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A Virtual Laboratory for Teaching Robotics*

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Technical teaching often requires the use of expensive laboratory materials which are frequently beyond the reach of many students. Students are also required to go to laboratories, which offer the appropriate facilities, according to a strict timetable. For these reasons, the need for alternative methods arises for teaching such as virtual laboratories via the Internet. In this article we present a virtual laboratory that is being applied to robotics teaching which allows the simulation and tele-operation of a robotic arm.

INTRODUCTION

NOWADAYS, several virtual systems exist via the Internet that allow a user to manage or learn disciplines like robotics, artificial vision, etc. [1, 2]. There are some systems that only permit simulation, and they do not give real data so can cause a loss of motivation in the students. Also, when users must be served sequentially, this becomes a major problem for the education of a group of users.

This paper presents an educational virtual laboratory for training in robotics that allows, on the one hand, the simulation of a robot arm, and on the other, the tele-operation of the a equivalent of a real robot arm by several students simultaneously without causing problems.

TELE-OPERATION OF ROBOTS

There are many ways of achieving environments that emulate reality. The most traditional method is to physically reproduce the original system to a different or to the same scale. Another way of doing this is through the use of visual feedback; the original system is recorded [3, 4] and this feedback faithfully reproduces the performance of the system. Currently, the most interesting way of doing this is through virtual environments, generated by computer simulations [5, 6].

Virtual environments are used to achieve real system simulations, and in so doing reducing costs on test measurements as well as providing a better way of learning for the user. Some of these environments also permit the 'immersion' of the user in the simulation through the use of stereoscopic glasses.

The use of robots in dangerous workplaces (such as the handling of radioactive materials, the detonation of explosives, as well as the realisation of various types of tasks in space, submarine exploration, micro-assembly, mining, etc.) has several advantages over a human workforce. Initially, a tele-manipulator is used for these tasks, which permits the commands of the user to be carried out by a set of simple controls without the need for direct control.

In the master/slave systems, a robot arm (master) of the same form as the remote robot (slave), but not necessarily the same size, is manipulated by the worker by reproducing its movements in the slave [7].

A new system could be achieve by mixing simulated environments and tele-operated systems, where the user has a simulation system which is faithfully reproduced by the real one [2]. This type of system could offer feedback to the worker through images, in addition to simulation [6].

The remote control techniques can also be applied to the tele-operated systems through virtual environments. The physical presence of the user near the system is not necessary as with tele-manipulators or traditional master/slave systems. The system's operation can be remotely controlled through the Internet by using technologies such as VRML and Java [8, 9]. The first language allows the user to simulate virtual systems easily, and the Java language lets the worker interact with the environment and the real system at same time [5].

VIRTUAL LABORATORIES

Practice lessons at the university should play an important role in any educational system, especially in technical and experimental studies and should obviously be as realistic as possible, as the students will have direct contact with the

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techniques and the equipment that they will have to use in their professional careers. But in many cases, educational laboratories do not have the proper equipment for economic reasons.

Virtual laboratories offer a great number of advantages, especially when specific equipment is required for practice. They simulate the devices, including all of the required parameters, so that the student could work with a complete and realistic environment. Also, real remote equipment can be managed in the virtual environment, since working with simulations can often be quite different from the real thing. Therefore, the educational practices based on the use of new technology (Internet, virtual reality, real-time, etc. . . .) give the student a real option of working with a remote system [10, 11]. The advantages of this are:

- Remote practices, in which the students can take part without having to be present in the laboratory.
- Learning in a free and flexible way in contrast to a fixed and regular class schedule.
- An easier self-evaluation process with its own automatic on-line correction and immediate display of the results.
- Remote access to real equipment permits the management of robots in dangerous environments.
- Expensive systems can be used, which would generally be impossible in common situations.

Sometimes, the virtual laboratory is used merely to access and display information whilst allowing the student to interact and use the equipment remotely [1, 10, 11].

The complexity of a virtual laboratory is variable. It may be classified as follows:

- *Test laboratory.* These are laboratories for practice where a physical system is not required. The student only needs a few calculation tools, handbooks, etc. Some examples of these involve the solution of theoretical issues (transformation-matrix in robotics, numerical calculus in physics and maths).
- *Simulation laboratory.* A simulation of a real environment can be performed through virtual reality in a virtual laboratory. To achieve a more realistic system, virtual reality is defined as a high level human-computer interface through which the user is able to interact with simulated environments in real time and through multiple sensorial channels [12]. It is possible to simulate the tools, the equipment (control systems, electrical systems, etc.) and all the parameters involved. One disadvantage is that the student does not get real data, but only the simulated results. Some examples of this sort of laboratory are Simulink, Labview, Pspice.
- *Remote execution and simulation laboratory.* In addition to the virtual reality simulation, real equipment is remotely controlled through a previous Internet session (with robots, electronic microscope, metallurgic tests, etc. . . .). The students receive an off-line video sequence of the accomplished task and can compare the results and take experimental measurements on a real system. The best features of this option are:
  – Greater student motivation, as the students are able to compare the real results with the simulated ones obtained previously.
  – The option of checking the results on expensive equipment or in a dangerous environment permits them to use such equipment without the need for duplication of the real system.
- *Real time tele-operation laboratory.* This is the most realistic virtual laboratory of all. It permits the tele-operation of the equipment (robots, electronics, microscopic, motors, metallurgic tests, etc.) in real time. Its main inconvenience is the need for using a real-time feedback, which could be limited by the bandwidth of the media that communicates the student with the real laboratory. However, the system introduces the option of performing a force feedback, an effort feedback, a visual feedback, etc.

THE VIRTUAL LABORATORY DEVELOPED

Our virtual laboratory is designed for the training of robotics. With it, users can both simulate the use of an industrial robot, and tele-operate a real robot which is present in a real laboratory. Both operations are achieved by accessing a web server through the Internet and the WWW. The real laboratory is situated in the Campus of the University of Alicante. The only equipment that each user requires is a computer connected to the Internet with the adequate software [6, 10].

The simulation is done by means of virtual reality software, whereas the tele-operation can be realised in several ways:

- by means of a recorded video sequence that users receive when a command finishes,
- as a remote execution using a video stream, or
- by a real-time feedback of the information of the basic robot parameters.

Bandwidth of common Internet access can limit the transmission of images and video in real-time considerably, so, in many cases a video stream only permits a deferred feedback. Systems which allow for Internet restrictions must be considered in order to do real-time tele-operation.

The solution that we have adopted for real-time tele-operation is the transmission of the information about the basic system parameters (position of robot joints, speeds, etc.) from laboratory to user, instead of a video stream. These values are used as inputs for the virtual reality interface. With this method, the user who tele-operates the system sees a simulation of it, but unlike a simulation based on a mathematical model, this one corresponds to the

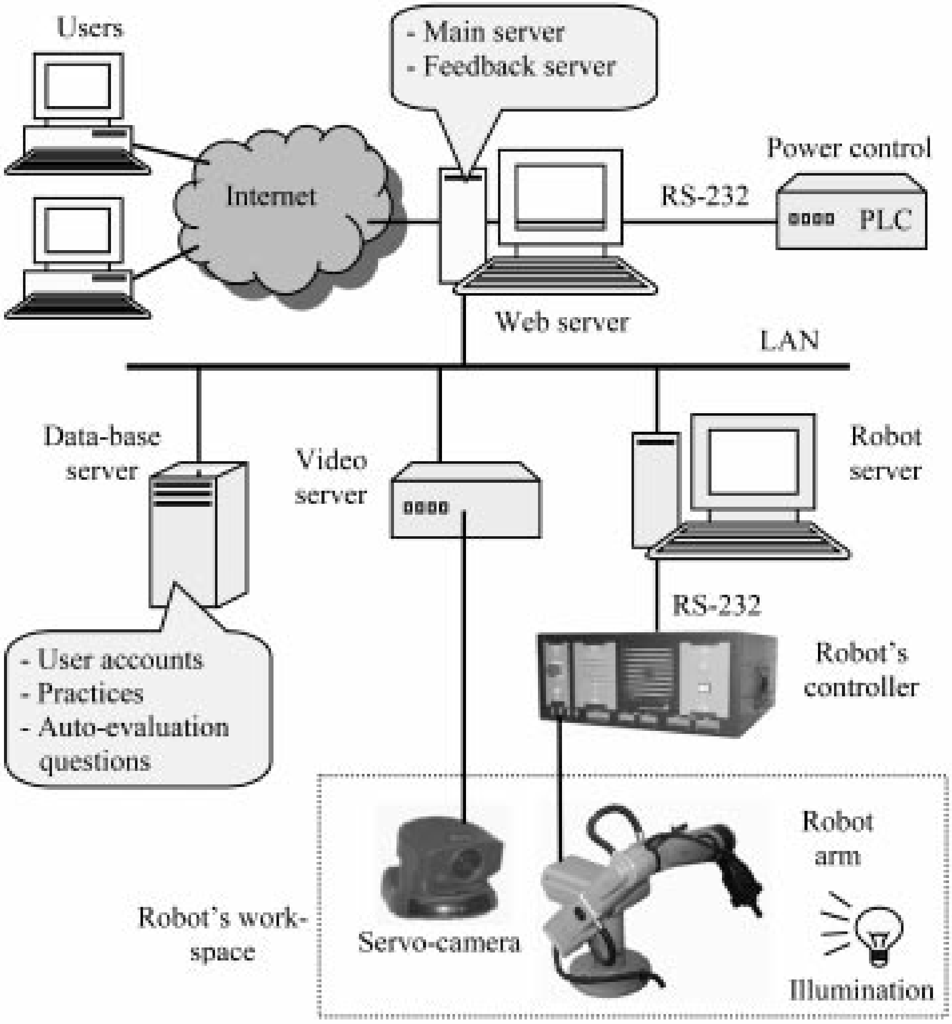

Fig. 1. Virtual laboratory architecture.

changes that take place in the real system, since the real values of the robot's positions are used as inputs for the simulation.

SYSTEM DESCRIPTION

Figure 1 shows the different devices of which the whole system is composed. There are two well defined parts that are interconnected through the Internet: the computer of the user and the set of devices that are located in the laboratory. The next sections describe the different devices as well as the functions carried out by each one.

Laboratory equipment

As Fig. 1 shows, in the laboratory there are other equipment in addition to the real robot and the web server.

The robot used is the Scorbot ER-IX from Eshed Robotec Ltd. This is a robot arm with five axes plus a gripper. It is able to handle a maximum weight of 2 kg, and the reach of the work field is 691 mm. The robot actuators are managed by a controller, also from Eshed Robotec, which can be programmed using SCORBASE or ACL languages for Windows. The former has been used to implement the virtual laboratory.

The controller is communicated with via a computer robot server through an RS-232 interface. The robot server is a 133 MHz Pentium whose function is, on the one hand, to manage the commands to the robot, and on the other hand, to obtain the information about the actual state of robot to make a real-time feedback.

The web server is the main computer in the system. It is a 200 MHz Pentium with the MS Internet Information Server as the web server. This equipment includes two server applications: the main server and the feedback server. The first one manages the user connections, the downloading of the applet for simulation and the remote execution. The second one is used for real-time tele-operation.

In the laboratory there are other two important pieces of the equipment: a database server and a video server. The first one (133 MHz Pentium) stores accounting information about the users, the practices and the questions for an automatic self-evaluation. The second one is a video server

AXIS 2400, which is employed to obtain video sequences or streams for the tele-operation. This server is connected to a servo-camera Sony EVI-D31, which is located close to the robot's workspace. The video server not only allows users to see the video signals given by the camera, but also permits them to control the orientation and zoom of the camera through its web page.

The different internal servers located in the laboratory are connected through a LAN. Nowadays, a 10 Mbps Ethernet offers an adequate bandwidth. The fact that the internal servers are not used directly through the Internet increases the protection in these equipments.

It is noteworthy that the virtual laboratory also includes a lighting system, and a power control system. The lighting system guarantees that the workspace is correctly illuminated so that the users can tele-operate the system. The power control system is based on a Siemens PLC (programmable logic controller) and its function is to switch several devices on or off, such as the lighting system, the robot, the cameras and the internal servers. This controller is directly connected to the web server through an RS-232 interface. As is obvious, the web server is always running.

The equipments described above, without considering the robot arm and its controller, are easily accessible (PCs, camera, video server, LAN, Internet connection, etc.), and the cost is not very great. Thus, the cost of implementing this virtual laboratory for robotics depends mainly on the robot arm required.

The user's interface

A user can access all of the functions of the virtual laboratory by means of a web page with a Java applet [8]. This language is used extensively for web applications. Also, VRML (Virtual Reality Markup Language) was chosen for the graphical simulation as it is a common Internet standard and it provides a simple interface with the user, which allows the definition of different views of the robot arm in the simulation [5, 9]. Another reason for the choice of VRLM is that it allows a simple connection with Java. So it is necessary for the student to have the appropriate software installed in his computer, that is, a web browser application with Java support and a VRML module.

Figure 2 shows the layout of the web page just as a user sees it in his web browser. The web page is composed of two parts: the Java applet with the different options for handling the robot simulation, and the VRML window with the simulated state of the robot [11, 13].

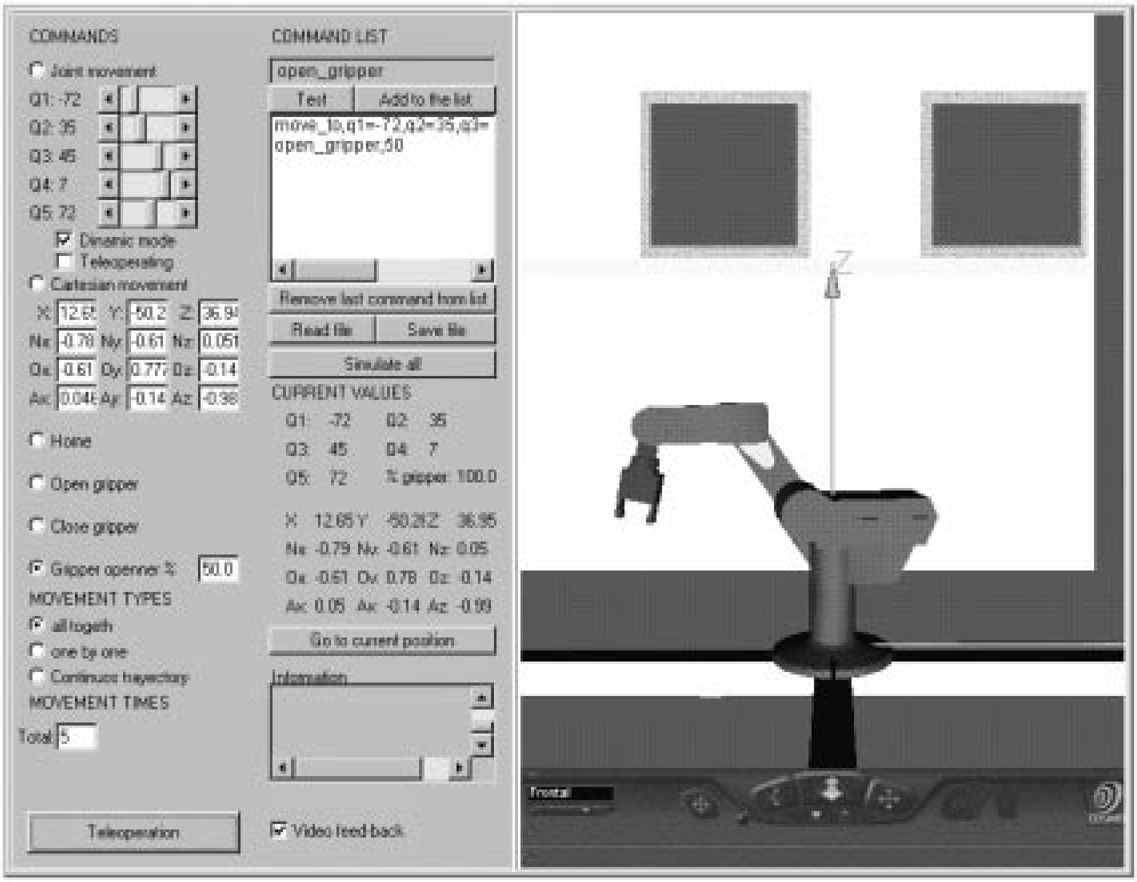

Fig. 2. Web page for simulation.

The different options are summarised next:

- To move the robot arm with the joint coordinates by entering the values, in degrees of rotation, for each joint or by using the dynamic mode by means of a displacement bar for each joint.
- To move the arm with cartesian coordinates by inserting the position of the robot's workspace where the user wants to position the final robot effector as well as its orientation.
- Initialisation of the robot arm (home command). The arm is positioned according to some predetermined coordinates and confirmed that it is working correctly.
- To open or close the gripper totally or partially.
- Type of movement. User can choose from three options: 'all together', 'one by one' or 'continuous path'. With the first type of movement, all the joints are moved simultaneously. The 'one by one' movement consists of moving joint number one first, then joint number two and so on, until the fifth joint. With the last type, joints are commanded so that the effector follows a straight line between the current and target points.
- User can select the duration of the movements.
- List of valid commands to be executed by the real robot. The previous commands have to be checked first to verify that they are correct. If they are not, then the system shows a window that alerts the user and does not insert the command into the list. If the movement is correct, it is entered into the list and the current position is updated. The last movement inserted can be deleted from the list. The entire list can be read or saved on a local disk. The system enables a simulation option for all the commands in the list in VRML.

After the simulation, a user can execute the tele-operation option. This requests the web server to execute the simulated movements that are stored in the list of valid commands with the real robot arm. The real robot execution can be evaluated in three different ways:

- The user receives a video sequence after the execution with the real robot, which can be watched with a video player. This option does not allow a real-time tele-operation.
- The user receives a compressed video stream while the real robot executes the commands. To do so, a connection with the video server is established. This option can provide the user with real-time video feedback depending on the network bandwitdh. Figure 3 shows the last image of the video sequence received for the simulation corresponding to Fig. 2.
- The VRLM simulation is updated in real-time with the information received from the web server while the real robot is moving. This option allows the user a real-time tele-operation.

The correct use of the real system is guaranteed since the practice is executed on a simulated system and only the valid commands are tested on real

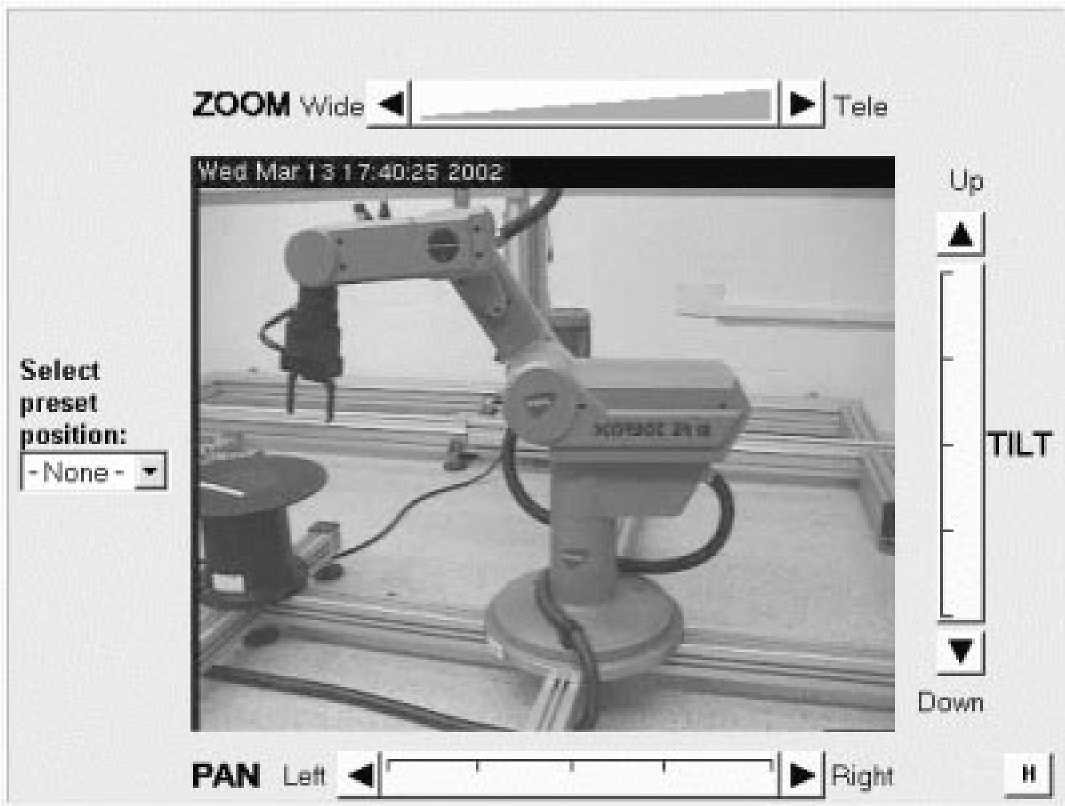

Fig. 3. Capture of the video corresponding to simulation shown in Fig. 2.

equipment. Moreover, a second validation of all the parameters is performed by the web server to prevent the system from been damaged, which increases the lifetime of the equipment for practices.

Finally, the user also has the option of tele-operating the real robot directly, without any previous simulation, by using the real-time feedback. In this case, the selected values in the Java applet are sent to the web server immediately, which verifies whether they are correct before moving the robot. However, this option is not the most suitable for educational purposes when there are many students.

Server applications

The web server contains the main server and the feedback server. When a user accesses the Virtual Laboratory web, his client browser first connects to the main server, and this provides the Java applet for simulation to the user. It is not necessary to be a registered user to access this applet. However, it is necessary to be an authorised user to gain access to the robot to tele-operate it and to use the auto-evaluation system.

The database server contains the information about the user's accounting such as his password, notes, time dedicated to each practice, list of commands executed, etc. This server also stores the test with questions and solutions used to carry out the self-evaluation for each practice. Also, it is possible to establish the tele-operation modes that can be used by the different kinds of users. All this information is used by the main server.

When the main server receives a list of tele-operation commands from an applet, it verifies the position of the parameters to prevent the robot from being damaged. If the commands are valid, and the robot arm does not have any risk of colliding with any object, they are sent to the robot server. If the command has invalid parameters, the applet is informed about the problem, the operation is cancelled and the main server waits for new commands.

The main server queues the list of commands for tele-operating and attends to it sequentially. The difference with other systems is that the same user can request the execution of the different lists of commands that he had simulated previously. For each list, the robot is restored to a position of reference before executing its commands. Furthermore, the time assigned to a user for each tele-operation is limited.

In the case in which the tele-operation is done with a deferred video sequence, the main server also connects with the video server to obtain and record a video sequence. When the robot gets to an end position, the main server finishes the recording and sends the video sequence to the applet. However, if the tele-operation uses the video feedback, the applet in the user's computer connects directly to the video server thought the main server.

The feedback server is used only when the main server detects an authorised user who has selected the option for tele-operating by means of the real-time feedback. The feedback server then connects to the applet directly, and it accesses the robot server to obtain the information concerning the position of the joints of the robot arm while the movement is being done. This information is processed and sent to the applet in order to update the VRLM simulation in the computer of the user. To reduce the information to be transmitted, the position values are only sent when the robot makes a significant change of position.

The robot server carries out two functions:

1. It queues, processes and translates the commands directed to the robot into ACL language.
2. It reads the position of joints when the feedback server demands it.

The closed loop for controlling the robot is achieved by its controller, and not by the robot server. So, the tele-operation feedback is just as Fig. 4 shows.

The server applications are also written in Java, and moreover, all the communications between the different applications in the system are made with Java sockets.

ACTUAL WORK LINES

New features are currently being incorporated into the virtual laboratory described here, such as a system for 3D recognition and modelling of the objects that the robot arm handles.

The actual simulation only permits a user to operate the robot arm. But it is very interesting

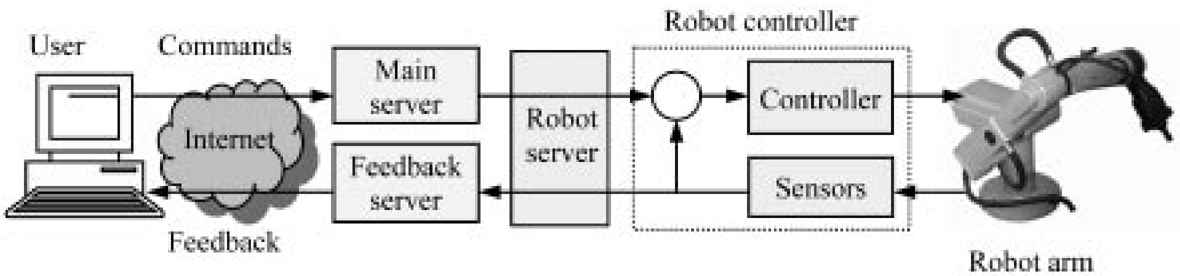

Fig. 4. Scheme of the tele-operation with real-time feedback.

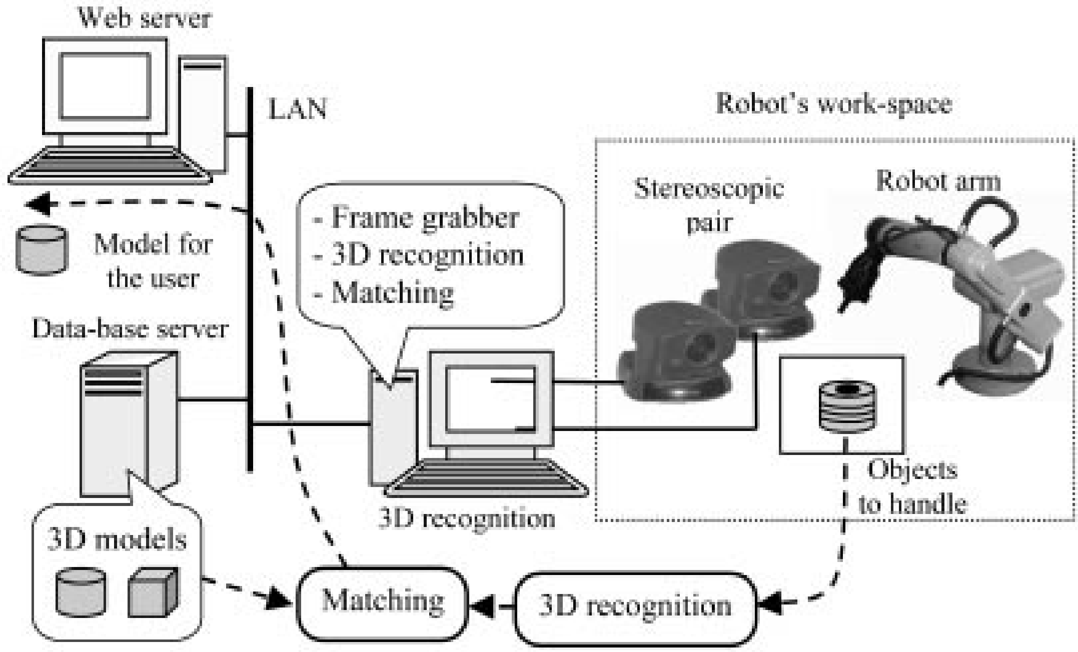

Fig. 5. Equipment for 3D recognition and modelling of the handled objects.

that users can also simulate and tele-operate the handling of objects with the robot arm. The tele-operation with video feedback is not sufficient for doing this, and it is necessary to model the objects to be handled in the VRLM simulation in the applet.

To include this feature, some new equipment has been added to the virtual laboratory, such as a pair of stereoscopic servo-cameras, CCD, and a new computer with a frame-grabber. The frame-grabber is a Matrox Genesys board for the PCI bus, and the servo-cameras are two Sony EVI-D31. Also, new information is included in the database server, such as the simplified 3D models of the possible objects that users can handle with the robot in its workspace. These new modules are represented in Fig. 5.

The new computer captures the images from the two calibrated cameras and detects the position and orientation for the different candidate objects in workspace. To identify the objects of interest in the robot workspace, each different object is modelled with several descriptors, and a matching with that model is searched for in the database of 3D models stored in the database server. When the model of an object is found, the actual information about it (position and orientation) is sent to the main server. To reduce the transmitted information, this is only sent when the position or orientation of the object has changed from its previous coordinates.

Next, the main server will send that information to the user's computer for the applet updates the VRLM simulation. In this way, the VRLM simulation will represent the objects that there are in the workspace or that the robots handles. This process is represented in Fig. 5.

CONCLUSIONS

In this paper, we present a virtual laboratory for teaching robotics that not only allows the simulation of the handling of a robot, but also the tele-operation of it by several students via the Internet. Also, the tele-operation can be done in different ways.

The creation of virtual laboratories in the educational environment performs a stage in the learning and assimilation of practical concepts. The employment of this type of practical allows students to access resources from any location without having to move physically to laboratories or classrooms for practical teaching.

It is important to highlight that the use of the Internet in the realisation of practical also implies a bigger profitability from the investment required for the operation of a laboratory, since all the users have virtual access to a limited resource. The access to these resources is carried out by means of the assignment of user keys with times of use, with which the security and access of all the users are guaranteed in the system.

The use of this new technology facilitates a reduction in the impact of the growing number of students on the familiar constraints of laboratory time and cost.

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