Abstract
This paper presents results of an investigation into delivery methods of a laboratory course to distance education students. An advanced robot programming course at the master's level is delivered to highly qualified students all possessing technical degrees at the bachelor's level. The course contains a significant laboratory component where students program two industrial robots (A PUMA 560 and a Staubli RX90) each positioned to manipulate objects on a shared conveyor utilizing information from a variety of sensors. The authors developed a prototype system for conducting this laboratory remotely using the Elluminate learning suite and a configuration of off-the-shelf camera and audio equipment, then tested the system by completing one of the assigned laboratory exercises. This paper presents the details of the laboratory exercise and the system developed to conduct the laboratory remotely. The authors present the technical considerations encountered when developing the remote laboratory and their experiences in completing the laboratory exercise remotely. The paper concludes with an analysis of the project and a discussion of future plans.

Introduction
Although the concept of distance education is by no means new, the offering of laboratory courses has trailed the offering of regular didactic courses due to the presence of significant technical obstacles. As the network infrastructure became faster and more ubiquitous, many researchers [1][2][3][4] began implementing remote laboratories in some form. Among the first to be developed were system providing remote access to laboratory equipment controlling fixed experimental apparatus. As systems developed, laboratories began to include moving apparatus with mechanical uncertainties [5][6][7][8][9] requiring video feedback. Remote laboratory experiences continued to gain more sophistication, both in user interfaces and in the design of the laboratory activities to be performed remotely [10][11][12][13][14]. Remote laboratories have also been previously developed specifically in the area Robotics [15][16][10][17][18][19]. As these systems have been put into practice, some researchers have attempted to assess the effectiveness of these labs versus traditional laboratory experiences [20][21][22][23]. Assessing the effectiveness of the remote laboratory experience requires consideration of the objectives the laboratory experience is meant to accomplish. As have other authors, we reference the report “The Role of the Laboratory in Undergraduate Engineering Education” [24] containing thirteen “Fundamental Objectives of Engineering Instructional Laboratories”. We attempted to design the remote laboratory experience that is effective in achieving these objectives.

We are offering an advanced robot programming course in the European Masters in Robotics (EMARO) program at the Master's level to highly qualified and rigorously selected students all possessing technical degrees at the bachelor's level. The course therefore covers material beyond
recorded motions or pick-and-place operations that can be found in similarly named courses at the undergraduate or technical college level. Rather, the course explores the complex nature of real-time asynchronous computation interacting with slower mechanical hardware and in the presence of significant mechanical uncertainties. For this reason we believe no accessible simulator system can encapsulate the variety and uncertainty of the mechanical and computational events that enrich the laboratory experience.

The laboratory component consists of programming two 6 degree of freedom industrial robots and a conveyor belt to cooperate on a task using a variety of external sensors, light, ultrasound, switches, encoder, etc., (See Figure 2). EMARO students are required to complete 24 hours of laboratory exercise as part of the course. The first 12 hours are dedicated to increasingly complex exercises intended to build skills necessary for the project. Only the simplest of these resemble undergraduate laboratory exercises using recorded motion playback, and the students move through these quickly. The latter exercises involve interrupt processing, priority-based scheduling and data management. The task is sufficiently complex that the robots may not be programmed to operate independently, as each has access to information that the other requires.

Motivation

The EMARO program is conceptualized as a true international program and actualized as three sites in three EU countries offering interchangeable courses to a geographically fluid student body. Although the program works admirably for traditional didactic courses where itinerant faculty deliver lectures in classrooms, there are greater challenges for laboratory courses. Because the laboratory cannot travel, either the students must; or there must be identical or at least substantially similar robotic hardware at all three sites. There is therefore practical motivation to pursue the option of completing the laboratory component remotely. We are also developing this project towards the potential of offering this this
course to a broader population than the EMARO program.

**Methodology**

We developed the experience in reference to the following *Fundamental Objectives of Engineering Instructional Laboratories* [24]. In the following section we describe to what degree the remote laboratory accomplishes the objective.

All objectives start with the following: “By completing the laboratories in the engineering undergraduate curriculum, you will be able to….”

- **Objective 1:** Instrumentation. Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.

Students use ultrasound sensors and optical encoders to measure sizes and locations of objects in order to successfully grasp objects with a robot manipulator.

- **Objective 2:** Models. Identify the strengths and limitations of theoretical models as predictors of real-world behaviors. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.

Students develop mathematical models of the robot manipulator in a prerequisite course. Students experience the degree to which these models reflect actual robot motion.

- **Objective 3:** Experiment. Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.

Students are provided little a priori information on the sensors and operation of the robot end effectors. Student must therefore device their own experimental procedures to gain the requisite understanding of these subsystems.

- **Objective 5:** Design. Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.

This objective is directly accomplished by this laboratory. Students must design and build a system using specific methodologies to meet client requirements.

- **Objective 6:** Learn from Failure. Identify unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions.

This objective is directly accomplished by this laboratory. Student designs rarely work on their initial attempt and students must learn from failure.

- **Objective 7:** Creativity. Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving.

The problem is real-world and open-ended. Students are free to develop any solution and each group develops a unique approach.

- **Objective 10:** Communication. Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.
Students deliver multiple forms of written reports.

- **Objective 11: Teamwork.** Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.

Students work in teams of two for all assignments and must deliver a work allocation plan prior to completing the assignment,

- **Objective 13: Sensory Awareness.** Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

Students use their own senses of vision and hearing to diagnose problems and determine success.

Appendix A contains objectives are not accomplished by this laboratory experience either due to the intrinsic nature of the laboratory or due to the remote location of the students. For example, although the laboratory in local form presents significant safety issues to the students, remote students are isolated from these issues.

From the analysis above, we see that the majority of *Fundamental Objectives of Engineering Instructional Laboratories* are accomplished by the laboratory in remote form, and we conclude that the concept is worth pursuing. The significant issue to be resolved is to what degree the remote laboratory experiences matches our expectations.

**Implementation**

The authors have developed and tested a proof-of-concept system assembled from off-the-shelf and inexpensive components. For application sharing and video communication we used the *Elluminate* learning suite. This learning suite is a commercial distance education system providing course management and communication tools. We utilized a free service of *Elluminate* named “learn central”, which offers a full-function version of the *Elluminate* system but limited to a maximum of three participants. The two functions we used most actively are the ability to broadcast the live image of a webcam and the ability to share applications. *Elluminate* also provides whiteboard, live audio and text exchange and powerpoint slide display, but we did not use these features.

In the advanced robotics course, students write robot control programs in the VAL or V+ robot control languages. The older VAL language is necessary for the PUMA robot while the more full-featured V+ language controls the Staubli RX90 robot. Students write text programs in these languages using the Jedit source code editor. Students use a command-line terminal to the robot controllers to debug and execute their programs and to directly control the robots. We use the MS Windows Hyperterm program for this purpose, but any terminal program could be used. Using the Elliminate system, we share the Jedit and HyperTerminal applications with the remote users. The remote user therefore interacts with the robots as if he or she were sitting in the lab. Students type commands, the controller responds, displays information and in some cases moves the robot in response to commands.

Figure 3 below shows the computer monitor as seen by the remote user. The remote user directly controls the jEdit and HyperTerminal windows. (The “.”’s in the HyperTerminal window are prompts from the robot controller inviting the user to type commands.) The jEdit window contains the user’s program, an ASCII text program of robot commands and programming structures. Students use the Hyperterminal to upload their program to the robot and then execute their program using the command line prompt.

Students view the resulting motions produced by their program using the two video windows shown in
Figure 3. These images are produced by off-the-shelf Logitech USB webcams. Because these are midrange price USB cameras, the images are relatively clear and arrive with sufficient update rate to allow clear viewing of the moving robots. The images also show the conveyor system and the some of the objects (cans) manipulated by the robots as these travel on the conveyor. The two camera images shown allow remote users to diagnose logical programming errors and obtain qualitative feedback from the execution of their program. For example, students can see that the robot was or was not in the correct position to capture the moving can. However, fine or rapid motions, for example the robot captures and immediately drops the can, would not be readily visible by the remote user.

The local laboratory presents significant safety risk to the student, to the degree that safety barriers (visible in Figure 1) are necessary to protect the students. There is no credible safety risk to the remote students, however, there is a genuine risk to the safety of the laboratory equipment. Other researchers [16] have shown that is possible to create a remote laboratory that contains all the relevant programming challenges while presenting no risk to the robot itself. Our preexisting laboratory does not afford this possibility: the robots may damage themselves, the conveyor and the environment while executing syntactically correct student programs. Our system therefore requires a local human operator to be present and near the emergency stop switch at all times. We envision the local human operator as more of an instructor than a safety monitor, and we will refer to the person performing this function as the “local instructor”. The local instructor will control access to the robot and monitor student actions both on the computer monitor and through constant audio contact. To allow unhindered motion of the local instructor we employ an off-the-shelf wireless headset. (Although Elluminate provides real-time audio exchange we found we had slightly better results using Skype for audio.) The local instructor informs the remote students that the robots are ready for a test, places objects on the conveyor and sends asynchronous signals to the robots through an instructor control panel. The local instructor also has complete view of student programs and can offer advice and assistance to students as they debug and test their programs. The local instructor can also provide qualitative feedback that may not be perceivable from the camera views, for example, “the robot knocked the object over while attempting to grab it”.
Experimental Trial

As a culminating exercise, the master’s level students must program both robots to perform a cooperative task. Big and small cans arrive on a conveyor at random intervals and in random order and the downstream PUMA robot must grasp each can by the top using a pneumatic vacuum gripper and sort small cans from large. The laboratory exercise is cleverly designed to require communication and coordination between the robots. The upstream RX90 robot has a conveyor belt encoder allowing it to track (hover above) the leading edge of the cans but it cannot measure their lateral position. The PUMA robot can measure lateral position using an ultrasound sensor but only if the sensor is triggered when the can is in front of the sensor. The PUMA has no sensor to determine this and so must rely on communication from the RX90. Two digital signal lines in each direction (see Figure 2) are provided for communication. Students, working in groups of two, must devise their own strategy and program each robot to accomplish this cooperative robot task; an exercise typically requiring 12 hours to design/program/debug.

The second author was a visiting scholar in the EMARO program possessing considerable expertise in robotics but no prior knowledge of this laboratory exercise. To test the remote laboratory delivery prototype the second author completed a portion of the laboratory exercise remotely as the first author acted as the local instructor. We conducted four, two hour experiments; two with the second author acting as remote student and two sessions with the roles reversed. In the latter case it was necessary to introduce challenges because the first author was the designer of the laboratory exercise and has encyclopedic knowledge of the workings of the laboratory equipment. In this case we presented the remote student (really the course instructor) unfinished and unfamiliar programs requiring debugging to simulate a level of confusion that would be present in a student.
Experimental Results

We found the system to be operational; meaning the remote student was able to write and modify programs and execute these on the robot. We found the video images were informative and sufficient to view the execution of the robot. We were able to continue the programming assignment making changes to the programs and testing these immediately on the robot. However, in the eight total hours we spent testing we did not complete the programming assignment.

Although basic functionality was established, the experiment also brought to light significant limitations and perhaps raised more questions than it answered. Below are a list of experimental observations for further consideration.

1. The process seemed to take about twice as long as the local laboratory. In each case we finished our two-hour experimental session feeling we accomplished what would normally require one hour. It is fair to say that if the authors had spent the eight hours locally in the lab they would have completed and tested the entire laboratory exercise.

2. We attribute the delays to two causes: the mechanics of remote operation and the introduction of addition protocol between the local and remote users for executing programs. The act of viewing, scrolling, saving and loading is measurably slower due to the remote connection and awkwardness of switching between windows. The remote student declares he is ready to test and the local instructor then activates power and awaits instructions. The remote student executes the program at the monitor and then issues instructions to the local instructor, for example “push the button, introduce a can, etc.”. This process takes much longer than the student simply performing these steps in person.

3. We observed that the video images were sufficient to obtain the predominantly qualitative feedback we needed to debug programs. The following list of examples demonstrates the nature of feedback we required to debug our programs:
   
   a. “The robot tracked the object for a little while then stopped.”
   b. “The program crashed when the first can crossed the broken-beam detector”
   c. “The operator pressed the interrupt button while the robot was tracking but nothing happened”

4. The remote student has nothing equivalent to a teach pendant, and this prevents the students from completing a small but important portion of the laboratory exercise. Even if the remote student had a teach pendant, the video image is not close enough for precise positioning. A remote teach pendant would also require careful consideration of camera location.

5. The free version of Elluminate was sufficient for our purposes but some aspects of moving windows in front of windows were awkward. A full version of Elluminate could potentially solve these problems.

6. The local instructor was in complete control and has the option of assisting the remote student at any time. If not actively tutoring the remote student, the local instructor is idle for significant periods and could therefore potentially coordinate several groups working in tandem.

7. The local instructor is greatly aided by a wireless headset.

8. Real time audio communication between the parties is very helpful, perhaps essential, for program testing. When the remote student is able to say: “push the button now.”; “introduce a can now”; and “When exactly did it stop?” the student can gain all the information he or she needs to debug robot programs.
9. An automatic power-off would enhance safety, but we observed no safety risk to the robot equipment. When the remote student declared the program ready to run, the local instructor manned the safety switch for the duration of the experiment, at most a few minutes.

10. We observed that Skype audio was significantly clearer than the built-in Elluminate audio and we used this, simply by opening a separate Skype channel.

Conclusions

Our review of the literature suggests that we are attempting a remote laboratory experience that is of much greater complexity than previously attempted. However, our motivation is unique as we are not seeking to economize instructor time nor provide ubiquitous access. Rather, we are attempting to offer a specific course to a specific set of non-collocated students. The issues are nonetheless similar, can we provide a remote experience rich enough to meet the objectives of a laboratory?

Our preliminary investigation suggests we can. The remote laboratory requires students to contend with real-world problems due to mechanical uncertainty, interrupt-driven asynchronous processing and sensor noise. We found that the remote laboratory proceeds slower than the local laboratory for the reasons cited. We found that high quality or closely focused video images were rarely required due to the qualitative nature of the information needed by the remote student. We found that the Elluminate learning suite had most of the tools necessary to conduct the course remotely and we are grateful they to offer a free version of their commercial software to allow this form of testing. The authors are installing higher quality PTZ cameras in the laboratory. These cameras will provide greater flexibility and increased field of view and will reduce setup time, but we do not expect these will fundamentally change the qualitative nature of the video feedback.

Although it is natural to first experiment on ourselves, the authors recognize that their own expertise in robotics makes them hardly representative of typical students. The next step will be to test this system on volunteer EMARO students taking the Robot Programming course in Spring 2011. The unanswered question is whether students without extensive prior knowledge of the laboratory can understand the video with sufficient clarity to diagnose errors in their programs.

Bibliography

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8: A. Balestrino, A. Bicchi, A. Caiti, V. Calabrò, T. Cecchini, A. Coppelli, L. Pallottino and G. Tonietti; From
Laboratory learning objectives not achieved by the remote laboratory.

**Objective 4: Data Analysis.** Demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions. Make order of magnitude judgments and use measurement unit systems and conversions.

**Objective 8: Psychomotor.** Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources.
Objective 9: Safety. Identify health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.

Objective 12: Ethics in the Laboratory. Behave with highest ethical standards, including reporting information objectively and interacting with integrity.