

# **Capturing the Interest of Future Engineers**

## **The Development of an Intensive Three-week Summer Academy in Robotics for High School Students**

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### **abstract:**

The General Robotics, Automation, Sensing and Perception (GRASP) Lab at the University of Pennsylvania has developed an intensive, three-week robotics program for high school students. It combines theory with hands-on technical experience in cutting edge technologies to dynamically engage students with the intent of sparking an enduring interest in engineering. The program uses a top-down approach by assigning the students a series of labs and projects designed to engage and challenge. The labs are building blocks for the main element of the program, which is the design of a semi-autonomous robotic vehicle whose mission emulates that of NASA's Martian rovers. The project culminates with graded testing of their vehicles on an obstacle course. To enable the students to succeed with their design project, we combine preparatory hands-on activities with a series of highly focused lectures that present the related theoretical material. This permits the program to progress quickly, enabling the students to learn by discovery. The course material and the projects on which the students work have evolved over the four years this program has been offered. The progress made by this approach is documented here by highlighting the successes and failures along the way.

### **introduction:**

In 2004, the General Robotics, Automation, Sensing and Perception (GRASP) Lab began to offer a robotics course in conjunction with the University of Pennsylvania Summer Academy in Applied Science and Technology (SAAST)<sup>1</sup>. There are four other engineering courses in this academy through which Penn seeks to attract talented prospective students. Indeed, many ultimately seek admission when they graduate and there are now undergraduates whose first Penn experience was the SAAST program. Success has also been measured by observing the number of students who return to take other SAAST courses and a succession of students through the years from the same schools as former students.

The structure of this program grew out of an undergraduate course in Mechatronics similar to many in this emerging field<sup>2</sup>. However, from the onset we recognized major changes in approach would be required for it to succeed.

At the collegiate undergraduate level, engineering programs must adhere to ABET standards in order to provide students with a strong analytical foundation<sup>3</sup>. Programs may periodically include small design projects in their curriculum to fortify student interest as they incrementally develop a strong foundation of analytical skills. In this manner, highly detailed projects, culminating with a senior design project, can be included in the latter parts of a program. A three week program for high school students must take a different view. Moreover, since robotics is a multi-disciplinary technology, with equal roots in computer science, electrical, and mechanical engineering, the situation is compounded. At the high school level, students may be attracted to such a program by interest alone and enter the program with little if any background in the underlying mathematics and physics of the technology. Student expectations are typically high despite the reality that prerequisite standards cannot be imposed to support them. To succeed in the face of these challenges, a high school program must highly motivate the students by capitalizing on their expectations and rewarding their dedication with incremental successes. We believe this is critical to ensure they are willing to make a sincere commitment of their time so the number of contact hours can be maximized and academic objectives can ultimately approach that of an introductory undergraduate course. Our program is built on the following concepts:

- Provide an overall immersive experience in engineering that would be unattainable except in a comparably scaled program
- Maximize student creativity within the bounds of a real design project
- Adopt a small group structure throughout all activities to instill the realization that engineering is a team effort
- Configure the design problem so there is no single correct answer but rather a conflicting design space to introduce students to the concept of technical risk within a firm schedule
- Ensure each team's project functions as close to the best performance attainable with their design concept, while also providing guidance to ensure their designs are viable within the schedule
- Require all students to present a product design review at the end to demonstrate their ideas and document what they learned along the way

#### **program structure:**

This program is built around a final project to develop a robotic ground vehicle, see Cappelleri et al<sup>4</sup> for a detailed description of the program. The challenge is inspired by the recent successes with the two generations of NASA Martian rovers. Specifically, the design task is to develop a platform that can enter and then navigate an obstacle course, explore the course to discover the location of objects that are to be collected. Finally, the platform must return to the starting point outside the course with its collection. In the spirit of other motivational approaches<sup>5-6</sup>, points are awarded for the type and quantity of objects that can be collected within a timed period and brought back to the starting point. Three types of objects that vary widely in shape, size, mass, and collection value are used to ensure a complex challenge. The obstacle course is configured to ensure students take vehicle maneuverability into account. All of its turns, except a cul-de-sac at the far end where the highest value objects are placed, are easily navigated by the basic vehicle the students are given. However, as the robotic elements to collect the objects are added, hasty designs could rapidly reduce maneuverability to unacceptable levels, so students are cautioned to

plan accordingly. At each stage, the program is structured to provide a hands-on learning experience to make a lasting impression.

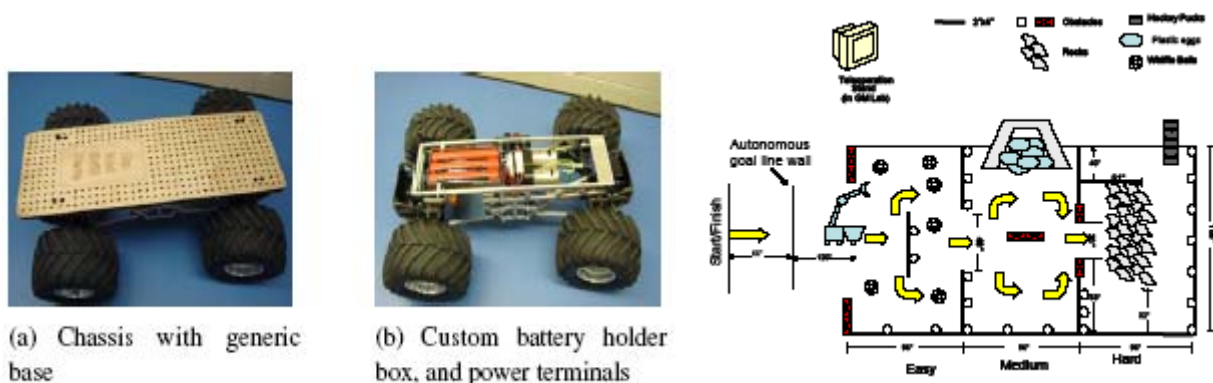


Figure 1: Robot base chassis and schematic of course

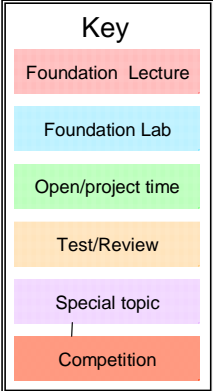
The design project is developed around a 1/10<sup>th</sup> scale monster truck from Tamiya (TXT-1 chassis<sup>10</sup>) as is shown in Figure 1. The BASIC Stamp II<sup>11</sup> is used as the microcontroller since programming it is easy to learn and it has adequate performance capabilities and constraints for our purposes. These hardware elements were selected, rather than Lego NXT<sup>9</sup> or other prepackaged robotic systems, so the students would be afforded a true sense of accomplishment that would be otherwise out of reach on their own. Since the complexity of autonomous operation of the vehicle would not be realistic in the time frame of our program, the students are directed to tele-operate their designs through a model airplane radio-controller. To further distinguish this program from other robotics programs which use tele-operation, such as FIRST<sup>7</sup> and BEST<sup>8</sup>, and to add a further dimension of complexity, the students remotely control their vehicle through a wireless video interface rather than directly observe the vehicle. This affords the operator a medium field of view image from the vehicle, which is projected onto a large screen in a remote location. In the first few years, instructions were provided so students could add a pan/tilt mount to the camera but this proved to be beyond the scope of what most teams could accomplish. Recognizing this, we now provide them with a modular video unit, complete with articulation in pan and tilt directions that can readily be mounted to the vehicles as a shared resource. In this regard, all teams are provided with the same video interface and one of their design challenges is to optimally locate it within their individual designs.

To support this program we recognized that highly focused lecture material, closely integrated with laboratory activities would be required to provide the students with the background they would need to undertake the final design project. While the material is presented in a technically rigorous context, in order to ensure there is sufficient time to execute the design project, the depth of presentations must be tailored to the specific requirements of the design project. Detailed references are provided for all presented material so that interested students can delve further on their own.

The syllabus and schedule of activities is presented below in Table 1. The class size is typically 24 students. Based on this, the SAST program<sup>1</sup> assigns 3-4 resident teaching assistants who follow the student 24/7 throughout the duration of the program. The core staff, directed by

Professor Kumar, is composed of a lab staff electrical engineer, a lab staff machinist, and 2-4 PhD students. In addition, we believe support from at least two undergraduates who are knowledgeable in all of the activities is indispensable. For the lab and project activities, the students are divided into groups of three. In an attempt to balance the starting competency of the groups, the students are surveyed on the first day to identify any prior related expertise they may have. When the survey is conducted we emphasize that when in doubt, students should not over-rate their competency since we do not require prerequisites with respect to admission to the program. Student hobby interests and participation in other robotics programs, such as FIRST and BEST robotics are highly valued. When groups are finally formed, the students have been in residence for a few days, so the resident teaching assistants who live in the dormitory with the students can provide further guidance to be sure there are no overt personality conflicts. We also try to balance gender across the groups, although male enrollment typically exceeds female enrollment by 3 to 1.

The color-coded syllabus/schedule easily reveals a moving wave of activities throughout the program serially progressing through foundation building lectures and labs, special topic lectures to enrich content, and open time for the students to develop and realize their ideas. It culminates with the design project competition and closes with a detailed review of the project. Parents are encouraged to observe the closing group presentations. Close coordination of all instructors and teaching assistants is required to ensure no one is left behind as material is presented.

Week One					<b>Key</b> 
Monday	Tuesday	Wednesday	Thursday	Friday	
Welcome & safety workshop	Lecture: mechanical design process, linkages	Lecture: gears, belts, pulleys and lead-screws	Lecture: sensors, measurements, and interfacing	Lecture: robot arm kinematics	
Break					
Robotics overview, lab tour, experience survey	Lecture: actuators & controllers Lecture: electronics And BASIC Stamp	Open lab/shop project time	Open lab/shop project time; SAAST Master Lecture	Special topic: H.S. robotics competition Test drive the robot w/ camera	
Lunch					
Introduction to final project competition, case study of past SAAST robots	Introduction to Solidworks and Solidworks Lab#1	Mechanical Lab#1	Solidworks Lab#2	Open lab/shop project time	
Break					
Introduction to Laser cutting system	Electronics Lab#1 and key fob engraving	Electronics Lab#2 and key fob engraving	Solidworks Lab#2	Open lab/shop project time Solidworks Lab#1 due	

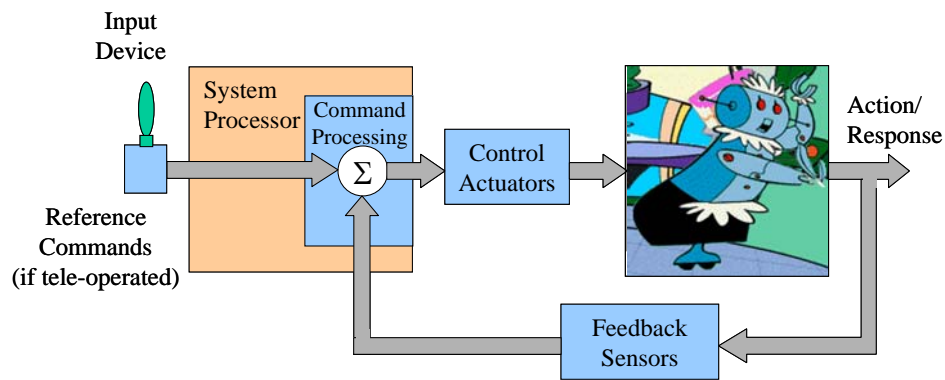
  

Week Two					Week Three				
Monday	Tuesday	Wednesday	Thursday	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
Design Review #1: conceptual design	Tour: GM robotic assembly line	Special topics: Uninhabited autonomous vehicles	Open lab/shop project time	Design Review #2: mech. prototype Electronics Lab #3 due	Special topics: personal service robots	Design Demo #1 Mechanical components	Design Demo #2 Electronic components and software integration	Robotic Monster Truck Competition	Project Presentations
Break					Break				
Design Review #1: conceptual design	Tour: GM robotic assembly line	Mechanical Lab #2	Tour: NASA Goddard Space Center	Design Review #2: mech. prototype SAAST Master Lecture	Special topics: mp3 design evolution; Open lab/shop project time	Design Demo #1 Mechanical components	Design Demo #2 Electronic components and software integration	Robotic Monster Truck Competition	Project Presentations
Lunch					Lunch				
Open lab/shop project time	Open lab/shop project time	Electronics Lab #3	Tour: NASA Goddard Space Center	Open lab/shop project time	Open lab/shop project time	Open lab/shop project time	Open lab/shop project time	Robotic Monster Truck Competition	Closing Luncheon for SAAST program
Break					Break				
Open lab/shop time; Solidworks Lab #2 & Electronics Lab #1 due	Open lab/shop time; Electronics Lab #2 due	Electronics Lab #3 Mechanical Lab #1 due	Tour: NASA Goddard Space Center	"World's strongest truck" competition	Open lab/shop project time	Open lab/shop project time	Open lab/shop project time	Robotic Monster Truck Competition	Open demonstration time

**Table 1: Program Syllabus/Schedule**

Without delving into the details of the lectures, the robot is presented as a closed loop system of systems, as depicted in Figure 2, and the purpose of each is discussed. For each subsystem, after

providing a general description, specific details of the components they will use in their project, such as mechanisms, motors, sensors, circuits, and processors are discussed. The emphasis in these lectures is based on common errors observed with past SAAST students, undergraduates, and even low experience practicing engineers. In the context of robotics, the critical topics with which many students lack prior exposure include trigonometry, calculus, electronics and programming. Therefore, all lecture materials present these in a self-contained manner. For instance, rather than presenting the relations of acceleration, velocity, and position as a set of ordinary differential equations, we note this for reference and then proceed to define the relations in discrete time difference equations that can be readily verified by the students. To be sure these lectures have met their mark, the material is presented in a highly interactive context, fostering an environment of discovery. Students who are completely unfamiliar with the concepts are encouraged to approach instructors on the side. An example of this focused approach is the model for a DC motor, where the starting point is an overview of the basic physics but the emphasis is how these devices can be selected and embedded in a design project. Three types of motors with a wide range of capabilities are made available to the students and they are challenged to select which type is best suited for their design project. The lectures are fortified with highly focused lab activities to reinforce the sense of discovery with self-demonstration.



**Figure 2: Robot Topology**

The lab activities are designed to permit the students to observe for themselves the concepts critical to the success of their projects. A noteworthy small early lab/project is our “World’s Strongest Truck” competition. Students are tasked to design and build a “truck” to maximize the payload that can be carried up an inclined plane. Each team is provided with a 4-speed crank-axle gearbox assembly from Tamiya USA (Part# 70110)<sup>10</sup>, which can be assembled in 4 different gear/speed ratio configurations. The students must apply concepts presented in the lectures to make their selection of gear ratio and other parameters. The payload compartment is constrained but all other dimensions are open for the students. At this stage, the students are shown how parts can be designed and fabricated using a CNC Laser Cutter. We encourage them to use similar construction techniques on their final projects to minimize the amount of free-form fabrication that can be excessively time-consuming or perform poorly. A sample of student designs and photos from the competition in 2007 is presented in Figure 3.

After the competition, we conduct a debrief to discuss the features that led to the success and shortcomings of the various design concepts. We use this opportunity to further reinforce concepts we know will be critical in their final projects.

After all critical concepts have been presented, the schedule is interspersed with lectures on special topics, such as autonomous air and undersea vehicles or service robots to emphasize emerging technologies and commercial markets. These are intended to demonstrate to the students that their generation will be the one to bring robotics out of the lab or factory floor and make the technology ubiquitous. Tours of facilities where robotics is prevalent are used to highlight the current state of the technology. We are grateful to the NASA Wallops Flight Facility and the GM Saturn plant in Newark, DE for directing our students on inspiring tours of their facilities.



**Figure 3: "World's Strongest Truck" Competition**

Since the entire program is built around the robotic monster truck project, it is critical that all teams field a credible entry to the final competition. So that this occurs, we conduct a series of design reviews with each student team. Experience has demonstrated the level of design maturity required at each stage to be successful. If teams appear to fall short of these objectives, they are provided with rigorous mentoring support from our staff. The final week is extremely labor intensive phase for staff and teaching assistants. While the phased designs reviews and dedicated mentoring efforts are necessary, they are by no means sufficient to guarantee the functionality of a design. The two topmost technical problems observed are failure to properly electrically ground all components and failure to properly estimate loads experienced by drive components. The overarching issue is typically underestimation of the time to bring ideas into reality. A variety of designs are shown on Figure 4.

The final project competition is conducted within a comprehensive set of guidelines to ensure fairness but we take whatever steps are required so that each vehicle performs to its intended design concept. While there are scoring deductions for breakdowns during the competition, we extend the period of performance of each entry to the maximum practical duration so that the students can see their designs in action.

In parallel with the build and test activities of the last week, the students are directed to develop a design presentation for the final day. The context used for the presentation is that our staff is a group of investors who are seeking to commercialize a product to execute the collection task and the students are invited to convince the potential investors that their conceptual design should be selected. Students are encouraged to freely discuss the design decisions they made to arrive at



their final designs. They are also asked to describe how they would improve their designs based on performance in the competition. All members of each team are required to present in this final review to foster a strong sense of teamwork.



**Figure 4: Gallery of designs during the 2005 competition (l) and 2008 (r)**

Student feedback from each year is used to judge success and to continually evolve the course materials. In the first year, the students assembled the truck chassis and scratch-built all of their mechanical components with the assistance of professional machinists to fabricate relatively complex parts. Assembling the trucks meant less time for conceptual design, so a fully operational standard base platform was provided in year 2 but the design task remained fully open-ended. This led to problems which will be noted in the following section, so by year 3 we provided students with a standardized set of actuation options: 3 motor types, an assortment of standard gears and chains, and a sample controller program to run the micro-processor. Results were outstanding based on student feedback and comments from the casual observers who gather at each year's competition. Two local TV stations ran stories on the competition when they saw the level of ingenuity displayed by the designs of the 2007 class<sup>12,13</sup>. The only downside was the extreme labor commitment required by the staff to realize every team's concept. To address this, in 2008, we added a basic robotic arm (see Figure 5, right panel) as a standard component and challenged students to design the end-effector needed to collect the objects on the course. They were given an electro-magnet as a starting point and shown other concepts developed by the staff to spark their interest. The arm was intended to minimize the amount of time required for mechanical fabrication while still retaining a high degree of openness to the project and injecting a higher level of programming. Student teams were also invited to revise the basic geometry of the arm. To accomplish this, the curriculum was revised to add depth to lectures emphasizing degrees of freedom, mechanisms, and design using Solidworks. The level of technological complexity was also elevated since full integration of vehicle and robotic arm required two microprocessors for control. While 2008 was highly successful based on robot design and performance, we observed that teams typically assigned a single member responsibility to code the microprocessor, so at the final stage when controls were integrated with the mechanical design, most relied inordinately on that person and the sense of teamwork was compromised. We will further revise the lecture materials for next year to enhance the content on programming to ensure balanced participation.

### **hard lessons along the way:**

Our first year was quite successful despite admittedly uninspiring lectures and only a few incremental design reviews throughout the 3-week period. However, our second year demonstrated how challenging the balance between maximizing creativity and realism could be. During that session, many of our groups proposed concepts that we knew would not be feasible. Rather than suggest they “go back to the drawing board”, we attempted to persuade them to retain their core ideas but revise them into more realizable designs. We also divided our staff amongst the groups to provide all who needed it with immediate feedback so they would not wander too far astray. Our belief was that a generous amount of direct mentoring would permit the students to retain their best ideas. The approach may have worked in a longer time frame but with just three weeks, time ran out on us and the students’ interest waned as the end approached. Despite constructive criticism, some student groups consistently over-estimated their ability to realize their ideas in the lab while others kept completely revising their designs. One group completely changed their design concept four times, including a major revision in the last two days. As we entered the last week of the program, no group was near the completion of their design. The class persuaded us to permit them to remain in the lab late into the evening, which then extended deep into the night as the week progressed. However, instead of making progress, the students began to burn-out in the final days with few robots in working order. When the time arrived for the competition, only one robot was fully functional with respect to its intended design. Intense support from our entire staff was insufficient to get all the projects to a competitive state. At the end, we had to acknowledge our naiveté of believing unconstrained creativity could be controlled with long hours of direct mentoring. From this, we drew the following lessons:

- Regularly scheduled design reviews must be conducted with cumulative but incremental objectives
- Student groups must demonstrate rather than describe their designs at each stage
- Lab time must be limited to 11PM until the last two days or so and even then, the goal should be lights-out by midnight.
- Expert mentoring of weak groups is essential to preserving balanced performance in the final competition
- The value of hardware testing must be constantly affirmed to ensure their design will function as intended during the competition.

Incremental design reviews were always a part of the curriculum but they were fortified by year 3 with specific performance requirements at each stage as follows:

- Design Review #1 is a conceptual overview of the entire design. Students are strongly encouraged to use CAD software tools to capture their ideas at this review so they can begin to understand the complexity of their ideas
- Design Review #2 is a review of any prototype mechanisms embedded in their design. Student must present on either foam-core realizations or CAD animations so that design complexity can be fully understood. At this time, the feasibility of their design is confirmed by having them document their analysis of the power and force requirements of their designs.



- Design Demonstration #1 is a demonstration of all of the mechanical parts of their designs. Parts can be moved manually rather than by onboard power but all parts must be fabricated and demonstrated by this point.
- Design Demonstration #2 is a full electrical demonstration. Mechanisms must be powered by the motors they are using, preferably using the software that will control their projects. Since software integration may not be mature enough to demonstrate at this point students are permitted to outline the structure of their final code.

During the first two years of this program, we used a piston-cylinder fabrication and assembly project to acquaint students with the machine tools and CNC mill available to them to build their designs. This project required them to learn to use a band saw, drill press, lathe, and milling machine to make the aluminum parts. Acrylic parts were cut using a Laser CNC mill while the boring of the body (cylinder) was manufactured using a traditional CNC mill operated by instructors while the students observed. All finished aluminum parts were anodized before assembly. Since this project was very time consuming and met with mixed reviews by the students, it has been downscaled to an acrylic key fob that could be custom designed by the students. Since we advocate they fabricate most of their structural components using a Laser cutter, this project is a valuable step to start them creatively thinking in this direction. Due to the time saved by removing this manufacturing project from the curriculum, a CAD module was added to the curriculum in the subsequent 2 years of the program. This module consists of lecture and labs on SolidWorks. This module greatly helped the students conceptualize and review their final project and allowed for easy part manufacturing since the 2D SolidWorks CAD files can be directly ported to the CNC laser cutter for fabrication.



Figure 5: Piston project from years 1 and 2 (l), 4 Degree of freedom arm from year 4 (r)

### conclusion:

Robotics can be a highly motivational context with which to interest students to consider an engineering education. However, since it involves the integration of many disciplines to be successful, a high school level program must be tightly focused and yet still be stimulating to students. By using an open design project based on current technology components (motors, processors, etc.), students will recognize the program as rewarding and be willing to invest their best efforts. Such an open design project is possible with a three-week program if proper constraints are included at all stages.

The course we have developed permits students to gain a working understanding of how to:

- Formulate and solve a design problem
- Integrate electrical and mechanical components in the design process
- Mathematically model physical processes and use models to design controllers
- Incorporate embedded software into products
- Be creative in a team environment
- Present and defend technical ideas in an open but time-limited forum

In general, these are completely new concepts for students at this level. While it is relatively straightforward to provide them with the academic elements of these, bringing them to a working level proficiency in the context of the design project is challenging but achievable.

Through the large number former students who contact us for references for their university applications, the number of students who apply to the Penn Engineering program, and those who are now undergraduates here, we are confident we are hitting our mark.

### **acknowledgement**

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