DEVELOPMENT OF A SUCCESSFUL OPEN-ENDED ROBOTICS DESIGN COURSE AT THE HIGH SCHOOL LEVEL

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Abstract

We have developed an intensive, three-week summer robotics program for high school students. The program requires special teaching methods since it is offered to rising 10th through 12th grade students with diverse backgrounds, and a low student/teacher ratio to ensure all students grasp the material. We use a project-based learning approach, assigning labs, projects, and competitions specially designed to prepare students for the main element of the program, the design of a semi-autonomous robotic vehicle. The project culminates with testing of their vehicles on an obstacle course. In this paper, we report on the special teaching methods required for the course, reflect on changes that have positively and negatively affected the success of the program, and discuss results of a recent survey of former students.

Introduction

The annual Summer Academy in Advanced Science and Technology (SAAST) Robotics program, founded in 2005, is an intensive, three-week robotics program for talented high school students. The program is taught primarily by graduate students, and is structured around a principal project modeled after NASA's Mars Rovers. The students must teleoperate (via remote control and a webcam feed) a semi-autonomous truck to navigate and collect objects of interest from an obstacle course with various difficulties of terrain. The mission objective is to collect as many points as possible in a fixed time, with varied points based on difficulty procuring each item.

Special teaching methods are necessary to ensure success, since the program is offered to rising 10th through 12th grade students without prerequisites. A Project Based Learning (PBL) approach is key to introducing a large amount of material to the students in this context. Open-ended, specially tailored problems serve as building blocks for and culminate in the comprehensive open-ended principal project. Students get hands-on experience with mechanism design, electronics, CAD/CAM, and microprocessor programming. Targeted design reviews guide students with their designs and ensure teams will successfully complete the principal project. A low student to teacher ratio (in 2009, the ratio was 25:8, or 25:12 including residential teaching assistants) ensures students get the one-on-one mentoring they need.

The recent survey of program alumni shows that the students enjoy the project based approach, and they feel they have learned a great deal while participating in SAAST Robotics. Furthermore, participation in the SAAST Robotics program has had a positive effect on determining their field of study at the college level.

Relevant Work

Robotics is a truly integrative engineering discipline, combining mechanical engineering, electrical engineering, and computer science in a truly comprehensive field of study. This poses challenges to teaching and learning robotics that cannot be addressed in the traditional disciplinary learning paradigms.

Interest in robotics education and curricula has been gaining momentum in recent years, with many workshops offered at prominent robotics conferences [1-3] as well as workshops and resources specifically for K-12 education [4,5].

Most of the literature in robotics education discusses learning through hands-on applications of open-ended problems [5-9]. We use a PBL approach [10,11], which promotes active-, collaborative-, and self-learning among the students. In PBL, students work to solve an open-ended problem, generating multiple artifacts along the way, culminating in the final product. In our case, the artifacts are specific subsystems of the robot, such as the mechanical design, assembly, or control software for the rover. Our approach is similar to a Practice-Integrated Curriculum [12] in that it is lab-focused, the project changes yearly (although not dramatically), and student autonomy has increased over the years. Using a project-based method for this course enables the students to bridge the gap between their classroom and real life experiences [13].

Competition has been discussed as a method of advancing robotics, motivating the roboticist, and making the learning experience more extensive [14-17]. This is not only the case for roboticists at or above the college level: robotics competitions for the K-12 set have been growing in number and gaining in popularity [18-22]. In our program, the PBL approach, with carefully integrated curriculum and friendly competition, has proven to be very successful and well received by the students.

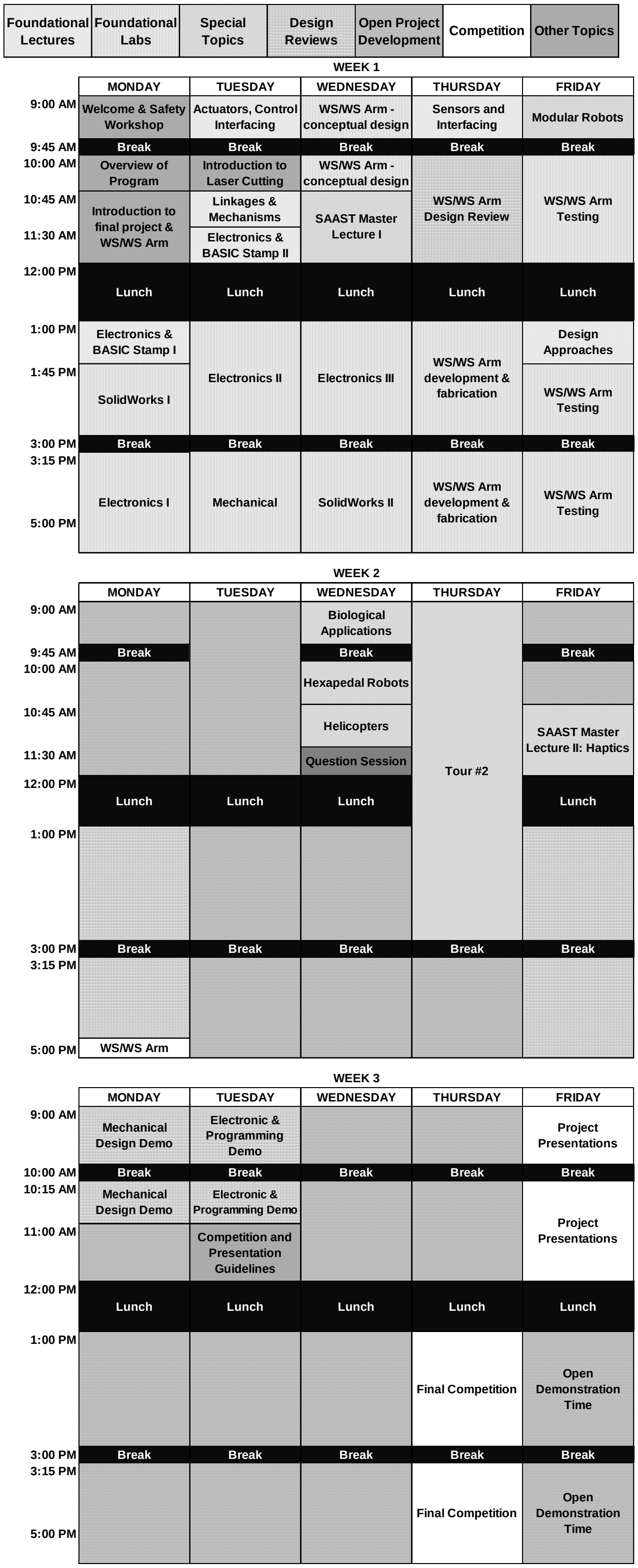
In this paper, we present our approach to teaching an intensive, three-week robotics program for high school students. The program is structured around a principal project modeled after NASA's Mars Rovers. We discuss our carefully designed, well-integrated curriculum, leveraging competition, and how the students receive the current program.

The paper outline is as follows. First we discuss the course schedule, the project-based curriculum, as well as how we overcome the challenges of teaching robotics to a diverse group of students. Then we present details of the principal project. We then discuss the results of a recent student alumni survey. Finally, we reflect on how the program has evolved over the past 5 years and conclude.

Course Curriculum

The curriculum is built around the principal project, with all direct instruction, labs, and assignments being relevant to the project. The course schedule is shown in Figure 1. In the first week, direct instruction by way of foundational lectures and labs on mechanisms, electronics, programming, and design ensure that the playing field is somewhat leveled and all students have the tools to solve all aspects of the problem on their own. Here we do not discuss the specific topics covered during these lectures and labs; the interested reader is referred to [23]. In the second and third weeks, student learning is generally self-directed, with mostly unstructured project development time. Intermittent design reviews and deliverables ensure that the students remain on track to successfully complete the principal project.

The principal project is a semi-autonomous robot that must maneuver an obstacle course. The students must teleoperate the robot from a remote location to navigate and collect objects of interest from an obstacle course with various difficulties of terrain. The students are able to view the course via an onboard camera and an overhead camera, and control the truck using a radio controller. The mission objective is to collect as many points as possible in a fixed time, with varied points based on difficulty procuring each item. The obstacle course used is shown in Figure 2. The principal project is a very challenging problem for even high school honors and AP students. A widely differing knowledge base among the students, combined



Foundational Lectures	Foundational Labs	Special Topics	Design Reviews	Open Project Development	Competition	Other Topics

WEEK 1

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
9:00 AM	Welcome & Safety Workshop	Actuators, Control Interfacing	WS/WS Arm - conceptual design	Sensors and Interfacing	Modular Robots
9:45 AM	Break	Break	Break	Break	Break
10:00 AM	Overview of Program	Introduction to Laser Cutting	WS/WS Arm - conceptual design	WS/WS Arm Design Review	WS/WS Arm Testing
10:45 AM	Introduction to final project & WS/WS Arm	Linkages & Mechanisms	SAAST Master Lecture I		
11:30 AM		Electronics & BASIC Stamp II			
12:00 PM	Lunch	Lunch	Lunch	Lunch	Lunch
1:00 PM	Electronics & BASIC Stamp I	Electronics II	Electronics III	WS/WS Arm development & fabrication	Design Approaches
1:45 PM	SolidWorks I				WS/WS Arm Testing
3:00 PM	Break	Break	Break	Break	Break
3:15 PM	Electronics I	Mechanical	SolidWorks II	WS/WS Arm development & fabrication	WS/WS Arm Testing
5:00 PM					

WEEK 2

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
9:00 AM			Biological Applications	Tour #2	
9:45 AM	Break		Break		Break
10:00 AM			Hexapedal Robots		
10:45 AM			Helicopters		SAAST Master Lecture II: Haptics
11:30 AM			Question Session		
12:00 PM	Lunch	Lunch	Lunch		Lunch
1:00 PM					
3:00 PM	Break	Break	Break	Break	Break
3:15 PM					
5:00 PM	WS/WS Arm				

WEEK 3

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
9:00 AM	Mechanical Design Demo	Electronic & Programming Demo			Project Presentations
10:00 AM	Break	Break	Break	Break	Break
10:15 AM	Mechanical Design Demo	Electronic & Programming Demo			Project Presentations
11:00 AM		Competition and Presentation Guidelines			
12:00 PM	Lunch	Lunch	Lunch	Lunch	Lunch
1:00 PM				Final Competition	Open Demonstration Time
3:00 PM	Break	Break	Break	Break	Break
3:15 PM				Final Competition	Open Demonstration Time
5:00 PM					

Figure 1: The course schedule. Note the emphasis on direct instruction in week 1, with weeks 2, 3 focused on open project development time, which fosters collaborative learning.

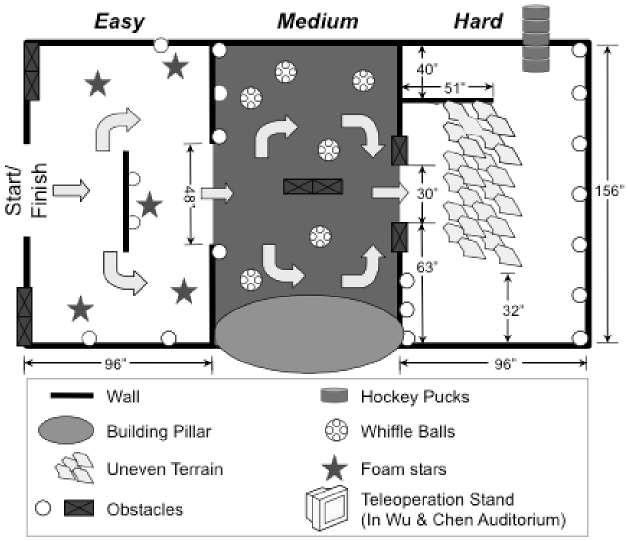


Figure 2: The obstacle course.

with the short three-week time frame, provides a difficult challenge to teaching robotics at the secondary school level. The curriculum is built to guide the students through the different aspects of the project even when they possess varying abilities.

Dealing with differing knowledge base

Robotics is an extremely multidisciplinary field, requiring an understanding of physics, mechanical and electrical engineering concepts, as well as computer science. In undergraduate courses, students have a basic understanding of physics, and at least some exposure to design, electronics, and programming. However, at the secondary school level, the multidisciplinary aspect of robotics poses unique and particularly difficult problems, compounded by the lack of prerequisites for admittance to the SAAST program. Specifically, since SAAST students are rising sophomores through rising seniors, levels of exposure to and understanding of physical concepts, CAD/CAM, and electronics vary widely. Programming experience also varies greatly among the students.

We address this problem by carefully choosing groups, ensuring the student to teacher ratio is small, and teaching basic concepts tailored specifically to the principal project.

Assigning Groups

Assigning effective groups is a critical step to ensuring success. To teach effectively, groups should be designed most importantly on diverse ability [24,25]. In order to gauge the students' abilities, each student fills out a survey on the first day of the course. The survey collects information about the students' past experiences, previous coursework, and any relevant hobbies. We use this information to form the most diverse groups of three possible, by dividing students based on their strongest of three subject categories: mechanical, electrical, and programming. We further divide the students into experience categories: novice, intermediate, and expert. Finally, we create the groups by combining one novice, one intermediate, and one expert, while taking care to include a person with knowledge in each of the subject groups.

In any setting, it is possible that one or more groups will fail to work together effectively. This can occur if students have clashing personalities, or if a student had embellished their experience on the survey. To overcome this, we reserve the right to change groups at the end of the first project, the World's Strongest, World's Smartest (WS/WS) Arm, which concludes in a competition on Monday evening of Week 2. Since the arm designed in this project need not be carried over to the principal project directly (indeed not all of the final robots included an arm), there exists an opportunity to switch groups if necessary without much disruption. This is still not a guaranteed method. In the past, we have been able to overcome poorly designed groups with close mentoring, equipping the students involved with techniques for overcoming disputes fairly, and advising the students to assign each team member specific roles and stick to them.

Teaching basic concepts

Since there are no prerequisites for applying to SAAST, some students have never taken a basic physics course. Programming, which may be offered in most secondary schools, is not often a required course, although approximately 20% of students in the SAAST Robotics program have experience programming. Other courses that would prepare students for robotics are engineering, electronics, and CAD/CAM, which are less available, and therefore need the most attention.

The instructional portion of the course is designed to provide the students with a basic understanding of the tools necessary to complete the principal project. The lectures and labs fall into these categories: linkages and mechanisms; actuators, sensors, control, and interfacing; the engineering design process; electronics and the BASIC Stamp; and SolidWorks. Since this is a short course, the information presented to the students is tailored specifically to the principal project. However, the students learn skills that they can apply to problems outside our lab.

Since most direct instruction occurs in the first week of the course, it is important to actively engage the students in the material right away. To keep the students engaged during lecture, we use active learning techniques such as asking the students questions, assigning short problems to be done in the classroom and reviewed, and non-graded oral pop quizzes. Demonstrations are used as often as possible, especially for difficult concepts such as linkages.

Carefully integrated projects

Completing the principal project successfully in a three-week period is extremely challenging and taxing on the students. By dividing the work into smaller, more manageable projects that integrate easily into the principal project, we are able to increase success rates and keep students on track.

The first project, the World's Strongest, World's Smartest (WS/WS) Arm, immediately engages the students in linkages and gear ratios, as well as programming and electronics. The goal of this project is to build an acrylic arm outfitted with an electromagnet that can repeatably pick up a hockey puck (with a metal plate glued on it) and deposit it on a target using a DC servo-motor (with potentiometer-based position feedback) or two RC hobby servos, a servo-powered rotating arm base, and an ultra-sonic range sensor. The objective is to autonomously transfer the puck to a bulls-eye target using the range finder and its proximity to fiducial markers on the game board.

The WS/WS Arm utilizes concepts taught in all of the labs and lectures, but in a smaller proportion than the principal project. This way, students have time to familiarize themselves with wiring, linkages, CAD/CAM, and torque calculations before it is time for the principal project. Furthermore, it gives teams the opportunity to learn about each other's strengths and weaknesses before they truly begin working on the principal project.

Periodic targeted design reviews of robot subsystems also ensure that students have a goal to work towards at least a few times a week, and motivates them by giving them a sense that they are getting something done.

Sparking student interest with competition

In such an intense course where students are prone to burnout, it is important to sustain their initial enthusiasm. We use competition in the WS/WS Arm and principal project to foster a desire to improve designs above the minimum required to meet the course requirements. Although students are not graded directly on how well they do in the competitions, they are motivated by winning “bragging rights” on who had the most superlative (fastest, most repeatable, longest, etc.) design. Even teams with excellent designs can lose a competition. For example, one team that was able to collect the most difficult items from the most difficult terrain had difficulty navigating back to the start point, and destroyed their robot along the way. The students who were RC hobbyists or gamers generally did the best in the final competition whether or not their designs were the best, since they had an easier time with the remote interface and were able to navigate back to the start line without destroying their robot or the course.

Principal Project

The principal project is modeled after the NASA Mars Rover. The students must teleoperate a semi-autonomous truck to navigate and collect objects of interest from an obstacle course with various difficulties of terrain. The students are able to view the course via an onboard camera and an overhead camera, and control the truck using a radio controller. The mission objective is to collect as many points as possible in a fixed time, with varied points based on the difficulty of procuring each item. Late return to the start line and damage to the course result in loss of points.

Each group is provided a 1/10 scale Tamiya monster truck (TXT-1 chassis), outfitted with a pre-drilled wooden base designed for easy mounting (see Figure 3). The students tele-operate the truck with a model airplane radio controller, via a wireless video interface (they have no line of sight to the vehicle or the obstacle course). We choose the BASIC Stamp 2 microcontroller since it is easy to program and has adequate performance capabilities and constraints for our project [26]. Although using a prepackaged robotic kit (such as the Lego Mindstorms® or Parallax Boe-Bots®) would perhaps give both students and instructors some more free time, they would not give students the same feeling of accomplishment derived from designing your own robot from the base up.

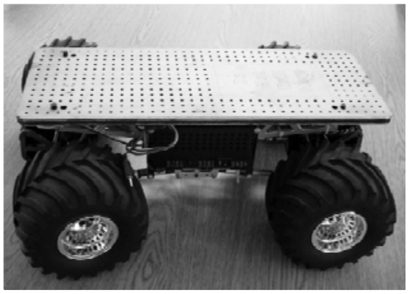


Figure 3: The Tamiya TXT-1 chassis with pre-drilled wood base.

Student Feedback and Discussion

The 2009 SAAST Robotics program was the most successful out of the 5 years the program has been offered. Every team competed in the final competition and was able to pick up an item. This is probably due to a number of reasons, including the lowest student to teacher ratio, the most integrated curriculum (labs, lectures, small projects, and design reviews all tailored toward the principal project), and the most constraints on manufacturing methods. Perhaps most surprisingly to us, the design parameters were also some of the least restrictive in all 5 years of the program.

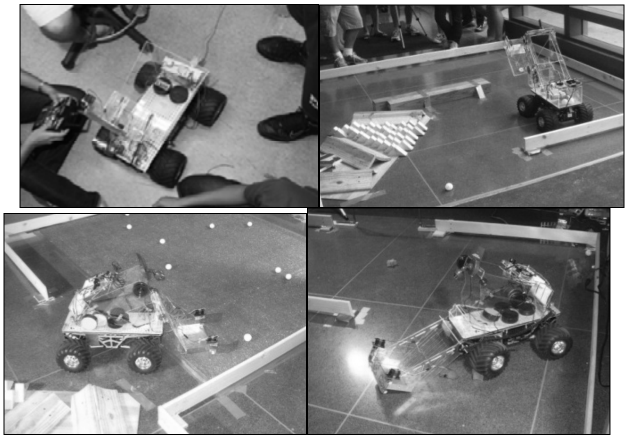


Figure 4: The robots designed by the students in action on and off the obstacle course.

It is obvious that lower student to teacher ratios improve success rates. More instructors are available more of the time (generally from 7:30 am to 10:00 pm, and even longer hours near the end). This enables the instructors to constantly monitor the process for all of the teams, guiding the teams away from dead ends, and providing mediation in team-member disputes. Low student to teacher ratios are expensive and also difficult to achieve since graduate students form a majority of the teaching staff.

Over five years, the curriculum has evolved into a very well integrated collection of labs, lectures, and projects. Previous to 2009, the curriculum included the World's Strongest Truck competition, which used a gear box kit to explore gear ratios and torque, and taught design principles by having the students design a truck around the gear box to haul items up an incline [0,0]. Although this taught the students a good deal about design and torque, it was not directly applicable to the principal project, and took the entire first week of the program. The WS/WS Arm replaced this competition, and gave the students a head start on designing and manufacturing an arm for their robot.

In 2008, with the intention to make the project easier on the students, the robot was required to use an arm with an electromagnet to gather ferrous items. Although the students could design special mechanisms to pick up other things, our intent was to have them focus on the arm and get it done. In that year, not all teams were ready for the competition. In 2009, we had very few restrictions on the mechanism design, but all teams had a working arm by the first day of week 2, which was their entry to the WS/WS Arm competition. Some decided not to use an arm for the robot and started from scratch. With the additional freedom, each team was successful. We believe that by requiring the robot configuration to use an arm in 2008, we stifled the creativity we had seen in prior years, and put some teams at a disadvantage. This was confirmed by the diverse designs we again saw in 2009.

To confirm our program is on target, and to enable former students to inform us of where improvements are warranted, we recently distributed an online survey to our alumni. Selected questions from the survey are presented in Table 1. Due to space constraints, the entire survey is not included, however, note that survey questions 4-7 in Table 1 are repeated for electronics proficiency and electronics lab and lecture evalution. Nearly half of the 2009 class responded; overall about 30% of the students from 2007 through 2009 responded. Since we only received one response for classes prior to 2007 and since the material has evolved significantly since the early years, we elected to only use responses from 2007 to the present for our analysis. Specifically, we

Table 1: Selected questions from the recent alumni survey.

(1) I enjoyed the project-based approach. no yes 1 2 3 4 5
(2) I liked that we didn't have tests. no yes
(3) I learned a lot about robotics in general. Not really yes 1 2 3 4 5
(4) On a scale of 1 to 5, rate your knowledge of mechanics/mechanical aspects of robotics BEFORE the program (Mechanics includes mechanisms, mechanical design, etc.). Very Little Very Strong 1 2 3 4 5
(5) On a scale of 1 to 5, rate your knowledge of mechanics/mechanical aspects of robotics AFTER the program. Very Little Very Strong 1 2 3 4 5
(6) On a scale of 1 to 5, rate the helpfulness of the mechanics labs with respect to enabling you to accomplish the final project. Not helpful Very helpful 1 2 3 4 5
(7) On a scale of 1 to 5, rate the helpfulness of the mechanics lectures with respect to enabling you to accomplish the final project. Not helpful Very helpful 1 2 3 4 5
(8) I learned a lot about the programming aspects of robotics no yes
(9) How would you rate your SAAST Robotics experience? Poor Excellent 1 2 3 4 5

were hoping to confirm the following:

- a PBL approach is the best approach to this introductory course;
- labs and lectures directly support projects;
- students left with a conviction they had truly learned the material;
- students have since broadened their interest in robotics.

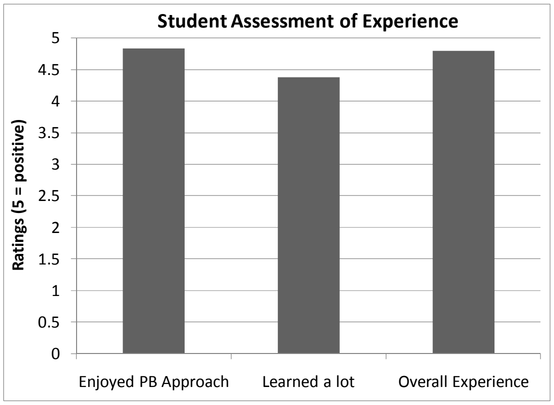


Figure 5: Average overall program ratings (on a scale of 1 to 5).

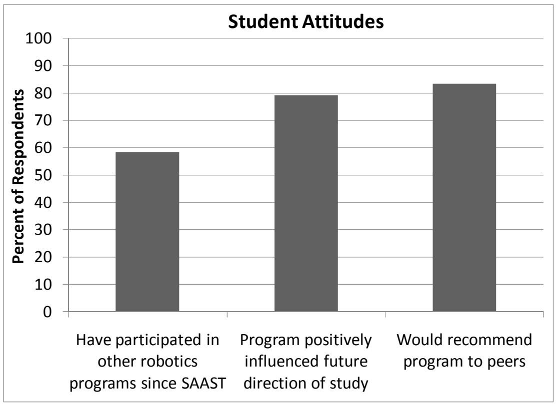


Figure 6: Student attitudes toward program.

An overview of this feedback is presented in Figure 5 and Figure 6. Students nearly unanimously rated the program a positive experience without any correlation to the grade they received. It is not surprising that their response was overwhelmingly in favor of the PBL approach, considering the alternative would have likely been homework sets and tests. However, we received a comparable response that they would recommend the program to their peers and that their participation was a positive factor in their selection of a course of study at the university level. Our survey also confirmed that most entered the program without any prior expertise and most continued on to become involved in other robotics programs, such as FIRST. One student went as far as starting a local robot club based on his interest following the program.

In 2009, the lectures were also more specifically tailored to the material necessary to complete the project successfully. For example, past lectures on gears and mechanisms went over specific details about different types of gears, and their attributes. In 2009, different types of gears were briefly discussed, but the focus was on the types of gears we had available to the students. This way, the students got a brief overview of the topic but were not preoccupied with details irrelevant to the project. It is reassuring to see their acknowledgement of the helpfulness of the material we compiled for labs and lectures, as rated on a scale of 1 to 5 (1 being not helpful, and 5 being very helpful) in Figure 7. The questions asked, specifically: "Rate the helpfulness of the (mechanics/electronics) (labs/lectures) with respect to enabling you to accomplish the final project." Labs scored slightly higher than lectures on this scale. This is probably due to the fact that lectures retain a 'big picture' framework, while providing depth, as required, to understand the labs and, ultimately, be prepared to tackle the project. Labs, however, are geared specifically to the project, such as electrical labs, in which the students get hands on experience using the electrical components of the robot, which translates directly to the project. The data indicate the students perceived this difference in focus.

One part of SAAST Robotics that has not changed much over the past 5 years is student evaluation. Design reviews have been used since the beginning, although the frequency has increased to ensure success. Grading itself has not changed much, as the students are evaluated mostly on their final presentation, which demonstrates their understanding of the material, and presents justification for their choices in the design process. The students' own sense of their level of expertise with respect to the core concepts we present, before and after the program, is presented in Figure 8. Although not graphically depicted, when these data are taken by program year, the benefits score increases by year, indicating a general trend towards improved course quality. After 5 years of development, we now believe we are on target and only minor curriculum revisions are required at this stage to keep the program current. Perhaps the only concern as we move forward is the high number of staff hours required to ensure the program is a success. At three weeks, the intense pace is exciting and manageable for all, even though it is exhausting as we reach the end. Indeed, we could not accomplish nearly as much in two weeks and four weeks would likely result in burn-out for students and staff alike.

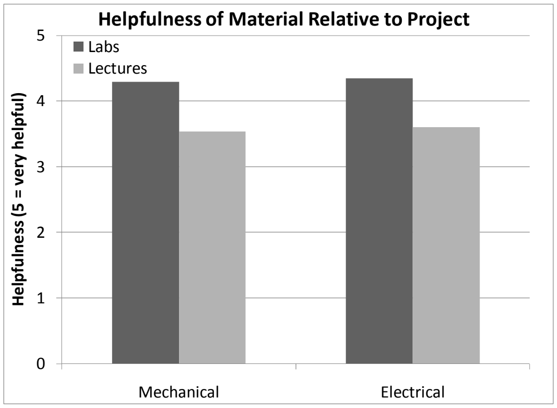


Figure 7: Student assessment of relevance of labs and lectures to the principal project.

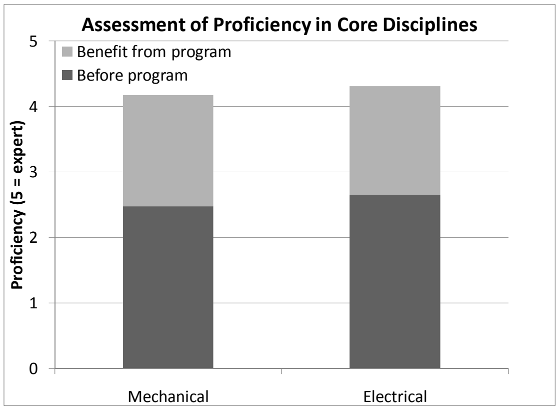


Figure 8: Student assessment of proficiency benefits in core disciplines for robotics (before and after program).

Conclusion

The breadth of material that must be covered to enable students to design, assemble, and control a semi-autonomous robot provides a serious challenge to instructors and students alike. What distinguishes our course from similar robotics academies is the open-ended project, in which students must make design decisions, choose between various components, and build a unique robot. Furthermore, we teach math, modeling, and decision-making skills the students can use outside of our program.

The key aspects to ensuring a successful outcome are a well integrated curriculum, frequent design reviews, assigning well balanced teams, and, if feasible, a low student to teacher ratio. A well-integrated curriculum is of paramount importance for such a short, intensive course. Concepts should be taught using lecture materials, labs, and projects that add value to the students' principal project, while providing a strong basis of the physical and mathematical concepts necessary for studying engineering and robotics. Carefully integrated mini-projects ensure that the students are working towards the principal project without sacrificing the quality and breadth of instruction. By scheduling frequent design reviews, we prevent the students from falling behind and setting unrealistic goals. Assigning teams based on diverse abilities ensures that all teams have an equal distribution of expertise. The evidence based on the surveys and our assessment suggests that we have a successful program that combines theory and practice in robotics and the three different engineering disciplines of computer science, electrical engineering and mechanical engineering.

Acknowledgements

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