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Remote Laboratory for Online Engineering Education: The RLAB-UOC-FPGA Case Study

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Abstract: Practical experiments are essential for engineering studies. Regarding the acquisition of practical and professional competences in a completely online scenario, the use of technology that allows students to carry out practical experiments is important. This paper presents a remote laboratory designed and developed by the Open University of Catalonia (RLAB-UOC), which allows engineering students studying online to carry out practical experiments anywhere and anytime with real electronic and communications equipment. The features of the remote laboratory and students' satisfaction with its use are analyzed in real subjects across six semesters using a self-administered questionnaire in an FPGA-based case study. The results for the FPGA-based case study present the perception and satisfaction of students using the proposed remote laboratory in the acquisition of subject competences and content.

Keywords: remote laboratory; online learning; digital electronics; FPGA; VHDL

1. Introduction

Laboratories are essential for technological degrees, where practical experiments are required to acquire the expected competencies and professional skills [1].

In this regard, the study of electronics and communications technology has been traditionally linked to the use of face-to-face hands-on laboratories. In recent decades, there have been technological advances that have opened the door to distance engineering education, with the quality of these courses being broadly accepted as comparable to that of traditional ones [2]. In this context, the challenge for technical degrees is how to provide the best laboratory experience.

Different approaches that attempt to provide solutions to these practical experimentational needs exist, typically proposed in a face-to-face learning context instead of a distance one. The first such approach is based on simulations (virtual lab). These resources are used by both distance and face-to-face learning [3–5], since these allow students to work with resources available all the time and offers the possibility of developing low-cost complex experiments.

Secondly, a variety of resources have been developed with the aim of allowing for hands-on experimentation outside of the physical laboratory and promoting flexibility during the study:

i. Mobile Studio Project [6]: a low-cost solution [7,8] with an oscilloscope, a function generator, a digital multimeter (DMM), a reconfigurable digital I/O ports, and power supplies.

ii. NI devices such as myDAQ [9], Analog Discovery 2-NI Edition [10], or USB-600x [11]. myDAQ is a data acquisition (DAQ) device used to measure and analyze live signals on a computer [12,13] alongside a DMM, an oscilloscope, and a function generator. Analog Discovery 2-NI Edition is a complete solution with an oscilloscope, an arbitrary

function generator, a logic analyzer and pattern generator, a network analyzer, and spectrum analyzer functionalities. In addition, NI USB-600x provides basic analog and digital I/O functionality.

iii. StudentEDEA [14]: a low-cost solution offering the possibility to perform electronics operations at home.

iv. Vernier Circuit Board 2 [15]: a basic electricity lab to connect series and parallel circuits, to examine the behavior of components, and to investigate RLC circuits.

v. Arduino Uno [16]: the simplest version of an open-source platform consisting of a microcontroller and an IDE (Integrated Development Environment).

vi. Lab@Home [17]: an electronics hands-on laboratory proposal to allow students to acquire the required practical competencies and professional skills related to telecommunications engineering.

Finally, during the last decade, many higher education institutions have developed a large number of remote access laboratories on different topics. Thus, proper resources are provided to the students to achieve the expected learning objectives. Some examples of these initiatives are as follows:

i. iLab [18]: initiated at the Massachusetts Institute of Technology (MIT) with the aim of sharing real instrumentation among students, which otherwise would be impossible considering the acquisition and maintenance costs.

ii. Labshare [19]: a project funded by the Australian government to create a national network of remote laboratories.

iii. LiLa [20]: a project co-financed by the European Community to promote remote and virtual laboratories in the fields of natural sciences and engineering.

iv. OpenLabs [21]: an umbrella project for the different remote laboratories at Blekinge Institute of Technology, with VISIR [22] being a successful case of a remote Electronics Laboratory.

v. WebLab-Deusto [23]: an initiative of the University of Deusto, started in the early 2000s, aiming to increase the experiential learning with the use and development of remote laboratories.

The use of remote laboratories is a challenge that takes into account some important issues such as usefulness, immersion, or usability due to the lack of physical access between the student and the experiment, bearing in mind the learning objectives and competence acquisition. Thus, considering the use of remote laboratory initiatives in a real context, we present and evaluate some examples. Firstly, the use of an iLab connection laboratory experiments was assessed in [24], where the results showed that most students favored iLab and felt that the lab made them think about and understand some things they would not have been able to from only lectures or textbooks. Nevertheless, more work to improve the satisfaction about its effectiveness as a real lab was suggested. Secondly, in [25], the use of VISIR was presented, showing that it was accepted among the students as a useful tool for practical sessions; however, it was considered a support tool and not as a substitute for real laboratories. Finally, in [26], WebLab-Deusto was analyzed, showing that, in general, the students think that the WebLab-Deusto experiment is a useful learning tool, although more work into immersion and experiment control would improve the results.

The Open University of Catalonia (Universitat Oberta de Catalunya, UOC), as a fully online university (eLearning) [27], requires complete laboratory experiences based on combining simulation, remote laboratories, and hands-on laboratories for the Bachelor and Master of Telecommunications Engineering degrees (BTE and MTE, respectively). These are two official degrees adapted to the European Higher Education Area (EHEA) [28], with more than 1000 students.

This paper aims to present the UOC's remote laboratory (RLAB-UOC) infrastructure, which allows online telecommunications engineering students to acquire the needed practical competences and professional skills. As introduced before, most initiatives were designed, developed, and evaluated from the point of view of face-to-face students and do not consider that experiments are tools for learning and acquiring the needed competences.

Therefore, using a fully online education perspective, the main points considered in this work are as follows:

1. What technological infrastructure is necessary to allow students to access laboratory resources in a fully online engineering education context? All devices are accessed remotely using the Internet, so a laboratory management system must be used to guarantee correct access for all students to the resources and their correct use.
2. How to design the laboratory infrastructure is an important issue that should be taken into account the integration of the laboratory with the university virtual campus. International standards and specifications are used as a solution.
3. How the use of remote laboratory is perceived by students needs to be evaluated. The use of a laboratory is focused on the improvement of students' learning. In this way, the use of a remote laboratory must be assessed for student perception. As such, the use of the remote laboratory is evaluated by means of an FPGA-based case study. Students enrolled in the Digital Electronics class used the remote laboratory to access a real FPGA and all of the needed resources for its configuration, programming, control, and experiment visualization.

The rest of the paper is organized as follows. The remote laboratory is presented in Section 2. Section 3 presents an FPGA-based case study for evaluation of the remote laboratory (RLAB-UOC) performed across six semesters to assess its use by students enrolled in a subject. Finally, the conclusions and future work are presented in Section 4.

2. RLAB-UOC: The Open University of Catalonia Remote Laboratory

2.1. Remote Laboratory Overview

This section presents the full system designed, developed, and evaluated by UOC, taking into account the student's needs for acquiring practical competences in an online engineering education. Three main issues should be considered:

i. The proposal must be a complete system for practical experimentation, where students can work with real devices and equipment that could be found in traditional electronics and communications laboratories.
ii. The proposal must allow for the integration of the laboratory with the university virtual campus.
iii. The experiments must be perceived in a real way by students and not as a simulation.

Firstly, Section 2.2 describes the developed remote laboratory. Secondly, Section 2.3 details how laboratory users are authenticated and can access the experiments to be carried out. Finally, Section 2.4 presents what types of experiments are conducted in the remote laboratory. The evaluation and analysis of RLAB-UOC are presented in Section 3 by means of an FPGA-based case study performed in a study subject for six semesters.

2.2. Remote Laboratory Description

The RLAB-UOC remote laboratory for telecommunications engineering experimentation take into account some special considerations. Firstly, all resources used by students are physically located and installed at the university; therefore, all resources are accessed remotely using the Internet and no physical contact exists between the student and the laboratory resources. Secondly, some specialized electronic devices are time-constrained because the number of devices is limited. Thus, they can only be accessed by one student at a same time and they are shared (including among study subjects); in this way, it is necessary to control their access using a management system composed of booking and experiment management systems. Finally, usability of the laboratory and how the experimentation must be conducted to acquire practical competences using this type of laboratory must be considered.

With regard to the building infrastructure, the laboratory is in the UOC building in the innovative district of Barcelona (Spain). The experiments were separated into two different spaces to host all resources: one to store all server infrastructures (rack, switch, and KVM)

and one to store specialized electronic devices such as communications equipment, digital electronics, etc., which are connected to the PCs located in the laboratory to be remotely accessed and controlled. Taking into account the expected 24/7 laboratory operation, the main issues considered are as follows:

1. Access. Students' access to the electronic hardware is controlled by means of a booking system, which controls who accesses each experiment and how much time they can be connected to it. In addition, laboratory experiments are controlled by means of a management system based on a Windows Service, installed on the computers of the laboratory, that guarantees a new, clean, and working user session each time.
2. Temperature. Temperature and air flow are controlled by means of air conditioning systems, ensuring correct operation of all devices.
3. Energy. Each room has an available UPS (Uninterruptible Power Supply) to ensure that all devices can operate even when problems occur with the power grid. Moreover, using a PDU (Power Distribution Unit), each outlet can be independently managed in order to power on/off hardware resources depending on their scheduled use.
4. Connectivity. The laboratory is connected to a Gigabit network using firewall security policies. The statuses of the network use, disk space, CPU load, or energy consumption are managed in a centralized way.
5. Illumination. Efficient LED illumination is available if the experiments need to be observed by students using webcams.
6. Monitoring. All laboratory activity is monitored and logged, such as student access, network use, disk space, CPU load, or energy consumption. If some error occurs, an alert is generated.
7. Control. Electronic equipment and devices can be remotely reset by students using a PDU. Moreover, each student session is cleaned to be prepared for use for subsequent experiments.

Regarding the availability of laboratory resources, the necessity for devices such as servers, software licences, etc. is estimated by taking into account their concurrent access. The use of a booking system allows us to apply an access policy, e.g., maximum time for each experiment. This is useful to improve the efficiency of the laboratory since resources can be accessed 24/7 in one or more subjects at the same time, and their use can be scaled according to demand.

Finally, as far as usability and experimental design are concerned, different prototypes were developed and evaluated, with the final aim of integrating the laboratory resources into UOC's virtual classrooms. Students use laboratory experiments as extra learning resources (such as a textbook). At the end of each course, a questionnaire was sent to the students to assess the necessity for (i) improving infrastructure/resources, (ii) designing new experiments, (iii) improving the availability of laboratory, and (iv) improving the teaching–learning process in general by using practical experiments along with theoretical contents.

2.3. Laboratory User Authentication and Access

In terms of the authentication of all users and their access to laboratory experiments and resources, some important issues have to be taken into account:

1. A key point to overcome is that users must log in to the lab-system (i.e., students, lectures, and system administrators). An automatic system is considered the proper method of authentication, since it uses all of the available campus information, avoids human errors, and makes it easy to manage the number of users in each course.
2. If all user information is available in the institution database, the best method is to use a standard specification. It could be even possible to share resources among institutions by using the same standard.

Therefore, the standard to meet the expectations is the Learning Tools Interoperability (LTI) specification of IMS Global Learning Consortium [29]. The principal concept of

LTI is to establish a standard method of integrating rich learning applications (often remotely hosted and provided through third-party services) with platforms such as learning management systems, portals, or other educational environments. In LTI, these learning applications are called Tools (delivered by Tool Providers) and the LMS, or platforms, are called Tool Consumers (see an overview of LTI in Figure 1).
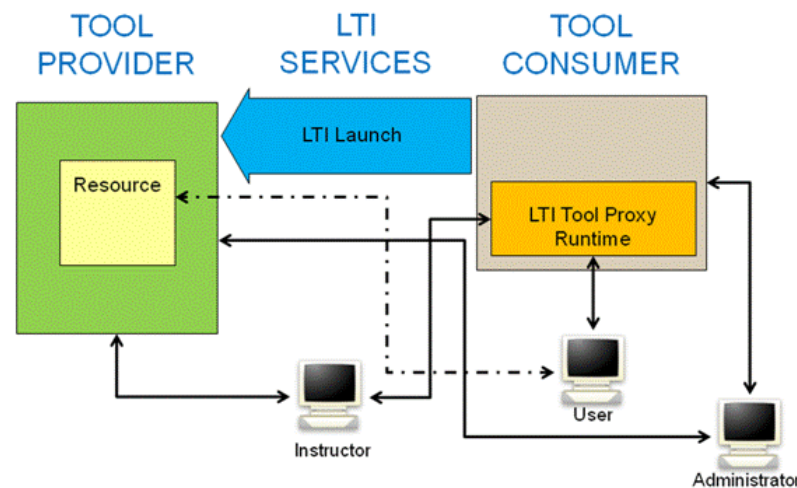

Figure 1. Overview of LTI [30].

The basic use case behind the development of the LTI specification is to allow for a seamless connection of web-based, externally hosted applications and content, or Tools (from simple communication applications such as chats to domain-specific learning environments for complex subjects such as math or science) to platforms that present them to users. In other words, if you have an interactive assessment application or virtual lab, it can be securely connected to an educational platform in a standard way without having to develop and maintain custom integrations for each platform.

In summary, LTI specification makes it easy to manage all laboratory users, avoiding the need for human participation in the laboratory management system. Moreover, it allows us to think beyond UOC's remote laboratory, degrees, and students, since it opens the door towards laboratory interoperability, sharing experiments and resources among institutions, and only using the proper LTI provider and consumer.

Taking into account the solution for authentication, we discuss laboratory access and experiment management. As introduced in Section 2.2, the laboratory is accessed by a management system. This management system is divided in two different parts:

1. A booking system to control the students' access to the experiments.
2. An experiment management system devoted to guaranteeing the integrity of experiments for each new working user session.

Firstly, the booking system is a PHP-based development devoted to guarantee student access to laboratory experiments. This booking system can be accessed by three types of users:

1. Administrator. The administrator manages all of the available resources in the laboratory, defines which subjects can use the laboratory infrastructure, and attends to experiment requests made by instructors.
2. Instructor. Instructors can request new experiments for their subject of study.
3. Student. Students can book experiments for the subject of study in which they are enrolled.

The booking system uses the LTI specification presented above in order to make access easy for the users. They can automatically be logged in from the virtual classroom (Figure 2) without the need for another authentication process. Moreover, when students are enrolled in a subject that uses the remote laboratory, they are automatically registered in the labora-

tory system upon first access. In addition, the system allows us to define local users in the database in order to have guest and test users.
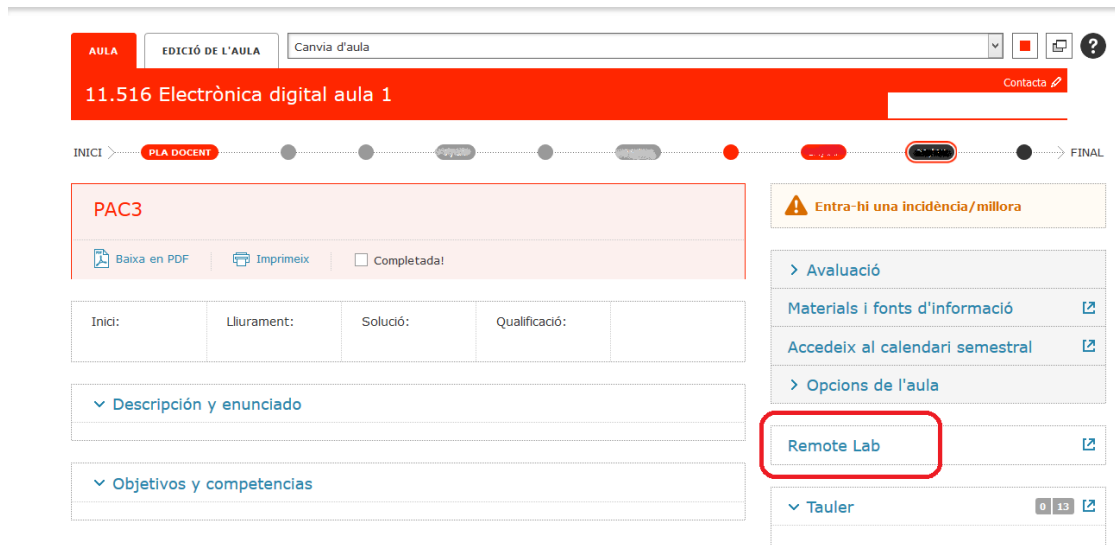
Figure 2. Booking system access from the virtual classroom.

The instructor can configure different rules to be applied when booking their experiments (Figure 3): total number of hours to perform the experiment, number of hours in a day to conduct the experiment, number of hours for cancelling before the reservation date, and number of hours before the reservation date to send students a reminder e-mail.

Figure 3. Instructor's view for experiment creation.

When the students are logged into the booking system, they can select the experiment to be carried out (Figure 4). Reservations are made and managed using the booking system. Finally, when the reservation date arrives, all of the information needed to access the experiment is shown to the student (Figure 5): user and password session, IP address of the computer, and the required communication port. The access is based on RDP (Remote Desktop Protocol), accessing a laboratory computer, where all of the required resources are available, being used by students to perform all practical experimentation. This access can be performed using a Windows, Linux, or Mac RDP client. Finally, instructions for connection between the student PC and experiment computer are provided for every operating system.
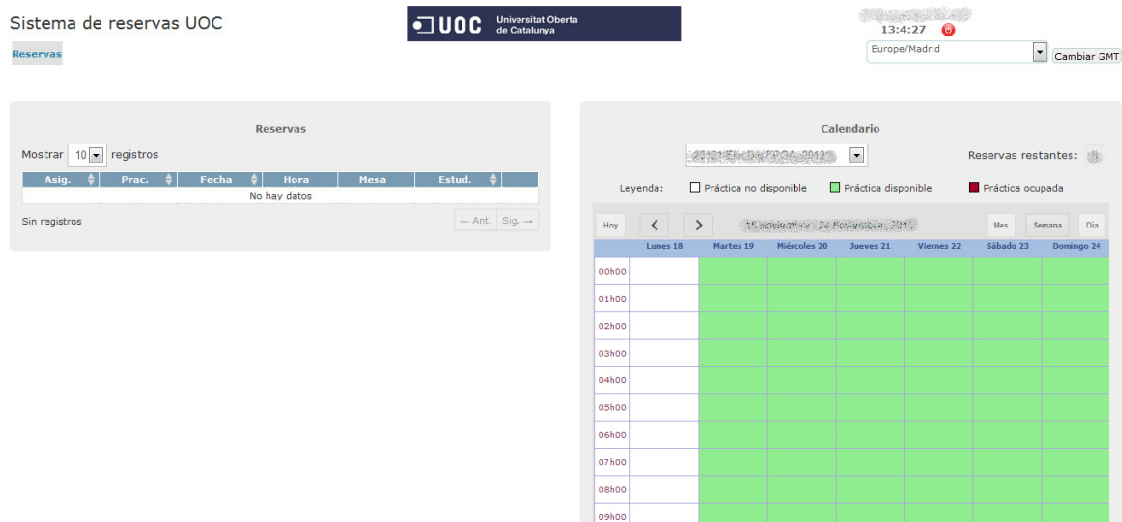
Figure 4. Student's view for experiment reservation.

Figure 5. Student view for experiment access.

Finally, as far as the experiment management system is concerned, it complements the booking system. Before the reservation date arrives, the booking system sends all of the information related to the next reservation to the laboratory computer, guaranteeing correct access to the resources during the students' working session:

- User id. It corresponds with the institutional e-mail address of the student that is able to access the experiment.
- Password session. It is the password assigned to the laboratory computer for the related experiment and session time.
- Starting time. It corresponds with the time when the student could access the experiment.
- Ending time. It is the time when the session will expire and be restored.

Every laboratory computer has a Windows-based client installed that controls all communication with the booking system server and manages the use of the computer by the student. The operation of a working session in the remote laboratory is as follows:

1. The student accesses the remote PC using all of the credentials provided by the booking system.
2. The student receives a warning message about logging off 15 minutes before of the session end time. This warning message informs the student about logging off and restoration of the session.
3. The student is logged off 5 minutes before the session end time.

4. During the last 5 minutes of the working session, all user files are deleted and the user session is restored.
5. The booking system provides the experiment manager system with the new student session information.

2.4. Laboratory in Use

Telecommunication engineering students need to acquire practical competences to improve their future professional skills. If online education is taken into account, a remote laboratory becomes a key tool during the teaching–learning process. Thus, the RLAB-UOC laboratory infrastructure was designed so that students can access experiments and be provided the best telecommunication engineering learning experience. If complex or costly equipment is considered, a remote laboratory is indeed more useful than other types of laboratories, such as virtual labs for simulations.

All experiments are devoted to enhancing the teaching–learning process, combining theoretical and practical resources according to the necessities of every subject, and can be grouped in two knowledge fields:

- Electronics. Both analogue and digital electronics experiments can be performed remotely. Firstly, analogue electronics experiments are devoted to designing, mounting, and studying different types of electronic circuits using UOC developments [31] and Keysight Technologies switching matrices or multiplexors, electronics components, and generator/measurement devices, constituting an original method that allows students to create their own electronic circuits in online education. Secondly, digital electronics experiments are carried out using a real FPGA board in which students can load a VHDL code and test it in a real device. These experiments use a National Instruments FPGA board [32] along with a LabVIEW-based interface [33] to interact with the loaded VHDL code.
- Telecommunications systems. These experiments allows students to practise different concepts of telecommunication engineering. A variety of devices are used with different aims:
  i. Communications systems. For example, NI Elvis II+ [34] is used along with Emona DATEx [35] and Emona FOTEx [36] to carry out communications systems- and fiber optics-related experiments.
  ii. Radiocommunications. For example, USRP 2920 [37] bundles are available for complex practise of radiocommunications protocols and signal transmission. In addition, Keysight Technologies [38] and Rohde & Schwarz [39] RF devices are used to learn about RF communications concepts.

In addition, the use of switching and multiplexing devices improves the experiments with flexibility (student experimentation) and make experiment creation (dynamic experiment development) possible.

Moreover, in order to carry out all experiments, complex signal generation and measurement laboratory equipment is needed. All of these devices are online accessible thanks to remote interfaces based on manufacturer or our ad hoc developments. Most of these equipment are Keysight Technologies (formerly known as Agilent Technologies) devices, such as the arbitrary signal generator, the oscilloscope, or the vector signal analyser [38].

Finally, all of these experiments use the laboratory infrastructure presented in Section 2.2: (i) the booking and experiment management system, (ii) the outlet control device in order to power on/off the selected devices, (iii) the monitoring of laboratory use, and (iv) efficient illumination, among others.

3. RLAB-UOC Assessment: FPGA-Based Case Study

3.1. FPGA-Based Case Study Description

The RLAB-UOC remote laboratory presented in Section 2 was assessed by means of an FPGA-based case study. This case study was designed to obtain relevant information

about the use of the general remote laboratory, both in terms of infrastructure and utility in the teaching–learning process.

The remote laboratory assessment was conducted across six semesters for a Digital Electronics class. This subject is studied for the Bachelor of Telecommunications Engineering (BTE) degree at UOC and is an advanced subject in the degree.

This subject deals with digital electronics concepts with the following learning objectives:

1. Low-level creation of digital systems (logic gates) by means of CMOS technology.
2. Implementation of elements belonging to the Medium-Scale Integration (MSI) by using logic gates.
3. Use of hardware descriptor language to create digital systems. Students use VHDL to design, implement, and simulate complex digital systems.
4. FPGA and embedded systems architectures are explained in detail.

During the course, students' work is evaluated by means of different theoretical and practical activities. Practical activities are designed to acquire the required practical and professional competences related to design, develop, simulate, device programming, and test solutions. It is within FGPA-related activity that students use the remote laboratory with the following main objectives:

i. Students can load the VHDL code developed and simulated in a previous activity by using Quartus II and ModelSim.
ii. Students can use an FPGA of a different vendor than that explained during the study of the subject. They can check that VHDL is a standard language and is compatible among models.
iii. Students can check how the selected FPGA is oversized, taking into account the real needs of the scenario.
iv. Students can observe all of the process: specifications, solution design, software development, simulation, compilation, and FPGA programming.
v. Students can control the application run on the FPGA by means of a LabVIEW graphical interface. All activity using LabVIEW is guided by the instructor.

The FPGA activity, as introduced previously, is the last part of the course, where the need to use the real FPGA device makes the remote laboratory necessary in a fully online engineering education context. In this case, sending this type of device to students was not cost-effective and no significant learning improvement was considered.

In terms of equipment, in the laboratory, the NI Digital Electronics FPGA Board [32] and a circuit development platform based on the XC3S500E Xilinx Spartan-3E FPGA were available. In addition, to manage it, LabVIEW software [33] is used, which is able to load VHDL code and to create a graphical interface to control the experiment.

Therefore, the laboratory activity to use FPGA was designed as follows, being different each year in order to be adapted to the real scenarios presented within the subject of study:

1. Students performed work previously in terms of the solution to a real design problem. VHDL code was generated and simulated.
2. The instructor prepared a standard solution for the previous activity, making the VHDL code that will be used by students during the FPGA experiment in the remote laboratory available.
3. The instructor prepared a LabVIEW project emulating the real problem in a previous activity. The VHDL code is loaded by the students in this project to control the graphical interface and to interact with different elements available in the FPGA development board (e.g., pushbuttons, switches, LED, or seven segments).
4. The instructor makes a guide for accessing, loading the VHDL code, and using the LabVIEW graphical interface available.
5. Students can book and access the remote laboratory, which has all available necessary resources to conduct the experiment. During the experimentation, students can see the FPGA board activity by means of a webcam.

An example of laboratory use is shown in Figure 6, where by using a LabVIEW graphical interface, the VHDL code is loaded and executed. Students have to load the VHDL code created during the course in a real FPGA and, by using this type of interface, different tests can be performed to know how real FPGA works when a code is compiled, loaded, and used. Thus, practical competences in digital electronics are acquired by students using real industry-related hardware.
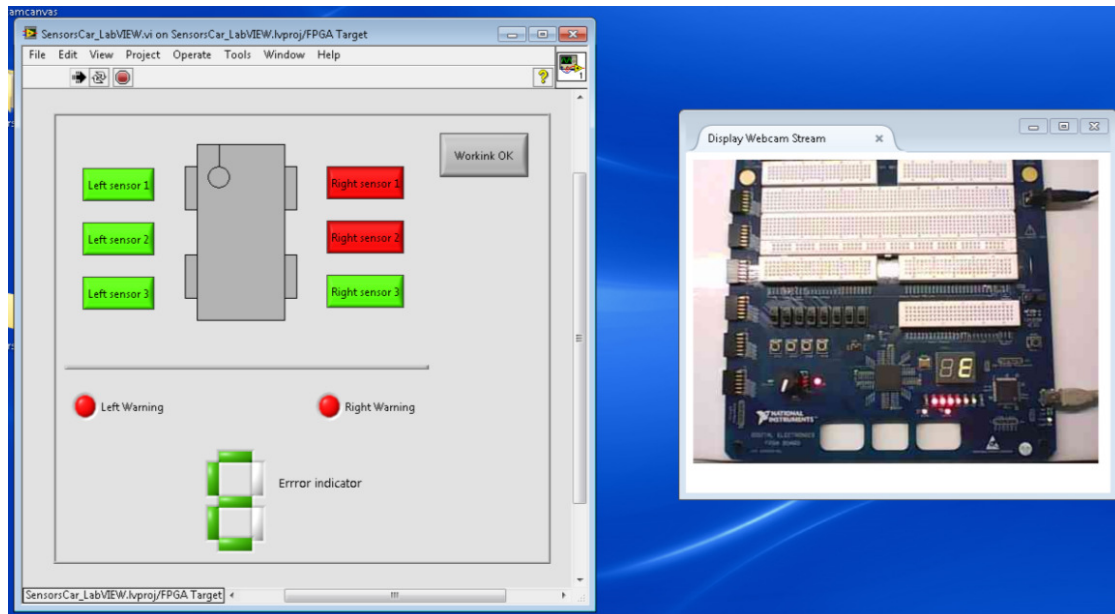
Figure 6. Example of an FPGA experiment using a LabVIEW graphical interface and webcam visualization.

3.2. RLAB-UOC Assessment

With regard to the remote laboratory and the use of FPGA in experiments, for each of the six semesters under evaluation, a self-administered questionnaire was sent to the students. Table 1 shows the number of students enrolled in the subject in each semester and the number of students that answered the questionnaire. Notice that a total of 292 students were asked and that 99 answered the questionnaire, 33.90% of the enrolled students in the subject.

Table 1. Number of students enrolled in the Digital Electronics course per semester and number of student answering the self-administered questionnaire (in brackets).

Semester 1	Semester 2	Semester 3	Semester 4	Semester 5	Semester 6	Total
64 (20)	35 (13)	44 (15)	57 (20)	45 (13)	47 (18)	292 (99)

The self-administered questionnaire was carried out with two main aims. The first one was to evaluate the perceived quality and utility of the remote laboratory in subjects of study for the telecommunications engineering degree, and the second one was to validate the perception of students by using real hardware in front of simulations. In this way, the following eight questions were asked to students to evaluate the remote laboratory and FPGA experiment experience by means of a Mean Opinion Score (MOS) with a rating between 1 (minimum rating) and 5 (maximum rating):

Q1 Which is your perception of working with a real FPGA in the subject? 1 (no sense of reality) to 5 (complete sense of reality).

Q2 In general terms, how do you rate the necessity of using remote laboratories in the degree you are enrolled? 1 (not necessary) to 5 (totally needed).

Q3 How do you rate the experience of using a real FPGA in this subject by means the remote laboratory? 1 (very negative) to 5 (very positive).

Q4 How do you rate the access to the remote laboratory (e.g., authentication or availability)? 1 (very negative) to 5 (very positive).

Q5 How do you rate the remote laboratory booking system (e.g., usability or availability)? 1 (very negative) to 5 (very positive).

Q6 How do you rate the use and visualization of the FPGA related experiment? 1 (very negative) to 5 (very positive).

Q7 Which is your general satisfaction by using the remote laboratory for real FPGA experimentation in this subject? 1 (very bad) to 5 (very good).

Q8 Should the use of the remote laboratory be extended to other technological subjects? 1 (not agree) to 5 (totally agree).

As presented in Figure 7, the overall results are mostly rated between 4 and 5, indicating a very good perception about the FPGA experiment and remote laboratory. The different issues evaluated are discussed next.

Regarding student's perception about the FPGA experiment, Figure 7a shows that the perception of using a real FPGA in the subject of study is mostly rated between 4 and 5, with a median rate of 4, indicating a very good opinion about the sense of reality. Moreover, the experience of using an FPGA by means of the remote laboratory, presented in Figure 7c, is very positive, with a median rate of 5 in most of the evaluated semesters. In addition, Figure 7f shows that the visualization of the FPGA experiment is very well received, with a median of 4 or greater.

With regard to the the remote laboratory infrastructure, use, and utility, some considerations can be made from the conducted assessment. Firstly, Figure 7b shows very good results according to the perception of the need to use the remote laboratory in the telecommunications engineering degree, with a rating between 4 and 5, with a median value mostly greater than 4. Secondly, according to the RLAB-UOC access and booking systems presented in Figure 7d,e, respectively, very positive results are achieved for both issues, obtaining ratings between 4 and 5 in all evaluated semesters, with a median value mostly greater than 4. Finally, Figure 7h shows the student's agreement with extending the use of the remote laboratory to other technological subjects, with a median rate of 5 in most of the evaluated semesters.

Eventually, taking into account the results for the general satisfaction by using the remote laboratory for real FPGA experiments in the subject, Figure 7g shows that students' assessments are mostly rated between 4 and 5, with a median value of 4 or greater in different semesters.

It is interesting that the opinion of students is consistent among semesters and items under evaluation. All median values are rated between 4 and 5, showing the good perception towards the remote laboratory and the performed FPGA experiment.
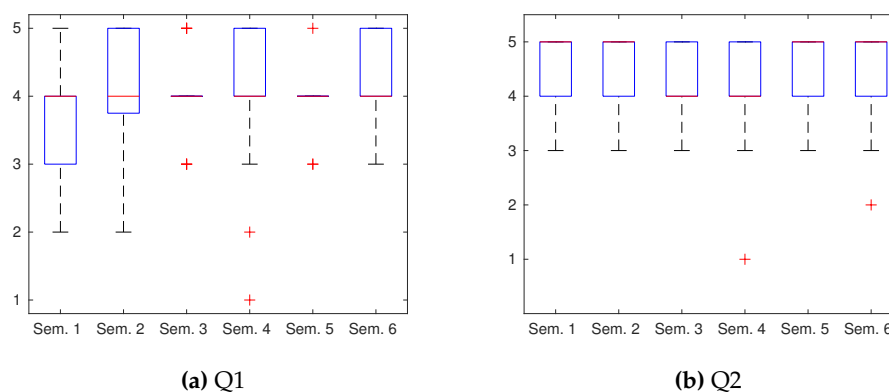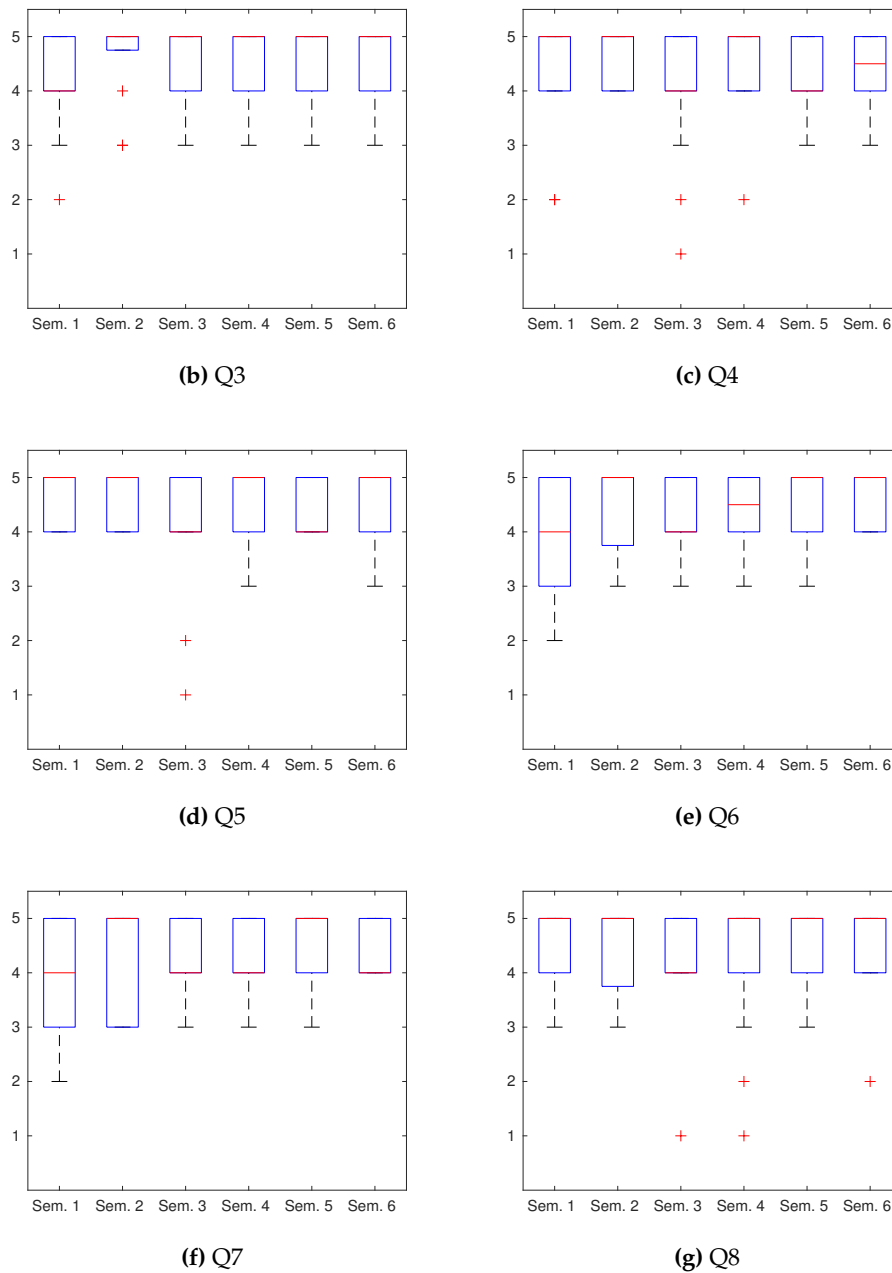

(a) Q1

(b) Q2

Figure 7. *Cont.*

(b) Q3

(c) Q4

(d) Q5

(e) Q6

(f) Q7

(g) Q8

Figure 7. Assessment results about the FPGA experiment and remote laboratory infrastructure, use, and utility.

4. Conclusions and Future Work

Practical experimentation is essential in technological degrees to acquire the required practical competences. However, as presented in Section 1, most of these initiatives consider face-to-face contact with students and are specific to face-to-face contact learning necessities. Thus, taking into account the perspective of distance learning becomes a real challenge. This work presents RLAB-UOC, the remote laboratory of the Open University of Catalonia (Universitat Oberta de Catalunya, UOC) for telecommunications engineering experiments, which intends to allow students to perform experiments anywhere and anytime with real hardware in a fully online engineering learning context. In addition, an FPGA-based laboratory case study is presented to analyze the remote laboratory features and students' satisfaction with its use.

In order to evaluate the RLAB-UOC in a real context, self-administered questionnaires were completed by the students of one subject of study at the end of six consecutive semesters. The results indicate that the remote laboratory is highly regarded and that the final aim of performing real experiments is achieved. In addition, the students consider it advisable to extend the use of this laboratory to other subjects. These results are consistent with the evaluation presented in Section 1, with an improvement in experiment immersion and is worthy of use to achieve the expected learning objectives and competences.

According to the conducted research, the real possibilities of using the proposed remote laboratory in a fully online context have been shown. In addition, the results support the use of our proposal from the point of view of usefulness, immersion, and usability.

Nowadays, new experiments are available based on the use of a remote laboratory infrastructure, working with complex telecommunication equipment and devices (e.g., RF generator, vector signal analyzers, oscilloscopes, etc.), and being able to perform experiments related to electronics communications systems. Finally, in the remote laboratory context, we obtained property protection by means of a patent [31].

5. Patents

One patent was derived from the conducted work in the remote laboratory context:

- Fundació per a la Universitat Oberta de Catalunya, "Device for switching a plurality of electronic components". Spanish ES2659995, 6 November 2018.

Author Contributions: Conceptualization, C.M., G.C., J.A.M., E.S. and D.G.-S.; funding acquisition, E.S.; investigation, C.M., G.C. and D.G.-S.; resources, C.M., J.A.M. and E.S.; software, C.M., G.C. and D.G.-S.; supervision, C.M. and G.C.; validation, C.M.; writing—original draft preparation, C.M. All authors have read and agreed to the published version of the manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

BTE	Bachelor of Telecommunications Engineering
DAQ	Data Acquisition
DMM	Digital Multimeter
EHEA	European Higher Education Area
FPGA	Field-Programmable Gate Array
LTI	Learning Tool Interoperability
MTE	Master of Telecommunications Engineering
RLAB-UOC	Remote Laboratory-Universitat Oberta de Catalunya
UOC	Open University of Catalonia (Universitat Oberta de Catalunya)
UPS	Uninterruptible Power Supply
VHDL	Very High Speed Integrated Circuit Hardware Description Language

References

1. Gustavsson, I.; Nilsson, K.; Zackrisson, J.; Garcia-Zubia, J.; Hernandez-Jayo, U.; Nafalski, A.; Nedic, Z.; Gol, O.; Machotka, J.; Pettersson, M.; et al. On objectives of instructional laboratories, individual assessment, and use of collaborative remote laboratories. *IEEE Trans. Learn. Technol.* **2009**, *2*, 263–274. [CrossRef]
2. Feisel, L.; Rosa, A. The Role of the Laboratory in Undergraduate Engineering Education. *J. Eng. Educ.* **2005**, *94*, 121–130. [CrossRef]
3. Jung, I. Quality Assurance Survey of Mega-Universities. In *Lifelong Learning and Distance Higher Education*; Christopher, M., Varoglu, Z., Eds.; UNESCO-COL: Paris, France; Vancouver, BC, Canada, 2005.
4. Kidney, G.; Cummings, L.; Boehmt, A. Toward a Quality Assurance Approach to E-Learning Courses. *Int. J. E-Learn.* **2007**, *6*, 17–30.

5. SNAHE. *E-Learning Quality Aspects and Criteria for Evaluation of E-Learning*; Swedish National Agency for Higher Education: Stockholm, Sweden, 2008.
6. Mobile Studio Project. Available online: http://www.mobilestudioproject.com/ (accessed on 21 March 2021).
7. Millard, D. Coming to a Desktop Near You—Mobile Studio. Available online: https://transistor-man.com/files/moiblestudio/sp07_pdf_mobile_studio.pdf (accessed on 21 March 2021).
8. Connor, K.; Ferri, B.; Meehan, K. Models of Mobile Hands-On STEM Education. In Proceedings of the 2013 American Society for Engineering Education Annual Conference and Exposition, Atlanta, GA, USA, 23–26 June 2013.
9. National Instruments. Ni myDAQ User Guide and Specifications. Technical Report, National Instruments Corporation: Austin, TX, USA, 2011. Available online: https://www.ni.com/pdf/manuals/373060g.pdf (accessed on 21 March 2021).
10. Instruments, N. Analog Discovery 2—NI Edition Overview. Technical Report, National Instruments Corporation, 2018. Available online: https://www.ni.com/pdf/manuals/AnalogDiscovery2NIDatasheet.pdf (accessed on 21 March 2021).
11. National Instruments. NI USB-6008/6009 User Guide. Technical Report, National Instruments Corporation, 2015. Available online: https://www.ni.com/pdf/manuals/371303n.pdf (accessed on 21 March 2021).
12. Walters, M.; Luther, E.; Dinolfo, J. Do Engineering—Anywhere, Anytime. In Proceedings of the Canadian Engineering Education Association (CEEA12), Winnipeg, MB, Canada, 17–20 June 2012; pp. 1–4.
13. Walters, M. Using low-cost technology and relevant challenges to encourage and retain engineering students. In Proceedings of the 2012 2nd Interdisciplinary Engineering Design Education Conference (IEDEC), Sanata Clara, CA, USA, 19 March 2012; pp. 121–123.
14. Ursutiu, D.; Dumitru, I.; Samoila, C. Student educational device for electronic applications (StudentEDEA). In Proceedings of the 2013 International Conference on Interactive Collaborative Learning (ICL), Kazan, Russia, 25–27 September 2013; pp. 552–555.
15. Vernier Circuit Board. Available online: http://www.vernier.com (accessed on 21 March 2021).
16. Arduino Uno. Available online: https://store.arduino.cc/arduino-uno-rev3 (accessed on 21 March 2021).
17. Monzo, C.; Cobo, G.; Morán, J.; Santamaría, E.; García-Solórzano, D. Lab@Home: The Open University of Catalonia Hands-on Electronics Laboratory for Online Engineering Education. *Electronics* **2020**, *9*, 222. [CrossRef]
18. iLab Project. Available online: http://icampus.mit.edu/projects/ilabs/ (accessed on 21 March 2021).
19. Kostulski, D.T.; Murray, S. *The National Engineering Laboratory Survey. A Review of the Delivery of Practical Laboratory Education in Australian Undergraduate Engineering Programs*; Technical report; LabShare Project: Sydney, Australia, December 2010.
20. LiLa Project. Available online: http://www.lila-project.org/ (accessed on 21 March 2021).
21. OpenLabs Project. Available online: http://openlabs.bth.se/ (accessed on 21 March 2021).
22. Gustavsson, I.; Zackrisson, J.; Håkansson, L.; Claesson, I.; Lagö, T. The VISIR project—An Open Source Software Initiative for Distributed Online Laboratories. In Proceedings of the 4th International Conference on Remote Engineering and Virtual Instrumentation (REV2007), Porto, Portugal, 23–24 June 2007; pp. 1–6.
23. WebLab-Deusto. Available online: https://weblab.deusto.es/website/ (accessed on 21 March 2021).
24. Chen, X.; Kehinde, L.; Zhang, Y.; Osakue, D.; Olowokore, D.; Darayan, S. Using virtual and remote laboratory to enhance engineering technology education. In Proceedings of the ASEE Annual Conference & Exposition, Vancouver, BC, Canada, 26–29 June 2011.
25. Tawfik, M.; Sancristobal, E.; Martín, S.; Gil, C.; Pesquera, A.; Losada, P.; Díaz, G.; Peire, J.; Castro, M.; García-Zubia, J.; et al. VISIR deployment in undergraduate engineering practices. In Proceedings of the 2011 Frontiers in Education Conference (FIE), Rapid City, SD, USA, 12–15 October 2011. [CrossRef]
26. Garcia-Zubia, J.; Orduña, P.; Angulo, I.; Hernandez, U.; Dziabenko, O.; de Ipiña, D.L.; Rodriguez-Gil, L. Application and user perceptions of using the WebLab-Deusto-PLD in technical education. In Proceedings of the 2011 First Global Online Laboratory Consortium Remote Laboratories Workshop, Rapid City, SD, USA, 12 October 2011. [CrossRef]
27. Gros, B.; Lara, P.; García, I.; Mas, X.; López, J.; Maniega, D.; Martínez, T. *The UOC's Educational Model: Evolution and Future Perspectives*; Universitat Oberta de Catalunya: Barcelona, Spain, 2009.
28. The European Higher Education Area (EHEA). Available online: https://ehea.info/ (accessed on 21 March 2021).
29. IMS GLOBAL Learning Consortium. Available online: http://www.imsglobal.org/activity/learning-tools-interoperability (accessed on 21 March 2021).
30. IMS GLOBAL Learning Consortium. Available online: http://www.imsglobal.org/specs/ltiv1p1/implementation-guide (accessed on 21 March 2021).
31. Fundació per a la Universitat Oberta de Catalunya. Device for Switching a Plurality of Electronic Components. Spanish ES2659995, 6 November 2018.
32. National Instruments. NI Digital Electronics FPGA Board—User Manual. Technical Report, National Instruments Corporation, 2009. Available online: https://www.ni.com/pdf/manuals/372809b.pdf (accessed on 21 March 2021).
33. LabView. Available online: http://www.ni.com/labview/ (accessed on 21 March 2021).
34. National Instruments. NI Educational Laboratory Virtual Instrumentation Suite II Series (NI ELVIS II Series) User Manual. Technical Report, National Instruments Corporation, 2011. Available online: https://www.ni.com/pdf/manuals/374629c.pdf (accessed on 21 March 2021).
35. Breznik, A.; Manfredini, C. Emona DATEx Telecommunications Trainer for NI ELVIS—User Manual. Available online: https://www.emona-tims.com/emona-product/datex/(accessed on 21 March 2021).

36. Breznik, A.; Manfredini, C. Emona FOTEx Fiber Optics Trainer for NI ELVIS—User Manual. Available online: https://www.emona-tims.com/emona-product/fotex/ (accessed on 21 March 2021).
37. National Instruments. NI USRP-29xx Getting Started Guide. Technical Report, National Instruments Corporation, 2012. Available online: https://eduscol.education.fr/sti/sites/eduscol.education.fr.sti/files/ressources/techniques/3801/3801-guide-configuration-usrp-29xx.pdf (accessed on 21 March 2021).
38. Keysight Technologies. Available online: http://www.keysight.com/ (accessed on 21 March 2021).
39. Rhode & Schwarz. Available online: https://www.rohde-schwarz.com/ (accessed on 21 March 2021).