,00	7,14	0,00	0,00	10,71	10,71	53,57	17,86
Booking system and platform access	-	-	-	-	-	0,00	0,00	25,00	10,71	25,00	39,29
Overall satisfaction	-	-	-	-	-	0,00	3,57	0,00	35,71	14,29	46,43

In this instance, a significant number of students provided positive feedback regarding signal manipulation and webcam utilization. For third practice, when students are suppose to have more control of the system, responses are even more positive, this may be due to the fact that students were already more familiar with the system and found it easier to use.

Another question asked about the time students spent on the development of the practices. Similar to the preceding question, students indicated that, initially, they invested more time in comprehending the web-based interfaces and its functionality rather than in programming. Nevertheless, once they became more used to with the diverse interfaces and applications, a majority of them observed that the optimization of time was more significant compared to traditional face-to-face laboratories.

The third question on which the students were asked for their feedback was whether they were able to complete and obtain results from the practices in the same amount of time as they would have spent in the on-site laboratory. For practice 1, only two students (7,14%) were able to obtain results in less time than in the face-to-face laboratory but they were a bit short of time. For practice 2, twenty-three students reported with different degree of agreement that they were perfectly able to finish their tests even earlier than they would do in the on-site laboratory. For the third practice, the majority of students were able to complete their tests earlier compared to the on-site laboratory. However, a few reported that they were unable to do so due to the complexity of this practice, which required more time for development.

The feedback given to the question on access to practice elements indicates that students, across varying levels of agreement on each practice, consistently reported having the necessary elements to conduct their practical tests more effectively in the STEM RRL compared to the on-site laboratory. A key advantage highlighted by most of the students was the elimination of the need to purchase components or microcontrollers, providing a significant benefit. Moreover, they expressed that the absence of physical connections between different elements required for the practice allowed them to concentrate more on programming tasks, in particular, in practice 3 where the complexity of programming posed a greater challenge for them.

In practice 1, students reported that their assessment of learning by doing was unfavorable. They expressed the challenge of having to dedicate more time to understanding the functioning of STEM RRL and mastering the various tools provided within a limited timeframe. Better feedback is provided for practice 2 and 3, as students became more familiar with all the tools provided and could completely focus on their programming.

For the last two questions, students were asked to give some feedback about the booking system and how was their experience accessing the STEM RRL from their personal laptop at home and give an overall satisfaction mark for each of the practices.

For most of them, creating new bookings using the interface developed for the LMS was a straightforward process, which minimized any potential confusion or technical barriers to booking laboratory slots. Also, they highlighted that there was no need to install any external software, as access was facilitated directly through RDP (Remote Desktop Protocol) installed by default on the user's computers. This approach significantly reduced the burden on students, eliminating the need for complex set-up procedures and ensuring a hassle-free experience when connecting remotely to the STEM RRL.

Despite the potential challenges students may have encountered during the development of the first practice, 42,86% of them reported that the overall satisfaction experience was relatively positive (shown in Table 2). In contrast, 39,28% of the students indicated that it was quite negative (below the pass mark), and none reported a very positive experience. This could be due to different factors:

First, distance laboratories, which allow students to conduct experiments and gain hands-on experience through virtual interfaces, can differ significantly from the traditional on-site laboratory environments students are used to. Moreover, navigating the different interfaces and understanding how to generate and control signals can be initial hurdles. Although, after overcoming this initial troubles, the experience for them get better (see Table 3 and 4). For practice 2, 60,71% of students reported a very good learning experience using the STEM RRL. This suggests that, after overcoming the initial challenges observed in Practice 1, students became more adept at navigating the tools and interfaces. On practice 3, 60.72% of students gave a very good overall satisfaction mark.This progression highlights the adaptability of students as they move from traditional laboratory environments to remote environments. As they gain more experience and confidence in using STEM RRL, their perceptions of complexity are likely to gradually evolve, ultimately contributing to improving the overall learning experience.

In Table 5 it is shown the mean value for all the evaluations given to the practices. Focusing on the ''Overall satisfaction'', 46,43% of the students expressed a very good experience on using the STEM RRL, believing that it improved their learning experience. A 35,71% of students thought it was a good tool to complement the on-site laboratory classes and resources, but they had in general a good learning experience. At last, 17,85% of students gave a negative overall satisfaction mark, This warrants further investigation into the specific aspects that led to a less favourable experience for this subset of students.

In the following section, conclusions are carried out about the use of an RRL focused on DECS and based on the feedback given by the users.

VI. DISCUSSION

Based on the responses given by the students that were able to try the STEM RRL, the opportunity to engage in remote learning while retaining access to the same resources typically available in on-site laboratories proved to be satisfactory.

The STEM RRL tests enabled students to conduct experiments, collaborate with peers and interact with educational tools and materials, without having to be on-site in the laboratory or using simulations but with the advantage of working with the same resources. The positive response from students underscores the value of remote learning solutions that effectively bridge the gap between traditional on-site laboratories and modern technology-driven approaches, fostering an environment where students can thrive academically while accommodating their needs and preferences. For example, one student reflected: ''In the first practice session, I consider that it was the easiest to program and check the results, but some time is spent until signal generation and visualisation are handled with ease. From then on, in the following, the time spent is less than in the on-site classes, and better use is made of the resources and set-ups. The handling of signals is intuitive and simple, the resources of the practice are easier to manage, and the learning process is detected a little better.''

Likewise, another student wrote, ''At first, it can be difficult to match the pins on the web-based application with the pins on the physical board which I'm programming. Also, generating signals from the web interface may take more time compared to the on-site approach. The same applies to the visualization of the results. Although, an important advantage of the remote platform is the absence of concerns related to physical connections, which are often time-consuming. In subsequent experiments, once familiarity with the platform is achieved, the overall process is faster than in the on-site case. In addition, signal generation and visualisation are simpler, as everything is properly connected.'' Another student reflected, ''In my opinion, I believe that the potential of the RRL is unlocked when complemented with in-person classes. Direct interaction in the classroom and access to physical resources are essential components of my learning process. While the RRL provides flexibility and additional resources, I feel that the combination of both, in-person and remote tests, creates a more comprehensive and flexible environment for my learning.''

At first, it seemed that users encountered challenges while working with the STEM RRL. These initial difficulties can be ascribed to their unfamiliarity with a remote system, such as the web-based interface designed for generating different input signals and the management of diverse applications for visualizing and programming the development board. This contrast was particularly pronounced in comparison to the traditional on-site laboratory approach that students are accustomed to working with. However, after engaging in the development and testing of an initial practice, these

TABLE 5. Mean values (%) of the student evaluations obtained after testing the STEM RRL.

Questions	-5	-4	-3	-2	-1	0	1	2	3	4	5
Signal handling and visualization of results	3,57	5,95	8,33	9,52	7,14	2,38	13,10	2,38	13,10	14,29	20,24
Practice development time	4,76	2,38	5,95	4,76	5,95	8,33	9,52	3,57	16,67	23,81	14,29
Percentage of reached results	8,33	0,00	1,19	7,14	17,86	8,33	5,95	9,52	20,24	9,52	11,90
Access to the practice elements	0,00	0,00	0,00	0,00	2,38	9,52	25,00	16,67	14,29	23,81	8,33
Assessment of learning by doing	0,00	10,71	1,19	3,57	17,86	5,95	2,38	7,14	14,29	30,95	5,95
Booking system and platform access	-	-	-	-	-	0,00	13,10	26,19	14,29	25,00	21,43
Overall satisfaction	-	-	-	-	-	1,19	4,76	11,90	35,71	28,57	17,86

difficulties transformed into a satisfying competence, making the remote laboratory approach a more suitable option for developing their experimental tests. Overcoming these initial obstacles demonstrated adaptability and highlighted the transition from frustration to achievement in mastering the remote platform and harnessing its advantages for a more efficient and flexible work experience.

The advantages of remote work, such as flexibility and improved productivity, also became apparent. A student reported: ‘‘Working remotely gave me the advantage of developing my practices at the time that best suits my schedule, being more productive and being able to work when the on-site laboratory is closed.’’ The use of a RRL can have substantial benefits for students facing various challenges, such as living far from the study location or dealing with work schedules, making it difficult for them to attend all on-site laboratory classes. Consequently, tools of this nature prove highly advantageous, enabling students under these circumstances to access the same resources as the ones from the in-person laboratories. Furthermore, as some have described, STEM RRLs empower users to work during the time frames in which they feel most comfortable and productive. This flexibility allows access to laboratory resources even during periods when the university is closed, such as vacations.

Most of the students reported that the adoption of STEM RRL provides them with the freedom to learn without time constraints and eliminates the need to invest in laboratory equipment such as microcontrollers, sensors, or other electronic hardware that is usually a bit pricey. For example, one student reported, ‘‘In my case, I sometimes feel some pressure in terms of the time we can spend in the on-site laboratories, which is limited, so I used to focus on ‘‘doing this’’ and did not contribute to understanding why I was doing what I was doing. But with this approach of working remotely from home, I have all the resources I need to carry out with my practices and I can set aside the time I need to analyse and understand the results obtained in a satisfactory way.’’ The student's opinion suggests a notable shift in their learning experience when transitioning from on-site laboratories to remote work. The observation that time constraints in on-site laboratories led to a focus on task completion rather than understanding the underlying concepts is a common challenge. However, with the remote approach, the student highlights the advantage of having ample time and resources at home. This change enables a more deliberate and comprehensive approach to experiments, allowing for thorough analysis and a deeper understanding of the obtained results, which is the main goal of the practical classes in laboratories. It supports the notion that remote laboratories offer a more thoughtful and meaningful engagement with the learning process, thereby enhancing comprehension and knowledge retention than in the on-site laboratory solution.

Finally, the point that most students agreed on was that by working on the STEM RRL they were able to have and develop practices for multiple practical scenarios as the platform built had many sensors and actuators, and by programming the same board they could test different approaches.

Moreover, the teachers who helped on the development of the tests for this work by the incorporation of the RRL system into their respective subjects were asked some questions about the perspective they had. One of the questions that were asked is how easy was it to transmit to the students the way of working of the developed system and to resolve the different problems they had to deal with? In response to this inquiry, one teacher articulated, ‘‘Facilitating an understanding of how to make reservations to access the RRL and generate and control various signals to assess the outcomes of their practical exercises proved to be straightforward. It resembled a supplementary tool that seamlessly aligns with the instructional methodologies employed in their regular coursework.’’

Another teacher response was ‘‘To enhance understanding of system interfaces, we developed tutorial materials and conducted live demonstrations, ensuring students were adept at navigating the RRL. Difficulties in signal manipulation were tackled through dedicated workshops with some students. Aligning the laboratory exercises with coursework was optimized by revising exercises to better integrate with theoretical concepts. In general, the response that students gave on the use of a remote laboratory was positive for them, but also for teachers, as these tools serve as valuable aids in illustrating the desired outcomes and achievements students should attain when successfully addressing problems and completing their assignments.’’

They were also queried about the utility of the remote laboratory for their respective subjects and whether they would contemplate incorporating it into their curriculum as a supplementary tool alongside traditional on-site laboratory classes. One of the teachers reflected that, ‘‘After the tests that were carried out in my subject, I believe that the use of a RRL offers additional practical insights and flexibility, providing a valuable resource for reinforcing theoretical concepts covered in their subjects. I would totally consider to integrate the system in my subject''. Another teacher argued, ''The use of RRL can be a very useful tool for students to conduct tests on physical hardware systems. However, it can also lead to the possibility that students, upon realizing they can perform the same tasks from home, might stop attending in-person classes. Therefore, it is a tool that I consider very beneficial for both students and teachers, but always contingent on being managed appropriately by both parties. But taking that into account and resolving all those minor inconveniences, the use of a RRL can absolutely enhance the teaching experience for both, students and teachers''.

VII. CONCLUSION AND FUTURE WORK

Based on the previous information, it is clear that RRLs present a multitude of advantages that could significantly enhance the STEM learning trajectory of students in the field of digital electronics and control systems. RRL delivers the inherent benefit of accessing real equipment and conducting experiments from anywhere, from different geographical locations. Another positive aspect lies in the convenience it offers, allowing students to practise and experiment in their own space, without being constrained by physical laboratory hours, increasing the usage of the equipment.

Compared to other similar laboratories, our contribution offers a complete system from which the user can reserve the time slots that best suit them to develop their programming project, giving great flexibility to the students and the ability to manage their work time. In addition, users are provided with remote equipment like the one used in the on-site laboratories and with the same pre-installed software, which facilitates user interaction with the system and makes it more user-friendly.

A highly distinctive aspect compared to other remote laboratories in the same field is that our system is adaptable and scalable to other areas. This is achievable through the same reservation system and signal generation board, allowing for practical exercises in different fields, such as FPGAs or SoC, merely by changing the user's development card. Furthermore, our contribution features a highly specific signal generation system (enabling the selection of frequencies, levels, and signal shapes, among others) and the control of various signals to stimulate the inputs of the student's development card, all from a simple and well-organised interface.

Furthermore, the developed system allows the integration of diverse subjects, providing students with a more tailored and comprehensive educational experience, letting understand better the knowledge they have included in their curricula. With the availability of testing the RRL, the students were able to check the real performance of their code developed. This not only motivates them to persist in their efforts, but also encourages continuous improvement in all aspects in which they have gained expertise throughout the course.

Additionally, our system incorporates feedback through cameras that provide real-time visualization of the hardware on which the user is conducting their practical work, in other remote laboratories approaches as the ones shown in the state-of-the-art of RRLs in Chapter II, only a graphic response on the interface is shown to the user after programming their practices, not being able to visualize a physical response on the hardware programmed.

Moreover, with our proposal students were able to carry out different experiments using the hardware that they would use on the on-site laboratory but with the advantage of being remotely. Also, users were able to access the RRL instance using the LMS they are used to work with in classes and generate different signals letting them modify their testing scenario without having to change any hardware module.

As we have seen previously, RRLs can be a useful tool for sharing expensive equipment with other remote students of lesser means, but access to a good internet connection is required as the environment attempts to replicate the end user's location as if they were in the laboratory itself, through remote desktop sharing and viewing the workplace with a webcam. One factor in favour of installing laboratory equipment that can be used remotely is the possibility of using it for a longer time, ideally 24/7, increasing the cost-effectiveness of the equipment. The depreciation aspect of the equipment is becoming increasingly important due to the ever-increasing advancement of technologies, rendering laboratory systems obsolete within a few years. Additionally, the cost of commercial software licenses should be taken into account.

However, it should be considered that the use of RRLs introduces the need for an online booking system and additional maintenance tasks for laboratory equipment. The booking system, far from being a wasted cost, can introduce an interesting control variable for infrastructure managers since it allows one to have analytical data on the use of spaces and installed equipment, whether they are used locally or remotely. The initial investment required for RRL instances is not a great cost, but it brings many benefits.

Future steps might involve the increase of STEM RRL instances, shared resources among HEIs, and building up a federation of trusted partners. RRLs might be useful to gain competencies related to internationalisation and multicultural skills. Collaboration between students from different countries and cultures would be easily adopted if administrative and bureaucratic barriers are overcome. Regarding new technology trends, the integration of augmented reality (AR) and virtual reality (VR) technologies into remote real laboratories has great potential. Future research could investigate the use of AR and VR to provide immersive and realistic laboratory experiences, allowing students to interact with virtual laboratory equipment and objects in a more intuitive and engaging manner. More powerful equipment and devices for remote students should be considered, reducing some of the benefits of the RRL approach.

AUTHORS' CONTRIBUTIONS

Conceptualization, José Luis LáZaro Galilea and Alfredo Gardel Vicente; data curation, Rubén Gil Vera, ÁLvaro De-La-Llana-Calvo, and Ignacio Bravo Muñoz; formal analysis, ÁLvaro De-La-Llana-Calvo and Ignacio Bravo Muñoz; funding acquisition, Ignacio Bravo Muñoz, Alfredo Gardel Vicente, and José Luis LáZaro Galilea; investigation, Rubén Gil Vera, José Luis LáZaro Galilea, Alfredo Gardel Vicente, ÁLvaro De-La-Llana-Calvo, and Ignacio Bravo Muñoz; methodology, José Luis LáZaro Galilea and Rubén Gil Vera; project administration, Ignacio Bravo Muñoz and José Luis LáZaro Galilea; resources, José Luis LáZaro Galilea and Alfredo Gardel Vicente; software, Rubén Gil Vera and Alfredo Gardel Vicente; supervision, José Luis LáZaro Galilea; validation, Rubén Gil Vera, Alfredo Gardel Vicente, ÁLvaro De-La-Llana-Calvo, Alfredo Gardel Vicente, and Ignacio Bravo Muñoz; visualization, ÁLvaro De-La-Llana-Calvo and Ignacio Bravo Muñoz; writing—original draft, Rubén Gil Vera, Alfredo Gardel Vicente, and José Luis LáZaro Galilea; and writing—review and editing, Rubén Gil Vera, ÁLvaro De-La-Llana-Calvo, Ignacio Bravo Muñoz, Alfredo Gardel Vicente, and José Luis LáZaro Galilea. All authors read and agreed to the published version of the manuscript.

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