

A Pilot Study of the Effectiveness of Augmented Reality to Enhance the Use of Remote Labs in Electrical Engineering Education

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Abstract Lab practices are an essential part of teaching in Engineering. However, traditional laboratory lessons developed in classroom labs (CL) must be adapted to teaching and learning strategies that go far beyond the common concept of e-learning, in the sense that completely virtualized distance education disconnects teachers and students from the real world, which can generate specific problems in laboratory classes. Current proposals of virtual labs (VL) and remote labs (RL) do not either cover new needs properly or contribute remarkable improvement to traditional labs—except that they favor distance training. Therefore, online teaching and learning in lab practices demand a further step beyond current VL and RL. This paper poses a new reality and new teaching/learning concepts in the field of lab practices in engineering. The developed augmented reality-based lab system (augmented remote lab, ARL) enables teachers and students to work remotely (Internet/intranet) in current CL, including virtual elements which interact with real ones. An educational experience was conducted to assess the developed ARL with the participation of a group of 10 teachers and another group of 20 students. Both groups have completed lab practices of the contents in the subjects *Digital Systems* and *Robotics and Industrial Automation*, which belong to the

second year of the new degree in Electronic Engineering (adapted to the European Space for Higher Education). The labs were carried out by means of three different possibilities: CL, VL and ARL. After completion, both groups were asked to fill in some questionnaires aimed at measuring the improvement contributed by ARL relative to CL and VL. Except in some specific questions, the opinion of teachers and students was rather similar and positive regarding the use and possibilities of ARL. Although the results are still preliminary and need further study, seems to conclude that ARL remarkably improves the possibilities of current VL and RL. Furthermore, ARL can be concluded to allow further possibilities when used online than traditional laboratory lessons completed in CL.

Keywords Robotics · Digital design · Augmented reality · Virtual worlds · Virtual scenarios · Online education · Augmented reality lab

Introduction

The main goal of this work is to achieve something that until now seemed very difficult: Students can carry out labs remotely on a real laboratory (not simulated or virtual), also including virtual elements that interact with the real elements of the laboratory, thus achieving an augmented reality scenario. This opens up enormous possibilities for students whose class attendance (for economic reasons, work, distance, etc.) is problematic.

Following Andújar and Mateo (2010), a VL simulates an actual laboratory, is contained within one or more computers and is equipped with content management and/or learning capacities. RL is an environment (computer application, VI, etc.) that allows acting on a real system

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remotely so as to teleoperate it, experiment and access data through the net to obtain real measures. Of course, VL and RL can integrate by performing supplementary but separate functions (different and distinguishable).

ARL is a step further in online lab teaching and learning, since—when endowed with all capacities for access, content and learning management available for VL and RL—it is capable of connecting the real world of RL and the virtual world of VL to set up scenarios where reality and virtuality interact with one another, thus shaping an augmented reality (AR).

AR—while incorporating virtual reality content—is a distinct technology from virtual reality (VR) itself. VR is isolated from reality and conforms to purely virtual scenarios. AR systems (Azuma 1997):

- 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 3D space: the real space observed by the user defines the context used to interact with and represent real and virtual elements.

In short, AR supplements real-world perception and interaction and allows the user to view a real environment augmented with computer-generated 3D information. AR applications, where virtual objects are aligned with and superimposed onto the real world, enable the preservation of the real user environment that provides a reference frame for user actions, thus making human–computer interaction more natural.

Between totally real and totally virtual situations there is a continuum (Fig. 1), characterized by various mixtures of virtual and real environments. In this mixed reality the concept of a virtuality continuum (Milgram et al. 1994) appears. This concept covers both AR and augmented virtuality (AV), which are a mixture of the real and virtual worlds. These intermediate points are also collectively known as mixed reality. Figure 1 shows a picture of one real and one virtual environment, as well as both environments combined by means of an AR application developed by the authors of the present work that shall be explained later on. AR can be observed to complete the observation of the real world with virtual elements related to the former. In this case, virtual objects are obstacles found by the real minirobot in the left-hand figure and with which it interacts. This is the key issue regarding AR: interaction between reality and virtuality to shape a richer “reality” offering further possibilities.

Regarding Fig. 1, the route from reality to virtuality (AR) can coincide in a specific point with the route from virtuality to reality (AV). However, the term AR is usually

employed for any intermediate point between reality and 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 3D 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 (Huang et al. 2009), training of operators of industrial processes (Schwald and De Laval 2003), system maintenance (Henderson and Feiner 2009), or tourist visits to museums and other historic buildings (White et al. 2004), among others.

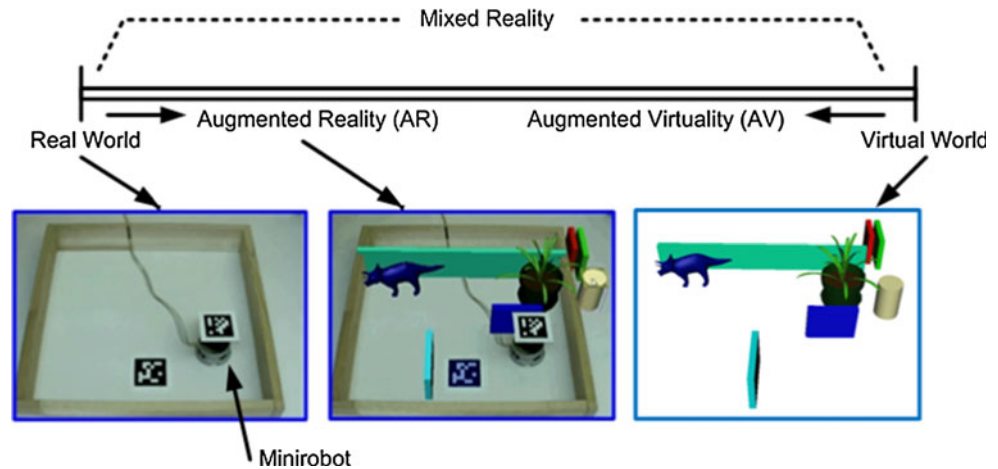
The need for laboratory practices in engineering (of course in other educational disciplines); to allow students to acquire skills in solving real problems can present logistical, economic and educational problems, including:

- 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 to provide 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 (twenty 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 ARL system developed by the authors, which improves real laboratory in various aspects among which include the following:

- Real laboratory models can be expanded, reduced or be 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 and in preparation time for whoever is teaching the lab sessions.

Fig. 1 Reality-virtuality continuum



- Laboratories with their plants and instruments can operate 24 h a day.
- Laboratories can be used concurrently. A group of users could be using a part of laboratory equipment remotely by ARL, while another group might be physically in the laboratory using other different equipment.
- Students interact remotely with real systems as if they were physically in the laboratory, in front of the equipment.

ARL is being tested in two required courses at the second year of the new degree in Electronic Engineering (EE), at the Higher Technical School of Engineering, University of Huelva, European Union. The specific courses are *Digital Systems* and *Robotics and Industrial Automation*. The EE degree come under The European Higher Education Area (EHEA), an initiative of the Bologna process (Bologna process 2011) designed to create more comparable, compatible and coherent higher education systems in Europe (European Commission website 2009).

By means of AR, ARL allows the student to explore learning experiences that may exceed those offered by traditional laboratory classes, in the sense that it is possible to develop virtual elements (only inside the computer) that interact with the actual present in the lab, which allows to configure an augmented reality. To illustrate the multiple capabilities of this proposal, two very different practical applications—the design of a digital control system based on an FPGA (Field-Programmable Gate Array is an integrated circuit designed to be configured by the customer or designer after manufacturing; the FPGA configuration is generally specified using a Hardware Description Language, HDL) development board and the interaction of remote real robots with virtual scenarios—are presented. The development of these two practical ARL applications has allowed to complete an educational experience in which both teachers participating in the experience (TPE)

and students have taken part and whose results are shown in this work.

To facilitate the reading of this work and due to the large number of acronyms that contains, these are included in Table 1.

Augmented Reality in Engineering Education, an Overview

The academic world 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 amongst the most important reasons why its still low level of implementation.

Several European projects have designed and developed innovative applications that integrate AR for educational purposes, such as CREATE (Loscos et al. 2003) and ARiSE (ARiSE Project 2009). These tools, based on 3D 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 (Liarokapis et al. 2004) puts forward an educational application for mechanical engineering teaching that allows users to interact with 3D content using web technology and AR-VR techniques. Esteban et al. (2008) show AR for math teaching, while (Kaufmann and Schmalstieg 2003) describes a system for geometry teaching based on these techniques.

An approach to the use of remote laboratories with AR techniques is described in (Salzman et al. 2000), where LabView™ is used to control an inverted pendulum in a laboratory, although no monitoring or video-image location

Table 1 List of acronyms

Acronym	Meaning
ANFIS	Adaptive neuro-fuzzy inference system
AR	Augmented reality
ARL	Augmented remote lab
ARRL	Augmented reality for remote laboratories
AV	Augmented reality
CL	Classroom lab
CMS	Control management system
DAQ	Data acquisition system
EE	Electronic engineering
EHEA	European higher education area
EPFL	Ecole Polytechnique Fédérale de Lausanne
FPGA	Field-programmable gate array
HDL	Hardware description language
HMD display	Head-mounted display
IR	Infrared light
LED	Light-emitting diode
PID controller	Proportional–integral–derivative controller
RL	Remote lab
RS-232	Recommended standard 232
TCP/IP	Internet protocol family: transmission control protocol (TCP) and internet protocol (IP)
TPE	Teachers participating in the experience
USB	Universal serial bus
VHDL	Hardware description language for very high speed integrated circuit
VL	Virtual lab
VR	Virtual reality

techniques are used, since the virtual image in this case is derived from measurements on the real system.

Dormido et al. (2008) also contribute a development for remote access to several types of experiments with AR-supported visualization. These experiments include the Heatflow system, which allows students exploring parameter estimation (identification) and controller tuning techniques in delayed transport systems, as well as controlling the position and speed of a DC motor.

Different e-learning systems using AR in the field of Robotics have been developed in the last years for educational purposes. Albeit with reduced capacities still, some representative examples are:

- *UJI On Line Robot* (Marín et al. 2005): A complete vision-based online robot system that allows controlling robots via web. Its interface is predictive: by means of a 3D virtual environment endowed with AR capabilities, the user can predict the results of the actions before sending the command to the real robot.

- The *ARITI system* (ARITI 2010) also presents a display interface enabling any person to remotely control a robot via web. The Man–Machine Interface (MMI) is based on the mixed reality concept, grouping VR and AR, allowing easily perform of a task and description of the desired environment transformation (to be completed by the robot).
- Jara et al. (2008) present the development and implementation of *RobUaLab*. In this approach the real information from the robot scenario is supplemented with some virtually-generated data from the virtual environment. Virtual projection is combined with the current state from the remote laboratory taking current IP camera setting and 3D environment into account. This feature helps to handle the robot, providing further information about its current and future situation.

All of these examples, but use AR techniques, none of them allow the robot to interact with virtual elements. This is precisely one of the successes of this work, which can be seen later in the Lab # 2.

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. Dormido (2002) 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 in this paper is aimed at giving the user the sensation that 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.

Another disadvantage listed in (Dormido 2002) is that certain scientific/technological 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 first practical application developed in this paper contradicts this assertion and shows how to include digital design in those areas that could be incorporated into remote experimentation.

With respect to the requirements listed in (Dormido 2002), 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.

As mentioned above, AR has potential to augment learning in many different knowledge fields as well as its evident potential in teaching. This paper puts forward two examples of a remote lab with AR techniques: the first one is a practical application of a simple digital system based on a development board with a FPGA. This implementation allows the remote use of the materials students normally use in classroom laboratories, particularly in the design of digital systems. This educational experience is focused on the interconnection of signals between virtuality and reality so that, by means of AR, the real system is augmented and improved by the virtual systems related to it. Both systems (worlds), real and virtual, share signals and communicate to one another creating synergy. Thus, the final result is more complete and offers more possibilities that obtained by real and virtual systems when acting separately (see Fig. 1).

The second example has a completely different approach: the remote implementation of a control system to allow a real robot moving in a virtual scenario by avoiding obstacles. The desired virtual scenario can be chosen previously. Besides, this scenario can be modified interactively in real time, remotely and even when the real robot is moving. This educational experience is aimed at making the robot interact with the virtual scenario and learn to move in it. Ultimately we aim at enabling students to train robots in scenarios and situations that would be rather hard to reproduce in lab.

The method proposed in this paper tries to meet students' needs to access the lab with a flexible schedule for two kinds of labs, without the need of 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.

Augmented Remote Laboratory

The ARL is a step above the VL and RL (Andújar and Mateo 2010); the height of this step depends on the degree to which it depends upon AR techniques. Access to the ARL is enabled by an application that we have called 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 which enable the interactive use of the lab equipment.

The tasks of the ARRL application can be summarized as:

- 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.
- Showing the results provided by the equipment. 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.
- 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.

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

- a. *Content Management System (CMS)*. 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.
- b. *Reservation manager and access control system*. 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.
- c. *Users (students)*. Students are asked to download from the CMS the wording of the practice to be completed, as well as the ARRL application which grants remote access to the experiment and allows them to interact with it so as to assess the result of their design.
- d. *Physical installation in the laboratory*. The different types of practices completed in the ARL share the following two elements:
 1. An IP camera. An IP Axis 211 camera is used in the examples put forward next. It obtains the original video image used by the ARRL application to display the experiment. The ARRL

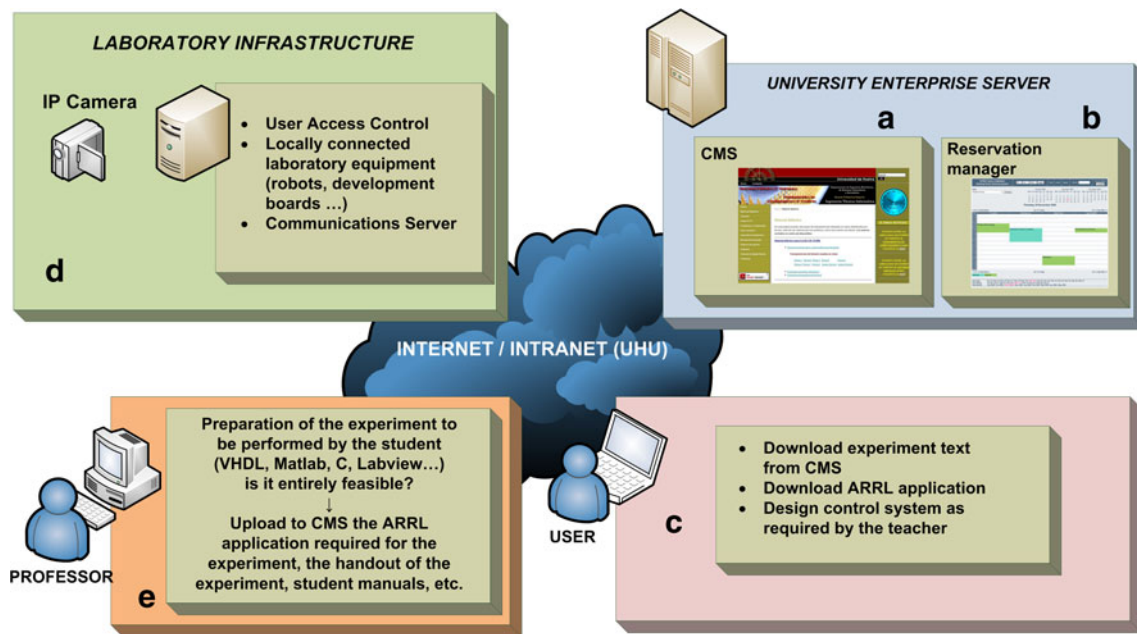


Fig. 2 General structure of the developed ARL system

- application also superimposes the 3D virtual elements with their correct position, size and orientation.
2. A communications and access-control server is used to provide access (from outside the University network) to the lab PCs that are directly connected to the experiments.
 3. PCs directly connected to the afore-mentioned experiments. A PC can be connected to multiple experiments by different resources (series ports, USB ports, etc.)
- e. *Teacher.* The teacher prepares the experiment that students are to complete in the usual way. Once that experiment suitability and feasibility is checked, the teacher uploads the wording of the practice, technical manuals and any other relevant information to the CMS. Besides, the teacher also uploads the ARRL application to the CMS for students to download and run it in their PCs.

It must be noted finally a quality that is provided with the ARL designed that might be able to pass unnoticed but which is of critical importance. It refers to the power supply of the equipment. All ARL equipments are powered via a rack with TCP/IP connection. When the student accessed remotely via the ARRL in order to log in ARL, communications system automatically powers the necessary equipment for the lab to perform (laboratory lighting, power supplies, camera associated with the experiment, instruments and equipment involved in the lab, etc.); similarly, when the student finishes his remote session, the

communications system switches off automatically the power of the material is no longer in use. In this way is optimized the energy consumption of the whole installation and preventing possible accidents.

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 experiment could be 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. In fact, we have already developed a generator of ARRL applications for one of the types of practices presented in Section “[Examples of the Application of the Developed Methodology](#)”.

Examples of the Application of the Developed Methodology

To illustrate the possibilities of the developed methodology and the ARL, this section is devoted to explain the two experiences completed for the first educational testing of the developed system: The design of a *digital sequential control system* using a development board with a FPGA (in the subject *Digital Systems*) and the *design of a control system for a robot to avoid obstacles in a given scenario* (in the subject *Robotics and Industrial Automation*). Particularly, it is about designing a control system and an interactive virtual environment in which a real robot moves like a Braitenberg Vehicle, an agent (an artificial intelligence-

based controller) that allows the robot to move around autonomously (Braitenberg 1984). For controller implementation, a fuzzy system obtained by adaptive techniques is used in this case. The purpose of the lab is enabling the robot to move without colliding with the user-created virtual objects that make up the virtual scenario. The user can choose the appropriate setting without modifying any equipment in the remote laboratory. The user needs not to put real obstacles around the robot, just load a virtual world. The world he has imagined.

The use of virtual environments presents many possibilities that would be unavailable in real environments. Among them the following can be mentioned:

- The virtual elements that form the virtual scenario can have virtually unlimited shapes and sizes. Moreover, their shape can be fairly complex.
- They can be modified (size, shape, texture, position) by the user remotely.
- Scenarios demand no maintenance in the lab, as they are entirely composed of virtual elements.
- Virtual elements cannot deteriorate, break or hit physical objects or equipment in the lab, or harm the robot, either.
- The set of virtual objects can be uploaded from the ARRL application and placed in the desired position remotely.
- Remote trial assemblage and/or modification reduces time consumption.
- Too complex and/or costly real scenarios (to be physically implemented as lab models) can be visualized.
- Likely scenarios are practically subject to the user's imagination.

Lab #1: Digital Sequential Control System: Mixing and Level Control in a Tank

TPE and students are asked to complete an experiment with a sequential system to control a tank (Fig. 3). 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 than can be opened at any time for mixture removal. Only when 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. Note that in order to simplify the experiment have not been considered

real world phenomena like stick slip in the valves, uneven mixing, etc.

The teacher prepares the experiment with the standard design method. In the example presented, the ISE WebPack software (ISE Design Software 2010) is used to complete the experiment ahead of time. This allows the teacher to identify potential difficulties for TPE and students.

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 (Hardware Description Language for Very high speed integrated circuit) project files, and collect and process the necessary data (development board type, camera, marker, IP configuration of server, etc.). With these data, the application builder creates an ARRL application ready to be placed in the CMS for TPE and students to download and run it from their own PCs. Figure 4 shows the aspect of the developed generator of ARRL applications. When available, the ARRL is uploaded to the CMS by the teacher, thus making it available for TPE and students to download and run it in their PCs.

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

Theoretical resolution: after downloading the experiment text from the CMS, TPE and students must theoretically obtain the state diagram of the digital system that controls the tank. Figure 5 shows the state diagram (Moore machine) of this lab.

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 (freely downloadable from the manufacturer's website) was used for this.

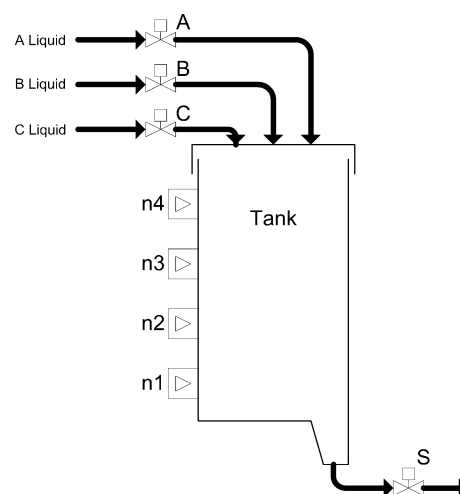


Fig. 3 Tank to be controlled

After syntax checking and design compilation, the TPE and students must simulate the VHDL implementation. To do this, from the above-mentioned software, TPE and students write a test file in VHDL to represent the different situations that may occur in the controlled system for subsequent design simulation. The simulation is carried out in the afore-mentioned design environment.

The TPE and students, whom 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 the classroom laboratory was introduced.

Design Verification in the Remote Development Board

This step clearly demonstrates the ARL possibilities. Figure 6 shows the general scheme of ARL to complete this kind of practices. The following elements can be observed:

- Content Management System (CMS)*. It contains the afore-mentioned educational material, which can be accessed from the ARRL application that runs the user through a menu on the video image.
- Reservations manager and access control*. The reservations manager ensures appropriate allocation of laboratory resources, allowing users to reserve slots for their use as restrictions imposed by the teacher. The access control system using the data provided by the reservations manager enables the necessary network resources.
- ARRL application*. This application is downloaded by the user from the CMS. Is ready to be executed locally within the runtime environment installed before, and common to all applications.
- Laboratory infrastructure*. The training materials are in laboratory as well as the necessary infrastructure for access and remote viewing. A development board connected to a PC (in experiments we use development boards based on a Xilinx FPGA Spartan 3E series, XC3S500E model with 232 IOBs and 10,000 logic

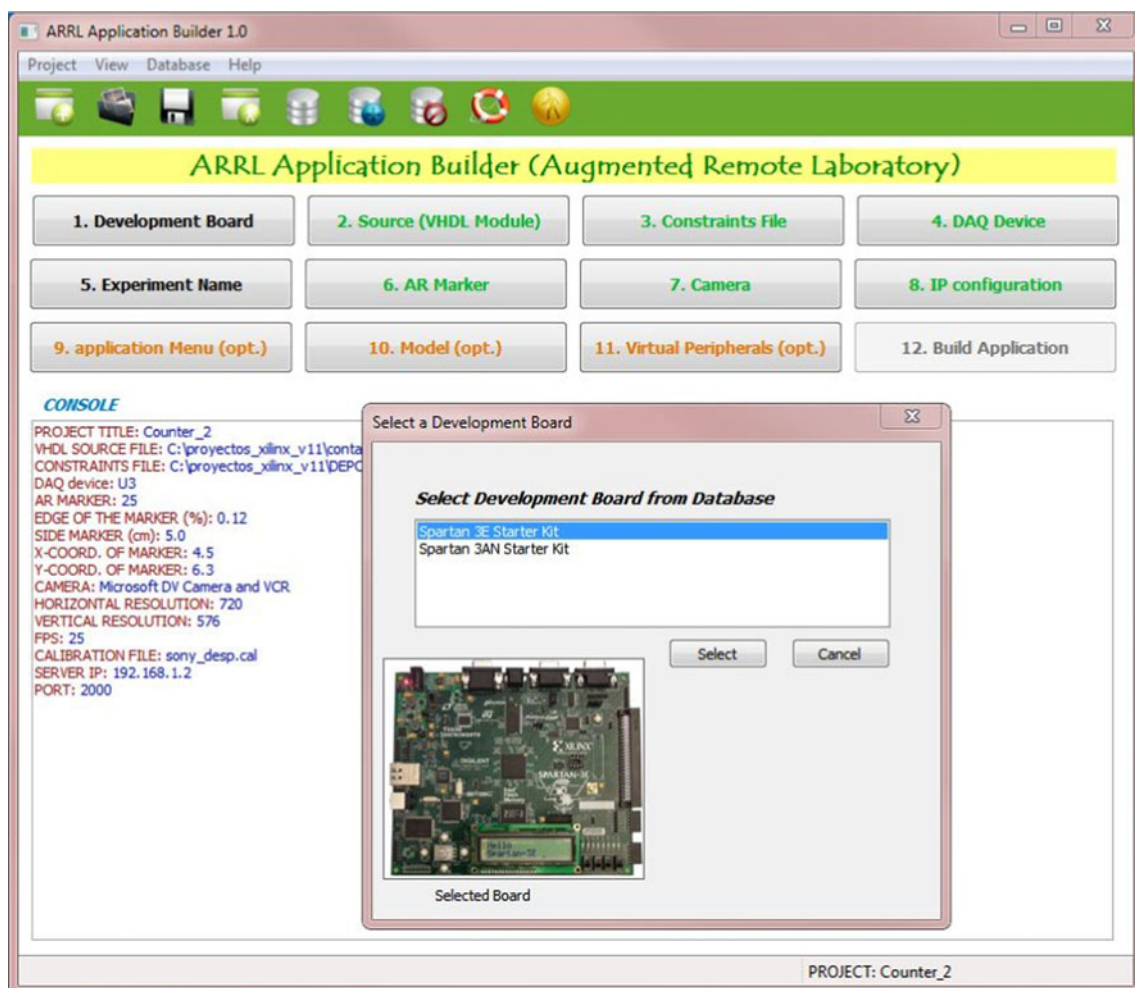


Fig. 4 ARRL application builder

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

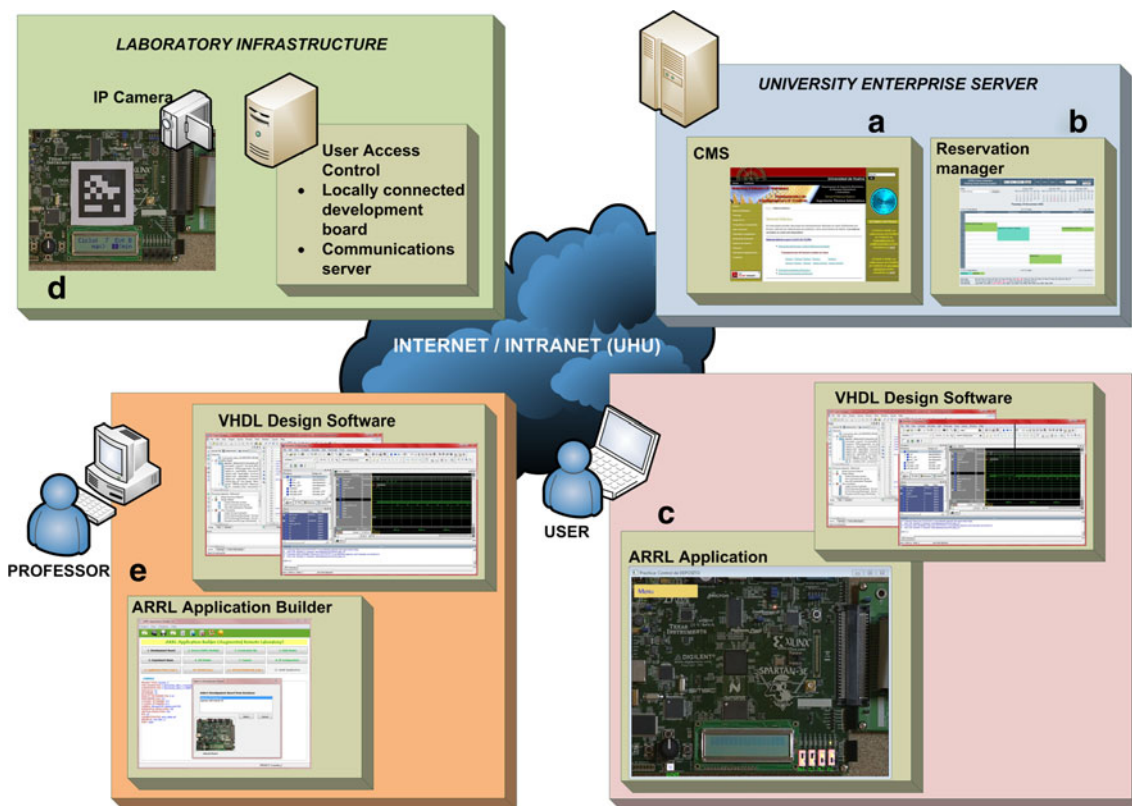
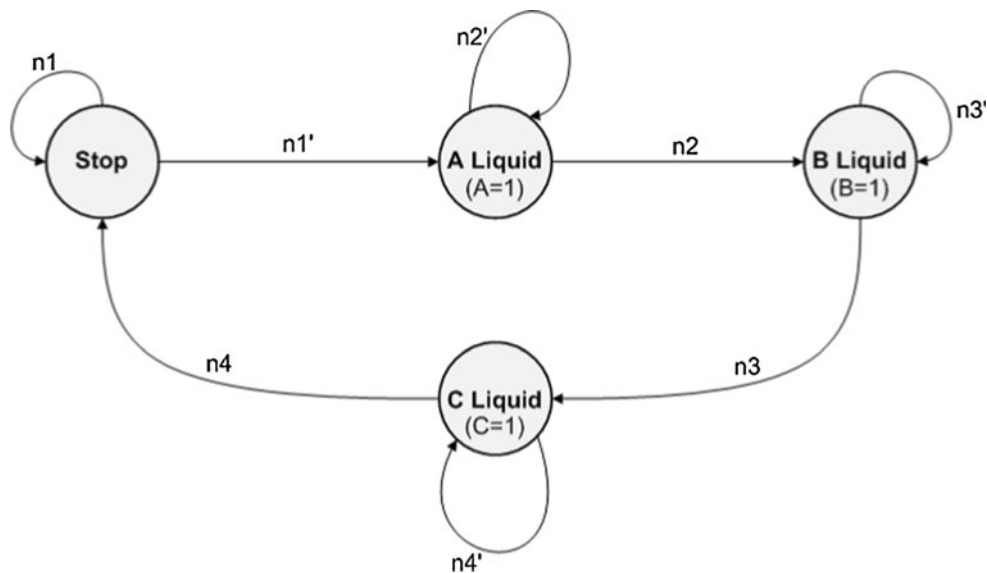


Fig. 6 ARL general structure for lab #1

cells), a DAQ device, a PC used to remotely program the board and an IP camera in front of the development board. It is responsible for obtaining the original video image, which is used by ARRL application to display the board and superimpose the 3D virtual elements with the correct position, size and orientation.

e. ARRL application builder.

Referring to Fig. 6: Once the ARRL application (c) has been downloaded from the CMS (a) and runs 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 reset button and four virtual switches (equivalent in this example

to the level sensors) located exactly on their real counterparts on the board (Fig. 7a). 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. Figure 7b shows the original image captured by the camera before virtual elements were put in place. As it can be observed in Fig. 7b, the marker of the original image is adequately covered by the ARRL application to show the full board. The markers in the ARToolkitPlus (2011) library were used.

The second ARRL application window is a console (not shown in text mode as it contributes no clarity to the explanation) where the application reports operational events (e.g., switch performance) and possible errors.

It is also possible to observe the remote board and AR elements overlapping with stereoscopic vision, which requires using a stereoscopic camera, and configure the application properly. We are evaluating whether this possibility brings benefits in this or other fields. Figure 8 shows a student performing the proposed experiment and using stereo vision to visualize the development board and a 3D model of the tank connected with the board. This requires the use of electronic shutter glasses and appropriate display and graphics controller. We use a *Samsung SyncMaster 2233Z* monitor, *NVIDIA 3D Vision* glasses and a *NVIDIA Quadro FX1800* graphics card.

Lab #2: Design of a Control System for a Robot to Avoid Obstacles in a Scenario

TPE and students are asked to contribute a design for a mobile robot to behave like a Braitenberg vehicle, but using a fuzzy system obtained by adaptive techniques. The purpose of the lab is that a real robot moves without colliding in a virtual scenario created by the user.

Before tackling the lab itself is necessary to perform a series of preliminary considerations, which will value the enormous possibilities of ARL developed.

Settings the ARL

For this lab, we use a robot Khepera II (K-team Corporation 2011), a miniature mobile robot with similar functionality to larger robots used for research and educational purposes. Khepera was originally designed as a research and teaching tool for the Swiss Research Priority

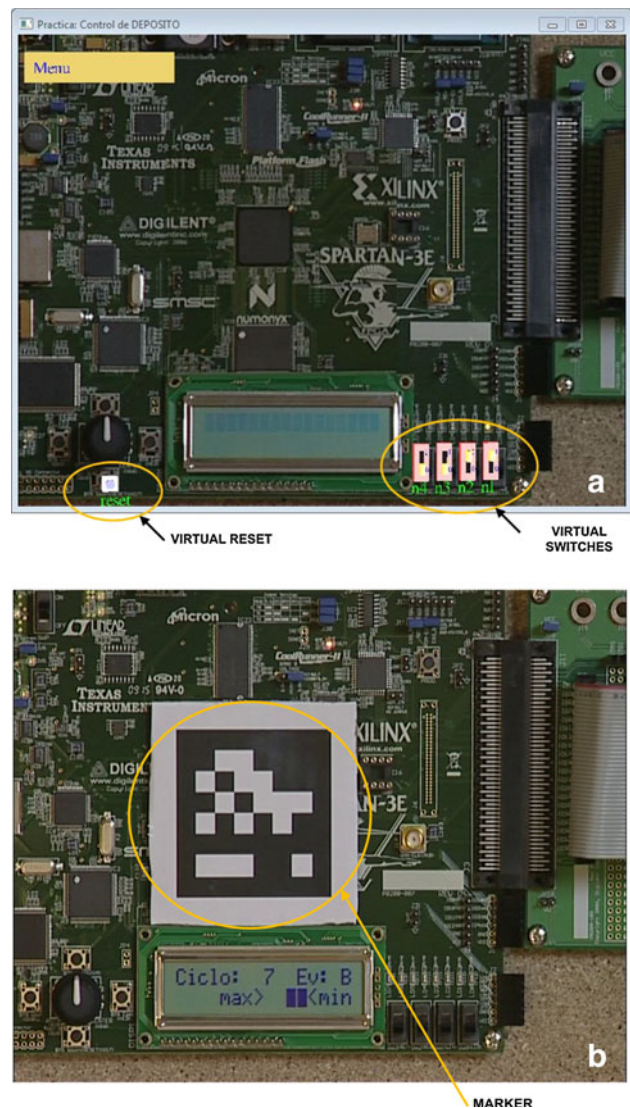


Fig. 7 **a** ARRL Application main window. A drop-down menu can be accessed in the upper left-hand corner. **b** Original image captured by the camera

Program at the *Ecole Polytechnique Fédérale de Lausanne* (EPFL). It allows real-world testing of simulation-developed algorithms for trajectory planning, obstacle avoidance, sensory information preprocessing, and hypotheses on behavior processing, among others. Khepera II (Fig. 9, left) is circular: a diameter of 68 mm at its base and a height of 30 mm. It includes on-board power supply and two independently-PID-controlled motors. Moreover, it is equipped with eight IR (Infrared light) sensors around the robot and positioned and numbered as shown in Fig. 9 (right). These sensors embed both an IR emitter and a receiver.

Robots must fulfill these two conditions to be able to interact with a virtual world:

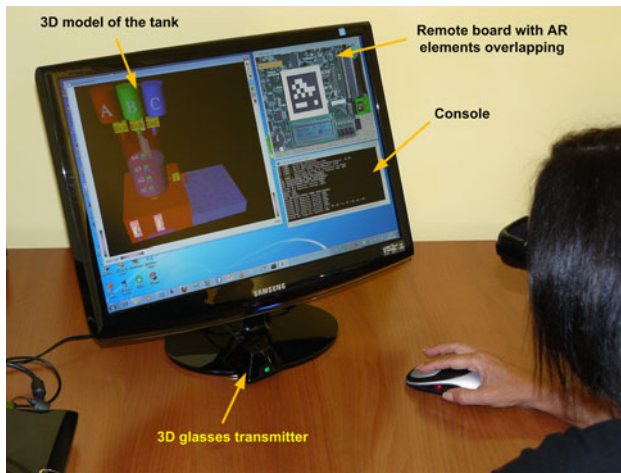


Fig. 8 A student performing the experiment using 3D vision

1. The virtual world must use the same coordinate system, which would have a real-world equivalent in shape and size.
2. The robot must be able to detect the status of the elements in the virtual world.

Both conditions can be solved through AR techniques. Indeed, regarding the first condition, AR allows computer-generated virtual elements to be referenced with a coordinate system to the real world observed by a camera by means of varied trackers: magnetic, optical, mixed, markers, etc. The marker used in this lab 2 is the same type as in lab 1. Obviously, is a very cheap tracking method (just print the marker), but the algorithm is highly time-consuming, because it must analyze each received video frame, locating the marker and calculating its position in the space observed by the camera, also using the camera's intrinsic parameters and distortion. The marker also has some limitations, as it must be completely visible in the

video image; thus, lighting becomes a crucial factor and must be as homogeneous as possible. The use of magnetic, optical or hybrid trackers significantly improves object tracking. It relieves the host CPU of tracking-calculus operations, operated by outboard processors, which are highly precise, but relatively costly too.

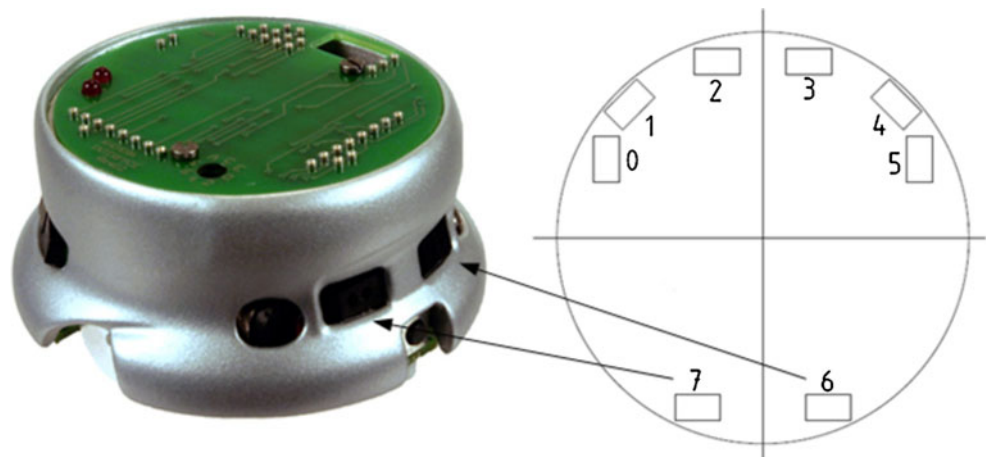
The second condition poses a very different problem: the actual robot sensors (proximity sensors in Khepera II) cannot detect a virtual world. This problem can be overcome by creating virtual sensors which function as those of the actual robot. Virtual sensors should be located on the real robot in the same position and orientation as their real counterparts. AR techniques also allow this overlapping of virtual sensors. Thus, the ARRL application substitutes the actual sensors with virtual sensors that can detect virtual worlds.

Each sensor is modeled with three beams (Fig. 10) and, when colliding with the virtual world, they return a value proportional to the distance from the collision. An algorithm within the ARRL application calculates the virtual sensor output value in the same format as that provided by the corresponding actual sensor in Khepera II. The virtual body observed on the robot (Fig. 10) allows it to detect collisions between real and virtual environments. In the implementation of the ARRL application, the virtual body and sensors are transparent, so that the user can only see the real robot. For real-robot monitoring (tracking), a marker allows software to calculate its position in AR space.

Figure 11 shows the general structure of ARL for lab #2, where it can be observed that it is a specific case of the developed general ARL system shown in Fig. 2.

A socket server was developed to send commands to the robot using TCP/IP communications. This server uses multithreading techniques and is installed in the computer directly connected to the robot. It receives and sends data

Fig. 9 Khepera II robot and distribution of proximity sensors



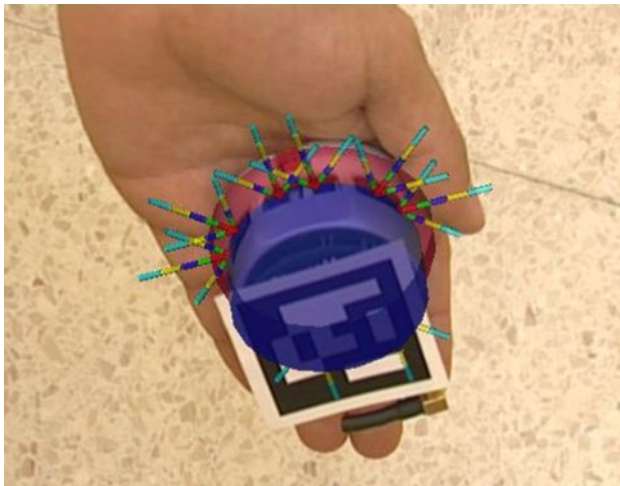


Fig. 10 Virtual items (virtual body and beams of virtual sensors) superimposed on the real robot (visible to illustrate their position)

to the RS-232 port that connects the robot (link 2 in Fig. 12). The ARRL application constantly updates virtual sensor readings and provides these data to the socket server (link 1). When it receives a request to read the robot’s proximity sensors, instead of sending this data, it returns the last value provided by the ARRL application (link 3).

However, there is no reason to replace any other subsystem in the real robot. Any other command sent from the robot control program is sent immediately to the real robot, and any response to this request is forwarded in turn to the requesting control application (link 2). One of the advantages of the developed methodology is that the robot is not a simulation. Thus, all robot capabilities and responses (except proximity sensors) are real. Link 4 in Fig. 12 shows the real time video from an IP camera located in the lab to the ARRL application. Another highly relevant advantage is that, as it can be observed, the objective of the lab (which is a function of each subject) and ARRL applications are completely separated. Thus, in this case the control application, objective of the lab, can be developed in any language or development environment (C++, Matlab, Python, LabView, etc.).

In the developed ARRL application (see bottom left of Fig. 13), the user can select and move any virtual obstacle with a simple mouse click. The selected element can also be rotated on its axes; its size or aspect ratio can also be altered, as show in the video (Online Resource 1). All these actions are unthinkable in a remote laboratory using real elements in the area surrounding the robot.

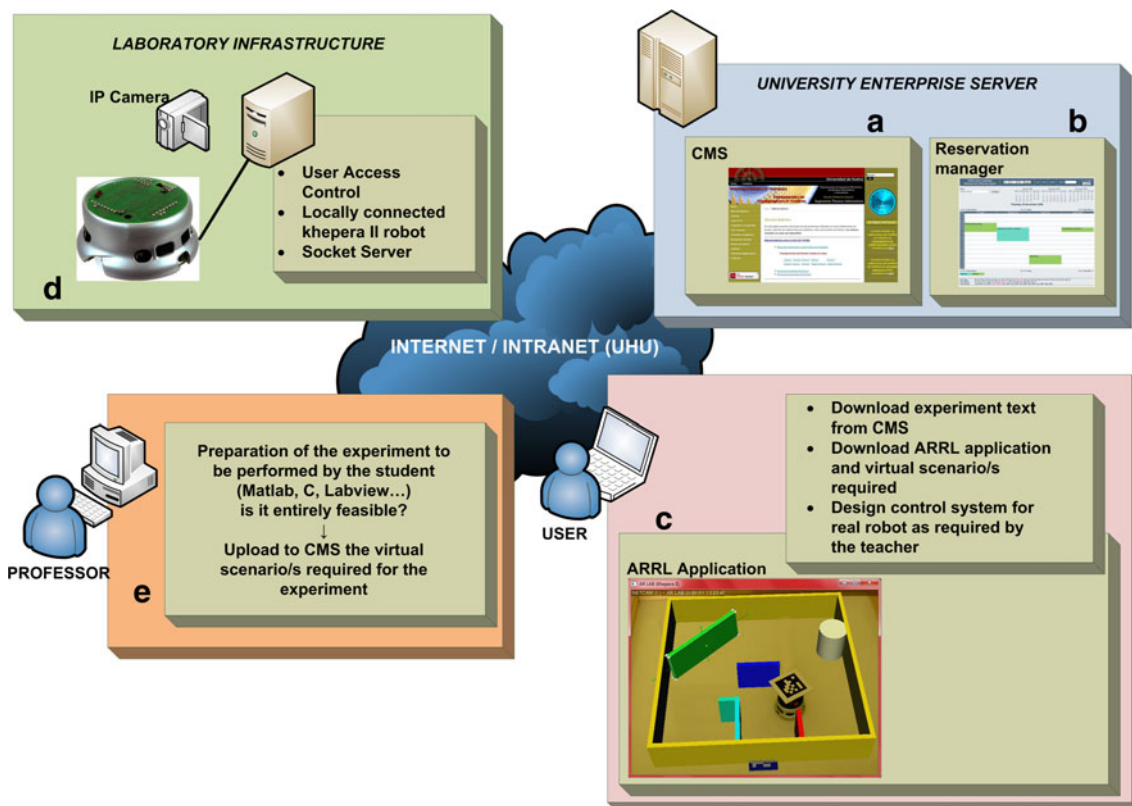


Fig. 11 ARL general structure for Lab #2

Fig. 12 Diagram showing the computer connected to the robot, the ARRL application and the communications server (Tunneling Server)

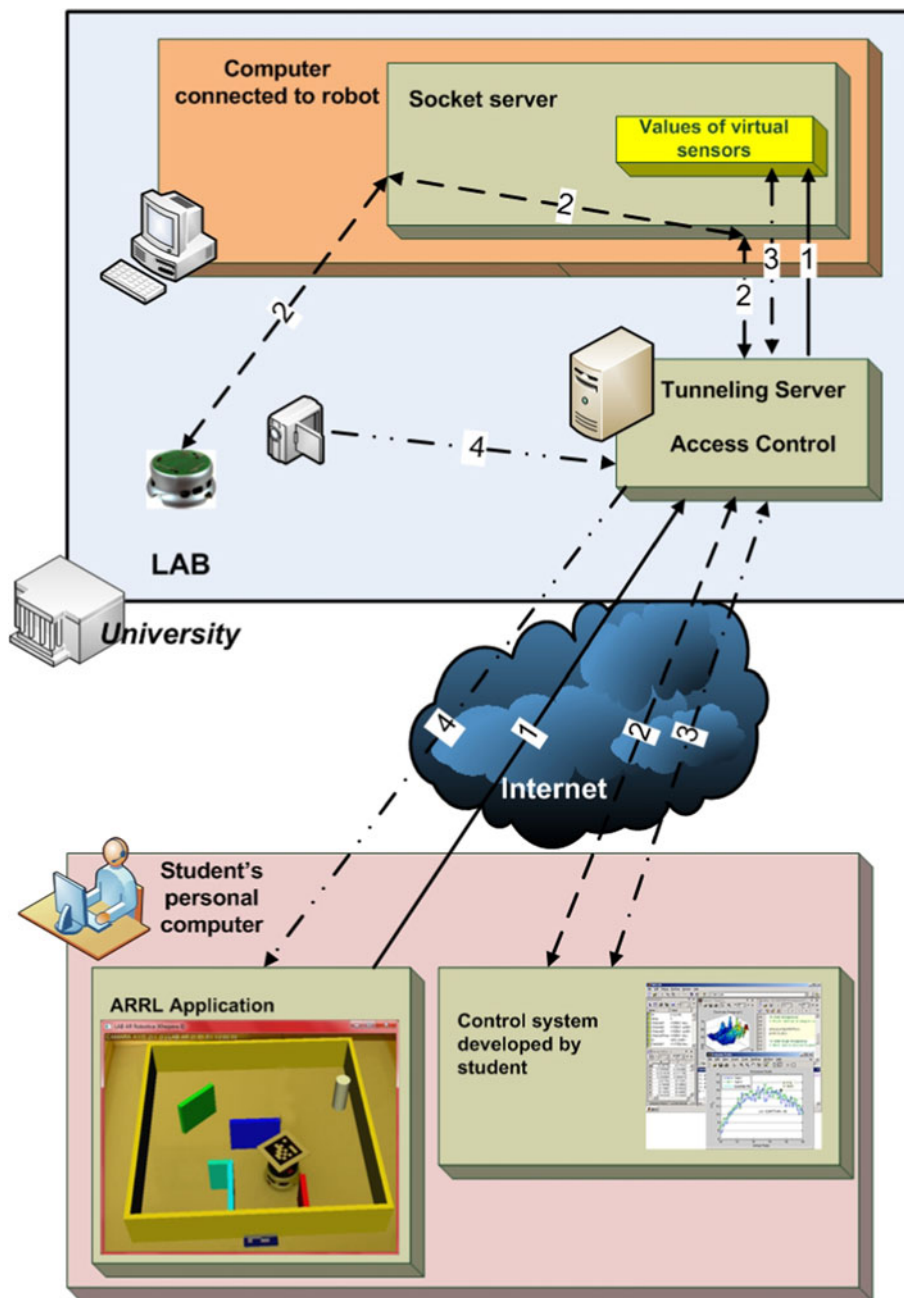


Figure 13 shows a simple teacher-generated virtual scenario (top left). This scenario is uploaded to CMS and TPE and students use it to develop the mobile robot control program. They can choose any of the obstacles and change its position (for example the green wall at the top right), rotate it (bottom left), or change its size (bottom right). Once the desired transformation is performed, the object is placed in the virtual scene with the new acquired characteristics. The robot acts according to the TPE and student-developed control program to try to avoid obstacles. These changes can be made in real time, even while the robot moves within the virtual environment. The Coin3D toolkit

(Coin3D 2011) is used for displaying 3D visualization. Coin3D is built on OpenGL (OpenGL 2011) and uses scene graph data structures to render 3D graphics in real-time. The virtual scenario is defined in Open Inventor (Open Inventor 2011) file format, which can be interacted with by means of Coin3D (this toolkit is fully compatible with SGI Open Inventor 2.1).

Performance of the Lab

To perform this lab the TPE and student must obtain the following from CMS:

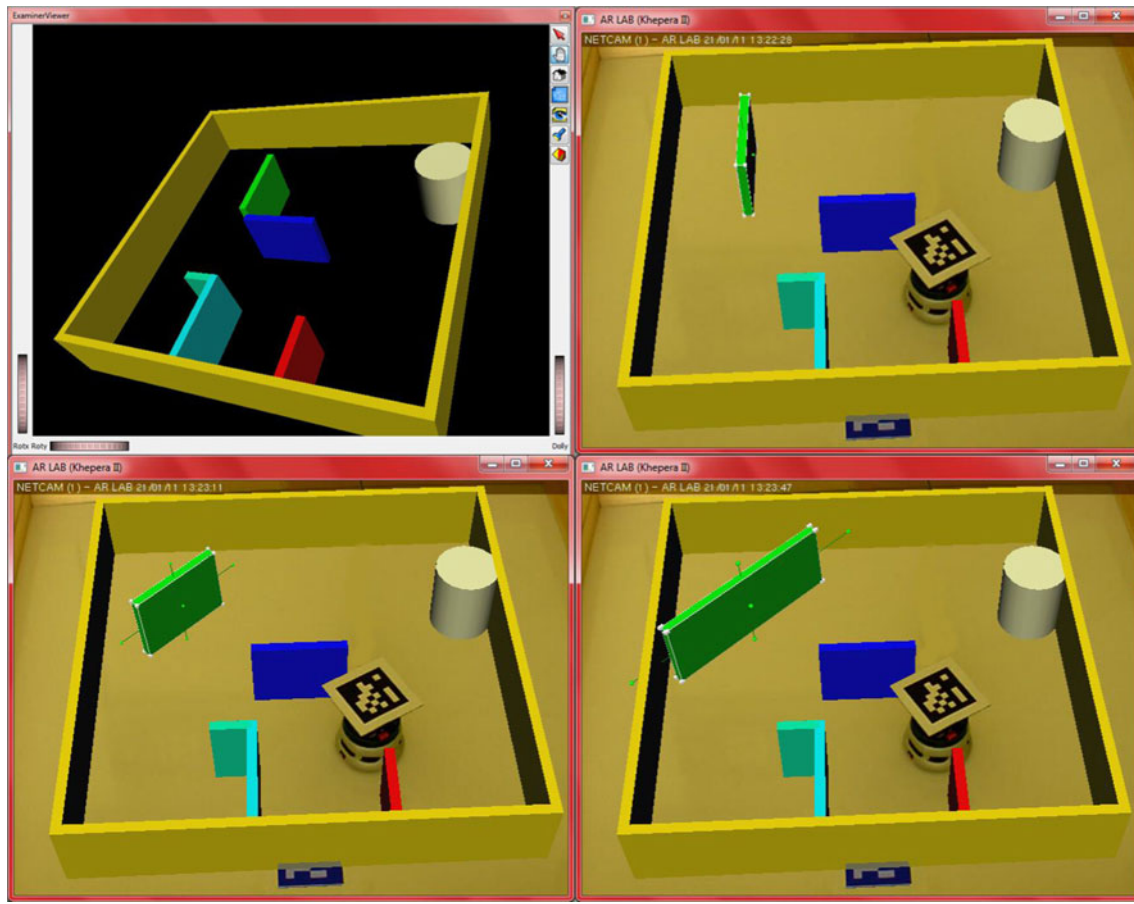


Fig. 13 Manipulating the virtual scenario from the ARRL application

- The experiment text
- The toolbox for the Khepera II robot. This toolbox is KMatlab (Piguet et al. 2010), but it has been modified to allow access to the robot via TCP/IP, as shown in Fig. 7. Matlab is used, as it is fairly common in educational contexts and allows control system design based on inverse model technique. It is probably the simplest method for controller design based on the adjustment of parameters from input–output data; however, it is widely used to create behavior-based control structures in mobile Robotics.
- The ARRL application, which includes two virtual scenarios:
 - The first scenario, used by TPE and students to obtain 300 input data (proximity sensors) and output data (speed applied to each wheel) from a teacher-provided function which allows the robot to evolve as a Braitenberg vehicle, storing the values of proximity sensors and speed applied to each wheel into a matrix.
 - A second scenario, different to the first, where the TPE and student must verify robot operation with

the designed control system, avoiding obstacles of various kinds in different positions.

For control system development, TPE and students are asked to produce two fuzzy systems to control two motors. Fuzzy systems are then trained by ANFIS (Adaptive Neuro-Fuzzy Inference System) (Jang et al. 1997) with the data obtained while the robot evolved in the first virtual scenario.

Finally, TPE and students must write a brief Matlab script that controls the robot using the inferred fuzzy systems. Logically, TPE and students can obtain many results with this experiment: graphs representing the training data and outputs provided by the inferred systems, errors, curves of relationship between the various inputs (sensors) and output, testing the inferred systems using a different set of vectors, verifying the results using different membership functions (Gaussian, triangle, etc.)

As explained above, control system design and TPE and student-provided results are entirely performed with Matlab (as in the lab with a real scenario around the robot). The ARRL application runs only twice: to obtain

Table 2 Lab # 1: Design of a digital sequential control system using a development board with a FPGA

Lab type	Description	Number and ratio of students that solve the practice (max. time allowed for completion: 90 min) (total no = 20)	Number and ratio of TPE that solve the practice (max. time allowed for completion: 90 min) (total no = 10)
CL	TPE and students design the circuit and program the development board in lab	16 80%	10 100%
VL	TPE and students design and simulate the circuit remotely by means of the manufacturer-provided software. However, they have no contact with the real lab, as everything is virtual	17 85%	10 100%
ARL	TPE and students design and simulate remotely, record the development board remotely and check its proper operation remotely on the real lab	16 80%	10 100%

Table 3 Lab # 2: Design of a control system for a robot to avoid obstacles in a scenario

Lab type	Description	Number and ratio of students that solve the practice (total no = 20)	Number and ratio of TPE that solve the practice (total no = 10)
CL	TPE and students design the control system and test the robot in lab in a scenario containing real obstacles	18 90%	10 100%
VL	TPE and students complete the lab practice by means of the simulation software KiKS (see Nilsson 2001)	13 65%	8 80%
ARL	TPE and students design the control system and ascertain its proper operation remotely by means of the ARL (real robot in a virtual environment)	18 90%	10 100%

the training data that TPE and students use to train the fuzzy systems with ANFIS and to visualize the robot evolving in the second virtual scenario, while controlled by the adjusted fuzzy systems.

First Tests as an Educational Tool

The developed work has a twofold purpose: learning and teaching, hence to test it we have counted with teachers and students. An educational experience was completed to assess the developed ARL with the participation of TPE and students. Both groups of users were asked to complete lab practices by means of three different possibilities: CL, VL and ARL. At the end of the educational experience, both TPE and students filled in some questionnaires aimed at assessing the improvement contributed by the ARL relative to the remaining lab options available: CL and VL. Each of both lab practices was completed by a group of 20 students (a whole group laboratory) chosen randomly among 4 possible and another group of 10 teachers (the number of 10 is casual, as that was the number of teachers who voluntarily decided to participate in the experience), and both practices are part of the contents in the subjects *Digital Systems* and *Robotics and Industrial Automation*, which belong to the second year of the new degree in Electronic Engineering (adapted to the European Space for Higher Education). Participating students were registered in the afore-mentioned subjects and teachers did not give lessons in these subjects, although they had enough training experience to complete the educational experience. The participating teachers and students belong to the Higher Technical School at the University of Huelva (European Union).

The lab practices completed by TPE and students include the design of a *digital sequential control system* using a development board with a FPGA (in the subject *Digital Systems*) as well as the *design of a control system for a robot to avoid obstacles in a scenario* (in the subject *Robotics and Industrial Automation*). The developments put forward in Section IV of this work were used in ARL.

The time that teachers and students have been available to accomplish each lab is an hour and a half. This duration was chosen because it is the usual in the classroom labs schedules. The data included in Table 2 refer to *individuals who perform the lab correctly in up to half an hour*.

Table 2 summarizes the completed practices and the elements used. After lab practice completion, with enough experience to compare the three types, both TPE and students were asked to fill in a questionnaire containing a set of questions on a 5-point Likert scale (1 = strongly disagree and 5 = strongly agree) to assess ARL relative to the other two proposals: CL and VL.

Tables 2 and 3 show that the use of ARL involves in principle no inconvenience regarding lab practices, as the number of students who are capable of completing the lab practices properly is the same as when completed in person (this is obviously a coincidence, yet it may also indicate a trend). From our viewpoint, it may be due to

Table 4 Evaluation questionnaire of the ARL

Question	Description	TPE		Students	
		Mean	SD	Mean	SD
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

LAB # 1: Design of a digital sequential control system using a development board with a FPGA

Table 5 Evaluation questionnaire of the ARL

Question	Description	TPE		Students	
		Mean	SD	Mean	SD
1	Your level on robot control systems design is high	2.5	0.71	1.88	1.06
2	The use of a graphic tool fosters the students' motivation and interest	4.2	0.63	4.16	0.84
3	Putting the application into practice is feasible in the university context	4.6	0.52	4.08	1.05
4	The application allows learning new theoretical concepts	3.1	0.87	3.63	1.26
5	The application allows consolidating theoretical concepts	3.1	0.57	3.97	1.13
6	Theoretical concepts can be learned through theoretical study alone	4.1	0.87	3.05	1.67
7	The software application has a clear and intuitive structure	4	1.05	3.86	1.15
8	The interface appearance is nice	3.5	1.08	4.05	0.89
9	The application is useful	4	1.15	3.69	1.06
10	The application is interactive	4.8	0.42	4.52	0.74
11	The use of virtual scenarios is easy	4.9	0.31	4.38	0.73
12	The installation of the ARRL application is easy	4.1	0.99	4.22	0.93
13	The application facilitates theoretical-practical understanding	3.9	1.19	3.88	1.00
14	The overall assessment of the application is positive	4.2	0.92	4.02	0.84

Lab # 2: Design of a control system for a robot to avoid obstacles in a scenario

the fact that ARL introduces no additional difficulty in lab practices, but it is only a tool that allows us to interact with the didactic material by means of AR and provides remote support. However, design steps remain as in CL. An analogous assessment would admit the results obtained for TPE. The most striking result both for TPE and students is in the case of VL in Table 3. The exclusively virtual completion of the practice in the robotic lab shows worse results. Undoubtedly this is due to the additional effort involved by familiarizing oneself with the simulator, as this step is not necessary in CL and ARL.

The questionnaires are shown in Tables 4 and 5 which contain the average responses of TPE and students on ARL (Lab#1 and Lab#2). Both contain the same set of questions, with two adaptations according to the lab (questions 1 and 11). Results show positive ARL general assessment (question 14). Both TPE and students agree that applications have positive aspects regarding their graphic interface, ease of use, installation and interactivity. Two sets of answers are clearly different in both groups of users (questions 5 and 6). They seem to show a trend in students to think that theoretical concepts are learnt better through practical applications. The authors of the present study

agree with this idea. However, TPE in Lab #1 do not seem to agree to such an extent.

Regarding the influence of the use of ARL on learning in the design of both VHDL-based digital systems and control systems for robots, the high scores registered in questions 2–5 prove that these tools facilitate learning and are highly useful in university contexts.

Finally, answers 7–13 show a high level of acceptance by the users (both groups) of the developed system for ease of installation, use, utility, etc. This opinion is even more pronounced in Lab 2, perhaps for having a moving element and make even more obvious (it is a visual perception) the capabilities of the developed system.

Conclusions

Lab practices are an essential part of engineering education and, therefore, efforts aimed at facilitating and bringing these activities closer to students are numerous in different universities.

The developments put forward in the present work are aimed at contributing new means to remote lab practices without neglecting the loss of realist sensation usually involved by simulation. Bearing this purpose in mind, AR is proposed as support technology in the education of future engineers. We present fully operative applications. All of them have been developed with free software tools, thus allowing their diffusion among students with no use restriction in educational contexts.

The possibilities contributed by AR are numerous. Thus, the Higher Technical School at the University of Huelva (European Union) is currently developing new applications according to the ARL concept developed in this work.

We are aware that the educational study carried out is very basic and may extend it more. In fact we think that the developed system offers extraordinary possibilities in this regard. However and according to the questionnaires, the result of the educational experience proves that the developed ARL may well be a powerful tool to improve the remote teaching/learning binomial, particularly in a highly difficult field such as remote lab practices in engineering subjects. We expect that completion of the course 2011/2012 (June 2012) we will be able submit to the scientific community a sophisticated educational study in which the main argument will no longer be the developed system (as in this work), but its statistical analysis as an educational tool.

Future research shall focus on extending its applications to other engineering fields (mechanic, chemistry, etc.) through collaborations with other Departments at the University of Huelva. On the other hand, the developed

ARL is currently being enriched regarding access control and learning management.

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