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Low-Cost Robotic Laboratory Exercises and Projects*

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In commonly used robotic texts, the introductory chapter defines robotics and explores the role of robotics in industry and society. This is followed by transformation matrices and forward and inverse kinematics. Homework, quizzes, and exams are used to reinforce lecture material. For some students, three-dimensional concepts and mathematical tools are obvious, but for others it is impossible to relate two-dimensional pictures (from a text or the board) to a three-dimensional reality. Furthermore, besides a poor grade, there is no immediate feedback on the consequences of incorrectly assigning coordinate frames or improperly deriving the inverse kinematics of a manipulator. This paper discusses laboratory assignments utilizing inexpensive hardware such as remote-controlled (RC) servomotors, ROBIX™ RCS-6 kits, and inexpensive vision systems such as CMU-cams and webcams. It is shown that low-cost systems are suitable for both reinforcing fundamental robotic concepts such as inverse kinematics and facilitating independent student research.

INTRODUCTION

THE NUMBER OF papers on robotics education has exploded in recent years. A recent search on the words 'robot' and 'education' reveals 354 IEEE publications, and the database INSPEC found 1,554 papers for the same topic. Adding the words 'low' and 'cost' to the search narrows the INSPEC results down to 50. In reviewing these papers, a variety of themes are obvious. There are papers on using robots to teach computer programming techniques [1], artificial intelligence [2], and control [3] as well as electrical or mechanical engineering concepts. There are a number of papers on mobile robot contests including RoboCup and the Trinity Fire-Fighting Home Robot Contest [4–6]. Robots are often used as a way of engaging K-12 students [7], under-represented minorities and young women [8–9] in the world of engineering and science. Robots are also used as undergraduate senior design projects in a variety of engineering disciplines [10].

This paper highlights a number of commercially available, low-cost products and discusses how they can be used in the classroom and the laboratory to teach the fundamentals of *robotics*, an engineering discipline of its own. The 'Background' section provides the curricular background for our undergraduate program and the following section lists some of the low-cost equipment that we utilize. The final section details some of our classroom and laboratory exercises and student designs that utilize low-cost equipment.

BACKGROUND

Midshipmen in the Systems Engineering major at the United States Naval Academy (USNA) take an interdisciplinary curriculum with an emphasis on control systems and dynamics. The Systems Engineering Department offers three robotics courses that satisfy senior-level technical elective requirements.

The first robotics course in Systems Engineering at USNA emphasizes manipulators and machine vision, including coordinate transformations, forward and inverse kinematics, Jacobians, and simple image processing. The second course covers camera-robot calibration, visual servoing, and pattern recognition. Both of these courses consist of three credit hours with two hours of instruction and two hours of laboratory exercises. The laboratory for these two courses consists of ten robotic workstations outfitted with machine vision systems. Both the SCORBOT ER-V and the ROBIX™ RCS-6 kits are used.

The third course in the Systems Engineering robotics curriculum at USNA covers mobile robotics, including the design and implementation of various locomotive methodologies, closed-loop control systems, sensor suites, novel actuators and path planning techniques for mobile robots using the Parallax Basic Stamp II™ and the RCX microcontroller from the LEGO® MINDSTORM™ robotics development kit. This is a three-credit

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course with one hour of lecture and four hours of lab.

Programming environments for all three robotics courses include MATLAB®, Borland C/C++, PBASIC and Dave Baum's NotQuiteC. A one-semester programming course is a prerequisite for all of the robotics courses. The curriculum that we utilize focuses on open-ended problems with more than one plausible solution. The use of reconfigurable kits (ROBIX and LEGO) permits rapid prototyping of solutions to challenging problems in a reasonable time-frame while still maintaining technical rigor and an appropriate level of intellectual challenge. As the United States military increases its use of autonomous vehicles, the students are becoming more aware of the relevance of the curriculum. With an excess of 100 robotics students each semester, and no teaching assistants, the authors seek equipment that is easy to integrate, suitable for use in multiple sections, and effectively reinforces classroom theory.

EQUIPMENT

A key component in the development and implementation of novel robotics exercises is a 'library' of simple, effective, low-cost equipment that can be used in a variety of applications. In this section, we outline some of the most valuable pieces of equipment that have been used in the robotics and design courses in the Systems Engineering Department at USNA.

R/C servomotors

R/C servomotors, designed for remote control vehicles, prove to be one of the most important components of the standard robotics equipment library. R/C servomotors are compact, lightweight and versatile. Available in a variety of sizes, all R/C servomotors share a common interface and control signal protocol called *pulse coded control* or *pulse coded modulation* (not to be confused with *pulse width modulation*). Essentially, the servomotor uses the width of an input pulse to determine the desired absolute output shaft angle. The built-in controller uses feedback from a potentiometer on the output shaft to regulate the position. R/C servos are internally geared to provide a reasonable torque/weight ratio, but most types have a full range of motion of approximately 180°. Common brand names of R/C servomotors include Hitec and Futaba.

While the servomotor is designed and intended as a position-controlled device, there are techniques by which these motors can be modified for continuous rotation and a form of speed control. Several online resources outline how to modify the servos to create a continuous rotation gear motor [11, 12].

Servomotor control/interface

Appropriate pulse code signals are easy to generate from standard R/C transmitters as well as almost any commercially available microprocessor, such as the Basic Stamp II or the Rabbit microprocessor. Additionally, there exist very useful devices that are designed to control servomotors, such as Pontech's SV203 or a SSC-II controller. The SV203 can control eight servomotors simultaneously, has five onboard analog-to-digital converters to read in data from analog sensors, and is configured using a standard RS-232 serial interface. The SSC-II features only serial servo control. These interface boards permit students to develop functions and to utilize advanced structures and data storage in a programming environment such as MATLAB or C/C++.

Reconfigurable robot kts

A standard ROBIX RCS-6 kit consists of six R/C servomotors and a variety of links and connectors (http://www.robix.com). These kits can be used to build small serial or parallel [13] manipulators. The ROBIX kits provide students with a quick and easy way to prototype simple robotic arms and investigate workspace design, and forward and inverse kinematics. The kits come with a parallel port interface, a program development environment, and a simple command set. Because the basic actuator in the set is a standard R/C servomotor, we have found the use of the Pontech SV203 board extremely beneficial for ease of implementation and uniformity of programming environment, as the provided interface and environment is non-standard for our robotics courses.

While ROBIX kits provide specialized hardware for manipulator design, the undisputed king of reconfigurable robot kits is the LEGO Mindstorms Robotic Invention System. Useful for rapid prototyping of everything from simple tank-like robots to highly complex planetary rovers and manipulator arms, the LEGO Mindstorms kit provides unparalleled functionality and flexibility. The standard kit is equipped with the RCX microprocessor (a Hitachi 8-bit system) that possesses three motor drive outputs and three sensor inputs that can be configured for a variety of sensor types. Included with the vast array of LEGO pieces are two motors, a light sensor and two touch sensors as well as an IR tower for communication from the PC. Many additional sensors and actuators are available from Pitsco and other vendors [14, 15]. In order to make effective use of the capabilities of the system, we use a version of NQC, standard freeware that uses C-like syntax for programming [16].

A higher-level reconfigurable kit is produced by Innovation FIRST, a company that provides the controllers and a variety of hardware for the FIRST Robotics competition [17]. The EDU-Kit includes a robot controller (built on two connected PIC18F8520 microprocessors), four highly modified R/C servomotors (intended for true speed control) and a variety of metal parts that can be

Fig. 1. Omni-directional wheel.

used to develop strong, robust mobile robot platforms and simple manipulation devices [18]. The controller is programmable in C using a standard C compiler, and has A/D inputs, standard RS232 and TTL serial interfaces, eight motor control outputs and six high-energy solenoid outputs. One nice added feature of the EDU-Kit is the R/C transmitter interface.

This interface, developed to parallel the methods of operation at the FIRST robotics competitions, is especially useful for low-end robotics courses or those in disciplines not aimed at autonomous robotics. Using a standard R/C transmitter and receiver, robots can be teleoperated.

Fixed robot platforms

In addition to the reconfigurable kits discussed above, it is also sometimes beneficial to use completed off-the-shelf robots for a variety of exercises. There are three low-cost robot systems that have been used successfully in the Systems Engineering Department at USNA in the last few years.

Developed by Carnegie Mellon University, the Palm Pilot Robot Kit features servomotors modified for continuous rotation [19]. The three equally spaced motors control omni-directional wheels (see Fig. 1) to provide holonomic motion. The kit includes the SV203 board to read in data from ranging sensors (Sharp GP2D12) and send control commands to the three motors. The kit is designed to be controlled by an onboard Palm Pilot (purchased separately). Alternatively, the SV203 can be connected to a wireless serial modem and controlled remotely by a PC or microprocessor. An overview of the system can be seen in Fig. 2.

This platform is of interest in robotics education due to the holonomicity implicit in the design and the associated set of applicable problems. This system can be used for novel control designs or as a hardware-in-the-loop simulator for spacecraft and even autonomous ships and surface vessels. The latter can be accomplished by limiting available control authority for the system while simultaneously using the full capabilities to simulate the effects of drift current, for example. This novel system greatly extends the range of potential applications in mobile robotics.

Fig. 2. Bottom view of a PPRK robot developed by Carnegie Mellon.

Single-board camera systems

One of the most significant developments in robotics in recent years has been the advent of inexpensive, single-board computer vision systems. Starting with the Spectronix RAMCAM and culminating now with the range of CMUCams developed by Carnegie Mellon [20], computer vision applications have now become relatively inexpensive and fieldable with very modest computational support.

The CMUCam is a CMOS camera with a single-board microcontroller that performs real-time vision processing. The camera can be interfaced to a standard RS232 serial port for configuration and data output. The device is capable of controlling a servomotor directly using built-in tracking commands, as well as outputting information regarding the center of mass, bounding box and area of a region of color specified by ranges of RGB values. The camera can also dump complete frames across the serial port, although this is a slow process. The CMUcam is capable of tracking color at 16.7 frames per second at a baud rate of 115200 and has a maximum resolution of 80 x 143 pixels (in RGB color). A picture is shown in Fig. 3.

The CMUCam2 is a more powerful version of the CMUCam, at a higher price. The resolution is increased to 176 x 255, and the system is capable of many more vision processing operations, including horizontal convolution filtering, tracking of color patches at 50Hz, etc.

Computer vision is one of the most compelling sensing modalities available, but it has been limited in application to either desktop systems connected to a PC or to high-end, expensive mobile robot systems such as the Koala [21] or the PC-AT [22]. With the capabilities of the CMUCam and the even more powerful CMUCam2, real vision appli-

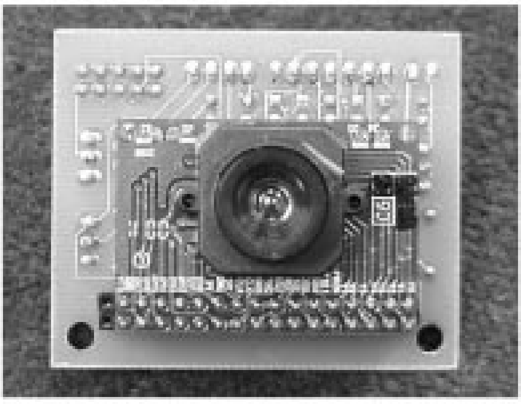

Fig. 3. CMUcam developed by Carnegie Mellon.

cations can now be achieved in mobile systems for only a few hundred dollars. Further, the ubiquity of RS232 communications in microprocessors indicates that these cameras can be easily interfaced to virtually any microprocessor system used by any education program.

IMPLEMENTATION AND SAMPLE EXERCISES

In this section, we discuss a few sample exercises and student projects that bring out the salient characteristics of the robot systems discussed above.

Reconfigurable manipulators: ROBIX RCS-6

In order to facilitate the investigation of various manipulator configurations in a first semester robotics course, we equip lab stations for two or three students with a PC, a Robix RCS-6 kit, an SV203 board, and a power supply. Software is written in the MATLAB environment, but any programming language with serial communication will work. A sequence of laboratory exercises reinforces topics covered in the classroom. For example, a 'spot-welding' exercise helps students experiment with manipulator design and issues such as throughput, accuracy, and repeatability. Spot-welding consists of affixing a star washer to various magnets located on a small toy vehicle (see Fig. 4). Other laboratory assignments include forward and inverse kinematics exercises to reinforce classroom theory in a visual manner. Students develop experience in writing computer functions as they develop their software, and have a feeling of ownership that comes from the design of their own robot for each exercise.

Student-designed mobile robot platforms: A walking LEGO robot

Robotics courses that focus on design face a variety of challenges for the instructor. Primary among these is that the students must be provided with sufficient time to develop a novel solution to a design challenge. The amount of time required for a given challenge will depend not only on the objectives of the exercise, but also on the set of available materials. Much more can be accomplished in a semester if appropriate rapid prototyping tools are available. This has been the prime motivator behind the use of LEGO Technics and Mindstorms systems in secondary education.

Fig. 4. A partially assembled Robix RCS-6 manipulator for 'spot welding' laboratory exercise.

What limits the effectiveness of LEGO systems for advanced designs is that the connectors and elements have a great deal of flexibility. This problem is compounded by the fact that complex gear trains require many connections and substantial physical space, and are in the end extremely mechanically inefficient. In our mobile robot design course, we use R/C servomotors coupled to LEGO parts to rapidly prototype walking robots. This approach allows us to place high torque, low weight actuators on complex appendages without a great number of extra linkages. Students are then able to investigate walking robot designs and novel locomotion methods over the course of just a few class periods. Examples of completed systems can be seen in Fig. 5.

While the use of servomotors substantially decreases the mechanical complexity of most LEGO legged locomotion designs, the motors must be coupled to the LEGO pieces. This turns out to be relatively straightforward using the screws and mounting horns provided with most commercial RC servomotors, as well as LEGO frames, zip ties, wires and even rubber bands. This component of the exercise also provides the students with some insight into issues regarding motor mounts and systemic stress.

The real difficulty with using RC servomotors with LEGO systems is that the LEGO RCX is not configured to drive the servos. As such it is generally necessary for the instructor to support

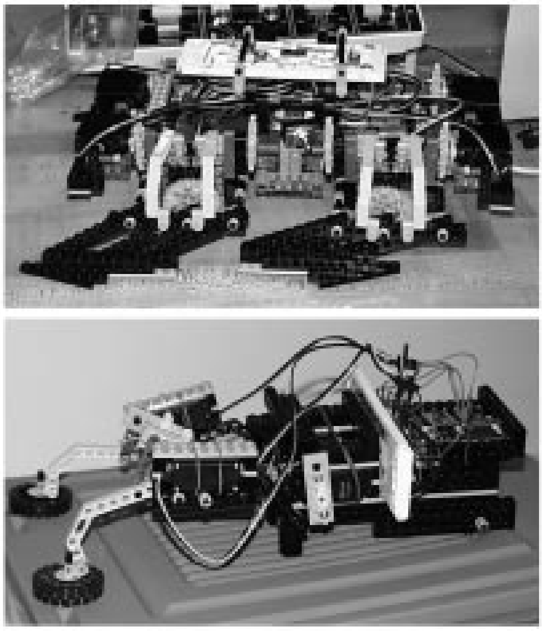

Fig. 5. Walking robot prototypes.

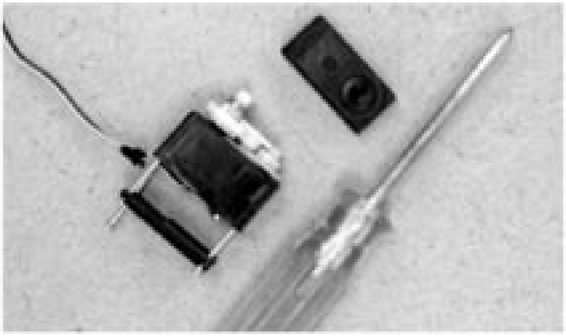

Fig. 6. Disassembled RC servomotor used for in-class exercise.

at least one additional computing or control platform (if the RCX is used at all), or to design a separate interface [23]. The Parallax Basic Stamp II has straightforward servo control commands and is both relatively cheap and easily embedded in a fully mobile design. Another method is to use a separate control board (such as the Pontech SV203) with any processor capable of serial communication.

By adding servomotors to a robot design course, it is possible to substantially increase the functionality of the parts kit with very little additional investment in time or resources. The internal gearing and control allow precise positioning without a great deal of additional hardware, and the motor itself is an excellent example for discussions on feedback control, gear ratios and gear train design.

In-class exercise: robotic actuation

R/C servomotors provide an excellent active learning opportunity. Students are broken up into groups of three or four. They are assigned the task of partially disassembling the motor (as shown in Fig. 6) to compute the internal gear ratio. They also compute the actuator resolution and look at the technical specification sheet to approximate the torque-speed curve. The computed resolution is used later in laboratory exercises. This exercise allows for discussions on how much weight a robot arm can lift and why some robot arms are actuated using belts or linkages.

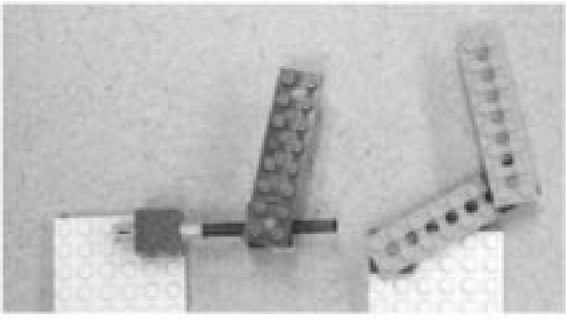

Fig. 7. Lego models of prismatic-revolute (PR) and revolute-revolute (RR) planar robot geometries.

In-class exercise: Inverse kinematics and Jacobians

In another classroom exercise, students use LEGO pieces (as shown in Fig. 7) to study the inverse kinematic problem. Small groups were given enough pieces to construct several two and three degree-of-freedom (DOF) robot geometries. For each geometry, the groups determined:

- if solutions exist for the general inverse kinematics problem;
- how many solutions exist; and
- a closed form representation of the joint variable values in terms of the desired end-effector pose (if possible).

Sample geometries included planar revolute-prismatic (RP), planar RPR, and a non-planar RPR, non-planar RRP, and planar RR configurations.

These manipulator 'kits' are also used to teach robot Jacobians. Students are tasked with computing and comparing theoretical and measured end-effector displacements for specific joint displacements, with two teams of two to three students working in pairs. One team computes theoretical values, while their partner group works with the LEGO pieces, protractors, and rulers. The two groups must reconcile their answers, providing immediate feedback and an excellent opportunity for peer-to-peer learning.

Design project: Palm Pilot robot for autonomous rendezvous and capture studies

There has been growing interest within the United States space community to develop autonomous rendezvous and capture (ARC) capability on unmanned space vehicles. There is, however, an inherent high cost associated with the research, development, and testing of autonomous rendezvous and capture in a space environment. Consequently, a robotic platform that is capable of accurately simulating spacecraft dynamic motion will enable students to study the problem in a low-cost environment.

An inexpensive test facility that uses mobile robotic platforms to simulate relative planar motion for evaluating ARC control system logic and sensing strategies has been developed using a desktop simulation computer, two mobile robot platforms, and a vision system [24]. The simulation computer computes the dynamic behavior of the space vehicles in the space environment. The robot platforms representing the space vehicles will move in accordance to the simulated space vehicle behavior. The mobile robotic platforms used in the simulator are based on the Palm Pilot Robot Kit (PPRK) that was designed by the Carnegie Mellon Robotics Institute. The robotic platforms use three omni-directional wheels in a triangular arrangement that can drive the platform in any direction with independent control of rotation, meaning it moves holonomically in the plane.

The main chassis of the PPRK was kept intact. The main feature of the PPRK is its ability to perform holonomic maneuvers and consequently it is able to simulate the orbital maneuvers of a satellite. The robot is intended to be controlled by a Palm Pilot Personal Digital Assistant (PDA), but for this project, a wireless modem replaced the Palm Pilot to allow the transfer of command inputs from the controlling desktop computer to the robot. Robot locomotion is provided by three hobby servomotors placed 120° apart, as shown in Fig. 2. The motors are controlled by a Pontech SV203 controller board.

A CMUcam vision system is used to provide continuous positional feedback of the robotic manipulator. The CMUcam plays a role similar to the Global Positioning System (GPS) in determining the position of satellites. The resolution is limited, but it is sufficient for determining the centroid of the robotic manipulator.

The system is controlled within the MATLAB programming environment, which is able to communicate to the wireless modem and the CMUcam via the serial ports. The code simulates the relative dynamic motion of the spacecraft (mobile robots) in accordance with the Clohessy-Wiltshire linearized orbital equations of motion [25, 26]. This set of experiments offered the students involved a unique opportunity to study spacecraft control using real hardware.

Design project: Urban search and rescue prototype

Urban Search and Rescue (USAR) is a challenging domain for robotic systems. The severe conditions present in most urban disaster sites require that platforms be small, powerful and flexible. These design requirements indicate that the actuators selected must have a small profile and low weight while still delivering sufficient torque to move the vehicle. Servomotors, with their high built-in gear ratio, make them an excellent, low-cost solution for these vehicles. Used in both positioning and locomotion, these devices are an excellent choice for prototyping USAR vehicles.

As part of a Trident Scholar project, a one year senior research program, Bryan Hudock designed and built a prototype for a USAR robot as seen in Fig. 8 [27]. The primary goal of this project was to develop a physical structure that would be sufficiently agile and flexible for the challenging terrain associated with USAR. The resulting vehicle is a segmented, tracked system with 'selective compliance'. All actuation uses off-the-shelf servomotors with brass gearing and high torque-to-weight ratios. The motors that drive the tracks have been modified for continuous rotation, while those that orient the segments have been left in their original condition. The system uses six servomotors per segment: four for tracks (two each top and bottom) and two for pitch and yaw control of the segments. The system is extremely agile and can 'tunnel' through loose material by pushing simultaneously with the top and bottom treads in the same direction (as opposed to a single-tread system, where the top of the tread impedes progress if it makes contact with the environment).

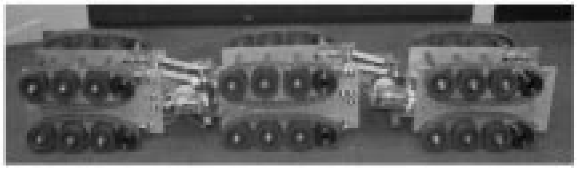

Fig. 8. Urban search and rescue robot prototype featuring dual treads and selective compliance joints between identical segments.

The selective compliance technique uses tensioning springs attached to the pitch controlling servomotors so that the natural equilibrium point of the system can be modified. The actual pitch of the vehicle is determined by the combination of spring tension and ground support, enabling motion over extremely uneven terrain without active control while simultaneously permitting controlled pitch motions for advanced locomotion.

This design relies heavily on the availability of compact, sturdy, geared electric motors. The use of standard R/C servomotors enabled the student to focus much more on the novel robot morphology than on the intricacies of actuation system design and enabled the undergraduate student to make a fundamental contribution to a field that generally requires a great deal of monetary support (typically unavailable at the undergraduate level).

Computer vision projects: The CMUCam and CMUCam2

The capabilities of computer vision systems with onboard processing are seen clearly in two senior design projects completed in recent years.

Under the National Naval Responsibility in Naval Engineering program from the Office of Naval Research, the Atlantic Center for Innovative Design of Small Ships was developed. As part of this ongoing effort, disparate areas of engineering are being integrated to bring modern tools and techniques to ship design as well as to motivate young engineering students to apply their skills in this domain. As part of this effort, a fly-by-wire system for a small R/C surface vessel was developed [28].

One of the main components of the developed system was the obstacle avoidance routine. Much as anti-lock brakes on a car prevent the user from exerting too much command authority, the obstacle avoidance system on the vessel limits throttle authority when an obstacle is nearby (see Fig. 9).

The obstacle avoidance system that was developed relies on two complementary sensing

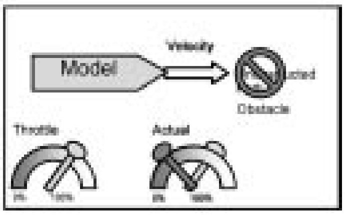

Fig. 9. Fly-by-wire obstacle avoidance.

Fig. 10. T1-CMOD automated sentry.

modalities. Primary among these is computer vision. A stereo vision system was developed using the CMUCam and integrated into the vessel. The system was tuned to look for a specific type of obstacle known to exist in the environment. The secondary sensor was an acoustic ranging sensor mounted on an R/C servomotor. Both systems output data to the microprocessor that was receiving commands from a laptop computer via radio modems. When the user drove the ship into a dangerous situation, the throttle authority was limited, as seen in Fig. 9.

The key feature of this system is that it relies on stereo vision, even though the main computational facility onboard is a simple microprocessor. Such functionality was unheard-of only a few years ago. Again, the availability of low-cost solutions for robotic subsystem requirements allowed undergraduates to develop a substantive contribution to an ongoing hardware research project.

Another example of the use of camera systems with onboard vision processing is an automated sentry. A custom-built all-terrain mobile robot was equipped with two vision systems to carry out security missions. One camera (a CMUCam) was used to guide the robot to designated waypoints in its environment. The other camera (a CMUCam2) was tuned to look for a specific color, designating an enemy. Standard R/C servos were used to actuate the targeting system and pull the trigger of the onboard paintball gun. The resulting system performed well, and once again shows the usefulness of the R/C servo, as well as cameras with onboard processing. An image of the final system can be seen in Fig. 10. Students involved in this project were able to investigate vehicle-level visual servo control, path planning and target recognition without a great deal of sophisticated hardware or a large monetary outlay by the department.

OBSERVATIONS

The use of small inexpensive robots in a robotics curriculum has a number of advantages. Manipulators and mobile robots created with servomotors permit students to quickly build and test robot designs, enabling experimentation-based courses to cover a much broader range of topics than traditional techniques allow. Further, the use of low-cost hardware with advanced capabilities allows undergraduate students to study high-end concepts without an undue burden on their technical skills or the departmental budget. In this work, we have illustrated projects ranging from hardware-in-the-loop spacecraft simulators to fully functional roving sentries using a simple library of actuators and sensors. Students have used this equipment to study problems ranging from robot-assisted urban search and rescue to autonomous harbor security. It is this sort of low-risk hands-on experience with high-end concepts that is the best outcome of the use of the techniques discussed in this work.

Our experience has shown that the most efficacious and straightforward interface technology is a simple RS-232 serial link, and that the Pontech SV-203 servo controller provides a simple interface between software and hardware.

The use of low-cost hardware does have drawbacks, such as limited accuracy, variations in resolution, dead-zone, and accuracy between motors of the same type, and (of course) limited capabilities, as compared with high-end versions. These limitations do, however, serve to force the student to be aware of such practical issues. Student investigations can range from a simple Denavit-Hartenberg forward kinematics assignment, to a genetic algorithm study of gaits for a modular robot design. It is hoped that these examples will serve as useful ideas in developing robotics laboratory exercises and projects.

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