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Laboratory Tools for Robotics and Automation Education

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***Abstract*— This paper describes our efforts and plans to develop a Virtual Laboratory for the education in Robotics and Automation. These efforts are characterized by the need of blending R&A subjects into a traditional Computer Science curriculum, thus forcing a specific selection of development topics. In this context, the Robotics Laboratory must provide basic as well as advanced experiments, to address the needs of students at different education levels. In this paper, we present the development of three main applications, to support Control Systems and Robotics classes, as well as thesis and dissertation research. Of particular interest is the effort in the area of teleoperation, preliminary to the opening, next year, of a new curriculum on Medical Informatics, in which Computer Assisted Surgery will play an important role.**

I. Introduction and Past Work

Robotic education has traditionally relied on standard classroom lectures combined with laboratory experiments to make the students understand the principles and the practice of this discipline. However the availability of fast computer connections and of powerful Internet servers makes it now possible to think of a hybrid approach in which students experiment the theory in virtual environments before starting the laboratory experiments. This approach has several advantages, including safety, unlimited laboratory availability, better curriculum integration and increased flexibility. The disadvantage of this approach is that it is not supported by standard equipment and commercial products, and that each laboratory must invest a significant amount of time to implement a useful set-up. During setup however, students in the laboratory acquire a valuable expertise in a very important field, i.e. remote control of complex electromechanical systems. Furthermore, the development of a virtual laboratory for robotics education offers significant benefits to Universities that do not have a large variety of engineering courses and laboratories, since the same laboratory can provide experimental support to a range of topics and classes requiring different expertise and schedule. In particular, our laboratory is in the process of developing a series of virtual experiments, connected to real laboratory experiments, which cover a few aspects of basic control theory, robotic analysis and programming, software architecture, teleoperation, and robot motion planning.

The design and development of virtual laboratories and experiments is made possible by the availability of technologies for the remote command and control of Internet-based devices. The basic technology elements have been gradually developed in the past few years and only now they are being put together in a consistent, integrated form. In particular, Internet-based communication is the key to allow users to interact with the laboratory experiments and exchange textual, audio and video information. As proposed in [1], teleoperation systems would form the base of several applications such as health care [2], tele-medicine, collaborative design [3], entertainment and teleconferencing. However, basis theoretical issues prevent a direct use of some of the experiments, since the communication time delay of the system may introduce dangerous instabilities. In fact, this is also an important area of research to which students can contribute, implementing and experimenting with the algorithms proposed in [4], [5], [6], for the compensation of time delay.

The specific applications that interface robots and the Web are very recent. One of the earliest examples of generalized use of a robot via Internet is the Mercury project [7] and the PumaPaint project [8]. These project did not have educational goals and explored various forms of interactions of people with remote robots. They were characterized by a Web interface allowing a limited set of commands.

In [9], [10], [11], [12], [13], [14] various examples are proposed of interfaces to remote robotic arms or vehicles via Internet. These applications experiment with the execution of robotic tasks, such as pick-and-place, tourguide in museums and in general interaction with people. A web site for motion planning of nonholonomic vehicles motions is described in [15]. In [16] the development is described of a laboratory similar to the one described in this paper is presented. Recently, a workshop was conducted on the subject of Education in Robotics [17], addressing the different areas of teaching using robots, learning with mobile robots and developing suitable teaching curricula.

Another essential element for the development of remote robotics experiments is the availability of a skilled and dedicated workforce. In our Department we could count on the support of the recently established (July

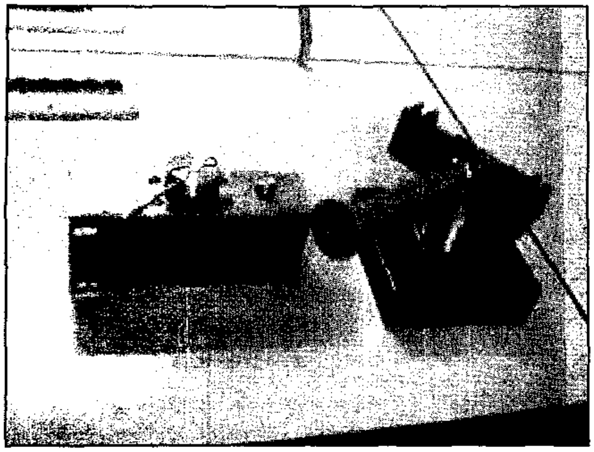

Fig. 1. Teleoperation bench

2001) IEEE Student Branch of Verona, that now counts about 30 student members. Further development will be to establish a Robotics Student Chapter, which will be the firs established in a Italian University. Although student members are interested in Vision, Electronics, and Information Theory more than 50% of members are also members of Robotics and Automation and Control System Societies, thus providing the necessary interest and motivation to support the development of remote laboratory experiments. During this year, for example, IEEE Student Members aided in the organization of a graduate course in robotics attended by many students coming from various member Countries of the European Community.

The efforts described in the paper take advantage of the available resources, both in terms of human power, equipment and technology, to build an infrastructure capable of offering remote laboratory experiments to University students. The paper is organized following the Automation and Robotics curriculum that the laboratory supports. In particular, Section II describes the experiments to introduce basic concepts of control system theory. Section III describes the development of graphical simulators for the learning of kinematic and dynamic aspects of robotics. Section IV describes the tools available for graduating students to experiment with advanced topics, such as software control architectures, operator interfaces, teleoperation systems and motion planning. Of course, many of the ideas described in the following Sections are still in the development phase and therefore Section V besides summarizing the paper presents our plans for future development and expansion of the virtual laboratory.

II. Control Theory Experiments

To share efficiently applications and instrumentation, all laboratory experiments share the common theme of robotics and teleoperation. However, since control systems understanding is essential, we decided to limit experiment complexity to their vary basic structure, so that hardware and software architectures would not confuse and distract the students. To achieve this result we are developing the single-axis force reflecting teleoperation system shown in Figure 1. This system is characterized by two parts, each with an independent motor, controlled by a single computer running Windows NT and a commercial servo board. The first part, called the master on the left side of Figure 1, is a motor with an encoder and an appendix on the shaft, used as handle of the teleoperation master. The second part, the slave of the teleoperation, consists of a three joint manipulator, whose first joint is shown on the right side of Figure 1. The research purpose of this set up is to compare the performance of teleoperation architectures in a minimalist environment, where the single axis system, and the very simple software do not shield the true characteristics of the architecture. The experiment is well instrumented and allows extensive data collection.

Because of the simple structure of this setup, it is possible without much effort to use the two parts as the basis of several Control System experiments. By controlling the motor of each part separately, one can use the same set up to demonstrate the performance of basic motion control algorithms. The handle of the Master can be used to simulate a a fixed load. A variable load can be simulated by changing the configuration of the second and third joints of the Slave part of the system, which can also be done while the first joint is moving, thus creating interesting identification and control experiments. The two motors are controlled through a Web interface, which is used by students to identify motor parameters and then design simple controllers for position and velocity tracking. Currently we are testing the first joint of the Slave, to find its dynamical parameters, before adding the remaining joints.

It is interesting to note that this simple setup, developed by students as a class project, has shown unexpected difficulties and challenges in terms of identifying the right motor control board, adapting the software drivers supplied by the manufacturers, identifying the motors, whose parameters are obviously unknown, and so forth. Thus, the educational aspects of the project lies not only in the experiments that are carried out with the system, but also in developing and maintaining a robust and efficient setup.

III. Robotics Experiments

Robotics can be taught in a single course or in a variety of courses, thus education has to be tailored to a specific curriculum, even though many important subjects can be left out. In our Department, only one course in robotics is available to the students, and therefore it was decided

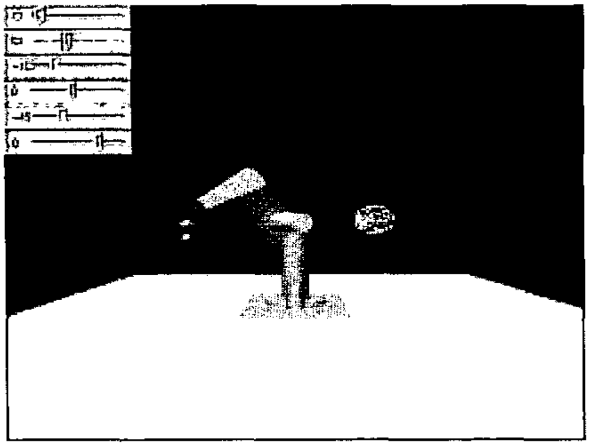

Fig. 2. Graphical simulation of the Puma robot

that the laboratory would cover only the main classical concepts, leaving the learning of more advanced topics to the preparation of the undergraduate, or graduate, thesis. We are fortunate that the laboratory is equipped with a variety of robots, acquired through loans, donations, and acquisitions. At the moment, course support is divided into two phases. The first, carried out in the computer laboratory, consists of developing algorithms to be tested on graphical simulations of a PUMA 560 manipulator and a Nomad200 mobile robot. Students have the opportunity to develop kinematic algorithms for the fixed robot and navigation and collision avoidance algorithms for the mobile robot. At a second time, working algorithms are tested on the real robots under very safe conditions. Figure 2 show the graphical interface used to test the algorithms for the fixed robot. The graphical interface can be connected to user-developed algorithms, both for direct and inverse kinematics, thus allowing the students to experiment with their own approach. Figure 3 shows the graphical interface used to develop and test motion planning algorithms. The environment is fixed, and represents a portion of the laboratory. Students can interface their algorithms to the graphical environment and test the quality of their code or of their implementation of known algorithms. Figure 3 shows an example of a program implementing the Tychonievich algorithm for trajectory planning in dynamic environments. At the moment only the first phase of the course support has been implemented. However, during the current year, class projects will be organized to extend this virtual approach and to let students become more familiar with the real equipment in the laboratory.

IV. Support for Thesis and Dissertation Research

Since robotics includes a significant experimental part, most thesis work is developed in the laboratory, by developing and testing new ideas within the scope of the research areas in the laboratory. Currently research is organized into three main areas: teleoperation, mobile robotics, and exploration robotics. These areas have emerged as those capable of attracting funds from various sponsors and therefore students learn very early on in their professional life, the fine art of balancing individual research interests with the hard deliverables of sponsored research. The main applications of teleoperation addressed in the laboratory refer to the needs of space exploration and surgical research. We have developed several algorithms for the compensation of time delay teleoperation under the sponsorship of the Italian Space Agency (ASI) in cooperation with the Robotics Laboratory of ENEA in Rome. However, the area in which we are investing the most, in terms of human and economic resources is the development of new procedures for Computer Assisted Surgery (CAS). Our laboratory is currently equipped with two joysticks capable of force reflection on all six axes, one of which is shown in Figure 4. These devices give Master and Doctoral students working in the laboratory a great opportunity, since force reflection is demanded by surgeons, and so far no commercial product is delivering it. Students are then in the position of cooperating with personnel of the nearby Medical School to evaluate the quality of their research with realistic experiments carried

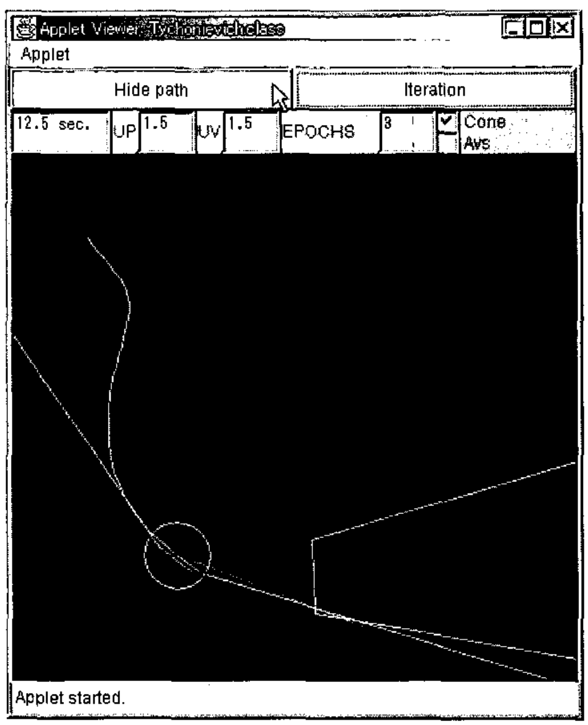

Fig. 3. Graphical simulation of motion planning algorithms

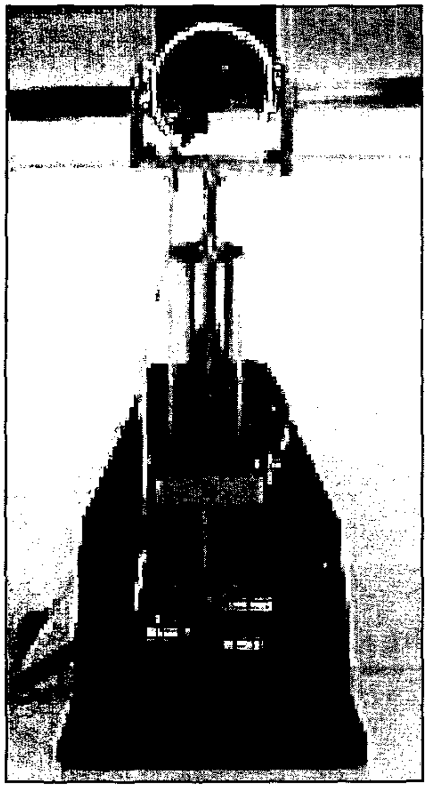

Fig. 4. One of the NASA-JPL force reflecting joysticks used in the laboratory.

out either in virtual environments, or with the fixed manipulator in the laboratory.

Mobile robotics research addresses problems related to service robotics and, in particular, to the development of mobile robots for the transportation of small objects. Automated logistics is an area receiving a lot of attention from the academic world as well as the industrial world, and we are addressing this emerging research area by equipping our Nomad200 mobile robot with a gripping device suitable for picking up and holding small parcels. At the moment, we are using the gripping device of the Nomad, shown in Figure 5. This area of research is extremely rich, since it includes the development of task as well as motion planning algorithms, the development of gripping devices for parcels of unknown size, material and weight (within the limits set by the project requirements), and of grapsing algorithms, to ensure that grasping is robust with respect to parcel position and orientation. A project currently under development addresses the problems of light logistics in the warehouse of a manufacturing company. One of the main challenges consists of developing a system that impacts as little as possible the existing plant. Students have been working with company personnel to identify the best type of automatic transport, i.e. the goods whose automatic transport would result in savings to the company, and thus justify the investment in the robotic transport system. If this project is successful, i.e. if tests will demonstrate the validity of the approach taken and that the operation selected can be successfully carried out by a robot, the Company is planning to extend this approach to several other plants and to introduce robots in other departments. The ultimate goal is to provide automatic monitoring and service to the production lines, achieving around-the-clock unassisted production and providing human workers with advanced robotic devices.

Finally, exploration robotics covers the broad area of design and algorithms for robots in extreme situations, such as Antarctica, space, and natural and man-made disasters. The main line of robot used in this research is represented by the family of hopping robots shown in Figure 6.

These devices, developed at NASA Jet Propulsion Laboratory in 1999 [18], are characterized by a pause between jumps to select the next hop direction and recharge the propulsion mechanism. They are a compromise between functionality and system's electromechanical complexity [19], [20]. The prototypes demonstrated that it's possible to develop a robot with mobility and sensing capabilities with only few actuators, provided that every operation is executed in a sequential manner. More precisely, the operational cycle of hopping robots is based on the orderly execution of self-righting, panning the camera to acquire images, recharge the thrusting mechanism in preparation

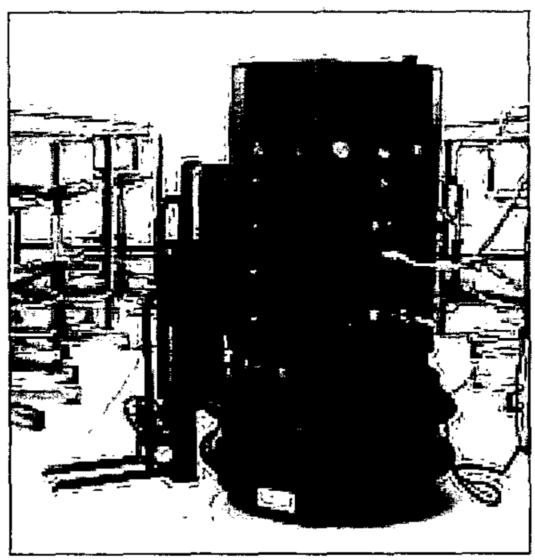

Fig. 5. The Nomad200 used for logistics development.

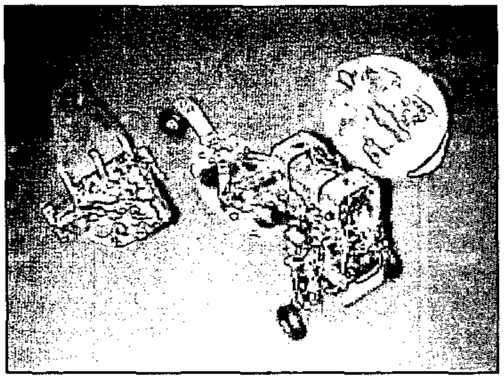

Fig. 6. Three generation of hopping robots

for the next jump, orient the robot in the desired direction, and execute the jump.

For these devices, students carrying out their Master thesis have analyzed and simulated a self-localization algorithm and a new stereo vision system, based on omnidirectional cameras. The objective of the localization algorithm is to be able to identify the landing position of a jumping robot, after landing, without the aid of sensors like radar and laser-scanner positioned on an external platform, and also without on-board vision, since

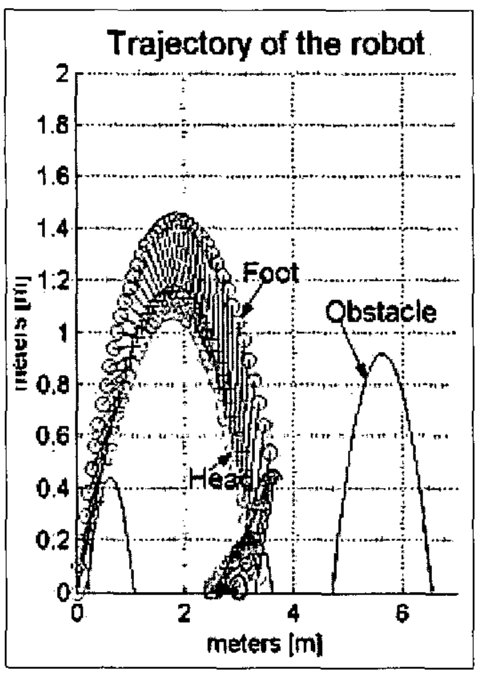

Fig. 7. Simulation of the hopper jump.

machine vision will be integrated at a later time. Currently, students have developed a simulation of robot flight and landing, assuming only the availability of accelerometers, a gyroscope and touch sensors, to detect the point of impact on the robot body. This keeps the sensor suite compatible with the robot characteristics and suitable for real hardware implementation. Since we are interested in outdoor localization and the proposed sensor suite lacks devices that can detect objects in the environment and extract features, we cannot use feature-based maps and triangulation techniques, commonly used in mobile robotics. Furthermore, the discontinuous locomotion modality of the robot prevents the use of simple, although inaccurate, odometric localization, typical of wheeled locomotion. Therefore, without visual references and odometry, the most immediate approach to localize the robot after a jump is an "a posteriori" reconstruction of its trajectory using data provided by the on board sensors before, during, and after the fly. Figure 7 show a simulation of a jump of the robot, used to estimate the landing position afer a jump. However, the estimation error in this probabilistic method can grow unbounded if it is not checked periodically. To overcome this problem, in a MAster's Thesis we have developed the geometrical analysis of a vision system that can be used in the development of a vision-based localization algorithm to reset the position estimate of the robot by using environment landmarks. The two methods combined will, eventually, provide a robust localization method for hopping robots characterized by discontinuous motion. The vision system for a hopping robot must take into consideration the specific nature of the robot motion, be robust to physical impacts, and provide enough information for precise navigation. For these reasons, we have selected a special type of omnidirectional vision system, the Panoramic Annular Lens (PAL), which has all the desired characteristics. Figure 8 shows the optical analysis of the stereo vision system proposed as the visual sensor for the hopping robots. We are hoping that in a near future this work could be continued under support of the European Space Agency (ESA).

Thus, also advanced reseach can be carried out using the set up in the laboratory, with satisfaction from the students who are able to produce innovative results.

V. Conclusions

The paper presents an overview of the experiments available in the robotics laboratory of the University of Verona (Italy) in support of robotics education. Since our University is not equipped with independent laboratories for all the disciplines contributing to robotics, this laboratory is used as a multipurpose facility, supporting education in basic Control System courses, Robotics courses, and the development of thesis for Master and Doctoral studies. By considering course support, the laboratory is

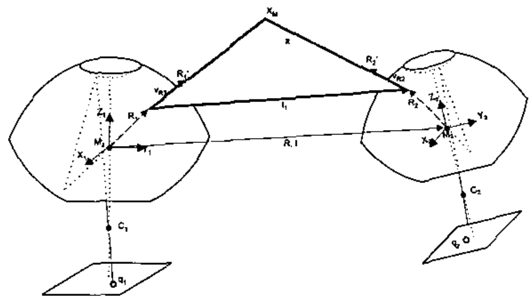

Fig. 8. The stereo omnidirectional vision system for hoppers.

clearly divided into three functional areas, control system experiments, robotics experiments, and research development. Since the research emphasis is on teleoperation, mobile robotics and exploration robotics, experiments are devised using elements of more complex setup. For example, control system experiments are carried out using a portion of a teleoperation system used also for quantitative analysis of teleoperation algorithms.

We think that in a few more months, we will be able to use the laboratory at its full potential, by completing some of the connections between the computer laboratory, whre students can develop applicaiton programs using graphical simulations, and the physical laboratory where the applications are tested on the real hardware. Safety is of paramount concern and therefore, before allowing the direct download of applicaitons to the robot servers and their unsupervised test by remote students, we must ensure that no safety requirements is violated.

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