Virtual and Remote Robotic Laboratory: Comparative Experimental Evaluation

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***Abstract*—This paper describes the development and experimental evaluation of an *e-laboratory* platform in the field of robotics. The system in its current configuration is designed to enable distance training of students in real scenarios of robot manipulator programming. From a technological perspective, the research work presented in this paper is directed towards the adaptation of concepts and techniques developed in the field of telerobotics and virtual reality, and their integration in such e-laboratory settings. This paper focuses particularly on the educational impact of such systems. The goal is to assess the performance of e-laboratory scenarios in terms of the efficacy of training provided to students. The results of a pilot experimental study are presented, providing a comparative evaluation for three training modalities: real, remote, and virtual training on robot manipulator programming. The experiments were conducted according to an evaluation protocol specially designed for the considered target training task, using scoring charts to obtain quantitative performance measures and assess the performance of the student groups participating in the course. Training, as a dynamic process, is approached according to a classical three dimensional model, and performance scores are accordingly assessed in these dimensions (namely: low-level versus mid and high-level skills and understanding). The obtained results reveal certain differences between the three groups, particularly as related to the low-level skill training score, giving some insight about the training 'dimensions' that are expected to be mostly affected by the absence of physical (or realistic virtual) presence in a real hands-on experimentation. Statistical analysis indicates, however, that, despite these apparent differences, such e-laboratory modules can be integrated quite effectively in practical scenarios, creating *virtual training environments* that can provide adequate learning elements, as related particularly to mid and high-level skill acquisition. Further work and large-scale studies are still needed, though, in order to explore the extent to which such a general conclusion is valid in different training settings, and to form the basis of a more theoretical evaluation for a comprehensive understanding of the pedagogical differences between real, virtual, and remote learning/training methodologies and experiences.**

***Index Terms*—Distance training, evaluation methodology, remote laboratory, telerobotics, virtual robotic laboratory.**

I. Introduction

DURING the last decade, many distance-learning platforms and applications have been developed, demonstrating the potential that is offered by new information and communication technologies (ICT), and particularly by the continuous evolution of those technologies related to the Internet. Nowadays, teaching from a distance in a synchronous or asynchronous e-learning mode, or attending and participating in classroom lectures and seminars remotely, constitute a common practice, as those technologies are mature enough and many application platforms have already been established as a standard. The development of such applications is often based on some type of teleconferencing (video/audio streaming) platform, with a multipoint conferencing unit (MCU) at the core of the system, enhanced by many software features, such as application sharing or other functionalities forming "virtual classroom" Web spaces.

However, in many cases, exchanging audio/video streams, sharing educational material (such as presentation slides) in a synchronous or asynchronous way, or interacting in a "virtual classroom" space is often not adequate to complete an efficient educational program. A typical example is teaching in engineering disciplines, where hands-on laboratory experimentation is essential for enhancing and completing classroom lectures. Although the development of systems that can offer some kind of practical laboratory-training courses from a distance has been in progress for almost a decade now, these efforts have been mostly isolated, and the related technological components are just now beginning to assemble into integrated platforms. However, no standardized or common-practice solution is available yet. Indeed, the difficulty here is related to the nature of such remote and/or virtual "e-laboratory" applications which involve interfacing through the network of many different physical devices and diverse experimental equipment needed to complete a real physical experiment. These devices must be remotely operated through the network, and a variety of different technological solutions may be needed, depending on the type of equipment and real physical experiment involved.

A. Literature Survey

During the last four to five years, a number of "remote laboratory" projects have been initiated on a national or international basis, aiming to teach fundamental concepts in different engineering fields through the remote operation and control of specific experimental facilities. A typical example is the project ReLAX (remote laboratory experimentation trial), funded by the European Commission within the IST framework. The goal of this project was to study the feasibility of making remote experimentation available as a component in distance learning, both from a technological point of view and from an economic perspective [1]. A continuation of this effort was the eMersion

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project aiming to study the deployment of innovative pedagogical scenarios and flexible learning resources for completing virtual or remote experiments via Internet [2].[1] A case study of the implementation of such remote experimentation scenarios in an automatic control course is presented in [3], where useful hints concerning best practices in deploying sustainable flexible education scenarios, from academic and pedagogical perspectives, are also given.

Similar activities towards the development of virtual and remote laboratory systems are also carried out by many other academic institutions, covering various engineering fields ranging from electronics [4] and control [5], [6], to a larger variety of mechanical and chemical engineering experimental set-ups [7]. Experience acquired from this work and from other similar initiatives [8], [9] reveals the difficulties and the challenges associated with the introduction and deployment of distance laboratory modules. From a technical point of view, such a goal requires adaptation of existing equipment, which must often be performed in a task-specific way. Each laboratory setup, and often each associated learning scenario, may call for a different type of operation and control, which raises considerable challenges when performed remotely.

From a didactical perspective, substantial effort is still needed for assessing the effectiveness of these learning modalities compared to traditional means of "hands-on" laboratory training. Some initial attempts to evaluate, in pedagogical terms, remote and virtual laboratory platforms are reported in [10] and [11].[2] In [10], a methodological evaluation approach is presented for a distributed Internet-assisted laboratory experiment. More results, however, are to be reported in the near future in the frames of ongoing international collaboration projects (such as the I-Labs project between the Royal Institute of Technology (KTH), Stockholm, Sweden; Hannover University, Hannover, Germany, and Stanford University, Stanford, CA). Reference [11] describes the methodology that was used in the frames of the eMersion project (mentioned above) for the evaluation of Web-based remote experimentation and student training environments. This evaluation was based on a usability engineering approach, preferred to a didactical approach that was left as an option for the future.

B. Research Objectives

Keeping in mind the various initiatives towards the development of remote laboratory modules worldwide, some of which are cited above, the authors focused the research presented in this paper on the following two goal directions.

First, from a technological point of view, the goal is to develop platforms that will enable both virtual and remote laboratory training scenarios, related to the operation, programming, and control of complex mechatronic devices, such as "robot manipulators." At this point, the use of the terms *virtual* and *remote* should be clarified, in describing different dimensions of what can be more generally termed *"e-laboratory" platforms*. *Virtual laboratory*, as the term implies, refers to the use of graphical user interfaces that incorporate interactive simulation techniques (particularly realistic three-dimensional (3-D) graphics animations) but provide no visual or teleoperation link to a real (remote) physical system (only simulation of the physical system is on the loop). On the contrary, a *remote/distance laboratory platform* involves teleoperation of a real, remotely located, physical system (e.g., a telerobot), including visual and data feedback from the remote site (that is, involving some type of "telepresence" to the remote site). A main part of the research presented in this paper focuses on the adaptation of concepts and techniques developed in the field of telerobotics and on exploring their implementation in such remote laboratory settings. Robot teleoperation technologies have been constantly advancing and evolving for more than two decades now [12], [13]. Initial teleoperation systems were deployed in dangerous and hostile environments (e.g., in the nuclear industry for the telemanipulation of radioactive material). With the advent of communication and networking technologies and the development of new human–machine interactive simulation media, particularly virtual reality systems [14], research in the field of telerobotics has shown considerable progress, with new concepts proposed and demonstrated with success, such as "predictive displays" [15], "shared-autonomy" teleoperation control [16], or the "hidden-robot" concept [17].

Second, from an educational point of view, teaching robot manipulation principles involves the familiarization with a variety of mechanical and control engineering concepts and skills, such as task- versus joint-space control of serial kinematic chains, programming and executing motion sequences to perform a desired manipulation task, etc. The goal here is to evaluate to which extent a combination of remote and/or virtual laboratory scenarios can be effectively implemented in practice and used by students to obtain practical training as a supplement to theoretical courses. A literature review shows that the majority of the research results in this direction are restricted either in a qualitative type evaluation or in a "usability-oriented" approach. On the contrary, the emphasis here is on the didactical/educational perspective of the learning process, to assess the performance of the e-laboratory system in terms of the "quality" of the training provided to students. This assessment is performed comparatively for various training modalities, to shed light on the pedagogical relations among different learning experiences. The assessment can be achieved by systematically conducting comparative experimental evaluation studies with different system versions, supporting specific combinations of "learning elements" integrated in the graphical user interface (e.g., virtual and/or remote control, interactive visualization modes, information feedback schemes, etc.). Quantitative performance measures are obtained through the use of specially designed *scoring charts* for each considered target training task.

The keyword here is *training*, which is often approached and modeled as a 3-D dynamic process, namely, that of building awareness, knowledge, and skills [18], [19]. In line with these models, the goal of the case study presented in this paper is to assess performance in these dimensions, comparatively for two different *e-laboratory* systems: a) a *remote laboratory* version, providing direct visual, teleoperation, and teleprogramming link

[1] The online Web server of "eMersion" Project is available at http://emersion.epfl.ch/]

[2] The online research group Web page is available at: http://kaos.stanford.edu/

with a real, remotely located, robot manipulator (but with a simplistic two-dimensional (2-D) graphical user interface), and b) a *virtual laboratory* interface, incorporating realistic, virtual (3-D graphical) animations of the robot and programming tasks (but with no visual and teleoperation link with a real remote robot). These e-laboratory modalities, which are described in Section II, are assessed in comparison to a classical "hands-on" training and experimentation on the real robot (onsite laboratory training), forming a total of three student groups participating in the controlled experiments (namely, group I: real; group II: remote; and group III: virtual). The comparative experimental results obtained for these student groups are presented and analyzed in Section III, followed by a discussion attempting to offer some insights on the design and efficacy of remote and/or virtual laboratory training scenarios. Finally, concluding remarks and future work directions are presented in Section IV.

II. Virtual and Remote Laboratory Platforms: Technological Aspects

This section describes the design and development of an "e-laboratory" platform, supporting both virtual and remote training scenarios in the field of robotics. One should note, particularly, that the primary focus is on *realistic emulation* of *target-training tasks*, to enable students to practice realistic robot-manipulator programming, that is, using the functionalities and programming modalities provided by the real robotic system. In other words, students must be offered the opportunity to learn how to program a real robotic system without having one at proximity, but in a way that realistically emulates how actual robot programming operations and procedures are performed in real practice. This process is more clearly explained in the following paragraph.

A. Target Training Task

Robot manipulator arms and related mechatronic devices are not always readily available for experimentation by students in their training program. Access to such equipment for education and practical training purposes is often either limited by very specific time restrictions or not provided at all. Moreover, cost of such equipment makes it infeasible for many academic institutes to obtain, and related laboratory training courses are completely missing from many educational curricula. Therefore, the benefits from providing a means for virtual and/or remote experimentation (for instance, in a "lab facilities sharing" context) are evident both from a socioeconomic point of view and from an educational perspective, directly related to the completeness and quality of practical training possibilities offered to all students.

A few attempts are reported in the literature, aiming to develop virtual and remote (Web-based) laboratory systems in the particular field of robotics education. Most of these research efforts cover the field of mobile robotics (remote mobile robot laboratories, e.g., [20]) as a means to enhance the teaching of basic sensing and intelligent control principles, and very few address problems in the field of robotic manipulation. One of these is described in [21], presenting a platform that includes, among other virtual (simulated) experiments, the control of a simple 2-dof robotic arm.[3] This research was based on a Java applet performing kinematic simulation of the robot arm motion (with 2-D-only graphical animation). Simple motion commands can be issued at the joint trajectory level and can be used to convey basic principles of robot motion characteristics. The system illustrates basic Web-based virtual laboratory concepts, but only in simulation (i.e., with no remote real robot in the loop). On the contrary, [22] presents a Java-based interface providing the functionality both to simulate and teleoperate a robot manipulator. This system can be used to practice movement commands of a simulated and/or remote robot manipulator and can, supposedly, convey in a more efficient way the same basic concepts of robot motion control.

From a literature survey of this field, therefore, one can state that existing virtual or remote robotic laboratory systems are very few and provide, in general, some limited spectrum of functionalities in the sense of 1) simulating and animating (in 2-D or 3-D) the motion of simple robot arms; 2) practicing movement commands, which are usually issued either as desired end-effector's position in xy coordinates, or directly as desired angles in the robot's joint space; and eventually 3) submitting these commands for execution by a remotely located real robot. Such functionalities can indeed demonstrate and teach students the basic principles of robot manipulation and control. However, programming a real robot arm to perform a specific manipulation task (e.g., a pick-and-place task in an assembly sequence) is usually more complicated. The human operator is often obliged to program the task directly using the robot's own programming language (usually some scriptlike interpreter language, such as VAL or V+); more often, however, an online robot programming scheme is employed, for instance, using the robot's Teach Pendant tool to teach (record) the intermediate configurations that will constitute the complete robot motion sequence.

Taking into account all these considerations, and keeping in mind the main research objectives as already stated, the key issue to be emphasized in the considered case study is the integration of realistic robot programming operations in the developed e-laboratory platform. Therefore, the work has been directed towards the development of a system that can be used to train students how to program a robot manipulator arm, in a way that closely resembles the functionality and programming operations provided by the real robotic system. In other words, the developed platform should be designed to provide students with realistic practical training modalities, emulating exactly how a complete robot manipulation program is actually created and issued in a real-world task scenario. For the case study that is presented in this paper, the task considered is that of programming a robot manipulation pick-and-place operation, using the functionality of the Manual Teach Pendant.

The rest of this section describes the main technological (design and implementation) features of the two prototype platforms that are used in the experimental evaluation study presented in this paper: the first one (remote lab) supporting real robot teleprogramming operations, using an emulation of the manual teach pendant of the robot; while the second one (virtual lab) integrating interactive, virtual (simulated) robot animation features.

[3]Online VIRTLAB Project information is available at http://www.jhu.edu/-virtlab/virtlab.html

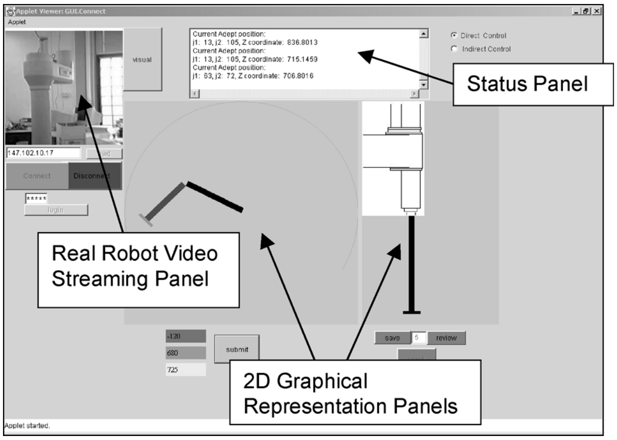

Fig. 1. Remote robotic laboratory: The first prototype graphical user interface.

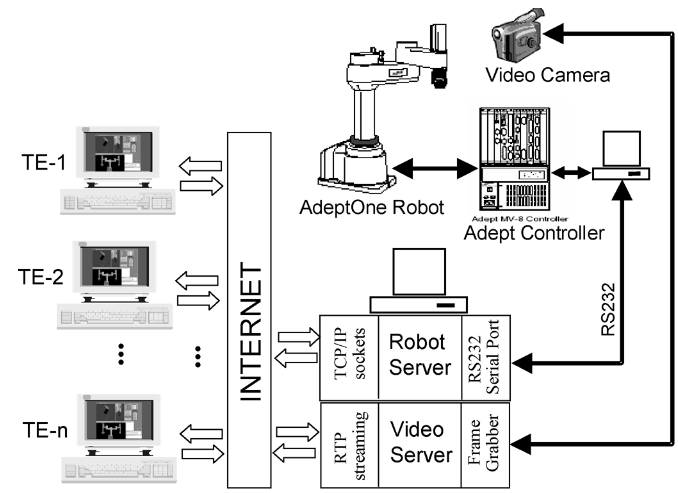

Fig. 2. Overall architecture of the remote telerobotic laboratory platform.

B. Remote Robotic Laboratory Platform: Design and Implementation

The remote laboratory system, described in this paragraph, was initially developed for teaching robot manipulator programming skills [23]. This system constitutes the first version (remote) of the e-laboratory platform used in the pilot evaluation study that is presented in this paper.

i) Web-Based Graphical User Interface: The graphical user interface of this first remote laboratory prototype platform (Fig.1) is based on Java technologies and incorporates: 1) a 2-D graphical representation (top-view and side-view panels), visualizing both actual and commanded robot configurations; 2) a real-time video streaming panel, based on RTP and implemented using JMF, showing (when online) the real remote manipulator in motion; and 3) a status-panel displaying messages regarding system (connections, etc.) and remote robot status.

According to the target training task and objectives discussed above, an interactive control panel has also been implemented and integrated, providing an exact emulation of the robot's manual Teach Pendant, called *Virtual Pendant*. The first version of this Virtual Pendant panel consists of a schematic representation of the real robot's manual programming interface, with active ("clickable"/"hot") areas to provide an exact emulation of all its main buttons and functions. The system enables students to learn and practice robot-programming routines, that is, to create and execute robot programs (complete motion sequences, such as a pick-and-place task) in exactly the same way as if they were using the real-robot's manual pendant tool. The user can add, edit, or delete intermediate robot positions, as happens with the real robot's programming interface. He or she can then either "preview" (in simulation) the robot program visually on the 2-D graphical representation panels of the interface, where an animation of the predicted robot motion is displayed, or "send" the program for remote execution on a real robot to see the results of the actual manipulator motion on the video streaming panel (and on the 2-D graphical panels that provide continuous position feedback to the user). Other real robot programming modalities, even direct text editing and remote execution of program code in the robot's own programming language, could also be implemented; these are considered for implementation in the near future.

ii) System Architecture: The graphical user interface described in the previous paragraph can run as an applet in any standard Web browser, enabling users to connect via Internet (or LAN). Fig. 2 shows the overall client–server architecture of the virtual robotic laboratory platform. The system supports multiple connected users (terminal TE-1 to TE- n), through the implementation of a specific protocol using TCP/IP sockets for communication and real-time data exchange with the "robot server." Each client (student) can connect to the robot server either as an "observer," or as an "administrator," in which case (after entering the correct password) actual control of the real robot is obtained. Robot "observers" have access (through continuous data-feedback) to the current status and motion of the remote robot, while local (simulated) robot programming can also be performed. The robot administrator (only one logged-on at a time) has additional rights to send motion commands or complete motion sequences (robot program) to the remote robot manipulator for real execution. The robot server communicates with the Adept robot controller via an RS232 serial link, using an application-specific protocol for real-time data exchange. In addition, a separate "video server" accepts calls from any remote location, establishing a direct video link that is based on RTP for real-time video streaming. In the current system configuration, only one user can obtain real-time video from the remote robot site. Multicasting has also been tested, but its potential application is limited, since it is usually not supported by any remote switching network.

The robot used in the experiments is a SCARA-type AdeptOne-MV manipulator, which has four degrees of freedom (three rotational and one prismatic joint) and is also equipped with a pneumatic parallel-jaw gripper. The AdeptOne robot is programmed using the V+ robot programming language, which provides fast and real-time response with multitasking capabilities. From its kinematic structure, this type of robot manipulator is designed to perform planar motion profiles and is, therefore, particularly suitable for assembly operations, such as typical pick-and-place tasks.

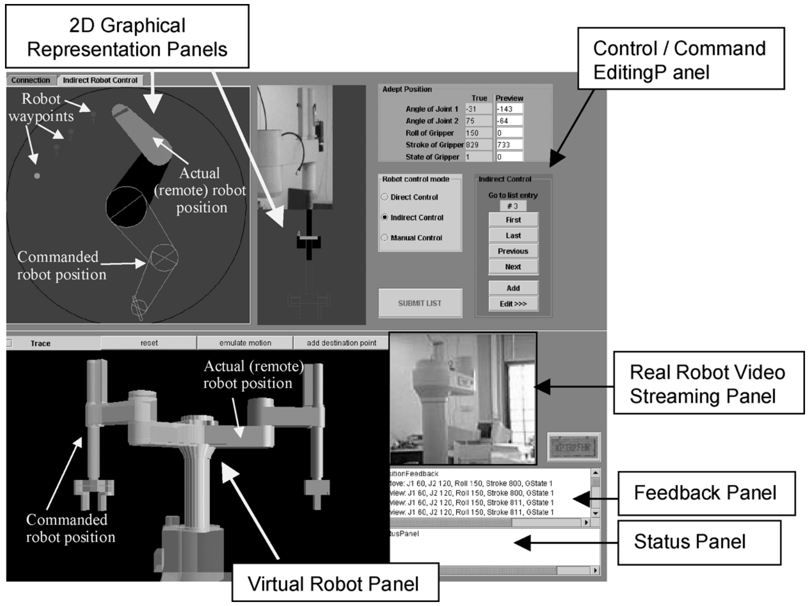

Fig. 3. Virtual robotic laboratory: The graphical user interface.

C. *Virtual Robot Laboratory: User Interface*

An enhanced version of the above telerobot interface has been implemented, also based on Java technologies, integrating additionally the following components (Fig. 3):

1) a control/command editing panel;
2) a virtual robot panel, implemented using Java3D, providing realistic 3-D graphics visualization of both the commanded (preview animation) and the current robot configuration;
3) a new implementation for the virtual pendant panel (manual control mode), based on a real high-resolution image of the robot's teach pendant (Fig. 4) to enhance the realism of the system's operation.

This e-laboratory platform is based on the same telerobotic client–server architecture, described above, supporting the following robot control modes: 1) direct teleoperation control; 2) indirect control, for robot teleprogramming via the command/editing panel; and 3) manual control, that is, robot manipulator programming using the Virtual Pendant functionalities. These control modes are inspired from the telerobotics field, particularly from work proposing various "shared-autonomy" and "supervisory" remote control modalities. In direct teleoperation, every command issued by the user locally (i.e., within the GUI master control site) is immediately transferred for execution to the remote (slave) robot. At the same time, two types of feedback displays can be active: 1) a predictive display (both in the 2-D and 3-D graphical panel) immediately visualizing the commanded robot motion according to the human operator issued commands and 2) a real robot feedback display (both in 2-D and 3-D animation), showing where the robot actually is (that is, visualizing the current remote robot configuration, in real-time through continuous feedback from the remote site).

As opposed to direct teleoperation, in the indirect "teleprogramming" control mode, the commands are generated offline, queued in a list, and submitted to the robot in a subsequent time frame selected by the human operator. The idea is offering the possibility to create a complete robot program offline and test its validity before actually sending the command sequences for execution by the real robot. The Virtual Pendant robot-programming scheme is based in fact on the functionality (robot command editing routines, waypoints list creation, etc.) of this teleprogramming mode.

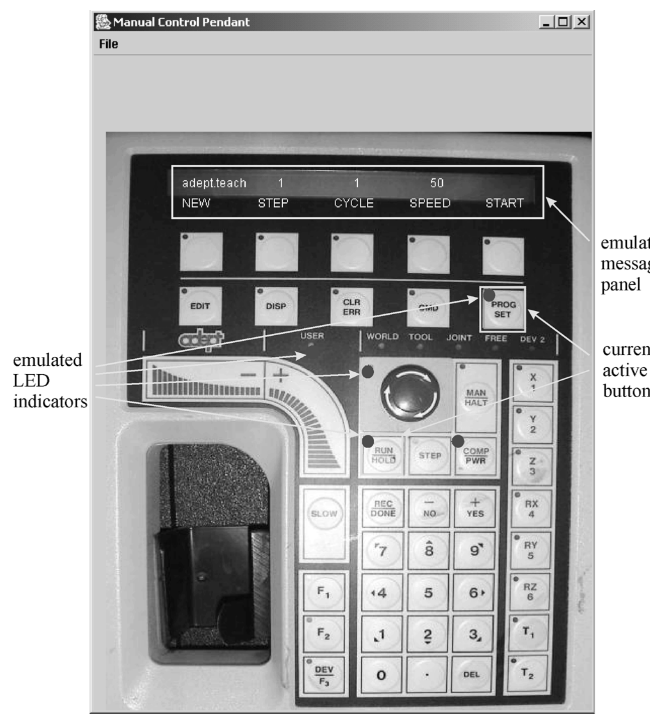

Fig. 4. An instance of the final virtual pendant implementation.

In the pilot study presented in the following section, the goal was to assess the relative performance of two "e-training" components: remote (group II) versus virtual (group III). For this reason, a reduced (local) version of the enhanced virtual laboratory platform, presented above in this paragraph, is used for experimental group III, in which case the system operates locally in simulation, incorporating the virtual robot and virtual pendant control modes, but having no liaison with a real remote robot manipulator (and no real visual feedback on the video streaming panel). In other words, the teleoperation/teleprogramming links are, in this case, emulated on a local server, and the system functions completely in simulation, with the animated virtual robot (2-D and 3-D panels) providing simulated visual information on the anticipated performance of the real robot. This system is referenced in the rest of the paper as the "virtual" version of the e-laboratory platform.

Therefore, the difference between experimental groups II and III, in this study, concerns basically the different mode of providing feedback from the execution of a program created by a user. In the first case (group II, remote) each time a user submits a robot program for execution, actual feedback is obtained from the real robot performing the commanded motion sequence in the form of visual (video streaming) and data feedback (animation of the simple 2-D top-view representation of the robot on the graphical user interface); however, in this case (group II), no virtual animation of the task being performed is provided (in the form of a realistic 3-D graphical model of the robot manipulator executing in simulation the program created by the user). On the contrary, when a user belonging to group III (virtual) "submits" a program, 3-D virtual animation feedback is provided to validate the robot program completely in simulation; of course, in this case (group III), no actual video or data feedback from a real robot is available. This process takes place each time a user creates a program and clicks the "SUBMIT" button for execution, that is, several times during each experimental training session. Getting feedback related to the execution of a program created by the user is a very important part in the training process since this feedback conveys information about correct and efficient robot programming, and about potential programming errors and/or misconceptions of the user/trainee. The difference in the training mode considered in this paper concerns the modality of conveying such information and interacting with the trainee in the absence of a real hands-on experimental setup.

III. Experiments: Methodology and Results

The objectives of the pilot study presented in this paper are: 1) to explore to which extent the considered e-laboratory modalities can be efficiently implemented in practice and used by students to obtain practical training as a supplement to a theoretical course module (in this case, an introductory course on robotic manipulation), and 2) to explore the relative importance of various e-learning elements, particularly virtual versus remote training modalities, in comparison with traditional hands-on experimentation. Of course, the context of this work is a continuous effort to contribute towards efficient engineering educational paradigms, which in this case-study would also suggest a more efficient exploitation of existing laboratory equipment by means of remote laboratory modules within a "lab-facilities sharing" network. The experimental protocol used and the results obtained are presented and discussed in this section.

A. Pilot Study and Assessment Methodology

To assess the objectives and goals that were set in this experiment, a strict methodological process was followed, based on a specially designed experimental evaluation protocol that was employed consistently throughout the experiments. According to this protocol, the students participating in the laboratory training course (that completes a theoretical introductory course on robot kinematics and control) were divided into three main groups. Group I (real) was trained the "traditional way" on the real robot, while experimental group II (remote) was trained on the first version of the remote laboratory platform (using the interface described in Section II-B). Experimental group III (virtual) was trained on the virtual robot laboratory, as described in Section II-C. Each group was subdivided into six teams of three to five students each (total number of teams 18). Each team of students was trained separately in different laboratory time slots (approximately 1 h 30 min per each). The total number of the sample of this pilot study was 60 (N) students. Both groups of students had the same training phases and were exposed to exactly the same educational material during each experimental session. The only difference among groups was the modality used to practice the robot programming procedures learned: 1) directly on the real robotic system (group I real, i.e., *physical presence* on the real-robot site), 2) using the remote laboratory platform (group II remote, i.e., *telepresence*), or 3) using the virtual robot interface (group III, *virtual presence*).

Each training session lasted approximately one hour and a half, with the tutor (always physically present) explaining all key issues to the students. Tutorial and educational support material was provided to the students describing: 1) the robot used in the experiment (its mechanical and kinematic characteristics, and its control and programming features) and 2) the exact procedure and steps needed to program a robot manipulation task using the pendant. By the end of each session, students of all three groups completed their training by performing a specific evaluation test on the real robot (test-3: final assessment test). During this final test, a robot programming task was assigned to the students (a pick-and-place operation using the real robot teach-pendant). This final assessment test was performed on the real robot for all three student groups (meaning that group II and group III students had to move from a remote location in a separate building to the real robot laboratory site to perform the final assessment tests). The test was subdivided into distinct time phases to facilitate tracking the performance of the students and identifying errors committed and/or difficulties encountered.

To help the trainer (examiner) assess students' performance during the final test, a specially designed *scoring chart* was used. It was organized into a sequence of: 1) rows, tracking the distinct time-phases, sub-tasks, and manual operations involved in the final assessment task and 2) columns, corresponding to the different categories of skills (respectively, errors) monitored by the trainer during the test. In line with the research objectives of this work, the errors committed by the trainees were classified according to three main categories: low-level technical skills, mid-level skills, and higher level understanding. The method used to grade students' performance consistently was to assign a pre-determined "penalty grade" for each specific error committed. Errors could, for instance, range from simply pressing the wrong button (or forgetting which button performs a specific function and referring to the manual, in which case a penalty grade of 2 points was added to the "low-level" category score) to higher level mistakes or misconceptions, expressed by an incapacity to create and implement a correct plan or sequence of actions for programming a robot subtask (5 points added to the "higher level" category; in case tutor intervention was asked, an extra 5 points were added to the score in the respective category). Moreover, teamwork and collaboration between students was qualitatively monitored, while total time needed to complete each phase of the test was also recorded. All these scoring items (indicating the frequency of the different types of mistakes) were coded in real-time on the scoring chart by the tutor monitoring the experiment, and were subsequently decoded to compute the final values for the different scores. For each final assessment test, a total score was computed giving a global measure of performance for the respective team of students, while individual categories scores give an idea of the type of difficulties encountered by the students, with respect to the three main dimensions used to model the dynamic process of training (often referred to as the *triad of training*). In the following section, some of the first results of the pilot study conducted are presented and analyzed.

B. Evaluation Results and Discussion

During the students' assessment process the tutor noted in the scoring chart the mistakes they made, according to the categories described above. This categorization constitutes a first qualitative approach to this experiment. Based on the scoring chart and the associated penalty grades, a quantitative analysis followed by means of specific statistical techniques; for this reason, SPSS 12.0 was used to obtain statistical analysis results.

More specifically, a t-test of independent groups was followed to find out whether statistically significant differences exist among the Means of the various test scores: (1) low, (2) mid/high (accumulated together), (3) time, and (4) total score, for the three groups (I, II, and III). Group is the independent variable, and score values are the dependent variables. The criterion that was set for the statistical significance was $p < 0.05$. In the following tables, the scores correspond to penalty grades, meaning that higher score values indicate worse performance of the student; scores correspond to absolute penalty grades since transforming the penalty scores into relevant percentiles was not considered necessary.

Table I shows means and standard deviations of the final assessment test scores for group I (real), group II (remote), and group III (virtual). The mean values of these scores for all three groups are also illustrated as a bar graph in Fig. 5. A review of means shows that some apparent differences exist among groups for the different score categories. In the "low" category (representing errors committed related to low level technical skills), group I (real) students made very few mistakes compared with students of group II (remote). By explanation, students forming the "real" group were trained the traditional way onsite, in physical contact with the real robot manipulator system, as opposed to group II students, who were trained remotely using the initial version of the graphical user interface and emulated manual pendant. Therefore, group I students exhibit a better "memorization" of low-level technical dexterities, and thus better performance in the manipulation of the robot's teach pendant. Such skills require a visual memorization of specific actions (e.g., button pressing, etc.), which was facilitated when the student training (i.e., the skill acquisition process) was performed while in direct visual contact with the real system. On the contrary, group II (remote) students had to rely, for their training, on the visual and "functional" quality of the virtual pendant (emulation) panel, which apparently influenced, to some extent, the skill acquisition process. However, this difference does not seem to persist for group III students, who used a more recent version of the virtual pendant panel, based on a high-resolution real image of the robot's controller.

As opposed to the above result, in the mid- and high-level category skills, the "real" group (group I) exhibited similar scores compared with the "remote" group (group II) (differences are much smaller, as can be seen in Table I). Furthermore, for this score category, group III results seem to be particularly superior, as compared with groups I and II. This result, though initially surprising, is quite interesting and could be partially explained by the apparently better concentration and motivation level shown by students who trained on a virtual environment

TABLE I
MEANS AND STANDARD DEVIATIONS OF THE FINAL ASSESSMENT TEST SCORES FOR THE THREE GROUPS (I: REAL; II: REMOTE; AND III: VIRTUAL)

	Low	Mid/High	Time	Total
Group-I mean	2.42	4.42	12.28	19.14
Group-I std	1.39	2.14	2.49	4.37
Group-II mean	4.60	4.80	15.60	25.0
Group-II std	2.88	3.03	3.78	9.43
Group-III mean	2.16	2.83	13.83	18.83
Group-III std	1.60	2.04	3.71	6.11

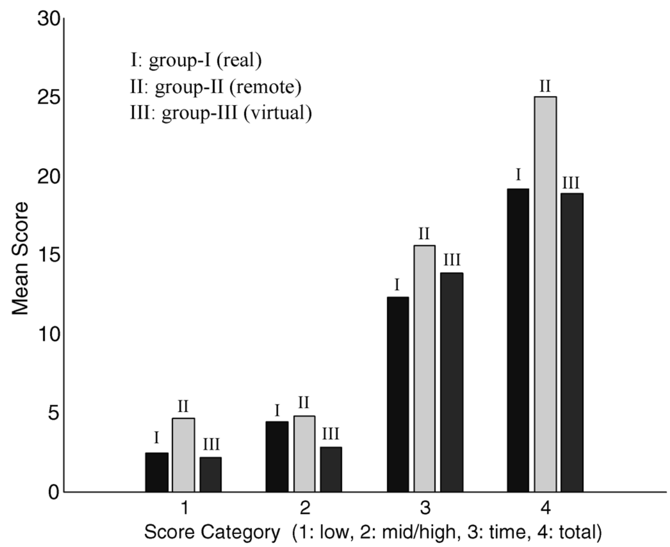

Fig. 5. Mean scores of the two groups in the final assessment test.

TABLE II
T-TEST RESULTS, COMPARING FINAL ASSESSMENT SCORES FOR THE THREE GROUPS (STATISTICAL SIGNIFICANCE, $p < 0.05$)

	Low	Mid/High	Time	Total
Groups I-II (p)	0.055	0.404	0.048	0.088
Groups I-III (p)	0.38	0.099	0.195	0.46
Groups II-III (p)	0.055	0.116	0.228	0.111

(as compared with students of the "real" group), which aided them to assimilate higher level concepts. However, these differences are not statistically significant because mid- and higher level skills are basically conveyed by the tutor (trainer), who was physically present for all student groups (no teletutoring or e-tutoring took place).

Indeed, according to the T-test results shown in Table II, no statistical significance was found $(p < 0.05)$ between the three groups for the "low," "mid/high," and "total" scores of the final assessment test. Therefore, all student teams from the three groups performed equally well in statistical terms, with no statistically significant deviations observed that can be attributed to the different training modality for each group. This result leads to the conclusion that an e-laboratory platform, comprising various remote and virtual control modules and learning elements, such as the ones developed and implemented in this pilot study, can be integrated effectively in the practical training of students.

Nevertheless, analyzing more in detail the differences observed among groups, one can add some comments to the above general conclusion.

1) The differences among the "low" score values for the three groups, particularly the observed performance degradation for the "remote" student group (group II), although not statistically significant ($p = 0.055$ in Table II, comparing both, group II to group I, and group II to group III) provides an idea about the training "dimension" that is most affected by the lack of physical presence and direct contact with the real experimental system, particularly observing that this performance degradation does not persist for the "mid/high" score values.
2) The score value that seems to be affected the most is time: group I (real) exhibits the best performance (mean value 12.28 (minutes)), while both groups II (remote) and III (virtual) show degradation in performance (mean values 15.60 and 13.83, respectively); however, only the difference between groups I and II is statistically significant $(p = 0.048)$.
3) Regarding the overall performance as reflected in the total score, groups I and III have practically identical results, while group II shows again a performance degradation, which is still not statistically significant $(p = 0.088)$.

An interesting conclusion can thus be drawn in relation to the comparative assessment between groups II and III, that is, remote/telepresence versus virtual presence, with an apparent benefit towards the latter, in terms of training performance. In other words, it seems that a realistic virtual environment, even with a complete absence of real (visual etc.) feedback, can provide adequate learning elements, particularly as related to mid- and high-level skills, compensating for the lack of direct physical presence on the real experimental site. This provision seems to be valid for the specific experimental scenario investigated in this pilot study (laboratory training course on robotic manipulation). However, a large-scale study is still needed to investigate these issues more profoundly.

Indeed, if more elaborated statistical analysis techniques are followed, such as one-way ANOVA or multiple comparisons tests (such as the Bonferroni test), no statistical significance is found among groups in all score categories (including also "low" score and total time values). Nevertheless, certain tendencies are clearly identified, as discussed above, indicating that larger sample studies are needed before more general conclusions can be drawn with certainty (though it seems that these findings do constitute useful indications about the relative performance of the considered training modalities). Such a larger scale study remains in the future work plans and can constitute the basis of a more theoretical evaluation to highlight the pedagogical differences between distinct real, virtual, and remote learning methods and experiences.

IV. CONCLUSION AND FUTURE WORK

This paper described the development and experimental evaluation of an *e-laboratory* platform in the field of robotics. The system in its current configuration is designed to enable distance training of students in real scenarios of robot manipulator programming. The goal is to offer students the opportunity to learn how to program a real robot without having one at proximity, in a way that closely resembles the real robot programming operations and procedures. From a technological perspective, this research work focuses on the adaptation of concepts and techniques developed in the field of telerobotics and virtual reality, and on exploring their integration in such remote laboratory settings. From a pedagogical perspective, the goal is to assess the performance of such e-laboratory systems, in terms of the *"quality" of training* provided to students. This assessment is performed comparatively for various training modalities to shed light on the pedagogical relations among different learning experiences, and on the relative importance of various "learning elements" integrated in the graphical user interface.

For this reason, a pilot experimental study was conducted comprising three student groups: group I (real) trained the traditional way on the real robot; group II (remote) trained using the remote laboratory platform, providing direct visual, teleoperation, and teleprogramming link with a real, remotely located, robot manipulator (but with a simplistic 2-D graphical user interface); and group III (virtual) trained on the virtual robotic laboratory interface, incorporating realistic, virtual (3-D graphical) animations of the robot and programming tasks (but with no visual and teleoperation link to a real remote robot). The evaluation methodology was based on the systematic application of an experimental protocol specially designed for the considered target training task, using scoring charts to obtain quantitative performance measures and assess the performance of the student groups participating in the laboratory-training course. Training is approached according to a typical 3-D model (i.e., building awareness, knowledge, and skills), and performance scores are accordingly assessed in these dimensions (namely, low-level skills versus mid and high-level skills and understanding).

Performing a statistical analysis of the obtained experimental results reveals that all student teams, from the three groups, performed well comparably (in statistical terms), with no statistically significant deviations observed that could be attributed to the different training modality of each group. Nevertheless, a closer look on the experimental results reveals some apparent differences, particularly for the "low" score (i.e., low-level skill training score). More specifically, a performance degradation is observed for the "remote" student group (group II), which, though not statistically significant, gives some clear insightful indication about the training "dimension" that seems to be mostly affected by the lack of physical presence (or realistic virtual presence). This finding is strengthened by this observed performance in which the degradation tendency does not persist for the "mid/high" score values. An interesting conclusion can also be drawn in relation to the comparative assessment between groups II (remote) and III (virtual), with the obtained results being particularly (and probably surprisingly) in favor of the "virtual" group. In other words, one finds that a realistic virtual environment, even with a complete absence of real (visual etc.) feedback from the considered experimental system, can provide adequate learning elements, particularly as related to mid and high-level skills, compensating for the lack of direct physical presence on the real experimental site. This finding seems to be valid for the specific experimental scenario investigated in this pilot study (laboratory training course on robotic manipulation). However, a large-scale study is still needed to investigate these issues more profoundly.

Based on these results, the main experimental conclusion can be summarized in the following statement: the proposed e-laboratory platform created a "virtual training environment" that provided adequate learning elements, as related particularly to mid and high-level skill transfer, compensating for the lack of direct physical presence on the real experimental site. The results presented in this paper provide conclusions about performance comparison between the different student groups participating in the specific pilot-study context for the different training dimensions analyzed above. These initial results do not lead to a general conclusion about what one should definitely expect in a completely different didactical context (since a larger scale sample and experimental procedure would be needed to draw such a conclusion, which remains one of the key future work priorities); however, these results can be helpful and insightful, indicating to which extent such remote and virtual laboratory modules could indeed be integrated quite effectively in practical scenarios.

Having explored, to some extent, important factors related to the efficacy of such virtual and remote laboratory systems from a didactical perspective, another key issue that needs to be emphasized in the future concerns their long-term deployment and the associated benefits that can result from such implementations (referring more to a "lab facilities sharing" context between academic and educational institutions, and not so much to other "flexible education" models). The aim in this direction is to explore ways for more efficient use of existing laboratory experimental infrastructure to the practical training of students through the implementation of remote laboratory scenarios. The benefits from providing the means to obtain remote access to experimental infrastructure existing in various dispersed laboratory facilities can become significant both from a socioeconomic point of view, as well as from an educational perspective. This significance is directly related to the quality and the equity of practical training possibilities offered to all students. In this context, a more thorough experimental evaluation study has to be conducted, regarding the feasibility of these goals and the acceptability of such new technologies by students in their education and training practice.

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