Robot Stories:
Interdisciplinary Design with Autonomous Mobile Robots

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Abstract

Over the past seven years, interdisciplinary teams of engineering students have designed mobile robots to compete in an annual robot contest. Open to all students that have completed engineering physics, the mobile robotics course requires teamwork, project management, and a mixture of theoretical understanding and laboratory skills. Mobile robots are constructed to compete in events ranging from maze navigation to sumo wrestling. Students develop skills in both mechanical and electrical fabrication while designing mechanisms, electronic circuits, and computer programs to support autonomous, situated operation. Each spring semester the students' work culminates in a public contest held during engineering open house that is viewed by several thousand students, parents, and visitors. Contest events are designed by a committee of past-year participants and are different every year. Robots are constructed from a kit of parts including a specific microprocessor, motors, batteries and an assortment of sensors. Students generally add a wide variety of creative accessories such as extendible manipulators, decoy beacons, and air cannons. Late night sessions in the laboratory, unique contest strategies, exotic robot features, and satisfying student outcomes provide an ample source of stories to be shared.

Beginnings

The first Kansas State University mobile robot contest (1993) was an offshoot of an informal experiment in undergraduate research, the MARS Lab (Mobile Autonomous Robotic Systems Laboratory) [1]. The following year, a mobile robotics course was developed to support and enhance these activities. The contest is now in its seventh year and continues to serve as a showcase of our students' work and as a vehicle for interdisciplinary engineering education. This paper briefly describes the mobile robotics course and the mobile robot contest [2] and then relates several stories about the students' robots. It is hoped that some measure of the students' success and excitement will be apparent and that this work may motivate similar efforts at other institutions.

Part I: The Robot World

The Mobile Robotics Course

The mobile robotics course is an interdisciplinary offering open to all students that have completed engineering physics. While virtually all engineering and physics departments have been represented over the years, the majority of students are drawn from electrical and computer engineering, mechanical engineering, and computer science. Course advertisements advise students to consider the multi-disciplinary nature of the course when forming teams. The instructor groups those students enrolling as individuals into suitable teams. It has become common practice for students either to repeat the course for additional credit (when permitted by their curriculum) or to participate in the course without additional credit in succeeding years. Enrollments in the course have varied between twenty and sixty students.

The course is offered for three semester hours of credit and includes two hours of recitation and a three-hour laboratory each week. Fundamental issues and operating principles of autonomous mobile robots are discussed in the recitation sessions. A wide variety of related technical topics are presented on a *just-in-time* basis. Laboratory activities include the design and construction of a working mobile robot. An underlying objective of the course is to support participation in the annual mobile robot contest.

Topics discussed in the course include microcontroller resources and programming, sensors and electronic interfaces, analog-to-digital signal conversion, dc motor operation, pulse-width-modulation, batteries, drive-train configuration, gearing and torque requirements, electromechanical efficiency, feedback control system fundamentals, robot navigation strategies, coordinate-system transformations, and C-language programming applications.

Each student team is required to purchase a kit of parts, which includes a microprocessor system printed circuit board set and the electronic components necessary for its assembly. In addition, the kit includes two dc motors, a set of rechargeable batteries, a variety of mechanical and optical sensors, a model airplane servo motor, a motor driver board and electronic components, a set of model car wheels and an assortment of related parts and supplies. With substantial bargain shopping, the current robot kits cost about $250 to assemble. They are sold to student teams for $150 and the engineering college subsidizes the difference.

The design teams are restricted only in that they must use the supplied motors, batteries, and microprocessor board set. Additional parts and supplies may be incorporated at the students' discretion and there is no requirement that all of the included parts be utilized. At present, the "robot brains" are based on the Motorola 68HC11 microcontroller and programs are written in "C". System power is derived from a 12V NiCad battery and the motors generate a maximum torque of 30 oz-in each at this voltage. Robot bodies are restricted only as to maximum size to maintain compatibility with contest events. Completed robots typically weigh about five pounds. Checkpoints are set throughout the course to encourage conformance to schedule. For example, dates are specified for completion of the microcontroller board set, the generation of robot movement, and the performance of a basic skill such as wall-following based on the utilization of one or more sensors under software control.

Following the robot contest, each team is required to write a report detailing the design of its robot. In addition to such things as mechanical drawings, electrical schematics, and program code, the teams are encouraged to include an informal narrative that chronicles the design experience. Because autonomous robots often exhibit emergent or otherwise unplanned behaviors that are easily ascribed to individual robot personalities, these descriptions can be very humorous. Copies of these reports are kept in the lab and provide a significant resource for future classes.

The Mobile Robot Contest

Each spring the Kansas State University College of Engineering holds an open house, which allows the public to view a variety of engineering faculty and student activities. The mobile robotics contest has developed into a focal point of this event. In each of the past several years over 10,000 students, parents, and visitors have viewed this contest.

In addition to staging the contest, design teams are required to develop posters describing their robots. Whenever robots are not running in the contest they are to be on display with these posters. The students are encouraged to discuss their robots and their course experiences with the public. For some students, this interaction is one of the more beneficial aspects of the entire enterprise. On more than one occasion these discussions have led to on-the-spot job interviews.

On the day before the contest, all robots are impounded and the class is invited to the City Park for a picnic. This arrangement effectively moves the series of "all-nighters" one day backward in time. All students are then encouraged to get a good night’s rest in preparation for open house weekend.

The Contest Committee

Each year a contest committee is formed comprised of students that participated in the contest the previous year. The committee is responsible for the design and construction of the contest, the development and interpretation of contest rules, and the judging of the contest.

Recent Contests: 1996-1998

In 1996, the contest was organized as a sequence of six events: line following, maze, quarter-pipe, beacon chase, cliff-and-tunnel, and blindfold football. Each event required a different combination of robot skills ranging from shaft-encoder-based navigation, to non-contact wall following, to object manipulation. One robot at a time ran the events with the winner being the robot with the shortest time of completion. The 1997 contest committee decided to implement a contest theme called "Escape from Alcatraz". The sequence of events included breaking out through the basement dungeons, calling the ferry (by placing ping pong balls in designated locations) to get off the island, riding the ferry across the bay, and getting past the robo killer-cops of San Francisco. The event was constructed in parallel, providing head-to-head competition, with the winner being the first robot to get past the robo killer-cops. The "killer-cops" were special-purpose robots programmed to chase and collide with the robot contestants.

In 1998, the contest was divided into two separate events, the first being an elaborate maze incorporating various ramps and tunnels, and the second a SUMO wresting competition. The first event was constructed as two mirror-image mazes leading to a common winner's circle. The SUMO event was returned to the contest by popular request after a two-year hiatus.

It is interesting to observe that those events involving robots crashing into one another (blindfold football, robo killer-cops, and SUMO) are the biggest crowd pleasers. The audience cheers most loudly when parts fall off the robots.

Mobile Robot Facilities

The primary home for the laboratory portion of the mobile robotics course is the Control Systems and Robotics Laboratory. This facility is provided by the Electrical and Computer Engineering Department and is dedicated to the mobile robotics course during the spring semester. The standard instrumentation required for the electronics portion of the work is available in the laboratory. Computers are positioned at each lab station to support programming and basic electronic fabrication tools such as soldering stations are located at each bench. Students also have access to a small shop that houses bench-top tools such as a band saw, drill press, and a sander-grinder as well as a variety of standard hand tools. Clean up and safety equipment is also provided.

Cabinets are provided in each facility to store miscellaneous parts and supplies. Students are encouraged to donate excess parts and supplies to the cabinets in exchange for needed items. Presently, the events are constructed on a total of eight 4x8 sheets of plywood and are positioned on the laboratory floor so students can practice on them with their robots.

Students check out laboratory and shop keys to provide access during the evening hours. As the intensity of student effort increases and the "all-nighters" begin, it is critical to maintain a helpful and enthusiastic faculty presence. This often entails sharing a pizza with students well after midnight.

Part II: Robot Stories

Robo Killer-Cops

For two consecutive years, the contest events concluded with a run for the finish line that required getting past a pair of robots designed to impede the robot's progress. Several of the stories recounted below involve these robots and the strategies used to bypass them. The first year they were simply called *guard robots*. The second year they were incorporated into the overall contest theme and became *robo killer-cops*. These robots were endowed with minimal sensory perception. They had two "eyes" implemented with modulated-IR detectors and a bumper system capable of detecting contact at left front, front, and right front. All robots were required to maintain an IR beacon so that the guard (killer-cop) robots could locate them. The guard robots would then attempt to ram the contestant robots. The guard robots were equipped with software routines that supported three modes of operation; search, attack, maneuver. The maneuver mode of operation prevented the robots from becoming stuck in a corner and allowed them to find their way around intervening obstacles while pursuing a beacon signal. In addition to being an integral part of the contest event, these robots served as an example of simple, yet ruggedly constructed robots of base-line capability. The software design was presented to the class in flowchart form as an example of useful coding structure.

Trickery and Deception

In order to avoid the guard robots a number of tricks were used. Two of the most notable were those employed by *Rho-Bot* and the *Mystery Machine*. The rules for the contest event involving the guard robots required that a 40KHz IR beacon further modulated at 125 Hz be carried by all participant robots at a vertical height of six to eight inches. The guard robots would then "home in" on this beacon.

Rho-Bot was designed to carry its beacon at a height of seven inches but at the end of a long, swinging tail. As the guard robots approached the beacon, it would move from side to side and additionally would focus the point of attack several inches behind the main body of the robot. While the guard robots vigorously and helplessly chased the swinging beacon, Rho-Bot located the exit beacon and drove into the winner’s circle.

Mystery Machine used a slightly different approach. This robot carried its beacon atop a six-inch pole mounted on a weighted base. While carried on-board the robot, the beacon height was eight inches. Upon entering the event, the beacon and pole assembly was released by the robot. While free standing on its base at ground level, the beacon height was six inches, still within the required vertical window. Electrical connection to the beacon was maintained by an umbilical cord slowly unreeled by the robot as it moved away from the point of deployment. As the guard robots attacked the beacon it would slide but not topple and the Mystery Machine proceeded directly to the winner’s circle.

Like Cats and Dogs

Much to the joy of the designer’s father, *Cobble Job* was constructed of forty-year-old "erector set" parts. Little did anyone know that this robot would provide one of the most hilarious episodes in the history of the mobile robot contest. Once again, the motivation was to avoid the dreaded guard robots. It was Cobble Job’s strategy to switch on its beacon while still in the preceding event thereby activating the guard robots prematurely and causing them to remain in "search-mode" for an extended period of time. It was hoped that Cobble Job could then enter the final event with the guard robots in disarray and race toward the exit before being discovered.
A bit of background information is required here. In this particular multiple-event contest,

entry into each event required passing through a gate of a specific height which would activate a top-mounted switch on the robots. This switch would signal a robot that a new event had been entered to which it would respond by executing a different code segment. The event immediately prior to the guard robot finale was a cliff and tunnel event requiring that the robots travel through dark tunnels and make hairpin turns while avoiding falling off cliffs. The event ended with a long tunnel to be entered at the rear of the event and exited toward the audience. The audience would wait in anticipation of the emergence of the robot and then would cheer its arrival. The robot would then make a ninety-degree turn to pass through the gate into the final event.

Now, how would this strategy work? Cobble Job would turn on its beacon while still atop a cliff and before entering the final tunnel. The beacon would be visible to the guard robots from that position. In response to the beacon the guard robots would enter the "search mode". Of course, Cobble Job would then disappear from sight. While searching, the guard robots would repeatedly spin (looking for a beacon signal) and then move forward (hopefully to a better vantage point). It was expected that by the time Cobble Job was to enter the final event, the guard robots would have wandered far out of position and might not be able to find and catch Cobble Job before it could exit the event. Cobble Job would not waste time with any additional maneuvers, but would beeline toward the exit, a distance of about eight feet.

Well, according to plan, Cobble Job switched on its beacon and entered the tunnel. The guard robots began searching. Randomly, one of the guard robots worked its way backward through the event gate and entered the cliff and tunnel event. This placed the guard robot at the exit of the long tunnel. It spun and located Cobble Job's beacon. Full speed ahead! The guard robot made initial contact with Cobble Job at about mid-tunnel. While in attack mode the guard robot was programmed to ram its victim, back up a few inches, and then charge forward again. Constrained by the tunnel, Cobble Job could not get away. Those close to the cliff and tunnel event could hear a mighty ruckus. Then, just as the need for a rescue became apparent, the second guard robot somehow wandered through the event gate and proceeded up the tunnel. Now three robots were engaged in mortal combat. Cobble Job could only assume that the tunnel walls were moving while the guard robots were locked in a frenzied attack. Lying prone atop the event, Cobble Job's designer reached into the tunnel from one direction while another student attempted to reach the warring robots from the opposite end. The crowd cheered. The contestants were helpless with laughter. Each time a helping hand managed to reach the robots, it was rapidly withdrawn, slashed by the sharp aluminum edges of the guard robots' bumper systems. At last the robots were extracted, wheels spinning and beacons flashing.

Vacubug and the Air Cannon

In the "Escape from Alcatraz" contest, the task of capturing ping pong balls and placing them in the locations required to either call the ferry or to inhibit the opponent from doing the same proved a difficult task. Actually, calling the ferry was easy enough, but inhibiting the opponent required placing a ping pong ball in a trough located some eighteen inches above the playing surface. Access to the trough required moving up a steep slope. Some of the contestant robots lacked either sufficient traction or power to make the climb. Others lacked the necessary clearance fore and aft to make the transition onto the ramp.

Only *Vacubug* found a solution. A small computer fan was mounted at one end of a cardboard tube just large enough in diameter to accommodate a ping pong ball. The tube could be rotated length-wise about this end by a servomotor. Thus the tube could be extended forward to touch the ground ahead of the robot in the manner of an elephant's trunk or could be rotated upward to a position several degrees beyond vertical.

Vacubug would approach a ping pong ball, rotate the tube forward and turn on the fan, drawing the ball into the tube. After rotating the tube through vertical and turning off the fan, the robot would move to a position at the bottom of the ramp and rotate the tube forward to a predetermined position. It would then turn on the fan in reverse direction and blow the ping pong ball out of the tube and into the trough. To the amazement and amusement of the crowd, Vacubug could fire the ping pong ball into the trough nearly every time.

A Tale of Two Extremes

How could two robots be less alike? *Speedracer* was meticulously constructed. A four-wheeled, automobile-like robot, it featured rack-and- pinion steering and a tubular frame with roll bars. Hollow axles permitted electrical connection to modulated, infrared transmitter-receiver pairs mounted within the wheels. This robot was capable of turning around in tight spaces by executing a "Y-turn" without contacting the walls of a maze. Speedracer had the feel and performance of a precision racing machine. The only difficulty with this robot was that the software code was so long that it required additional memory chips and intricate paging schemes. In addition to providing amazing maneuverability, provision was made for precisely calibrating sensors under varying conditions of ambient light (both visible and infrared). The software listing was impressive in both its complexity and in its length.

In contrast, *Gremlin* was held together with hot-glue. Viewed from a distance it looked like a ball of spaghetti with electrical wiring to sensors and actuators being longer than necessary and randomly routed. Modifications could be quickly made, but repairs were constantly required. Software for this machine was developed in an atmosphere of marginally adequate sensory input. Actuators could not be counted on to execute instructions with any precision. Maneuvers were approximate. The software needed to be more clever than precise.

Whereas Speedracer was mechanically robust, Gremlin was fragile. In the laboratory, and during practice runs on the contest events, Speedracer consistently out-performed Gremlin. However, on contest day, while Gremlin was bumbling along, bumping into walls, but making progress, Speedracer was not working at all. Its precision performance was too dependent on carefully situated calibration and the varying light conditions with shadows and flashbulbs and atrium lights precluded the necessary measurements and calculations. Gremlin worked as well (or as poorly) as ever, and completed the contest events oblivious to its surroundings.

Beefcake and the Automatic Transmission

One design team endowed their robot, *Beefcake*, with a two-speed transmission. A model-airplane servomotor activated shifting. The robot was designed with a very low gear for the SUMO contest and a higher gear for the other events. Also, the robot used tank tracks for locomotion and sharp turns required additional torque. Shaft-position encoders provided the capability of making exact ninety-degree turns. So, as a corner was approached in the maze event, Beefcake would shift gears just long enough to make the turn.

Beefcake was certainly the robot to beat in SUMO and promised to be a formidable competitor in other events as well. However, Beefcake sustained damage to one of the slotted disks used to measure shaft position during a heated SUMO competition. As a result, the robot became rather helpless in the other events. Beefcake's designers could only point to their pride and joy, the automatic transmission, and dream of the championship that could have been.

Coolest

Each year a "coolest" award is presented by a panel of judges selected from the office support staff from the several engineering departments having students in the contest. The term "coolest" has never been defined but is instead left to the interpretation of the judges. One year the winning robot, *Rob* spoke to the judges. It identified itself and wished them a good day. Another winner, *Pandora's Box* was constructed entirely within an aluminum box with the only visible signs of operational apparatus being narrow tracks on the bottom for locomotion and a band of tiny holes around the periphery used for sensors.

Much to the frustration of the designers who are justifiably proud of the many technical capabilities built into their robots, a noticeable trend in the judging has emerged. The judges seem to consider the robots with the least outward sign of technology to be the "coolest".

Part III: Perspectives and Directions

Student Comments

There is ample evidence that the mobile robotics course works. Anonymous comments on student course evaluations, conclusions drawn in final reports, and personal communications from past and present students indicate this to be an important and valuable experience. The following student comments reflect the nature of the experience from the student's perspective.

"This class is one of the few where you get hands-on experience, to apply what you have learned, and a chance to utilize your own ideas. It is easily the class I have learned the most from in college" [Student course evaluation, 1997].

"...every problem yielded a new thing learned. I feel lucky to have had the experience. The hands on experience taught me more in a semester about some things than I have learned in summed years prior, about the same things. It's a great class, and a great opportunity. It's the kind of thing that hooks you and makes you wish you could do it full time." [Student final report, 1998].

One team describes several built in functions periodically executed by their robot but hidden from the programmer [Student final report, 1996]. Printable functions include:

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RELEASE_SMOKE (int TIME, int AMOUNT)
BLOW_MOTOR_DRIVER (int WHICH)
IRITATE_PROGRAMMER (int TIME)
IRITATE_PROGRAMMER'S_GIRLFRIEND (int WHICH)
YOU_CAN'T_MAKE_ME_DO_IT (int ROBOT)
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"I learned a lot from this class, both from the work we did on our robot and by observing others. By the end of the competition, the better features of the successful robots became apparent. Some of these were *planning ahead and time organization!* " [Student final report, 1996].

"The phrase, *let's do something even if it's wrong,* has a home in robotics. The fact is you are going to do something wrong, it's called learning. The sooner you get started, the sooner you will discover your errors, and the more time you will have to correct them." [Student final report, 1998].

"Overall I found this to be the most rewarding experience in my career at K-State, and I think I learned a lot about engineering that I never would have in a regular classroom." [Student final report, 1997].

New Directions

Currently, the microcontroller system used in each of the robots is based on a Motorola 68HC11 board set designed at the Massachusetts Institute of Technology and the Interactive-C language developed for this application [3]. The system has evolved through several modifications and includes a motor driver and power supply board of original design based on the SGS Thompson L6203 H-Bridge. Students have modified the software so that it requires less memory overhead and have written several custom library functions. They refer to this software as "small-IC".

A new microcontroller system based on the Motorola 68HC12 is being designed. Sensor- and actuator-specific software routines are written in assembly language as functions callable from a version of BASIC developed especially for this processor. The hardware sub-systems are designed to be modular allowing multiple levels of functional complexity. The motivations for this project are several, but a particular outcome will be the better support of both introductory- and advanced level course offerings while retaining hardware and software compatibility.

Work is underway to develop a mobile robotics web site to include a bulletin board, which will facilitate interaction among current students and past participants around the country. Many contest veterans are interested in keeping up with current activities and will serve as a resource for new students who will be encouraged to post novel design ideas for discussion. The web site will include links to past and present students' home pages as well as pictures of past robots and access to the reports written by former design teams.

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