Robot Soccer for Undergraduate Students

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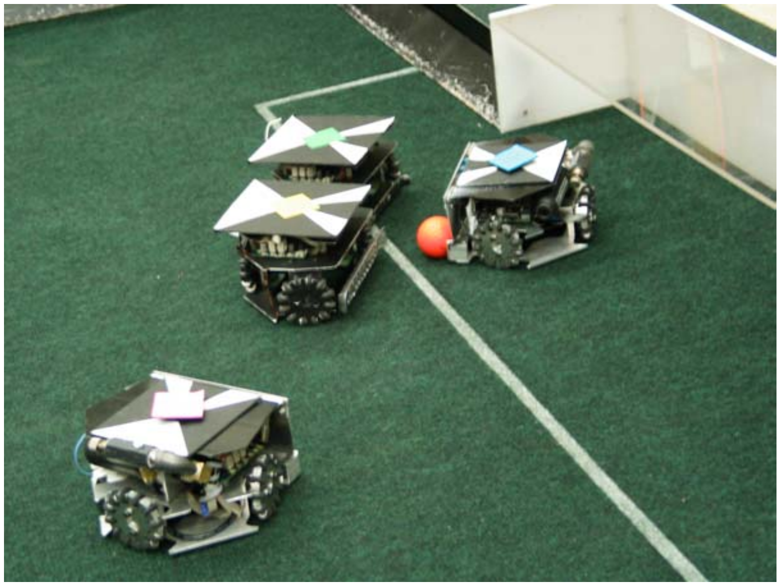

Current ABET criteria for engineering programs include the longtime requirement of a “major design experience” with “realistic constraints” in which students apply knowledge and skills acquired in earlier courses [1]. This article describes a capstone design experience employed successfully for the past five years in which teams of senior engineering students design, build, and program robots to play soccer.

Our decision to pursue a robotics approach was originally motivated by [2], which describes a senior level project to design robots that can follow a maze of white lines on a dark floor. We started with a similar line-tracking robot project in 1997 with a small number of students participating. After reasonable success in that initial experience, we changed our focus to robot soccer. From the outset, we patterned our project after simplified versions of international robot soccer competitions [3,4,5] in which a dedicated computer processes images from an overhead camera and sends commands to the robots via wireless links. To fit the constraints of senior-level design projects, we chose a format in which teams built a single robot that fit in a 12 inch cube. The robots and the competition have evolved considerably over the years; competition is now two-on-two with much smaller robots and the quality of play has steadily improved.

We feel strongly that the design and development of autonomous robots provides an ideal capstone design experience. Several reasons can be identified. First, robotics requires true system-level design. Teams in our project must integrate a wireless communication system, computer vision, feedback control, real-time programming, artificial intelligence, and mechanical design. Second, the overall project is much too ambitious for a single student, so teamwork is essential. Moreover, teammates come from different majors (electrical, computer, and mechanical engineering) with different areas of emphasis within those majors, so teams are inherently multidisciplinary, thus addressing an important need in every engineering curriculum [1, 6, 7]. Third, the design space is large, and students are free to explore a wide variety of design alternatives. As students move from general product requirements to detailed specifications, it is natural to have regular design reviews and to teach principles of effective system design, project management, and communication – valued skills in all graduating engineers [8, 9, 10]. Fourth, while few employers will hire students to build robots, the project management and technical skills the students develop are widely applicable. Finally, robotics is fun and students are naturally motivated to build the best systems they can, leading to an exciting final competition that attracts many spectators and builds enthusiasm for engineering.

Our success with robot soccer has resulted in a complete overhaul of senior projects in our department. Students select one from a set of well-defined projects, each patterned on a template originally developed for robot soccer. The next sections discuss this project framework, how the robot soccer design project functions in that framework, the current status of our project, and our plans for the future.

The Senior Project Framework

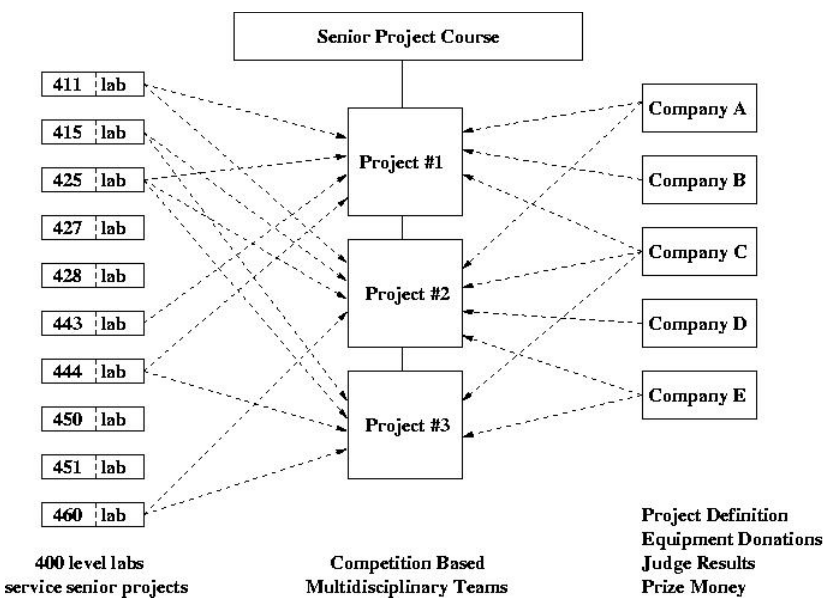

Figure 1. Senior project framework.

Prior to the development of the robot soccer project, students in our department were essentially on their own in defining a senior project, obtaining necessary resources, and completing the work. Convinced that the overall quality of the experience could be improved significantly by giving the students more direction while still giving a choice, we envisioned a more structured framework for capstone projects as shown in Figure 1.

The figure depicts the general structure of senior projects in our department today. Students must register for a one-semester class associated with the project of their choice, making sure that they have taken the prerequisite senior-level courses. Each project is completed by multidisciplinary teams of students, most are structured in the form of a competition, and many were developed with some form of industrial participation. In this framework, industrial partners can work with the faculty to define or modify a project to make use of specific skills they would like the students to develop. This may, in turn, necessitate changes elsewhere in the curriculum to give students adequate preparation. Based on our experience, this type of input from industry helps keep a department's curriculum current and relevant.

Without any pressure from the department to do so, several of our colleagues have developed projects related to their own areas of interest and the mix of available projects changes each year. We feel that faculty sponsors are motivated in part by the success of the robot soccer project in increasing student interest in robotics and in preparing participants for graduate research in our robotics lab. Examples of other current design projects include: a software radio, a VLSI chip, an MP3 player on an FPGA, and the human interface for an optical fiber activity center.

Each senior project is structured as a one-semester, four credit hour class. (Robot soccer was originally taught as a two-semester sequence, but fitting each project into a single semester makes scheduling easier for faculty and students alike.) Each class has a *technical portion* specific to that project and a *business portion*, shared by all concurrent projects, that teaches a systematic design process. The content of both portions is concentrated into the first four weeks of the semester. All students registered for a senior project meet for two hours each week for the business lectures, generally taught by an adjunct faculty member with significant industrial experience.

The business part of the senior project framework gives us an excellent opportunity to expose students to important topics not specifically addressed elsewhere in the curriculum. Since the students are themselves involved in a significant design experience, it is natural to address topics that help them produce a better design, work better as a team, and better manage the development process. For example, teams are required to produce written control documents summarizing their design decisions and laying out their future schedule. Teams must also prepare presentations for design reviews. Business lectures and associated assignments are timed in such a way that teams can immediately apply what they have learned in their own projects. Examples of topics addressed in these lectures are given below.

- Working effectively in teams
- Finding out what the customer wants and needs
- Moving from customer needs to product specifications
- Product architecture and concept generation
- Developing project schedules
- Giving effective presentations
- Business processes overview
- Engineering economics

Class Structure

In addition to the two hours of business lectures, students enrolled in the robot soccer class have two hours of technical lectures each week. These lectures cover a variety of essential topics and each is accompanied by a laboratory assignment to be completed by each team. The pace of coverage is aggressive: teams are formed the first day, and by the second week they will have built a prototype robot that can be driven from the computer keyboard via a wireless signal. While a lot is required of them in the first month, students see tangible results from their labors and the experience gives them confidence to complete their own design and implementation.

The technical portion of the course is divided into a *low-level* and a *high-level* track, each of which has one lecture and one lab assignment per week. Each lecture presents information required to complete the associated lab. The low-level track focuses on the components in the hardware block (shown in Figure 2), as well as the creation of fundamental skills and utilities. The contents of labs in the low-level technical track (LLT) are summarized below.

- LLT 1: **Robot construction and design**. Each team builds a prototype robot that can be driven from the computer keyboard. The RF link, the microcontroller, and the DC motors must be integrated. Unoptimized prototype software is provided to the students so they can get something working right away; most teams start optimizing that software from the outset.
- LLT 2: **Computer vision**. Students are given unoptimized software to process the image from the overhead camera. They must modify the software to return the ball position, the position and orientation of both robots, and the velocity and angular velocity of each. With some effort, most teams are successful in optimizing the code to achieve sample rates of 30 frames/sec, about three times the rate of the unoptimized code they start with.
- LLT 3: **Low-level control**. Students write the C code for a specified set of skills and related utilities. Skills developed in this lab include (a) moving with a particular angular speed for each wheel, (b) moving with a particular linear and angular speed, (c) moving to a particular point with a particular orientation, and (d) turning to a particular angle.
- LLT 4: **Motion planning**. Students implement a waypoint path planning technique of their choosing that can be used in conjunction with a deliberative AI approach. They also explore a potential fields method suitable for use with a reactive AI approach.

The high-level track focuses on the creation of a software decision structure to support intelligent play, corresponding to the plays and AI in our layered control architecture. The associated labs use a custom simulator that has the same interface (desired velocity and angular velocity) as the hardware robot, as shown in Figure 2. The contents of current labs in the high-level technical track (HLT) are summarized below.

- HLT 1: **Simulator and software architecture**. Students are introduced to the recommended software architecture (shown in Figure 2) and to the simulator and its operation. They are given sample client code that handles the connection to the server, and they are given object code for a set of unoptimized skills. Each team must write code to make its simulated robot score on a simple play against an immobile opponent.
- HLT 2: **Play construction**. Students are shown alternative methods of implementing plays, each a sequence of skills, discussed in LLT 2. An example play might be blocking a moving ball, pushing it up field, and taking a shot. Students must implement at least 4 plays of their choosing, and they are to develop enough code to defeat a relatively unskilled opponent that we provide.
- HLT 3: **Artificial intelligence**. Students explore methods of picking good plays given the current game situation. Each team is required to devise and implement a consistent AI mechanism. Commonly selected approaches include deliberative, reactive, and hybrid techniques [4]. Each team's simulated robot must defeat a reasonably capable opponent that we provide.

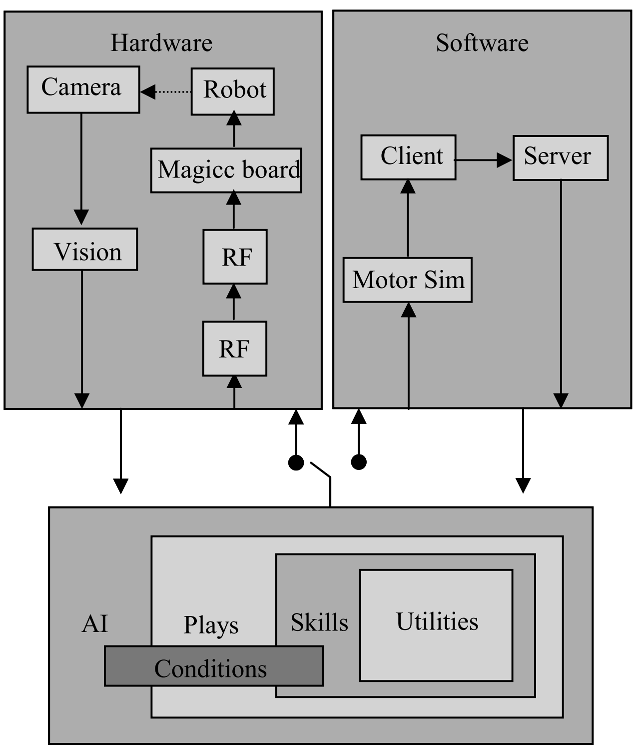

Figure 2. System architecture.

Less than one week following the last of these technical lectures, students participate in two practice competitions, the first using the simulator and the second using their prototype robot. Throughout the semester, practice competitions using hardware robots are held approximately every other week. Each team also has a monthly design review in which they present key elements of their design and strategy and discuss their progress. Students may not attend another team's design reviews so all information presented remains confidential through the final competition. At the end of the semester, each team is required to create a website containing all code and design documents. These websites are available to teams in the next year's class and play an important role in the steadily improving level of play.

Competition Rules

The first set of rules in our competition has to do with equipment constraints. Teams are free to choose from our collection of used wheels, motors, batteries, and other miscellaneous parts, or to purchase their own.

However, we require them to use major hardware components that we provide. These include a Linux machine, a framegrabber connected to the overhead camera, a single wireless transmitter and two receivers, and a computer board developed at BYU containing a 30 MHz microcontroller, 1M memory, A/D and D/A ports, and digital I/O port [11] for each of their robots. Each team is limited to the available computing resources: all their code must run on the Linux machine or the on-board microprocessor. Each team is entirely responsible for the physical design and construction of their robots.

The second set of rules has to do with the robots and the playing field. Beginning in the 2003 competition, we adopted the specifications of Robocup Smallsize (F-180) League [4]. The field is 290 cm long, 240 cm wide, and consists of a green carpet with white lines painted for the halfway line, center circle, and goalie box. The field is surrounded by a wall that is 50 mm high and 50 mm wide, forming a 45-degree slope that faces the field of play. In an extension to the Robocup regulations, a piece of aluminum is attached to the outside of the walls that extends upward and bends to the center, keeping the ball in play. An orange golf ball is used for the soccer ball. Each robot must fit inside a 180 mm diameter cylinder and has a maximum height of 150 mm. At no time during competition can any part of the robot (such as a kicker) extend beyond the 180 mm limit. The 150 mm maximum height includes the robot’s removable and uniquely colored top that allows identification by the vision system. Any portion of the robot visible to the overhead camera other than its colored top must be black or dark gray. Finally, robots are prohibited from controlling the ball in such a way that opponents can’t take it away. Nothing can be used to physically attach the ball to the robot (such as adhesive, or suction). Concave openings in the perimeter of the robot that allow unfair control are prohibited; from any perspective above or to the side of the robot at least 80% of the ball must be visible.

The final rule set deals with the actual competition format, the details of which have changed significantly over the years. The final tournament uses a double-elimination format. Games are divided into three-minute halves; the clock stops only when a team calls a timeout or when the referee suspends play. Teams place their robots in the field according to normal conventions; the ball is placed in the center circle, and then the referee signals for play to begin. Once play begins and is signaled to the robot, no further human interaction is allowed, including touching the robot or entering directives via the computer.

To handle notification of goals and fouls, we use a simplified version of the Robocup Referee Box that sends (from a human operator via a referee interface) each team’s computer a message with appropriate details. After fouls and goals, a team’s robots must autonomously position themselves relative to the ball for the ensuing kickoff or free kick. No offsides calls are made, and teams do not have a designated goalie. Fouls are called at the discretion of the referee. Physical contact is discouraged but unavoidable in practice. Robots that exhibit aggressive or uncontrolled behavior can be called for fouls and even ejected if an opposing robot is damaged.

April 2003 Tournament

The tournament hosted at BYU in 2003 consisted of six teams of students with five students on each team.

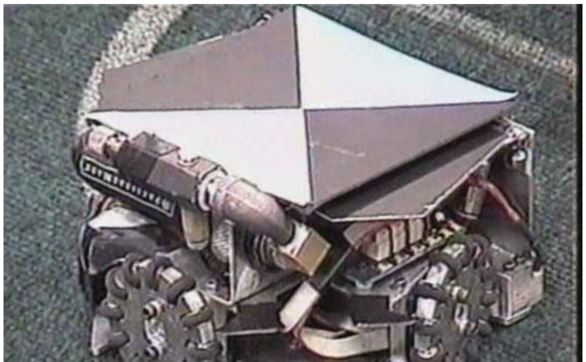

Figure 4. Los Tiburones omni-directional robot.

The tournament was a double elimination tournament lasting approximately two hours and was attended by approximately 300 spectators. Figure 4 shows one of the two identical robots of Los Tiburones, the winning team in 2003. The robot is a three wheel omni-directional design that also has a kicker powered by a $C0_2$ cartridge. Figure 3 shows one of the robots of team Pilas, a strong contender with solid performance. This team opted for simple, light-weight hardware which enabled greater agility and a more complex playing strategy. Figure 5 shows one of the robots of team Xbots. This robot included a protruding tail that facilitated an extremely effect spin-and-score maneuver. Figure 6 shows additional photos from the tournament.

Figure 3. Pilas vs. Los Tiburones.

In the final tournament, some robots were still getting stuck on walls, and one team's robots were top heavy and occasionally tipped over. Overall, the level of play was very respectable. Only one team did not score a goal in the tournament, and 4.4 goals were scored in each game on average. In this first year of two-on-two play, most teams adopted fairly simple playing strategies, usually keeping one robot forward and one behind, and switching in certain recognized cases. We believe that intelligent multiagent play and teamwork will increase significantly in the next few years. A summary video of the tournament can be downloaded at http://www.ee.byu.edu/~beard/.

Figure 5. Team Xbots

The popularity of the final competition is a noteworthy measure of success. To accommodate many more spectators, it is now held in an open commons area on the ground floor of the engineering building, and crowds in excess of 200 people are common. Moving the camera, field, and computers to a different location just days before the final competition presents significant challenges, but students appreciate the opportunity to better showcase their work. The competition is exciting to watch and often gets covered in local newspapers and television.

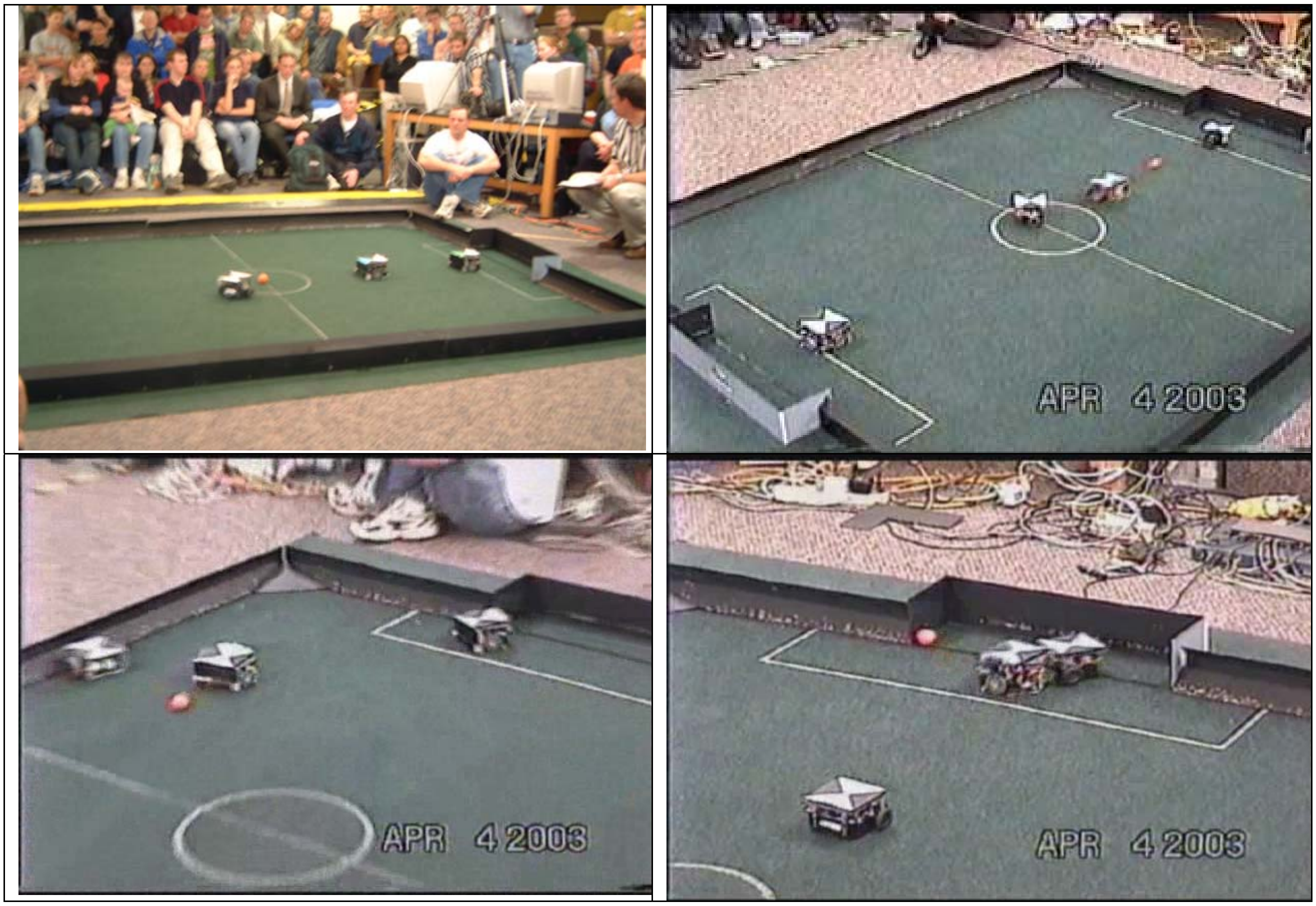

Figure 6. Action shots from the tournament.

The competition also generates significant student interest. Of approximately 120 graduates from our department each year, we had 24 participants in robot soccer in 2001, 40 in 2002, and 30 in 2003. The project's popularity has also affected enrollment in other courses; we've seen significant increases in the real-time systems and feedback control classes that are prerequisites for robot soccer. The project has also affected the content of other courses: the control class has been reorganized with labs focusing on mobile robots. Control theory and robot soccer are taught alternate semesters, so they are able to share the lab facilities.

Students participating in the class are, by and large, successful in completing their projects. Thanks to helpful labs, good documentation, and great TAs, we have had only one team out of 34 that was unable to field a working team by the final competition. The project is successful in promoting teamwork skills. In general, teammates pull together, cover for each other in times of need, and develop a strong team identity, often to the point of having team logos and team shirts. Students note several benefits of participating in challenging, team-based competitions, not the least of which is the course that job interviews take once they mention their involvement in the project. Interviewers ask questions about the technical design and about how the team worked together in completing an aggressive project with hard deadlines, topics about which robot soccer participants can talk enthusiastically.

Our industrial sponsors continue to play an important role in the success of the robot soccer project. Although expenses for the project are relatively modest, industrial funding has helped leverage departmental resources in acquiring cameras, frame-grabbers, RF links, microcontroller boards, and motors. In addition, our sponsors have generously provided $2000 in annual prize money for the top two teams. Notably, none of our sponsors do business in the area of robotics; they were attracted because of the systems engineering aspect of the project, teamwork requirements, the in-depth exposure to the design process, and the enthusiasm the project engenders. We invite our sponsors to send a representative to design reviews and most arrange their schedules well in advance to ensure that they won't miss our final competition.

In the future, we hope to expand industrial support for the project. Increased funding would allow year-round financial support for our TAs to keep our infrastructure up to date, to support outreach programs to local schools, and to provide support to partner schools. We would like to join with faculty at other schools to create an inter-collegiate competition for top undergraduate teams. To this point, participation of other universities has been limited to an IEEE Spectrum-sponsored student team from San Diego State University that participated in our tournament in 2000. We would like our students to have the opportunity to benefit from more interaction of this type, and our sponsors would support such a competition. We invite interested parties to contact us.

Conclusions

In this article we have described a new approach to the undergraduate capstone design experience that has been used successfully for the past five years in the Electrical and Computer Engineering Department at BYU. The project is built around a robot soccer competition in which students design small autonomous robots to play with two robots per team. Our experience shows that robotics provides a set of engineering challenges that are ideal for senior design projects, because it is naturally multidisciplinary and requires the integration of knowledge from across the curriculum.

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