Augmented Reality for the Improvement of Remote Laboratories: An Augmented Remote Laboratory

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***Abstract*—Augmented reality (AR) provides huge opportunities for online teaching in science and engineering, as these disciplines place emphasis on practical training and unsuited to completely nonclassroom training. This paper proposes a new concept in virtual and remote laboratories: the augmented remote laboratory (ARL). ARL is being tested in the first and second years of the new degrees in industrial engineering and computer engineering, respectively, at the School of Engineering, University of Huelva, Huelva, Spain. By means of augmented reality techniques, ARL allows the student to experience sensations and explore learning experiences that, in some cases, may exceed those offered by traditional laboratory classes. The effectiveness of this methodology for remote laboratory work is evaluated by comparing it to practical sessions in the laboratory at the university itself with the same group of students. Students completed a questionnaire after having experienced both types of practicals, and the results show that the use of ARL improves student outcomes. As discussed in the paper, the potential of AR to configure different experiments from the same physical configuration is virtually limitless.**

***Index Terms*—Augmented reality (AR), augmented remote laboratories (ARLs), remote laboratories, science and engineering education, virtual laboratories.**

I. Introduction

THIS paper presents research aimed at developing augmented reality (AR) tools and techniques for virtual and remote laboratories. Within this field, the classification and definition contributed by [1] (virtual instrument, remote instrument, remote laboratory, virtual laboratory, and virtual and remote laboratory) are extended with the augmented remote laboratory (ARL). To illustrate the capabilities of this proposal, a practical application demonstration—the design of a digital control system based on an FPGA development board—is presented.

These new techniques are being used by students to access laboratory in the new degrees in electronics engineering (EE) and computer engineering (CE) in the School of Engineering at the University of Huelva, Huelva, Spain. The specific courses are Fundamentals of Computers (first year of CE) and Digital Systems (second year of EE). Both degrees come under the European Higher Education Area (EHEA), an initiative of the Bologna process designed to create more comparable, compatible, and coherent higher education systems in Europe [2].

The need for laboratory practicals in engineering (and of course in other educational disciplines) to allow students to acquire skills in solving real problems is unquestionable. Fulfilling this need, however, can present logistical, economic, and educational problems, including the following.

- There are limited resources in the laboratories, both of software and hardware.
- Real laboratory models are expensive. It is very difficult to provide individualized material for each student. Moreover, many universities will have problems providing scaled-down industrial plants (in this paper, the concept of "plant" is that usual in control engineering: the system which is to be measured and controlled) for each working group (18 students in this case).
- Laboratory schedules must conform to the university hours.
- The time available for each working group is always insufficient since the laboratories are shared between different degrees and courses.
- Virtual laboratories typically have the added problem of a lack of contact between the student and the laboratory equipment.

These and other problems that arise, depending on each individual institution's situation, can be overcome using the AR techniques developed in this paper, according to the following proposals.

- Real laboratory models can be expanded, reduced, or modified. This allows a single plant to be used for different experiments without having to modify the physical environment. This can provide great savings in cost, as well as in preparation time for whoever is teaching the practical sessions.
- Laboratories with their plants and instruments can operate 24 h a day.
- Laboratories can be used concurrently. One group can access the lab through the network by ARL, while another group may be physically in the laboratory using different pedagogical material.
- Students interact remotely with real systems as if they were physically in the laboratory in front of the equipment.

A. Augmented Reality

AR, while incorporating virtual reality *content*, is a technology that is distinct from virtual reality (VR) itself. VR is

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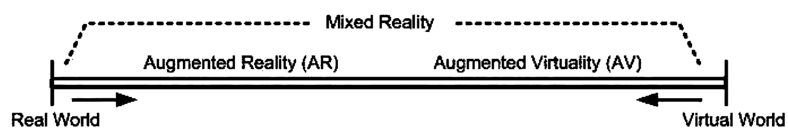

Fig. 1. Reality–virtuality continuum proposed in [3].

isolated from reality and conforms to purely virtual scenarios. AR systems [3]:

- combine real content (usually observed through some electronic device such as cameras and HMD displays) and virtual computer-generated content, adequately superimposed on the real content;
- are real-time interactive systems;
- must be registered in 3-D space. The real space observed by the user defines the context used to interact with and represent real and virtual elements.

AR systems are not limited to graphical applications, as spatially positioned sounds can also be used. Moreover, and depending on the application, the user may need to move within small or large spaces. This movement involves monitoring (tracking) the user's position and orientation by means of local devices (magnetic and/or optical) or external monitoring devices such as GPS systems. These systems can be combined, thus resulting in a wide range of possible applications.

In short, AR supplements real-world perception and interaction and allows the user to view a real environment augmented with computer-generated 3-D information.

Between totally real and totally virtual situations, there is a continuum, shown in Fig. 1, characterized by various mixtures of virtual and real environments. In this mixed reality, the concept of a *virtuality continuum* [4] appears. This concept covers both *augmented reality* and *augmented virtuality* (AV), which is a mixture of the real and virtual worlds. These intermediate points are also collectively known as *mixed reality*.

Nowadays, the term augmented reality has become more common than the term augmented virtuality since its current applications are closer to the real than to the virtual world, among other reasons. AR systems offer a clear advantage: the use of the real world. Indeed, AR applications need not model every little detail of reality; these details are already physically present because they are real. It is only necessary to superimpose those 3-D virtual elements meaningful for the application with which the user wants to interact. The user never loses contact with the real world and, at the same time, can interact with the superimposed virtual information.

AR is currently being introduced in new application areas such as historical heritage reconstruction [5], training of operators of industrial processes [6], system maintenance [7], or tourist visits to museums and other historic buildings [8], among others. The academic world has some connection to these initiatives and has also begun to introduce AR in some academic disciplines, although its teaching applications are still minimal. The still-embryonic state of this technology and its high development and use costs, as well as its low presence in the everyday world, are among the most important reasons for this low implementation level.

B. Augmented Reality in Education

Here, some educational applications of AR techniques are reviewed, such as the *Magic Book*, developed in *The Human Interface Technology Laboratory (HIT Lab)* [9]. This application enables the user to read a book through a display and see, on the pages on the book itself, virtual content associated with those pages. These techniques are used in social science teaching, but can be extended to other disciplines. The *Massachusetts Institute of Technology (MIT)* created AR simulation games that combine PDA-provided real and virtual content [10].

Several European projects have designed and developed innovative applications that integrate AR for educational purposes, such as CREATE [11] and ARiSE [12]. These tools, based on 3-D presentations and user-interaction, facilitate science comprehension, as students can interact with virtual objects in an augmented real environment and develop learning experiences.

In another, the educational use of AR [13] puts forward an educational application for mechanical engineering teaching that allows users to interact with 3-D content using Web technology and AR–VR techniques. Reference [14] uses AR for math teaching, while [15] describes a system for geometry teaching based on these techniques.

An approach to the use of remote laboratories with AR techniques is described in [16], where LabView is used to control an inverted pendulum in a laboratory, although no monitoring or video-image location techniques are used since the virtual image in this case is derived from measurements on the real system.

C. Advantages of AR Techniques for Remote Lab Experimentation

One of the most evident advantages of remote labs is that the process of preparing and carrying out the experiment is very similar to that followed when physically in the lab. Reference [17] lists the disadvantages of a remote testing environment (e.g., the lack of physical contact with the experiment can reduce the sense of realism). For this reason, the AR-based method proposed here is aimed at giving the user the sensation that certain lab functions can be handled just as they would be in the lab itself, thus reducing possible discouragement due to the lack of physical contact. In addition, the use of virtual models connected to lab materials and the possibility of stereoscopic vision are user-friendly factors.

Another disadvantage listed in [17] is that certain areas are unsuitable for remote testing (e.g., chemical labs and the assembly of combinational and sequential digital circuits in a digital electronics lab). The practical application developed in this paper shows how to include digital design in those areas that could be incorporated into remote experimentation.

With respect to the requirements listed in [17], having an open and modular architecture is necessary for the success of a remote experiment, as it allows new components and exercises to be included with minimal effort. AR techniques allow the same physical configuration of lab equipment to be adapted for a wide range of different experiments since their respective equipment needs are replaced by virtual elements that only appear if a specific experiment requires them. In this sense, this proposal presents important advantages since the elements and virtual models connected to real equipment allow many different experiments to be designed without altering the real lab environment. If the remote laboratory is considered as an online educational service, this conception dramatically reduces the down time required for physical configuration modifications in the lab.

D. Application of AR Techniques in Remote Labs

As mentioned, AR has great potential in many different knowledge fields as well as its evident potential in teaching. This paper puts forward an example of a remote lab with AR techniques, namely a practical application of a simple digital system that is focused on demonstrating the possibilities of the developed technique, rather than on solving a complex problem. This implementation allows the remote use of the materials students normally use in laboratory classroom practicals, particularly in the design of digital systems.

Development boards based on high-capacity FPGAs are used for practicals. These boards also include a complete set of FPGA-connected elements such as memory (RAM, EPROM, …), A/D and D/A converters, LCD displays, switches, pushbuttons, serial ports, VGA ports, clock generators, and so on, which increase their potential as systems for lab work.

Experiments with these development boards are traditionally developed in the laboratory classroom. Boards are programmed according to a previous design (usually VHDL). In these designs, result verification requires the introduction of input variables (for example, switches and buttons) and analysis of board response using LEDs, LCD displays, D/A converters, etc.

The method proposed in this paper tries to meet students' needs to access the lab with a flexible schedule for this kind of practical, without their having to come to the university and with the same feelings as when being physically present in the lab, while also adding new educational features.

This paper is organized as follows: Section II describes the elements of the proposed system. Section III details the design and implementation of a case study. Section IV presents other possibilities for AR techniques in lab testing practices, such as the use of virtual models and peripherals connected to the development board. Section V shows a statistical study of the ARL completed in the second semester of the academic year 2009–2010. Finally, conclusions are drawn and future research lines in this field are identified.

II. Augmented Remote Laboratory (ARL)

The proposed ARL is a step above the virtual and remote laboratory [1]; the height of this step depends on the degree to which it depends upon AR techniques. The word *virtual* was deleted from the lab name not because the virtual reality technique is not applicable to this proposal, but because the lab is AR-intrinsic.

Access to the ARL is enabled by an application known as ARRL (augmented reality for remote laboratories). This application is locally run on the user's computer and grants access to the remote lab via TCP/IP by means of AR techniques that enable the interactive use of the lab equipment.

The tasks of the ARRL application can be summarized as the following.

- Showing the student the remote device through a real-time image taken by a remote camera located in the lab.
- Overlaying virtual elements (which enable the student to interact with physically remote elements while having the feeling of working directly on them) correctly on this image. These elements must maintain an appropriate position, scale, and perspective in relation to the received video image. The switches and buttons on the development board—as well as additional peripherals connected to the motherboard that allow student interaction—would be a typical case in the practical application discussed in this paper.
- Showing the results provided by the equipment used (e.g., displays connected to expansion ports). These devices can be *real* (and thus seen in the video image) or *virtual* (application-generated and properly placed depending on the implemented design), with the information being updated according to lab equipment-provided data.
- Although the development board can be connected to a physical model located in the lab, the ARRL application can also connect a *virtual model*, entirely controlled by the board-provided signals. If the experiment includes controlling a model, this can be fully integrated into the ARRL application, so that the student runs it locally. An example of this is presented in Section IV.
- The ARRL application must provide the student easy access to experiment-related educational materials provided by the teacher (e.g., the handout for the experiment, tutorials, student manuals, etc.). The access to a content management system from the ARRL application facilitates both the student's access and the teacher's information distribution.

Fig. 2 shows the general structure of the developed system, where the following main elements are distinguished:

a) Control Management System (CMS);
b) Reservation manager and access control;
c) ARRL application that runs locally to the student;
d) Physical installation in the laboratory;
e) ARRL application builder.

A. Control Management System

This contains the educational material that can be accessed from the ARRL application run by the student through a menu on the video image. *Mambo* CMS is used in the prototypes.

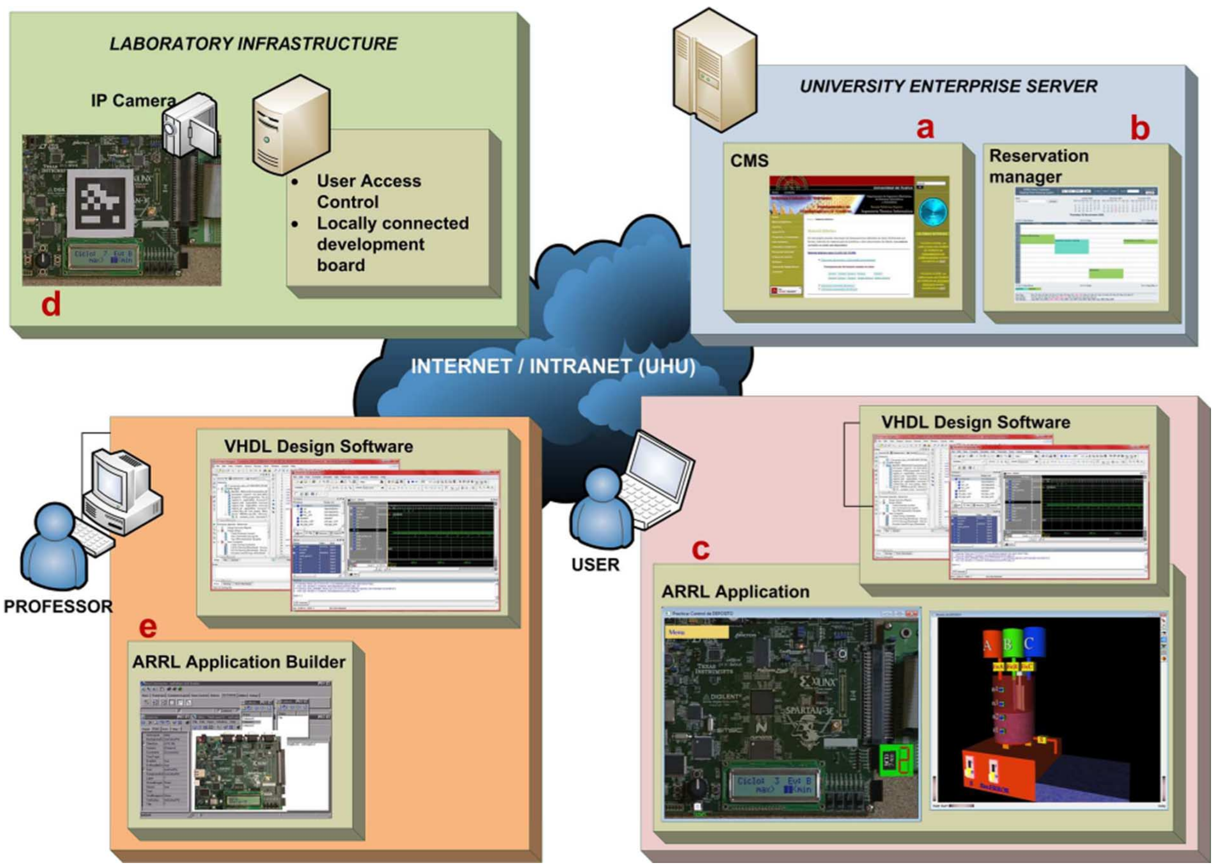

Fig. 2. General structure of the developed system.

B. Reservation Manager and Access Control

The reservation manager ensures appropriate lab-resource allocation, allowing students to reserve slots for their use according to teacher-imposed restrictions.

The access control system uses the reservation data provided by the reservation manager and enables the necessary network resources. These elements are currently under development.

C. ARRL Application

This application is downloaded by the student from the CMS and is ready to be executed locally within the previously installed run-time environment, shared by all applications.

D. Physical Realization of the Lab

The training materials are in the lab itself, as is the necessary infrastructure for access and remote viewing. Fig. 3 shows the enabled experimental prototype area; video cameras and other different equipment can be seen. In the case study reported in Sections III and IV, the following elements are used (see Fig. 3).

1) A development board connected to a PC. Development boards based on a Xilinx FPGA Spartan 3E series, XC3S500E model with 232 IOBs and 10 000 logic cells.
2) A DAQ (LabJack U3LV or U12 USB devices) connected to the PC, with its port expansion bus connected to the development board.
3) A PC server for board remote programming, with the Xilinx-provided software, available in the Xilinx design environment *ISE WebPack*. This server includes software for receiving and sending data over TCP/IP from the DAQ. The ARRL application is a client of the Xilinx server, enabling remote connection to the DAQ.
4) An IP camera (Axis 211 Network Camera) located in front of the development board. It obtains the original video image used by the ARRL application to display the board and superimpose the 3-D virtual elements with their correct position, size, and orientation. These elements are referenced by a marker placed on the board itself. Other types of cameras (see Fig. 3) were also evaluated: a professional camera, Sony DVCAM DSR 570WSP (5), and a stereoscopic camera made of two identical professional cameras Panasonic AW-E600 (6).

E. ARRL Application Builder

The main difficulty in the development of the entire methodology for ARL implementation is undoubtedly the ARRL design, development, and programming. Furthermore, ARRL is a highly time-consuming application, and a different version for each student is necessary. Few teachers will have the desire or time necessary to develop this application. Therefore, the ultimate aim is to create an *ARRL application builder*.

Its operation is based on the teacher preparing an experiment with the standard design method. In the example presented, the ISE WebPack software is used to complete the experiment ahead of time. This allows the teacher to identify potential difficulties for students.

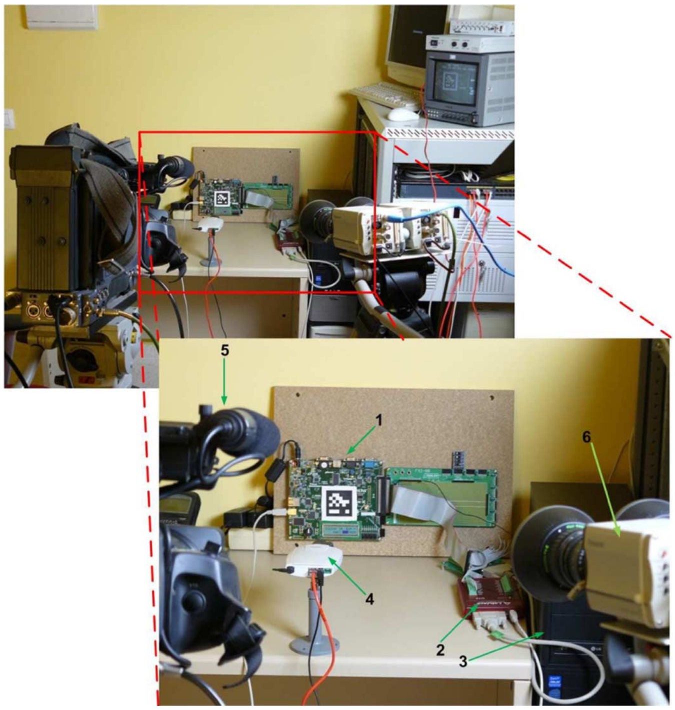

Fig. 3. Infrastructure enabled for prototyping.

When the experiment has been shown to be entirely feasible, the ARRL application is generated with the builder. This application builder will examine the teacher's VHDL project files and collect and process the necessary data. The teacher indicates whether it should use virtual peripherals, and if so where to connect them, or whether it should include a virtual model from the model library to be controlled in the experiment. With these data, the application builder creates an ARRL application ready to be placed in the CMS for students to download and run it from their own PCs.

III. Design and Implementation Phases: A Case Study

To illustrate the use of an ARRL application, an example that can be given to students as an experiment is the design of a very simple digital sequential system. Next, a more sophisticated version of this experiment is presented, which contains a higher number of development-board elements and connecting to a virtual device and a virtual model that must be properly controlled for satisfactory design.

A. Simple Sequential Control System: Mixing and Level Control in a Tank

Suppose the students are asked to complete an experiment with a sequential system to control a tank (Fig. 4). The tank is to be filled with a mixture of three different liquids, for which purpose there are three valves (**A**, **B**, and **C**) that control liquid input and four digital level detectors (**n1**, **n2**, **n3**, and **n4**, where **n1** represents the minimum and **n4** the maximum level). The tank is assumed to have a continuous internal agitator that ensures uniform liquid mixing. The tank has an output valve **S** that can be opened at any time for mixture removal. Only when

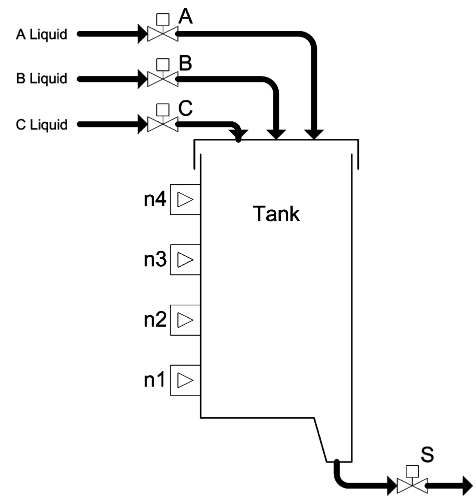

Fig. 4. Tank to be controlled.

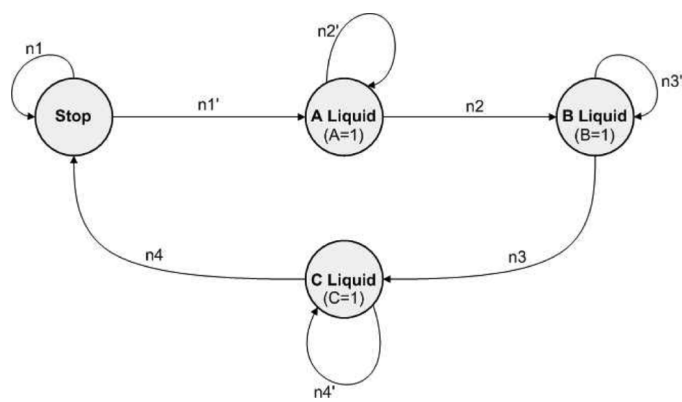

Fig. 5. State diagram (Moore machine) of the system.

the reservoir level falls below the minimum level **n1** does a fill cycle take place: first with liquid **A** up to level **n2**, then with liquid **B** up to level **n3**, and finally, with liquid **C** to fill the tank (**n4** level). The liquid can then be removed from the tank.

The following are the phases necessary to complete the experiment, which ends with the programming of the remote development board and the checking of its actual operation.

1) *Theoretical resolution*: After downloading the experiment text from the CMS, students must theoretically obtain the state diagram of the digital system that controls the tank. Fig. 5 shows the state diagram (Moore machine) of this simple example.
2) *Writing of the VHDL module that describes the design, simulation and programming of the development board.* The next step is obtaining a VHDL module that describes circuit-design operation. The Xilinx ISE WebPack software [18] (freely downloadable from the manufacturer's Web site) was used for this. Fig. 6 shows an editing stage in this design environment.

After syntax checking and design compilation, the student must simulate the VHDL implementation. To do this, from the aforementioned software, students write a test file in VHDL to represent the different situations that may occur in the controlled

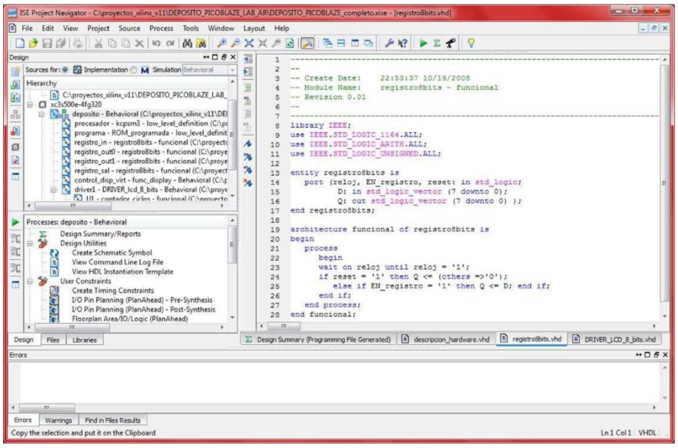

Fig. 6. Design phase in *ISE WebPack*.

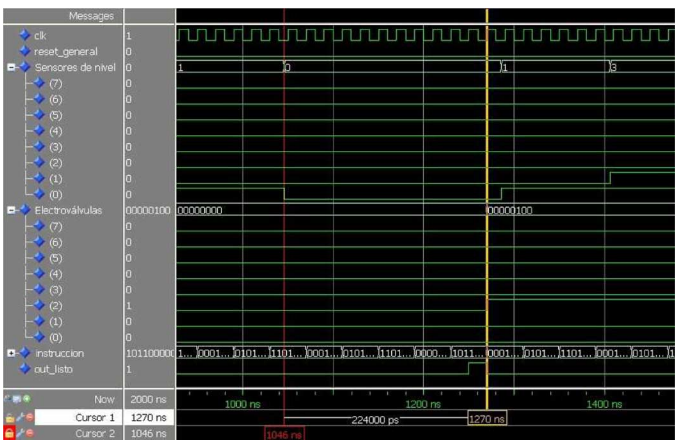

Fig. 7. Detail of a *ModelSim XE* simulation.

system for subsequent design simulation. The simulation software used is *ModelSim XE*. Fig. 7 partly shows a simulation with this application.

The students, who have previously reserved a post at the remote laboratory through the reservation management system, program the development board remotely from Xilinx software. Up to this point, no variation with respect to the usual steps necessary for system design, simulation, and board programming in de laboratory classroom was introduced.

1) *Design verification in the remote development board*. This step clearly demonstrates the ARL. Once the ARRL application has been downloaded from the CMS and run locally, two windows appear, one of which is the main application, displaying a real-time video of the programmed remote development board. In addition, the AR system is already enabled on the actual image, appearing in this case as a reset button and four virtual switches (equivalent in this example to the level sensors) located exactly on their real counterparts on the board, as shown in Fig. 8. These virtual elements can now be manipulated with the mouse (also noting the change in the position of the switch buttons), and the system operation can be tested (the operation of valves A, B, and C) by the board LEDs (real), just as when physically in the lab; this creates a synergy between the real and virtual elements. Note that all the virtual elements are interacting with the physical element (board) and vice versa, therefore signals move from one element to another transparently to the student.

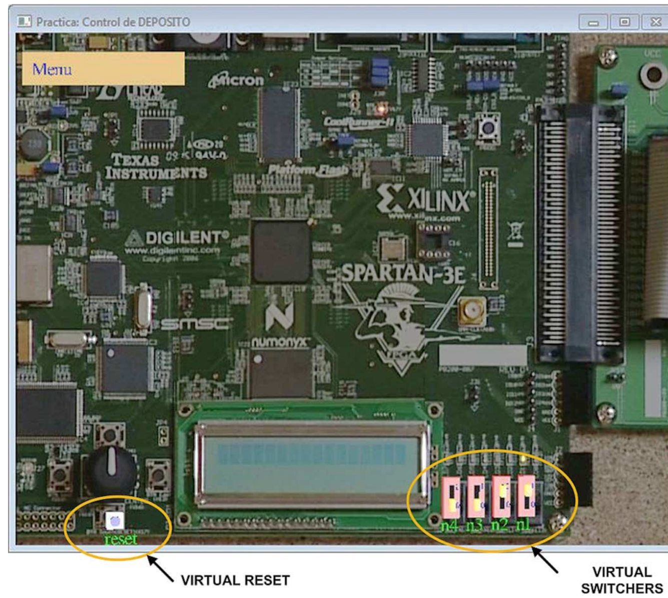

Fig. 8. ARRL Application main window ARRL. A drop-down menu can be accessed in the upper left-hand corner.

The second ARRL application window is a console (not shown) where the application reports, in text mode, operational events (e.g., switch performance) and possible errors.

IV. Further Step in Chances of ARLs: Using Virtual Peripherals and Models

Connecting the real world, the remote development board in this case, to locally run virtual models and virtual peripherals is another interesting possibility with obvious educational benefits.

Virtual peripherals are 3-D equivalents to real peripherals (e.g., 7-segment displays, groups of switches, pushbuttons, LEDs, etc.), but can also be provided with different functions. Fig. 9 shows some real peripherals. A virtual peripheral would be, for example, a 3-D representation of a 7-segment display located in the appropriate connector board that, receiving actual board-provided values, updates their numerical presentation.

One of the advantages of virtual peripherals is that no real peripheral needs to be attached to the board. Thus, the same physical lab configuration works for different experiments.

Another possibility, that can be combined with the previous one, if desired, is connecting the physical board in the lab to a virtual model to be controlled. The tank example could be modified to use the board's LCD display as well as a virtual peripheral, a decoder that receives a 4-bit binary code and represents the hexadecimal equivalent in a 7-segment display. This display should show the actual level in the tank (0–4) and "E" in case of error. In addition, the board is connected to a board-controlled animated 3-D tank model.

The LCD display shows the active valve (if any) and possible error conditions caused by malfunction of the digital sensors.

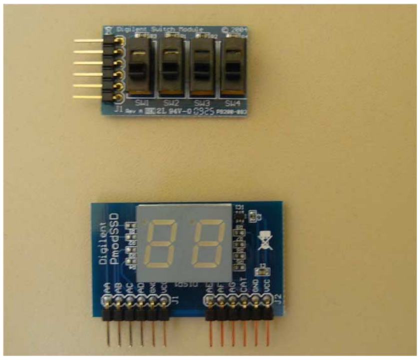

Fig. 9. Simple real peripherals for the development board.

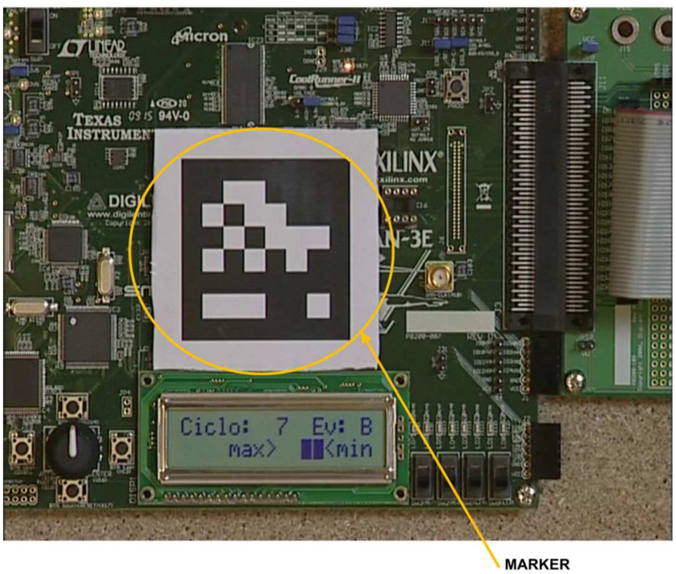

Fig. 10. Original image captured by the camera.

Additionally, the current fill level of the tank is displayed as a bar diagram.

This experiment is clearly more complex, due to the huge time difference between the original board clock (50 Mhz) and the much slower LCD-display response time, together with the large number of necessary states. Thus, it cannot be solved by a simple state diagram, as in the previous case. Therefore, the design is now based on a PicoBlaze microcontroller embedded within the FPGA, programmed specifically for this problem in assembly language, and additional circuits designed using VHDL and connected to the microcontroller. This illustrates another important feature of the ARRL application: its independence from the programming complexity of the experiment to be completed.

Fig. 10 shows the original image captured by the camera before virtual elements were put in place. Fig. 11 shows the ARRL application main window, where the marker of the original image is adequately covered to show the full board. Comparing Figs. 8 and 11, it can be observed that the real world is the same, but the virtual has been changed to perform other tasks with the same physical setting. Now, Fig. 11 shows no virtual switches since the board receives the level-detector signals directly from the virtual model. This model (Fig. 12), which is

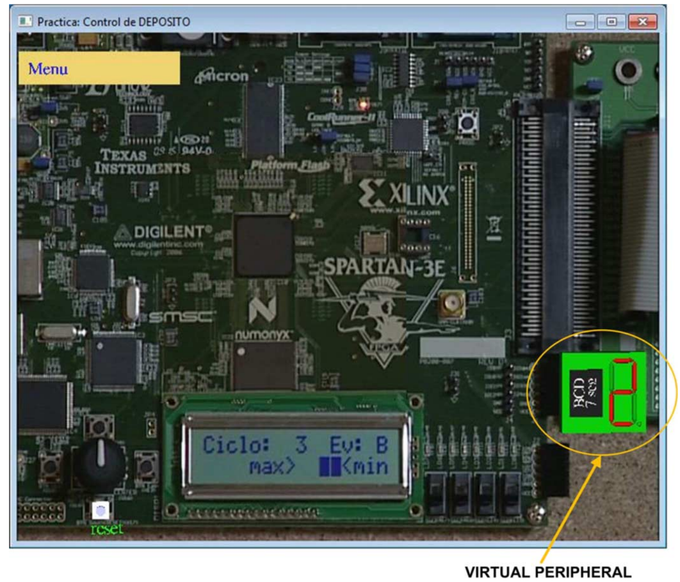

Fig. 11. ARRL application main window.

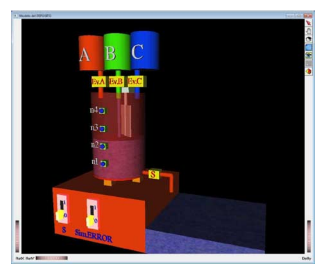

Fig. 12. 3-D model of the tank (filling phase of liquid B).

part of the ARRL application used by the student, is locally run as a part of the application. The model uses the same graphics libraries as the application's main window, so the 3-D feature holds.

If the necessary software is available, the virtual model can be observed in 3-D with stereoscopic vision. This requires the use of electronic shutter glasses and an appropriate display and graphics controller; a *Samsung SyncMaster 2233Z* monitor, *NVIDIA 3D Vision* glasses, and a *NVIDIA Quadro FX1800* graphics card were used.

These benefits, unavailable at high-end workstations until very recently, are now available for PCs at reasonable prices. The possibility of observing the 3-D virtual model as if it were in front of the user, coming out of the screen, has great potential for two reasons: 1) it allows the exploration of complex models with different scales and perspectives (even from the inside); and 2) it is undeniably attractive for students. Fig. 13 shows a student performing the proposed experiment and using stereo vision for 3-D model visualization.

The remote board and AR elements can also be observed with stereoscopic vision, which requires the use of a stereoscopic camera, as well as the proper application configuration.

V. Validation as an Educational Tool

"Digital Systems" is a required course in the Electronic Engineering and Computer Engineering degrees at the Univer-

TABLE I
EVALUATION QUESTIONNAIRE OF THE ARL

Question	Description	Teachers		Students	
		Mean	Deviation	Mean	Deviation
1	Your level on digital systems design is high	2.8	0.63	2.05	1.28
2	The use of a graphic tool fosters the students' motivation and interest	4.1	0.57	4.25	0.87
3	Putting the application into practice is feasible in the university context	4.4	0.52	4.30	0.85
4	The application allows learning new theoretical concepts	3.3	0.95	3.6	1.26
5	The application allows consolidating theoretical concepts	3	0.82	4.5	0.84
6	Theoretical concepts can be learned through theoretical study alone	4.3	0.82	2.33	1.58
7	The software application has a clear and intuitive structure	4	0.94	3.94	1.17
8	The interface appearance is nice	3.7	1.06	3.75	1.27
9	The application is useful	3.9	1.10	3.80	1.17
10	The application is interactive	4	0.94	4.38	0.90
11	The use of virtual models is easy	4.1	1.20	4.19	0.95
12	The installation of the ARRL application is easy	3.9	1.19	4.3	0.88
13	The application facilitates theoretical-practical understanding	4	1.24	4.14	0.96
14	The overall assessment of the application is positive	4	0.82	4.2	0.89

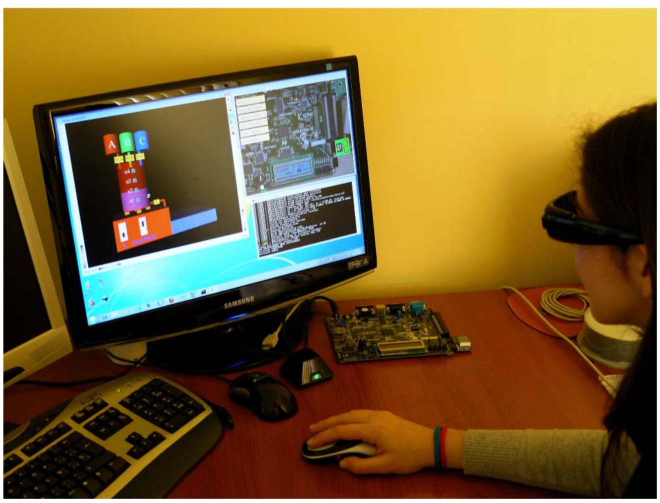

Fig. 13. 3-D student evaluation of the implementation ARRL with stereoscopic glasses.

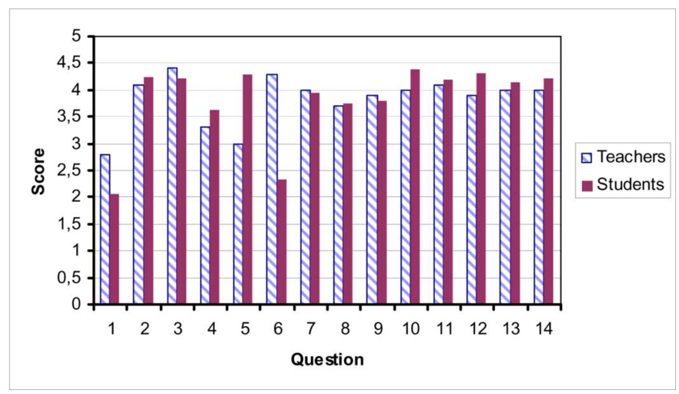

Fig. 14. Average responses of students and teachers on ARL.

sity of Huelva; innovating the teaching of this course was the driving force behind this work. With the aim of showing the contributions and capabilities of the educational tool developed, a statistical study was completed in the second semester of the academic year 2009–2010 (see Table I). It includes aspects that referred to the tool's features and its acceptance and use. Two groups of users (36 students of this course and 10 teachers who are not specialists in this field.) were required to rate the questions on a 5-point Likert scale (1—strongly disagree and 5—strongly agree). Their initial knowledge level of digital systems was low (question 1). Regarding the teaching and learning of digital systems, the users confirm, by means of high scores, that these concepts are strengthened and improved by the use of the ARL (questions 2–6). In this sense, students declare they disagree with the idea that theoretical concepts should be learned only by studying, without the need for practical work. Considering the aspects related to the user graphic interface, its ease of use, installation, and interactivity stand out dramatically. Besides, students stress how theoretical and practical concepts are related, thus allowing quick learning (questions 8–13). Fig. 14 shows the average responses of students and teachers on ARL.

VI. CONCLUSION

This paper presents an evolution of the concept of virtual and remote laboratories toward the augmented remote lab, which offers, at a minimum, the following advantages: 1) a greater sense of realism; 2) the same physical laboratory settings can be used for different experiments; and 3) easier experiment verification and generation since, as well as offering other possibilities, experiments may be the same as those traditionally carried out when physically in the lab.

From a concrete practical application, this paper analyzes the advantages offered by AR techniques for remote labs to develop and prove the many possibilities of practical online training in the fields of science and engineering. The main area of interest is for electrical engineering since that is where the illustrative examples are based, but the fundamental concepts would apply to many courses, in areas such as civil or mechanical engineering, or even in areas such as history or geography.

While this work is implemented as an application case study in the field of sequential digital systems (a project of educational innovation for the development of a library of peripherals and virtual models that can be used in any experiment is under current development), the current development of educational material for other disciplines, such as control engineering, robotics, and others, according to the scheme presented in this work, will demonstrate the usefulness of this approach.

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