Interaction of Real Robots with Virtual Scenarios through Augmented Reality: Application to Robotics Teaching/ Learning by Means of Remote Labs*

ANDRÉS MEJÍAS BORRERO and JOSÉ MANUEL ANDÚJAR MÁRQUEZ
Escuela Técnica Superior de Ingeniería. Universidad de Huelva. Ctra. Palos de la Frontera, s/n, 21071, Palos de la Frontera, Huelva, Spain, Email: mjias@diesia.uhu.es, andujar@diesia.uhu.es

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. This paper poses a new reality and new teaching/learning concepts in the field of lab exercises in Robotics. The developed augmented reality-based lab system (which we have called augmented remote lab, ARL) enables professors and students to work remotely (Internet/intranet) in current classroom labs (CL), including virtual elements that interact with real ones. An educational experiment was conducted to assess the developed ARL in the lab component of the *Robotics and Industrial Automation* course, which is part of the new Electronic Engineering degree (adapted to the European Space for Higher Education). The labs were carried out by means of three different possibilities: CL, VL and ARL. Although the results are still preliminary and need further study, they seem to conclude that ARL remarkably improves the possibilities of current VL and RL. Furthermore, the ARL allows further possibilities when used online than traditional laboratory lessons completed in CL.

Keywords: robotics; augmented reality; virtual scenarios; online education; augmented remote lab

1. Introduction

The main aim of this work is an educational one. Therefore, we do not attempt to put forward new developments in the field of the science of Robotics but new proposals that contribute advances to distance Robotics teaching/learning. The ARL presented in [1], that enables professors and students to work remotely (internet/intranet) in current CL, including virtual elements that interact with real ones, was created with this purpose. The readers are advised to consult the details of this concept in [1]. This conceptual and experimental framework enables distance Robotics teaching from a rather more demanding viewpoint than the common concept of e-learning (completely virtualized distance education) and even traditional CL.

The ARL allows the real robot interacting with realtime modifiable virtual scenarios. Although the presented concept is likely to have multiple applications, the present paper focuses on educational spheres, as these were the main inspiration behind this work. More precisely, the present research was triggered by the following question: how can you go beyond the concept of virtual and/or remote lab [2] to improve online teaching/learning in Robotics? The ARL is proposed as a concept that includes and improves the capabilities of VL and/or RL. That is, a lab constituted by both a real and a virtual environment which are interconnected to and interrelate with each other by means of augmented reality (AR) [3].

Unlike other subjects, whose lab practices could be somehow known as static (button pressing, electrovalve triggering or signal measurement), Robotics contributes specific casuistry and difficulties, as it involves movement. This is a further element of the practice which constitutes a further difficulty in online teaching/learning, where labs are usually virtual (easy to implement, as students work with models and everything is inside the computer) and/or remote (harder to implement, as the ultimate aim is the remote control of real robots).

The ARL is being tested in two required courses at the second year of the new Electronic Engineering degree (EE), at the Higher Technical School of Engineering, University of Huelva, in southwestern Spain. The specific courses are *Digital Systems* and *Robotics and Industrial Automation*. The EE degree is recognized by The European Higher Education Area (EHEA), an initiative of the Bologna process [4] designed to create more comparable, compatible and coherent higher education systems in Europe [5]. This paper focuses on the performance of the series of lab exercises for the *Robotics and Industrial Automation* course. According to the foregoing, the starting point is that students are expected to complete online Robotics exercises by accessing a remote lab. Among other challenges, these lab assignments include a changing environment where a mobile robot is located. Students are asked to design a control system for the robot to move across the changing scenario avoiding obstacles. The ARL can complete this kind of lab exercise

remotely. It should be noted that the problem goes beyond teleoperating a robot via the Internet (most, if not all, commercial providers of robotic platforms these days offer software featuring robot web-control capabilities), since the remote completion of this practice with traditional media involves certain easily imaginable drawbacks:

- People must be physically in the lab to modify the scenario.
- What should students do if their robot crashes with an obstacle and knocks it over?
- How can situations of unforeseen obstacles be produced?

On the other hand, the preparation of physical environments for robot development entails a series of difficulties, such as:

- Achieving the required textures, shapes, etc.
- Implementation of lab models which reflect different working environments realistically.

In an attempt to overcome the aforementioned problems and other likely drawbacks, the present paper puts forward a system that grants remote access to a real robot (a Khepera-II [6]—see Fig.

1—mobile minirobot was used for practical implementation, although if any other mobile robot had been used, the concept would be the same) that can interact with an obstacle-containing virtual scenario by means of AR techniques. The desired virtual scenario can be chosen a priori. In addition, this scenario can be modified interactively in real time, remotely and even when the robot is moving.

1.1 Augmented reality and AR systems for robotics education

AR supplements real-world perception and interaction and allows the user to view a real environment, usually observed through some kind of electronic device such as cameras and HMD (head mounted displays), augmented with computer-generated 3D information. AR systems are real-time interactive systems and 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.

Between totally-real and totally-virtual situations there is a continuum (Fig. 2) characterized by varied mixtures of virtual and real environments. In this
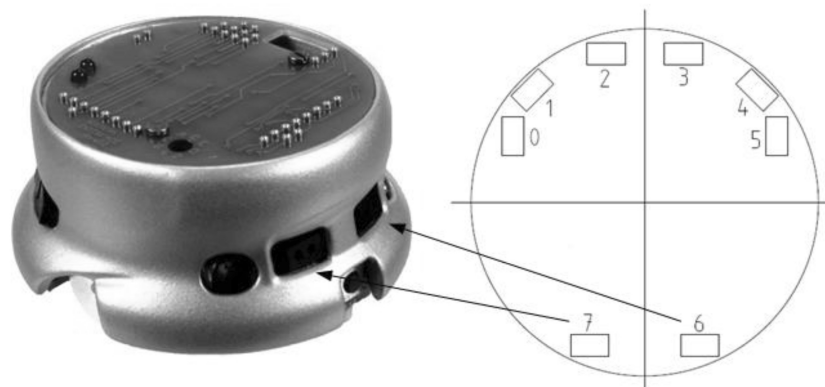

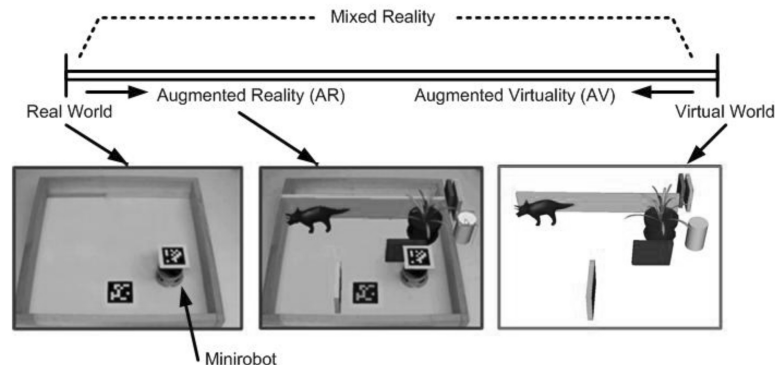**Fig. 1.** Khepera II robot and distribution of proximity sensors.

Fig. 2. Reality-Virtuality Continuum.

mixed reality the concept of a virtuality continuum [7] 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 known as mixed reality. Fig. 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 with which it interacts. This is the key issue regarding AR: interaction between reality and virtuality creates a richer reality offering further possibilities.

Different e-learning systems using AR in the field of Robotics have been recently developed for educational purposes. Although still in an embryonic state, these include:

- UJI On Line Robot [8]: 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 [9] 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 Virtual Reality (VR) and AR, allowing a task to be easily performed and a description of the desired environment transformation (to be completed by the robot)
- Jara et al. [10] present the development and implementation of RobUaLab. In this approach the real information from the robot scenario is supplemented with virtually-generated data from the virtual environment. Virtual projection is combined with the current state from the remote laboratory taking the current IP camera setting and the 3D environment into account. This feature helps to improve user performance and provides further information to control the robot.

The aforementioned applications are designed to facilitate robot programming and AR is used to complete the user's information with a virtual version of the robot. The proposal presented in this paper goes beyond this approach: robot programming is entirely separate from the AR application. Indeed, AR creates an environment of 3D virtual objects (obstacles for the mobile robot) with which the robot can interact. This concept is completely different from other developments in which the remote real robot only interacts with actual physical items.

2. The ARL in robotics education

In this paper, The ARL access is enabled by a developed 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. The reader is advised to consult reference [1] which details the structure of the ARL. Figure 3 shows the general structure of ARL, particularized for mobile robotics practices.

Regarding physical realization in the lab, Fig. 4 shows the experimental area fitted out for prototypes. The following elements can be observed in it:

1. AXIS 211 camera, which obtains an original video image of the real robot and sends it to the ARRL application through a real time message protocol (RTMP) for appropriate generation and location of the necessary virtual elements. A Sony DVCAM DSR 570WSP (7) was also used to evaluate other video sources.
2. A communications and access-control server is used to provide access (from outside the University network) to the PC located at the lab which is directly connected to the robot.
3. A physical framework which prevents the robot from leaving the area covered by the camera due to possible programming errors committed by the user.
4. A PC at the lab directly connects to Kephera II by means of a serial port and also runs a server program which allows the robot to connect to the remote applications the user wants to interact with.
5. Khepera II robot with a fiducial marker.
6. Reference marker for the virtual environment.

2.1 Interaction between the real robot and the ARRL-provided virtual environment

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

(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.
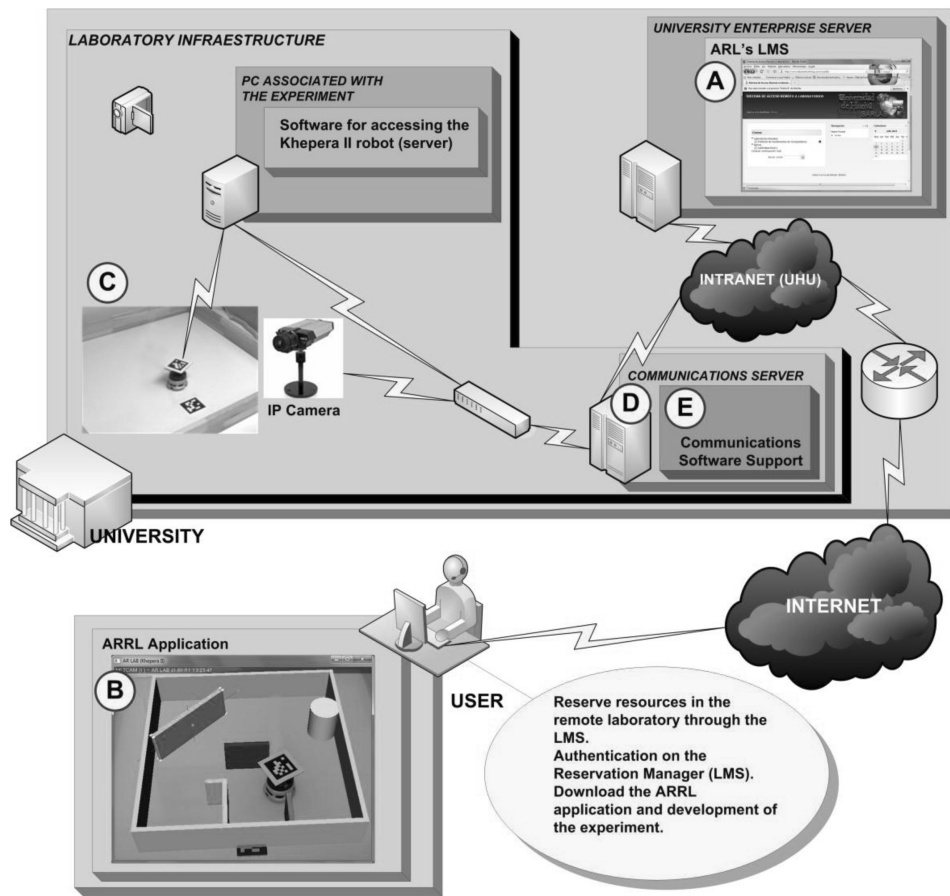
Fig. 3. ARL general structure (mobile robotics).

Fig. 4. Infrastructure enabled for prototyping.

The markers in the ARToolKitPlus [11] library were used. This is a very inexpensive 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, so that a real robot can detect virtual worlds.

Each sensor is modeled with three beams (Fig. 5) 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. 5) allows it to detect collisions between real and virtual environments. In
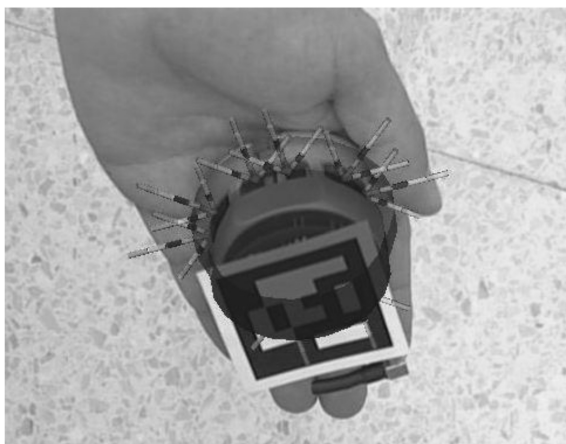
the implementation of the ARRL application, the virtual body and sensors are transparent, so that the user can only see the real robot. For real-robot monitoring (tracking), a marker allows software to calculate its position in AR space.

The structure shown in Fig. 6 shows the control and ARRL applications. This shows one of the main advantages contributed by the developed system: 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, which is the aim for the student in this lab exercise, can be developed in any language or development environment (C^{++}, MATLAB, Python, LabView, etc.)

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 to the RS 232 port that connects the robot (link 2 in Fig. 6). 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). 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). However, there is no reason to replace any other subsystem in the real robot. One of the advantages of the developed methodology is that the robot is not a simulation. Thus, all robot features, capabilities and responses are real (chassis, wheels, motors, controllers, mass, inertia, etc.), with the obvious exception of the proximity sensors. Link 4 in Fig. 6 shows the real time video from an IP camera located in the lab being sent to the ARRL application.

2.2 Advantages of virtual environments

The use of virtual environments in remote lab practice with real robots presents many advantages in education that would be unavailable in real environments. Among them the following can be mentioned:

Fig. 5. Virtual items (virtual body and beams of virtual sensors) superimposed on the real robot (visible to illustrate their position).

- The 3D (virtual) elements that form the virtual scenario can have nearly 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.
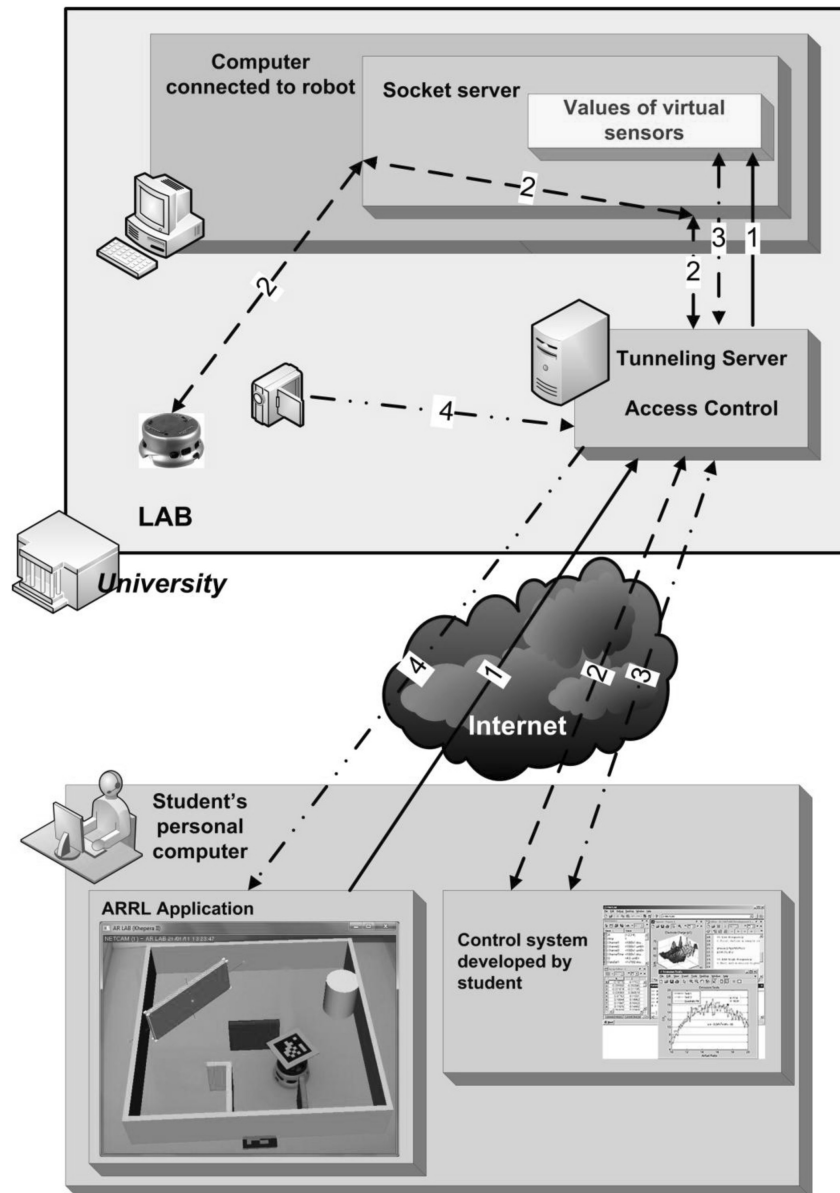- Virtual elements cannot deteriorate, break or hit

Fig. 6. Diagram showing the computer connected to the robot, the ARRL application and the communications server.

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 reduce time consumption.
- Very 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. For instance, Fig. 7 shows a scenario with some more complex obstacles (a small set of virtual toys).

In the developed ARRL application, the user can select and move any virtual obstacle (see bottom-left Fig. 8). The selected element can also be rotated on any of its axes.

As an educational example, Fig. 8 shows a simple teacher-generated virtual scene (top left). This scenario is uploaded to LMS (Learning Management System) and students use it to develop the mobile-robot control program. They can choose any of the obstacles with a simple mouse click and change its position (e.g., the green wall at the top right), rotate it (bottom left), and its size or aspect ratio can also be altered. All these actions are unthinkable in a remote laboratory using real elements in the area
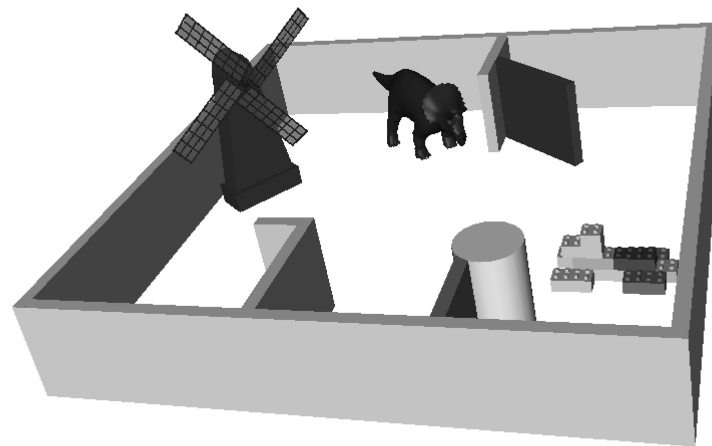
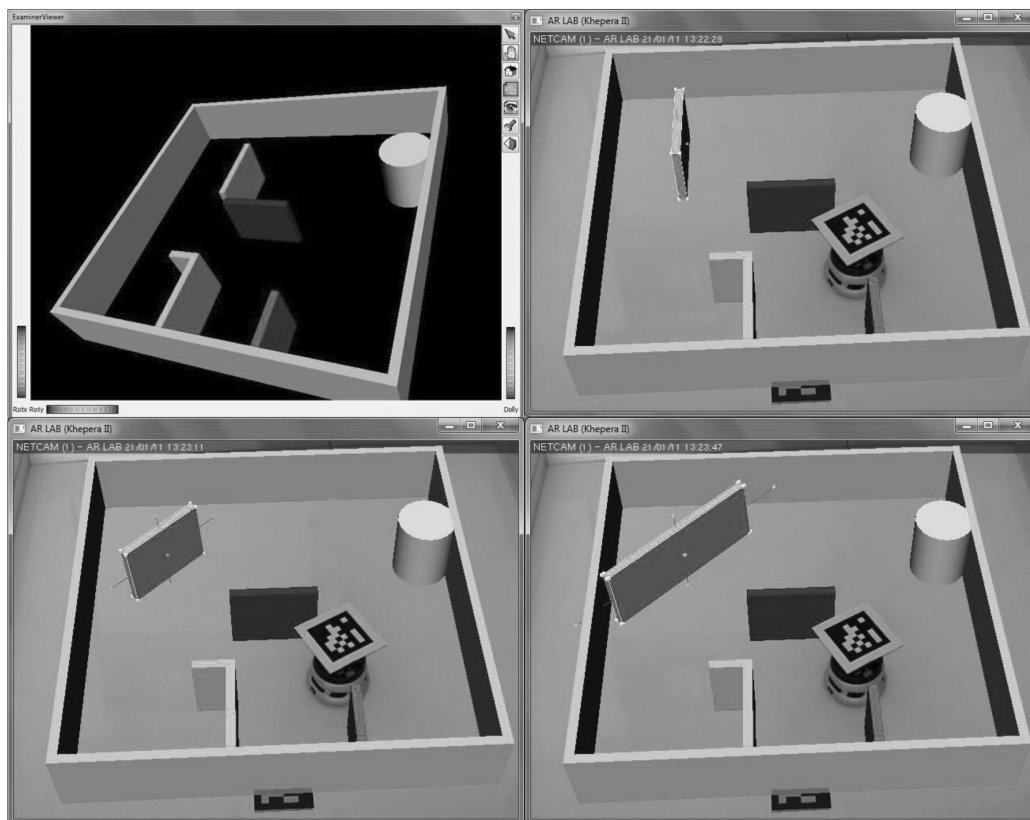**Fig. 7.** Virtual scenario with complex obstacles.

Fig. 8. Manipulating the virtual scenario from the ARRL application.

surrounding the robot. 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 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 [12] toolkit is used for displaying 3D visualization. Coin3D is built on OpenGL [13] and uses scene graph data structures to render 3D

graphics in real-time. The virtual scenario is defined in Open Inventor [14] file format, which can be interacted with by means of Coin3D (this toolkit is fully compatible with SGI Open Inventor 2.1).

2.3 Other possibilities of virtual scenarios: integration of a dynamics engine

One of the biggest differences that virtual three-dimensional objects that are part of a virtual scenario present is the fact that they have no physical

properties such as equivalent real objects (mass, density, velocity, acceleration, etc.). Thus if the robot moves to a virtual three-dimensional object and does not detect it or the robot is not programmed to avoid it, the robot will pass through it without being able to affect the position of the virtual object. If this happens, the perception of reality by the student who is performing the remote practice is lost.

It seems logical to think that certain practices would be interesting if the robot hits an obstacle, it should reacts in a similar manner as a real object with the same physical characteristics located in that same position. This means that if the robot hits an object and it falls and/or is moved, it will produce an unforeseen change in the distribution of one or more objects on the virtual scenario, because of possible collisions that may arise between them.

To include physical properties on three-dimensional objects in the virtual scenarios of ARL applied to mobile robotics, it is necessary to add to these objects the ability to simulate the dynamics of rigid bodies through a dynamics engine. In the prototypes made, a dynamics engine of free distribution, Open Dynamics Engine [15], is included. The interested reader can view in [16] a short video about the behaviour of a virtual object with physical properties that is hit by the Khepera II robot.

3. Practical example

As a practical example, this section puts forward one of the practices completed by students to test and end the ARL presented in this work. Students were asked to contribute a design for a mobile robot to behave like a Braitenberg vehicle [17] (an agent that can move around autonomously), but using a fuzzy system obtained by adaptive techniques. The purpose of the lab is that a real robot moves without colliding in a user-created virtual scenario.

To perform this lab the students must obtain the following from LMS:

- The details of the experiment.
- The toolbox for the Khepera II robot that can manage it remotely from a MATLAB environment. This toolbox is KMatlab [18]. However, it has been modified to allow access to the robot via TCP/IP (as shown in Fig. 6). MATLAB is fairly common in educational contexts and allows control system design (for example based on an inverse model technique as in this lab). 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 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 from the first, where the student must verify robot operation with the designed control system, avoiding obstacles of various kinds in different positions.

For control system development, students are asked to produce two fuzzy systems to control the two motors of Khepera. Fuzzy systems are then trained by ANFIS [19] (Adaptive Neuro-Fuzzy Inference System) with the data obtained while the robot evolved in the first virtual scenario.

As explained above, control system design and student-provided results are independent from the ARRL application and this one runs only twice: to obtain the training data that students use to train the fuzzy systems with ANFIS and to visualize the robot evolving in the second virtual scenario, while controlled by the tuned fuzzy systems. The URL in [20] displays a video of the evolution and interaction of a Khepera II robot provided with the control system developed in this section in a virtual scenario according to the methodology proposed in the present work. This video clearly shows an important restriction of the robot used in this case: its scarce battery autonomy. Consequently, for permanent ARL operation, the robot had to be fed by means of an electrical intake cable. It is known that the presence of wires may prevent some robot trajectories. However, in this case we count on a great advantage: the cable cannot get entangled with the obstacles as these do not exist physically. Consequently, we only had to keep the cable straight by means of a pole so as to prevent it from troubling the robot's wheels.

4. First tests as an educational tool

An educational experiment was completed to assess the developed ARL with the participation of professors and students. Both groups of users were asked to complete lab exercises by means of three different possibilities: CL, VL and ARL. At the end of the educational experiment, a questionnaire aimed at assessing the improvement contributed by the ARL relative to the remaining lab options available: CL and VL.

The lab work was completed by a group of 20 students (a whole laboratory) chosen randomly

among 3 possible groups and another group of 10 professors. Who voluntarily decided to participate in the experiment. Participating students were registered in the aforementioned subject and professors did not teach these courses, although they had enough training background to complete the educational experiment. The participating professors and students belong to the Higher Technical School at the University of Huelva.

The time that professors and students had available to accomplish the lab was an hour and a half. This duration was chosen because it is the usual timeframe for the labs. The data included in Table 1 refer to individuals who perform the lab correctly in up to half an hour.

Table 1 summarizes the completed labs and the elements used. After completion of the lab, with enough experience to compare the three types, professors 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 the ARL relative to the other two proposals: CL and VL.

Table 1 shows that the use of the ARL involves in principle no inconvenience regarding lab work, as the number of students who are capable of completing the lab exercises 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 the fact that the ARL introduces no additional difficulty in lab experiment, 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 validate the results obtained for professors. The most striking result is in the case of VL in Table 1. The exclusively virtual completion of the lab work in the robotic lab shows worse results. Undoubtedly, this is due to the additional effort involved in familiarizing oneself with the simulator, as this step is not necessary in CL and ARL.

Table 2 shows the questionnaire which contains the average responses of teachers and students on ARL. Results show positive ARL general assessment (question 14). Professors 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 who think that theoretical concepts are learnt better through practical applications. The authors of the present study agree with this idea.

Table 1. Lab experiment: 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 teachers that solve the practice (total no = 10)	
CL	Teachers and students design the control system and test the robot in the lab in a scenario containing real obstacles	18	90%	10	100%
VL	Teachers and students complete the lab exercises by means of the simulation software KiKS (see [21])	13	65%	8	80%
ARL	Teachers 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%

Table 2. Evaluation questionnaire of the ARL: Design of a control system for a robot to avoid obstacles in a scenario

Question	Description	Teachers		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

Regarding the influence of the use of the ARL on learning in the design of control systems for robots, the high scores registered in questions 2–5 support the fact that this tool facilitates learning and is highly useful in university contexts.

Finally, answers 7–13 show a high level of general acceptance of the developed system for ease of installation, use, interactivity, etc. As Robotics and Industrial Automation has been offered for the first time this year, it has not been possible to make a deeper study of its weaknesses and strengths, and the presented data must be considered a preliminary study.

5. Conclusions

The developments put forward in the present work are aimed at contributing to remote lab work without neglecting the loss of realist sensation usually involved in simulation. Bearing this purpose in mind, AR is proposed as a support technology in the education of future engineers, allowing real robots to interact with virtual 3D scenarios, which have many advantages over the use of real scenarios in a remote lab. Although this system and methodology is aimed at academic training spheres, applied to the field of Robotics in this case, it can also be applied to other scientific and technological fields.

A study was carried out in order to evaluate the laboratory from the pedagogical point of view. A group of students and instructors were invited to participate in the study with its criteria. Teaching experiences indicates that this approach has been well received among students, and they think that the Augmented Remote Laboratory helped them to understand theoretical-practical concepts, and that use of this new tool was simple and intuitive. In addition, our impression, after talking to students, is that experimentation with real robots awakens their curiosity and motivation to learn. These results demonstrate the positive influence of the remote experimentation in its development for engineering students. In the future, to obtain better results in the study, we would perform a statistical analysis of variance (ANOVA) on the scores of the selected students.

Another important aspect of this work is the fact that all software has been developed with free software tools, thus allowing their diffusion among students with no use restriction in educational contexts.

Regarding future works, the main focus could be related to the development of an AR application builder and the integration of the AR application into the Learning Management System. Thus, the student would not have to install any application, and could access the experimental system directly from a web browser. We are already developing this version using Java for web integration.

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Andrés Mejías Borrero received his Industrial Engineering degree, Dipl. Computing degree, and Master's degree in production systems engineering from the University of Seville, Seville, Spain, in 1989, 1993 and 2005, respectively and his Ph.D. degree in industrial engineering from the University of Huelva, Huelva, Spain, in 2012. He is currently a Full Professor with the Department of Electronic Engineering, Computer Systems and Automatic Control, University of Huelva, Huelva, Spain. He was the Director of the University's Scientific Computer Centre from 1995 to 1998 and Sub-Director of the Central Computing Service. His research interests include new e-learning technologies and engineering education.

Jose Manuel Andújar Márquez received his Industrial Engineering degree (with Honors) from the University of Seville, Seville, Spain, in 1984; his Industrial Physics and Automatic Control degree (with Honors) from the Universidad Nacional de Educación a Distancia (UNED), Madrid, Spain, in 1998; and his Ph.D. degree in industrial engineering from the University of Huelva, Huelva, Spain, in 2000. He is a Full Professor in systems and control engineering with the University of Huelva, where he has been the Head of the Department of Electronic Engineering, Computer Systems and Automatic Control since 1993. He has authored and co-authored over 160 technical articles, four book chapters, and three books. He has led or co-led 22 research projects. His current research interests include engineering education.