TECHNICAL RESEARCH REPORT

Robotics for High School Students in a University Environment

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Abstract

The Young Scholars Program at the Institute for Systems Research of the University of Maryland at College Park is an innovative summer research experience for high school students from Maryland, Virginia, and Washington D.C. Its goal is to steer talented high school seniors toward higher education and careers in science and engineering. One particularly popular component of this program is a two-week mini-course in robotics. This course utilizes the resources of the Intelligent Servosystems Laboratory of the university to introduce and demonstrate theoretical and practical aspects of robotics. This paper reports on the characteristics that make this a unique effort in robotics-related education for both the Young Scholars Program participants and the small group of University of Maryland graduate students who have been responsible for the development and instruction of this course.

1 Introduction

The Young Scholars Program (YSP) is an innovative summer research experience for talented high school students from Maryland, Virginia, and Washington, D.C. The program is organized each summer by the Institute for Systems Research (ISR) at the University of Maryland at College Park (UMCP), an interdisciplinary Engineering Research Center of the National Science Foundation (NSF). Approximately twenty pre-twelfth grade students have attended this six week program each summer since its initiation in 1991. The goals of the YSP are to make the participants aware of and excited about the role of engineers in confronting technological challenges, to introduce them to the set of tools available for solving those problems, and to steer them towards an education and career in engineering or science.

A two week mini–course in robotics is a particularly popular component of this program. During each of the summers of 1991 and 1993–1995, two groups, comprising five or six students each, have participated in this course developed especially for the YSP. The course, developed and taught by University of Maryland graduate students, takes place in the Intelligent Servosystems Laboratory (ISL) of the ISR. It consists of lectures which present the basic notions and problems of the field, and of experimental projects which explore selected issues in more depth and familiarize the students with the experimental and computational tools used to attack these problems.

Robotics is, by its very nature, an interdisciplinary field. A typical introductory course in robotics usually appears at an advanced stage of an undergraduate curriculum and relies heavily on skills developed in earlier courses such as physics, mechanics, calculus, differential equations, linear algebra, circuit theory, control systems, and computer programming. The participants in the YSP, while very intelligent and highly motivated, do not have such skills at their disposal. This fact, together with the limited length of the YSP course, forces the instructors to structure it in a manner radically different from traditional robotics courses.

The designers of this course aspire to present as complete a picture of the field of robotics as possible, without using the powerful mathematical tools generally associated with the subject, while maintaining the interest of the students. In the "taste of engineering" spirit of the YSP (as opposed to a rigorous study of it), a solution to this problem was found by presenting the students with a conceptual view of the subject combined with the "just-in-time" paradigm of learning. Over several years, the YSP robotics course has evolved in order to reach these objectives. Details regarding the course development are presented in Section 3.

The course content and structure, including details regarding the various topics and experiments, is discussed in Section 4. We present some of the basic tools that were used, such as the ISL's General Electric GP-110 industrial manipulator, ISL's three–fingered Modular Dextrous Hand (MDH) [1], and ISL's tools for rapid controller design, which are centered around Integrated Systems Inc.'s AC-100 system. We show, for example, how the students were able to build and test a full proportional-integral-derivative (PID) controller for the MDH fingers without having to machine fixtures, build sensor and computer interfaces, or deal with any of the many other technical aspects of motor control which might cloud the presentation of the main ideas of open–loop and closed–loop control. Other research projects include building sensor–based legged and wheeled robots, programming microcontrollers, collecting and processing tactile information, and using lasers and photodetectors to estimate position. Among the topics introduced are robot structure, kinematics and dynamics, sensor and actuator technology, circuit theory and electronics, computer programming, and path planning.

One way to measure the results of this course is by examining its impact on the students and the instructors. Additional evidence of the success of the YSP can be found by examining the paths that the Young Scholars have chosen since completion of the program. These indicators have been exceptionally encouraging and have motivated the continuous evolution and improvement of this course. The results are presented in Section 5.

2 Background

This section provides some background information including a brief overview of the YSP, a description of the ISL which served as the forum for the robotics mini–course, and some particulars about the instructors who designed and taught the course.

2.1 The Young Scholars Program

The NSF established the Young Scholars Program to assist high school students in reaching an informed decision about a potential career in science and engineering, and selected the ISR at UMCP as a site for the program. The program attempts to reach academically talented Maryland, Virginia, and Washington, D.C. high school students interested in exploring higher educational opportunities and careers in science and engineering. Talented pre-twelfth grade students spend six summer weeks involved in a mixture of coursework, group projects in laboratories, seminars, and field activities.

The YSP participants are chosen based on their academic achievements and potential, their motivation to participate in the program, and the impact that their participation might have in determining their future plans. A special effort is made by the organizers to solicit applications from women and minority students.

The program includes a freshman design class (ENES 100 "Introduction to Engineering Design"), daily work at ISR's research laboratories in the areas of robotics (at the ISR's Intelligent Servosystems Laboratory), speech processing (at ISR's Neural Systems Laboratory), CAD/CAM technology (at ISR's Advanced Design and Manufacturing Laboratory), alternative energy vehicles (at UMCP's Society of Automotive Engineers Laboratory), and Internet tools (at ISR's Open Workstation Laboratory).

[1] Modular Dextrous Hand, J.Loncaric and F. de Comarmond, October 1, 1991, US Patent No. 5052736.

2.2 The Intelligent Servosystems Laboratory

The Intelligent Servosystems Laboratory (ISL) [2] is one of the constituent laboratories of the ISR; its primary goal is to advance the state–of–the–art in the design and real–time control of sophisticated servosystems. The introduction of intelligent control systems in a variety of critical applications ranging from space exploration to underwater manufacturing and from surgery to nuclear plant maintenance is an emerging technological challenge which has spurred a significant research effort. The attempt is to produce controllers that will guide mechanical systems under sensory feedback to accomplish desired tasks in the presence of environmental constraints and uncertainties. This may involve some human guidance (as in telerobotic systems); otherwise, it must be ensured that the robotic system possesses sufficient "intelligence" in order to adapt to new environmental or working conditions.

The interdisciplinary area of robotics encompasses developments in mechanical, electrical, computer and sensor systems, control systems theory, artificial intelligence, and neurophysiology. Research goals include the design of novel mechanisms with varying degrees of autonomy. These mechanisms not only assist humans in hazardous, boring, or precise tasks, but also provide platforms for testing our theories on man and his development. The research interests of the ISL faculty and students span most of these areas and focus on the theoretical study and the experimental evaluation of control systems and the proper use of sensory feedback (visual, tactile, proprioceptive) for planning of robot motion. Prototypes of walking robots, telerobots for use in space, lightweight flexible space structures with distributed sensors and actuators, computer–controlled dextrous hands, and snake–like locomotors are being built. Computer simulations on the ISL's network of diverse computing systems including SUN SPARCstations, Hewlett–Packard and Silicon Graphics workstations, as well as IBM and Apple personal computers are used extensively to test new ideas.

2.3 Course Instructors

Each summer, one or two graduate students are selected to be the course instructor(s) for the YSP robotics mini–course. These graduate students work in the ISL as graduate research assistants performing research and developing expertise in robotics–related areas such as control and sensor systems, computer vision, motion planning and control, dextrous hands, and smart structures and materials.

3 Course Development

In the development of this course, the instructors set out to present the students with a clear picture of the field of robotics without overwhelming or boring them. Ideally, one would like to present the contents of a traditional undergraduate robotics course. This goal is not possible for several reasons, forcing the instructors to take a more innovative approach to developing the course.

3.1 Difficulties Involved in Teaching Robotics to High School Students

In designing the curriculum for the YSP robotics course, the instructors faced several major challenges. In order to achieve its goals, the course needed to be tailored to the educational background of advanced high school juniors, provide proper motivation in a situation with few tangible incentives, and overcome severe time constraints.

Typically, an introductory course in robotics occurs late in the undergraduate curriculum and relies heavily on material gained in earlier courses in mathematics, physics, engineering and computer science. The subjects presented almost always include mechanics and control systems, and often include subjects such as path planning, computer vision, development of dextrous hands, and real time implementation issues.

[2] More information is available via WWW at URL: http://www.isr.umd.edu/Labs/ISL/isl.html.

In the area of mechanics, students typically study kinematics and dynamics of serial and parallel manipulators. A portion of this material requires no more than high school trigonometry and algebra, while other material requires some facility with calculus (e.g. kinematics of velocity), and some material requires knowledge of differential equations and physical concepts such as torque, moment of inertia, and Newton's Laws (e.g. dynamics). Similarly, the subject of control systems for robotics contains a variety of topics with differing levels of prerequisite knowledge. For example, sensors and actuators can be studied with minimal background information. On the other hand, classical control theory relies heavily on the theory of ordinary differential equations. Controller implementation may require knowledge of computer interfacing, programming, and analog circuit design.

The YSP students are among the best students in their high school classes, bright and very hard working, but still they lack the math, science, and computer skills necessary for a traditional robotics course. In mathematics, the students typically have had one year of algebra and trigonometry, one year of Euclidean geometry, and one year of pre-calculus. The lack of any calculus or differential equations precludes any discussion about the topic of dynamical systems, which is a major aspect of a traditional robotics course. Similar problems arise in the field of science. The students have generally had one year of physics which, obviously, is not calculus based. Concepts such as Newton's Law and Ohm's Law are familiar to the students, though not well understood. The students have widely varying backgrounds in the field of computer science. Most of them have some experience using computers. Some of them have done some programming in BASIC; a few even have experience programming in C. None of them have experience using UNIX. This is unfortunate because most of the computer systems in the ISL run on UNIX. This wide spectrum of experience presents an additional challenge: the instructor must be able to present the necessary information without boring the advanced students or confusing the less experienced students.

Motivating the YSP students in an enviroment with few if any tangible incentives presents another challenge. The course is not graded. The participants are teenage high school students on their summer vacation. About half of them are not even sure that they want to go into engineering. For these reasons, it is important to keep the class interesting and fun as well as informative.

A major difficulty for the course instructors is the limited time alloted for the Young Scholars Program. The instructor is with the students three hours per day, four days per week, for two weeks. This is significantly less than the time provided in a typical fifteen week college course. Hence, topics must be selected carefully and the instructor must make the most of every minute in the classroom.

3.2 Approach to Overcoming the Difficulties

The aforementioned difficulties provide a formidable challenge to achieving the goal of teaching a complete and interesting course in robotics to the participants of the Young Scholars Program. The following is a description of the authors' solution to these problems.

First, the "just-in-time" method of teaching was employed. In this paradigm, the students are presented with the material as it is needed to perform tasks and experiments. Also, the material was presented in a highly conceptual manner. A high school student may not understand all of the theory behind a PID controller, but with a careful presentation the concept and its implications can be made clear.

The careful selection of topics and experiments was the second aspect of the solution. Here, the instructors chose topics which would challenge the students without going beyond their abilities. More importantly, the experiments were carefully chosen to reinforce the presented material in an interesting way without allowing unrelated technical details to distract the students from the subject at hand. This was accomplished using existing experimental set–ups in the ISL.

A simple example of this method is the subject of motor control. In just one lecture, the students are introduced to the concepts of motor control. Then they immediately proceed to an existing ISL test bed. This test bed allows them to implement and experiment with a controller without having to worry about interfacing the motor with the computer, building analog circuits, or other details which would almost certainly distract the students' attention from controlling the motor. As a result, the material presented in the lecture is strengthened by the laboratory experiment.

Using “just-in-time” learning with carefully chosen laboratory experiments in this manner, the instructors were able to overcome many of the difficulties outlined in the previous sections. The next section contains a list of the specific subjects covered and their corresponding experiments.

4 Course Contents

This section provides details regarding the contents and structure of the robotics mini-course. Since the course evolved over a period of several years, we include examples from each of the summers that the course was taught. However, the presentation is not chronological; rather it is structured by course topic.

4.1 Introduction to Robotics

One important concern for the instructors in the Young Scholars robotics course is that for high school students, ideas and perceptions about robots and robotic manipulation have likely been influenced more by the images portrayed in futuristic science fiction films, television shows, and books than by news reports and articles that provide a more realistic view of what is currently happening in the field of robotics. For example, when students in the course were asked to define the word “robot”, and to provide examples of robots that they were familiar with, the responses invariably focused on “machines that act in a human way” and “machines that perform human tasks”. Fictional characters such as the “Terminator”, Star Trek’s “android” character “Data”, and Star Wars’ “R2D2” and “C3PO” were often cited examples.

Thus, the first goal of the course is to open the students minds to a more comprehensive, interesting, and realistic view of robotics. By providing a variety of examples, some familiar and some unfamiliar to the typical student, the instructor can force them to think about what might (or might not) be considered a robot, and more importantly about potential applications, problems, and challenges.

4.1.1 Lecture

The instructor begins the introductory session by initiating a discussion of the question, “*what is a robot?*” After each student is given the opportunity to present his/her ideas, the instructor encourages the students to analyze each other’s statements, to point out where each might be taking too narrow a view, and to formulate more interesting or even unconventional examples. In the authors’ experience, this opening discussion not only generates interesting ideas and gets the students thinking about important issues, but also engages the small group in a lively discussion thus immediately fostering the student participation which is very important in the course.

To complement the opening discussion, the instructor then presents a variety of examples of robots and robotic manipulators from industry and academia. Some examples used by the authors include the JPL-Stanford 6-DOF arm, the Stewart platform, mobile robots such as the Supplemental Camera And Maneuvering Platform (SCAMP) of the University of Maryland Space Systems Laboratory, X-Y color plotters, and the University of Maryland Walking Robot. For each example, the important parts and related concepts are introduced. Students learn by example what is meant by the terms end-effector, rotary joint, prismatic joint, link, base, sensor, actuator, rotary motion, and linear motion. However, there is no immediate attempt to introduce details or specifics regarding these general concepts. For example, in this first session, it suffices to point out encoders and motors on the example robots and identify them as sensors and actuators without delving into the details of their operation.

One concept of particular emphasis is the idea of degrees of freedom (DOF). This crucial idea is introduced carefully since most of the students have never thought deeply about mechanics, constraints on motion, or how one gets an object from one place to another in light of given constraints. The instructor begins by presenting simple one-link (one-DOF) rotary and prismatic manipulators, and asking the students to describe the locus of achievable end-effector positions in the X-Y plane. The students quickly realize the limitations imposed by this one-DOF configuration.

Next, the students are asked to design more complicated configurations in order to allow the end-effector to reach all points in a given region of 2-dimensional or 3-dimensional space. Ideas for connecting links via various combinations of rotary and prismatic joints are presented. Finally, the instructor introduces examples in which not only the position but also the orientation of the end-effector or the entire robot is crucial for the given application. For instance, the students are asked to place propulsion jets in an appropriate fashion on the SCAMP underwater robot in order for the robot to have complete freedom in positioning and orienting itself in 3-D space. This becomes an interesting problem when we place constraints on the number of propulsion jets allowed.

4.1.2 Laboratory

The introductory laboratory session consists of two parts. The first part is an introduction to the various robots and manipulators available in the ISL. The instructor points out the various parts of several machines in the lab. Some machines that were presented in the introductory session include the General Electric GP - 110 industrial robotic arm (see Figure 1), the UM Walking Robot, the dual arm flexible flyer, the one-link backlash free manipulator, the one-link flexible arm, and the Modular Dextrous Hand. The students are then asked to relate what they see on the actual robots to the concepts they learned in the introductory lecture.

The students then have the opportunity to operate the GE GP-110 industrial robotic arm by entering commands via its teach pendant. The pendant provides inputs for control of six degrees of freedom, three for position and three for end-effector orientation. This not only allows the students to immediately "get their hands dirty" on the first day but also allows them to observe some of the potential problems in robotic manipulation. For example, the students attempted to pick up a ring–like object with a metal hook which was attached as the end–effector for the GP-110 arm. The students quickly realized that both the position and the orientation of the end-effector is important for such a task.

The second part of this lab session is a design exercise, in which the students are asked to design a gripper to be used for grasping objects of unknown size, shape, and constitution. The gripper may be designed with any construction materials in mind and any mechanism or configuration the students can think of. Hence, the design is essentially free of constraints. The authors have conducted this exercise by forming teams of two students each, allowing the students time to formulate their designs, and then having each team present their designs to the entire group. Again, this exercise encourages participation and gets the students thinking about issues in an open-minded way. It is important that the students realize that there are usually several ways to solve a given problem and that solutions usually can be refined once the given task or problem is narrowed. Some designs presented by the students include a vacuum type "sucking" gripper, and a multi-fingered gripper with multiple DOF fingers.

4.2 Robot Kinematics

By the end of the introductory lecture, most of the Young Scholars students have grasped the idea that computing the position of the end-effector of a robotic manipulator will be important and useful. With this problem in mind, the instructors introduce the students to the subject of robot kinematics.

4.2.1 Lecture

For this lecture, the instructors select some examples of manipulator designs and ask the students to answer the following questions for each design: *Given manipulator data such as joint angles and link lengths, what are the position and orientation of the end-effector or some other point of interest on the manipulator? Given a desired position and orientation of the end-effector or other point of interest on the manipulator, what are the required joint angles and/or link lengths?*

Since there are numerous manipulators that provide interesting kinematics problems, the instructors have chosen example designs which provide a progression of degree of difficulty and involve mathematical

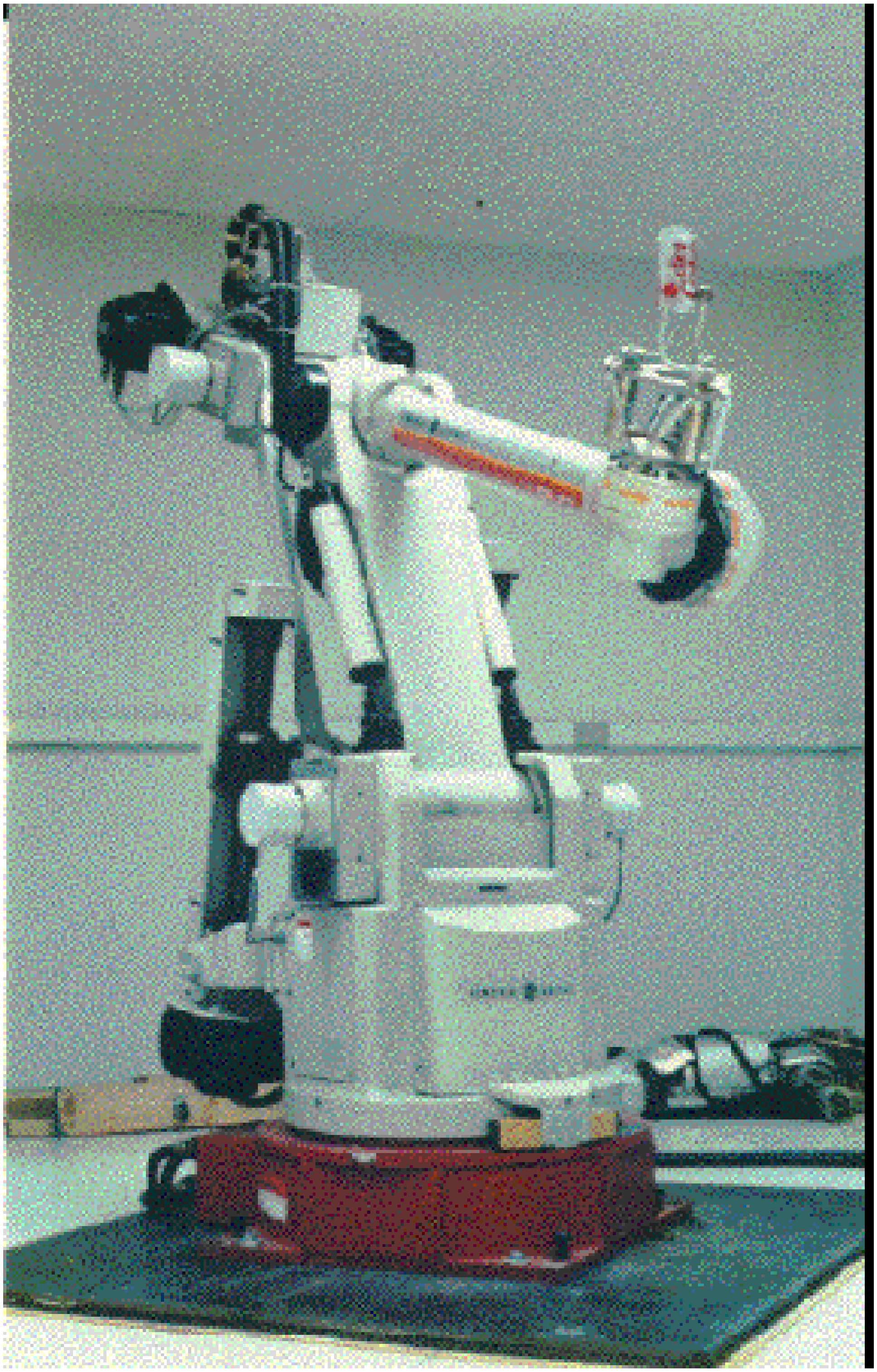

Figure 1: GE GP-110 Industrial Manipulator.

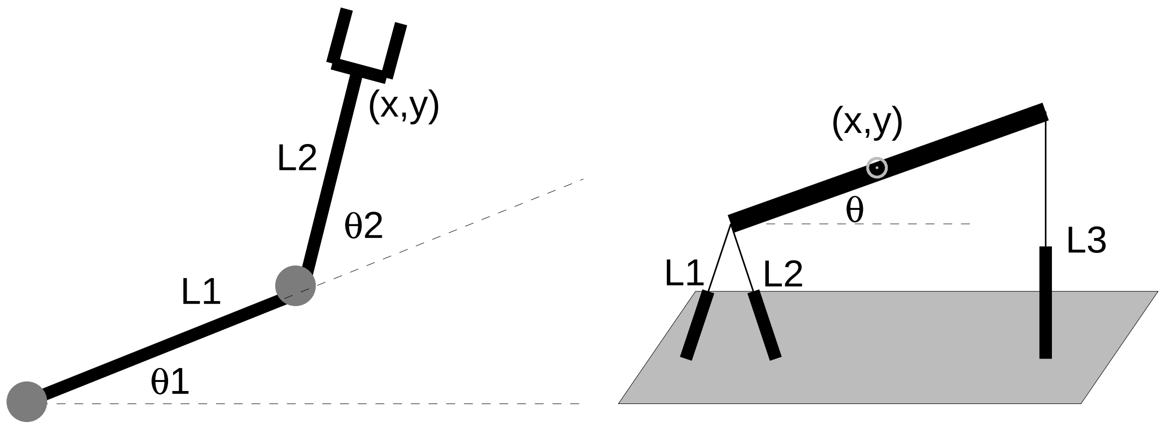

Figure 2: Manipulators used for kinematics problems: two-link serial planar manipulator (left) and parallel planar manipulator (right).

concepts which the students should be familiar with but may not have applied to a practical situation. It is also important that the kinematics problem be treated not merely as a mathematical exercise but as it relates to specific manipulator configurations that the students will work with later in the course. With this in mind, the instructors posed kinematics problems to the group based on two example manipulators, the two-link serial planar manipulator and the planar parallel manipulator (see Figure 2). The first is composed of two rigid links mounted sequentially on a basis and a gripper mounted at the end of the second link. It is powered by two rotary actuators located at the joints of the mechanism. The second consists of a platform mounted on a basis by three extensible legs. The length of the legs can be adjusted by linear actuators. The following problems were solved in class as a group discussion, with the instructor providing guidance where necessary.

- *Two Link Serial Planar Manipulator Forward Kinematics.* For this configuration, the forward kinematics problem is simple and straightforward. The students must compute the end-effector position (x, y) given the joint angle configuration (θ_1, θ_2), where the link lengths L_1 and L_2 are fixed. This is a good introductory problem and they have little difficulty deriving the correct answer.
- *Two Link Serial Planar Manipulator Inverse Kinematics.* The inverse kinematics problem is slightly more complicated, and requires the students to recall and use formulas such as the law of cosines. The students must derive a formula to compute the required joint angles (θ_1, θ_2) given a desired end-effector position (x, y). For some groups in recent years, the instructor needed to guide the group toward the solution and remind the students of the various required formulas. In at least one instance, a group of students reached the correct answer with almost no assistance.

  In addition, the significance of the possibility of multiple solutions or no solution is discussed. Here the students see how the mathematics can be enlightening, and recognize that the existence of multiple solutions to the inverse kinematics problem corresponds to the fact that for all achievable configurations, except those where $\theta_2 = 0$ or $\theta_2 = 180$, there are two sets of joint angles which achieve the desired position ("elbow up" and "elbow down").

  Finally, the students discover how to handle problems with more than two rotary joints by systematically calculating angles and lengths starting at the base and moving out to the end-effector. The students also discover that the complexity of the inverse kinematics problems grows quickly as the number of joints and number of DOFs increases.
- *Planar Parallel Manipulator Inverse Kinematics.* The parallel planar manipulator is based on the design of the Stewart Platform [1]. For this manipulator, the link lengths are adjusted (usually by linear actuators) to achieve the desired configuration. Thus, the inverse kinematics problem is to find the required link lengths (L_1, L_2, L_3) for a given desired position and orientation (x, y, θ). In contrast

with serial manipulators, for parallel manipulators the inverse kinematics problem is less complicated than the forward kinematics problem. The solution for the two-link planar parallel manipulator is straightforward, and requires the students to recall the formula for the distance between two points in the plane.

- *Planar Parallel Manipulator Forward Kinematics.* Here we ask the students to compute the manipulator position and orientation (x, y, θ) given a set of link lengths (L_1, L_2, L_3). This is the most difficult of the four problems posed so far, and requires a systematic approach to the geometry.

An interested reader can find solutions to these problems in [2].

4.2.2 Laboratory

In the laboratory session, the students use the concepts and formulas they have learned in order to program a manipulator that grasps a pen to draw a given figure. Points on the figure (e.g. the vertices of a polyhedron) are specified by the user with X-Y Cartesian coordinates. However, the manipulator requires a set of corresponding joint angles in order to complete the task. Therefore, the students must write a simple program which employs the inverse kinematics formulas to convert the grid points to joint angles.

For this experiment, we use a graphical three-dimensional simulation of the manipulator carrying a writing instrument developed by Martin Paredes on the ISL's Silicon Graphics Inc. workstations (see Figure 3). The manipulator in this simulation has two links, two rotary joints, operates in the X-Y plane, allows the pen at the end-effector to be raised and lowered. The simulation reads a sequence of joint angles from a user-specified file. The manipulator is then moved so that the joint angles correspond to the first element of this sequence. The "pen" is then placed down on the "writing surface." The simulation program then computes a path from the initial configuration to the next configuration in the sequence and moves the joints accordingly. As the joints move the "pen" leaves a mark on each point that it "touches." The simulation proceeds in this manner for each configuration of joint angles in the sequence until the final configuration is reached.

Each student has the job of drawing a simple figure on paper, and recording a sequence of X-Y grid points on the figure, between which lines will be drawn. Then the X-Y grid points which correspond to pen positions must be converted to joint angles. The students must develop an inverse kinematics program to perform the required conversion. The input of this program is the sequence of grid points, and the output is the sequence of joint angles. This sequence is then used as input to the manipulator simulation which produces the student's desired figure. Note that there is more for the students to think about than just the inverse kinematics problem. By constraining the pen to remain down throughout the entire sequence of joint angles, we indirectly introduce the concept of path planning since the order of motions becomes important in correctly producing the final result.

4.3 Actuators and Sensors

The objective here is to introduce the students to some of the common examples of sensors and actuators used in robotic applications and to explain the basic principles behind their operation.

4.3.1 Lecture Session

The topic is introduced with a discussion about the need for sensors in robotic tasks. The students are quickly able to realize that sensors are useful for providing information necessary for interaction with the environment, such as feedback for an accurate positioning task. The discussion is then oriented towards different kinds of sensors that the students have encountered in their everyday experiences. These included sensors used in automatic doors, cars, house alarms, and radar guns. The authors have observed that students have a reasonable idea of the kind of sensors that might be needed for a specific task, but in many

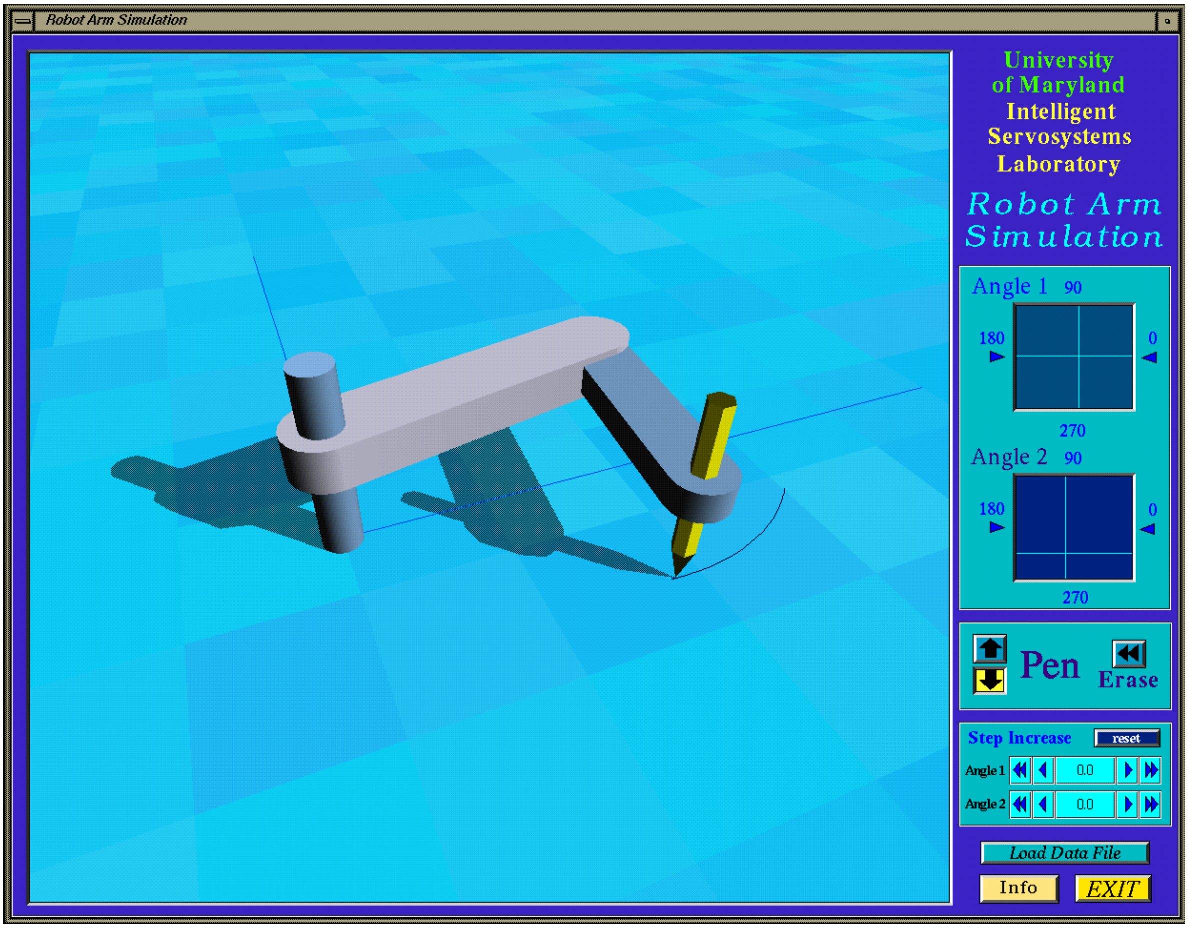

Figure 3: Simulation of Writing Instrument Manipulator.

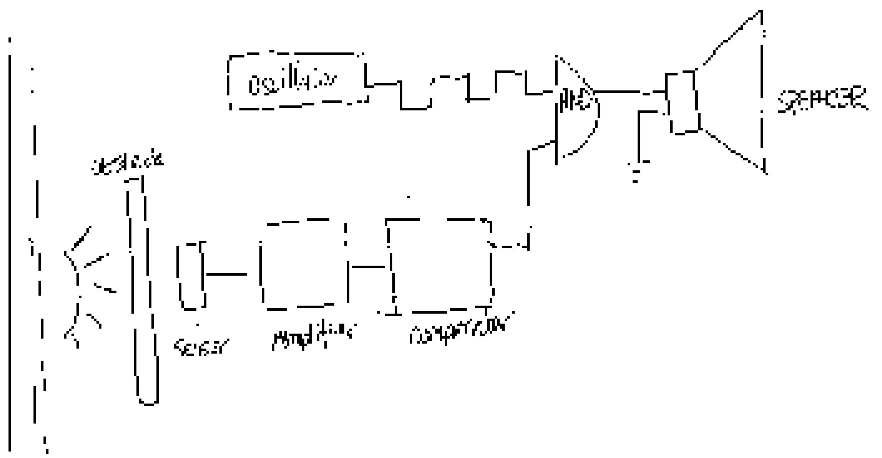

Figure 4: A student's understanding of the operation of the burglar alarm.

cases are unable to think of an example of each kind. They also do not have a clear understanding of the underlying physical principles.

The instructor presents various sensor classifications according to their physical characteristics and purpose, like analog versus digital, contact, proximity, sound, heat, range, and vision sensors. An example of each of these classifications is then discussed in detail, each discussion being complemented with laboratory work. Some of the sensors discussed are relatively simple, such as microswitches, potentiometers, and infrared sensors, while others are more complicated, such as tactile sensors, optical encoders, and laser-based sensors. During their laboratory sessions, the students observe that the outputs of various sensors are often not in the desired form. The output signal either needs to be modified or in many cases it needs to be decoded or processed before it can be used in a control system (for example the output of a CCD camera). This leads to a discussion of interfaces between actuators and sensors, processing of sensory information, different types of actuators, and control systems.

To provide some exposure to the basic concepts involved in circuit design and interfacing of a sensor with an actuator, the instructors decided that it would be an informative experience to let the students build an alarm, that would sound when a light beam falling on a light dependent resistor (LDR) was blocked. To understand the building blocks of such a circuit, the operation of simple components like logic gates, transistors, diodes, light emitting diodes (LEDs), and capacitors is explained [3, 4]. Amplifiers, comparators, and timers are introduced using graphs and timing diagrams. The use of a transistor as a switch is also discussed. A simple circuit for a burglar alarm (see Figure 4), using basic analog and digital components, is then presented and explained using timing diagrams. Other topics included in the discussion are the operation of a DC motor, explained from basic principles, and a brief discussion of different kinds of motors such as servo motors and stepper motors.

4.3.2 Laboratory Session

Having been introduced to some basic principles of electronics and sensors, the students are taught to identify various electronic components such as resistors, capacitors, potentiometers, LEDs, diodes, transistors, and logic gates. They are also taught how to use some basic lab equipment including a multimeter, a signal generator, an oscilloscope, and a breadboard. The students are then asked to plot the input/output (I/O) characteristics of some sensors and identify which of them have a linear or nonlinear characteristic. The plots include the intensity of light versus resistance of a light–dependent resistor (LDR), pressure versus resistance of the tactile sensor, and the angle of a potentiometer versus output resistance. A simple optical encoder is also built and its operation is explained. Having been exposed to various sensors and actuators, the GP-110

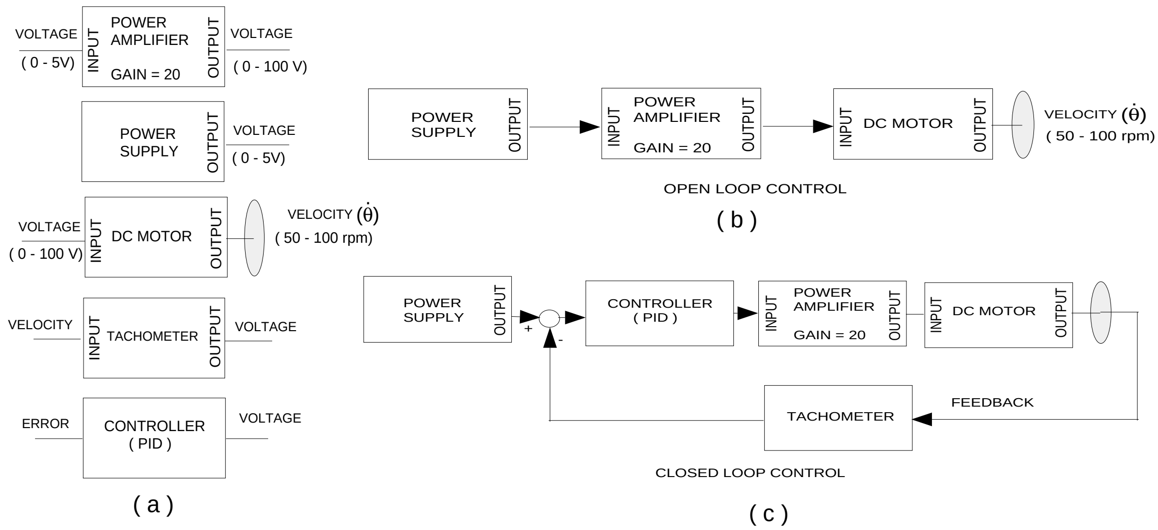

Figure 5: Figure 5: An example of a control system. (a) Components of the control system. (b) Open-loop control. (c) Closed-loop control.

robot is then dismantled, and the students are asked to identify some of the sensors and actuators that have been discussed.

The students then proceed to build the burglar alarm that was discussed in the lecture session. They are divided into groups, each one of which, assisted by the instructor, assembles a burglar alarm circuit on a breadboard. The circuit uses an LDR, a transistor, a comparator, an AND gate, a timer (IC555 chip) and any necessary capacitors and resistors. This is a rather unique and challenging experience for the students.

4.4 Control Theory

The students are now introduced to the following subjects: the importance of control systems, the basic components of a control system, open-loop versus closed-loop control systems and the proportional-integral-derivative (PID) control law.

4.4.1 Lecture

The instructor initiates a discussion of these subjects by asking the students to solve the following problems. *Given the first three blocks shown in Figure 5(a), interconnect the blocks in such a way that the output voltage of the power supply could be used to control the speed of the motor. Given the speed versus voltage plot of the motor and that the gain of the amplifier is 20, calculate the voltage that the power supply must provide such that the motor rotates at a speed of 75 rpm.*

The students are then made to realize that the system (see Figure 5(b)) they have designed is in fact a simple example of an open-loop control system. The “objective” (rotate at a speed of 75 rpm) of the control system is to control the “output”(speed) in some desired manner by generating the appropriate “input”(reference voltage) through the elements of the control system (e.g. power supply, amplifier). Some examples of controls systems that we come across in everyday life, robotics, industry, and space technology are then discussed. In each case the instructors emphasize the objectives, inputs, outputs, and the components of the control system.

The concept of closed-loop control is then introduced by trying to achieve the same objective as before, i.e. drive the motor at 75 rpm, but this time introducing a load on the motor shaft. The students observe that the introduction of a load causes the output (speed) to deviate from the desired value. A possible solution to eliminate this error is suggested using the two additional blocks, a tachometer and a "controller"(see Figure 5(a)). Some simple examples of feedback control laws used by the controller are then introduced and the PID control is discussed in some detail. In particular, the process of forming an error signal by subtracting the current system output from the desired one is described. The instructor also explains how to use the error signal, together with its derivative and integral, to generate a motor input that will eliminate this error. The role of the derivative control is explained as an anticipatory control, that measures the instantaneous slope of the error, predicts the large overshoot ahead of time, and makes a proper correction before the overshoot occurs. The role of the integral term is explained as one that reduces the steady state error.

This simple example is then generalized to others such as position control of a robotic arm for applications such as welding and part assembly in a factory floor. For these examples the instructor points out the advantages (in some cases disadvantages) of closed–loop control over open–loop control.

4.4.2 Laboratory

Given that the students have an insufficient mathematical background to understand the details of a PID controller, these concepts are explained via some simple experiments set up using ISL's tools for rapid controller design, which are centered around Integrated Systems Inc.'s AC-100 system. Software tools contained in AC-100 provide the user with the ability to design and simulate controllers, select input and output devices, generate C code to run the controller, download the controller code to a digital signal processing (DSP) chip, and execute the controller in real time. To facilitate use of the AC-100, a special cart has been designed and constructed. The various I/O devices have been connected to a number of easily accessible and appropriately chosen connectors mounted to a large panel on the front of the cart. Two power supplies and three general purpose amplifiers also reside on the cart. Hence, it is equipped to serve as a controller for a wide variety of plants with little or no additional equipment.

The students are allowed to experiment with controllers for an existing experimental set-up, the three fingered Modular Dextrous Hand [5] (see Figure 6), without having to machine fixtures, build sensors or design computer interfaces. Effects of changing the gains (proportional, integral, and derivative) can easily be observed both via the final position of the fingers of the hand, and graphical plots generated by software, using sensor information from optical encoders.

Very often topics are taught in the classroom and are not complemented with experiments and laboratory work. This tends to leave the students unconvinced that the theory presented will work in practice. In such an undergraduate robotics course sensors are often treated as a black box with an input output map. Many students have little or no idea as to how some common sensors such as optical encoders or tactile sensors are actually applied to a practical situation. In this sense, the exposure of the Young Scholars to actuators, sensors, and control is more informative than the exposure of a typical undergraduate student to these topics. In addition experiments of the nature described in this section give the Young Scholars an opportunity to see how various aspects of courses like physics, circuits, mechanics and mathematics fit together to solve a problem.

4.5 Computer Interfacing

Once the students learn some fundamental control strategies, the subject of implementing controllers using a computer is introduced. Most of the students understand that a computer is capable of complex numerical calculations, but few understand how the computer is able to interact with the outside world. One goal of this lecture is to explain how a physical signal such as a voltage is converted into a binary number, which can be used by the computer. A second goal is to explain the opposite conversion: how a number generated by a computer is translated into a physical signal. To accomplish this, the concepts of analog to digital (A/D) and digital to analog (D/A) conversion are introduced and discussed.

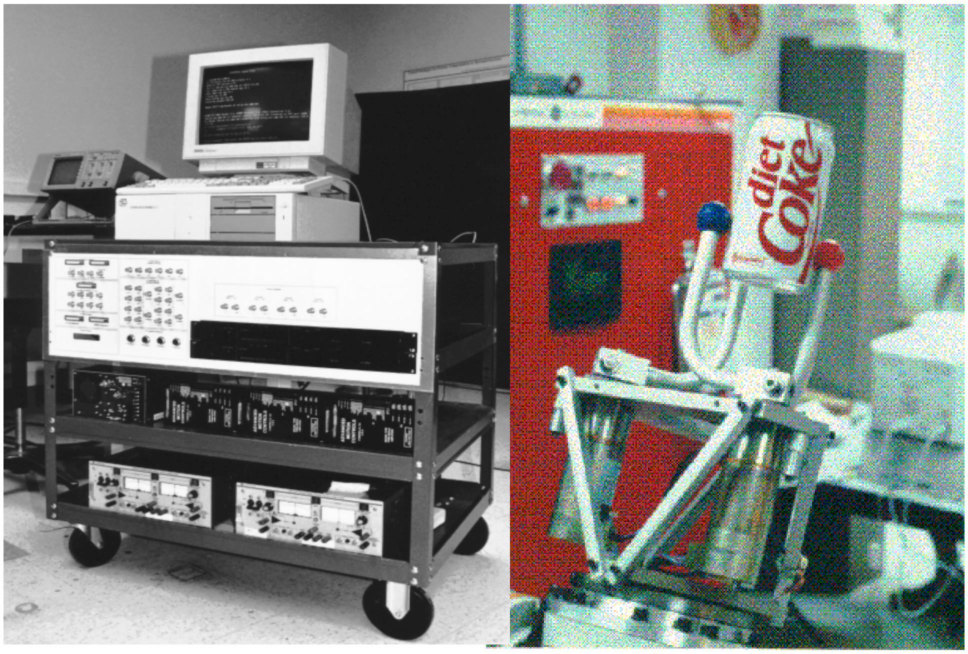

Figure 6: The AC-100 cart (left) and the Modular Dextrous Hand (right).

4.5.1 Lecture

After a brief introduction explaining the relevance of the subject, definitions of analog and digital signals are presented. To demonstrate the characteristics of the two signal types, an analog wristwatch is compared to a digital wristwatch. The students are able see that the hands of the analog watch move continuously around its face while the display of digital watch changes in discrete steps. The hands on the analog clock represent the exact time at every instant, while the digital watch displays the time rounded to the nearest second. Through this example, the students are able to get a physical understanding of concepts such as continuity and infinite resolution versus discrete time and finite quantization. Once the students understand these ideas, extending this discussion to include general analog and digital signals is easy.

Now A/D and D/A conversion can be discussed. Here, the basic ideas are presented without going into the details of how they are actually implemented. The students are told to think of the A/D converter as as "magic box" which takes in an analog signal and feeds the computer the corresponding string of numbers. This level of detail provides the students with enough knowledge to be able to use most commercially available D/A and A/D conversion boards.

The mechanics of the two conversions are shown graphically. For A/D, a continuous time signal is turned into a string of numbers by sampling (taking value of the signal at equally spaced instants of time) and quantizing (rounding the value to the nearest number that the computer can represent). This is demonstrated by drawing a continuous signal on the board and drawing a dot on the signal at each sampling instant. The sequence of dots is then written as a string of numbers, ready to be used by the computer. D/A conversion is shown to be the reverse of this process. The string of numbers is plotted as a sequence of dots at fixed time intervals. The dots are then made into a continuous time signal using a method for converting impulses to analog signals known as zero-order hold.

4.5.2 Laboratory

Here the students are asked to implement a proportional controller for feedback control of a DC motor. A 10-turn potentiometer is used to sense the position of the motor and the 6.270 board [6] developed at

MIT is used to implement the controller. The 6.270 is a microcontroller board which is used in MIT's annual 6.270 Lego Robotics Design Competition and contains, among other things, A/D inputs and outputs designed to drive a DC motor. The board can be programmed using Interactive C, a language which uses high level commands to access the board's inputs and outputs. Using this set–up, the students are able to send commands to the motor and read the value of the potentiometer easily. Hence they can concentrate on the subject of interface and control without getting distracted by unrelated details such as soldering a circuit or writing low-level code to drive the interface.

For this experiment, the students measure the voltage drop across a potentiometer and display its value on the 6.270 board's LCD display. This allows them to see first hand the conversion of a physical quantity (the position of the potentiometer) to its corresponding numerical representation. Likewise, they can easily send a velocity input in the form of a number to the motor and see it be translated into motion. Finally, they can use these features to implement a closed loop position controller. Hence, the experiment provides the students with a practical application of the material presented in previous lectures.

4.6 Path Planning

Once the students understand some basic concepts involved in the design and implementation of robot controllers, the more abstract problem of path planning is investigated. The goal here is to motivate the students to think creatively about the problem rather than present a rigorous theoretical solution.

4.6.1 Lecture

First the students are reminded of what they have learned so far. Using previously presented material, it is now possible to design and implement a controller capable of placing the end effector of a robotic manipulator in any desired position. At this point, most of the students are confident with this material. Now the topic of path planning is introduced by posing several questions: *How is the desired position determined? Once the desired position is known, what is the best path to take to that position? How is that path chosen? What makes one path better than another? What if there are obstacles in the workspace? What if there are other constraints, such as those on the wheels on a car which can roll forward but cannot slip sideways (nonholonomic constraints)?*

Humans are intelligent, resourceful and have years of experience to help them make such decisions. Computers can only do exactly what their programs tell them to. Developing a computer program which incorporates the knowledge and intelligence necessary to solve these problems is a very difficult task. One example which demonstrates this fact well is the problem of parallel parking an automobile. Most of the students have been driving for less than a year and the difficulty of learning to parallel park is still fresh in their minds. Still, the students are encouraged to think hard about these problems and find solutions.

4.6.2 Laboratory

For the laboratory, the students are asked to program the GP-110 robot to pick up a styrofoam cup and place it in a trash can. The GP-110 is programmed to perform point to point motion using a teach pendant. Instead of programming the manipulator directly, one group of students is asked to write a specification explaining exactly how to choose the path for the general problem. For example, one entry to this specification might be *"move manipulator to a position 5 inches directly above the cup"*. The cup and trash can are then placed randomly in the workspace and the other group is asked to implement the specification exactly, as if they are a computer and the specification is their program. If the second group runs into problems, the first group is asked to revise their specification. This process is repeated until the first group produces a specification with enough detail to work for any configuration of cup and trash can. More often than not, the specification requires several revisions before becoming satisfactory. For the students, experiencing the difficulty of planning a path for this seemingly trivial task forces them to better understand the problems associated with planning more general tasks.

4.7 Lego Robot Project

In the summer of 1995, half of the course was dedicated to a single project which encompassed all of the relevant course topics. The goal of this project was to build an autonomous mobile wheeled robot capable of locomotion and steering. The mechanical components were constructed using the parts from a Lego building kit. The electrical and computer components were implemented using the 6.270 board. This project is motivated by MIT's annual Lego Robotics Design Competition [6].

The students were broken into two groups. One group was responsible for designing and constructing the mechanical parts of the robot. The other group was responsible for the electronic interfacing and the programming of the 6.270 board. The two groups spent approximately 15 minutes each day coordinating their work. Each group spent the rest of the time working on its own part of the project.

The Lego building set included most of the parts necessary to build the robot. The kit contained many blocks of different sizes as well as axles, gears, and wheels which were used to build the transmission. To create a "Lego motor", an existing motor was mounted onto a modular Lego platform. This platform effectively served as a big Lego block and could be mounted anywhere on the robot. Two such motor platforms were constructed: one for locomotion and one for steering. A potentiometer was glued into a Lego brick in a similar fashion.

This use of the Lego kit fits in well with the general philosophy of the course. Using the Lego kits, the students were able to quickly design and implement various ideas. The students were able to concentrate on real mechanical problems like load placement and gear ratio instead of spending time machining parts and driving screws. As discussed previously, the 6.270 board provides similar benefits for the electronic and controls aspects of the project.

The result was that the students successfully constructed a mobile robot in the alloted four days. The angle of the steering wheel was measured with a potentiometer and the steering was controlled using a PID loop. The locomotion was controlled with open loop commands. The project was a success on other levels as well. It provided the students with a practical feel for the uses of control theory, mechanical design, electronics, and computers. Additionally, they learned first hand about the communication which must take place between two groups of engineers working on different aspects of the same project. Finally, this project piqued their imaginations and inspired a great deal of interest in the subjects at hand.

5 Results

The impact of the robotics mini–course on the YSP participants can be observed in the responses of the students and course instructors and in the educational and career paths of the program graduates. These indicators have been overwhelmingly positive.

The YSP participants are usually very enthusiastic about the robotics component of the program and provide valuable feedback to the instructors. The small size of the groups allows for personal interaction of the students with the instructor, which facilitates communication of problems and suggestions. Moreover, each student submits evaluative comments of the course along with his/her final report. Additionally, the faculty member who acts as YSP principal investigator, holds regular meetings with both students and instructors where the progress of the program is discussed. This same faculty member Feedback and criticism has had a significant effect on the course over the years.

The positive reaction of the participants is exemplified by the following excerpt from a 1993 report, which also points out problems encountered: "*The main complaint about this lab project would be the last day I did not understand the talk about signals at all. I thought it was very confusing and beyond my level [...] However, the rest of the lab was great. I really liked the robots and everything and it was my favorite lab. Really! I'm not just saying that. It was definitely the best. Thank you!*" One participant in the initial year of the program (1991) said: "*One suggestion for improving this lab project would be to create more interesting and in–depth experimental projects and to allot more time so that we could both program the GE* *robot and play with the kinematics program on the [Silicon Graphics Inc.] IRIS computer.*" The initial aim of the course, which was to give as broad an overview of the robotics field as possible, shifted in subsequent years towards fewer theoretical discussions and more hands–on experimental projects, allowing for a more in depth coverage of some key issues. One response which typifies student sentiment is: "*The ISL has been a challenging , educational and memorable experience. The lectures, hands-on experiences and visits to related labs were very helpful.*"

Particularly satisfying for every instructor was the feeling that new horizons were being opened for students, who proceeded to explore them with remarkable eagerness. Furthermore, the students appreciated the fact that it was possible to integrate material from their various high school courses in order to solve real-world robotics problems. One participant in 1993 wrote: "*It was great to see that things you learn in high school are used elsewhere and can come in handy when you need them.*" Another in the same year said: "*The lab took away my fear of taking objects apart to learn about them. It also gave me a desire to take physics during the school year, because I want to learn more about resistance, voltage, and current.*"

The experiments at ISL were sometimes unsuccessful (as real–world projects often are) as the following comments from a 1995 group report show: "*The goal of this project was to build a truck–like device, whose movements would be guided by a closed–loop control system. The group's truck ended up literally in smoke when the potentiometer acting as feedback for the turning mechanism burst into smoke. [...] After this incident, the potentiometer was unrecoverably damaged.*" However, important lessons about engineering practice were drawn: "*[...] it might be advantageous if better documentation could be provided initially along with a strong admonition to whoever is doing the electrical work to carefully document everything that is done with the electronics*" and "*The mechanical subteam developed the final design in a patchwork manner; with each new insight, the team would modify the design. [... They] needed to have integrated their ideas before putting together the Lego pieces. In this way a more coherent and aesthetically pleasing device could have been built. With better foresight, a better steering mechanism could have probably been built.*"

Overall, the robotics component of the YSP seemed to contribute to the goals of the program. One 1993 participant wrote: "*The laboratory project reaffirmed my desire to become an engineer*," while another one in the same year said: "*I am very grateful for this experience and I feel that I will definitely become some sort of engineer.*"

Additional evidence of the success of the YSP can be found by examining the paths that the Young Scholars have chosen after completion of the program. From 1991 to 1995, ninety-six students participated in the program. Of these, sixty-two went on to pursue an undergraduate education in engineering, computer science, physics, or mathematics. Twenty-four chose to study at the University of Maryland.

Much time and effort was devoted to teaching this course, resulting in a rewarding and exciting experience for all who have been involved. The authors are fortunate to have had the satisfaction of seeing students get excited about some new gadget that they built (students could be seen crawling on the lab floor after a new mobile robot they just turned on!), watching the level of understanding of the students grow, participating in many interesting discussions, and seeing a YSP participant return to the ISR as an undergraduate student after entering an engineering program, and comment on the benefits he/she received from the YSP.

6 Conclusions

This paper describes a robotics course developed for the Young Scholars Program at the Institute for Systems Research of the University of Maryland. The goal of the course has been to provide a broad introduction to robotics, while presenting the material at a level accessible to high school students with limited exposure to physics and calculus. The combination of classroom teaching with lab experimentation and projects appears to achieve these goals and stimulate the students for more advanced study of engineering and science. The authors hope that this course will continue to evolve and improve, and that this paper will provide a basis for future programs with similar objectives.

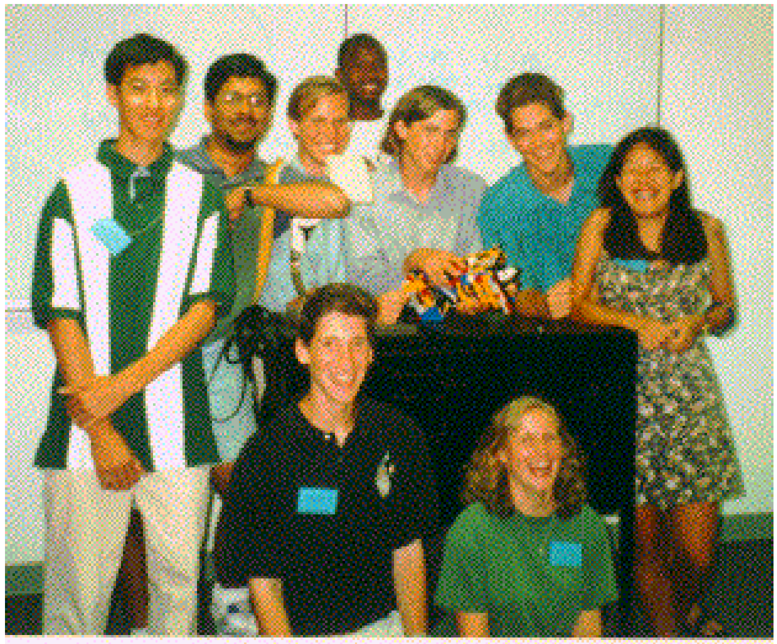

Figure 7: The Young Scholars of 1995 with Lego Robot

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