Design Education Using the International Aerial Robotics Competition

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Abstract

The Rose-Hulman Aerial Robotics Club is a student team, which participates in the International Aerial Robotics Competition. Their entry consists of a small robotic helicopter instrumented with navigation and video sensors and an on-board computer. The vehicle must navigate *autonomously* over a simulated disaster scene and produce a map of victims and hazards for use by rescue workers. As the students design, build and test their vehicle, they get excellent design experience at a level beyond what is offered in the academic curriculum. The first half of this paper describes the competition, the club history and organization, and their vehicle. The second half of the paper compares alternative forms of design education in the curriculum and discusses the relative advantages and disadvantages of competitive teams like the Aerial Robotics Club in design education. Competitive teams are clearly an excellent motivational tool and educational experience for the students who participate.

The International Aerial Robotics Competition

The International Aerial Robotics Competition[1] was created by Rob Michelson in 1991 when, as president of the Association for Unmanned Vehicle Systems, he wanted to create a forum for both advancing and publicizing the capabilities of unmanned aerial vehicles. Michelson continues to operate the competition each year, with a major event scheduled for the year 2000 competition. Each year the quality and capability of the entered vehicles improves, and the organizers make the rules and mission more difficult and realistic.

The mission for the first competition was not trivial. The vehicle was required to autonomously take off, locate a small metal disk, retrieve it, move to the other end of the field and then deposit the disk. All of this had to be accomplished without human intervention. At the first competition, none of the vehicles had stable autonomous flight. For four years, no team accomplished the mission. In 1995, Stanford brought a helicopter-based vehicle with GPS navigation and essentially accomplished the mission. Since then the mission has steadily increased in difficulty, aiming for a simulated disaster scene in the year 2000 in which the vehicles will map hazards like 40 foot flames, toxic waste barrels, and water spouts, while trying to locate victims and survivors on the field. This difficult mission is designed to showcase the usefulness of unmanned systems in dangerous situations, but it also challenges the engineering students who participate to press themselves to the limit. Controlling an air vehicle to stable autonomous flight is quite a challenge by itself. The rest of the mission just gives the flight a purpose and allows the students to do creative work in a truly open-ended problem.

The Rose-Hulman Aerial Robotics Club

The Rose-Hulman Aerial Robotics Club began in 1995 and took a vehicle to the competition for the first time in 1997. The club is composed of between 10 and 20 active students, with 5 or 6 students usually forming a core group that does the majority of the work. The makeup of the team is surprisingly diverse in terms of both age and major. The team has operated using enthusiastic students from freshmen to graduate students, and has been led by sophomores in applied optics and chemical engineering. Although the students near graduation are more technically capable, much of the work is usually done by underclassmen who have more time and fewer job-search distractions. Because so many of the skills required are not taught in classes, a willingness to learn is usually more helpful than coursework background. In fact, the Aerial Robotics Club is a classic example of problem-based education, where the students routinely learn what they need to know in order to solve the problem at hand.

The team is organized as a club and as such receives significant support from the student government. Most of the club officers are technical team leaders in charge of the major systems, including the ground station, the helicopter, the image processing, and the flight control system. The team also receives significant support from industrial sponsors, some primarily associated with the competition, and some specifically with the Rose-Hulman team. A list of industrial sponsors is given at the club web site[2].

The Vehicle

After several years of refinement, and a few substantial changes in the competition rules, the 1998 vehicle consists of a large model helicopter with on-board computer and sensors, and a ground station for image processing and path planning. Because of planned changes in the competition mission for 2000, the club is also adding a ground robot to the system, although this part is not expected to be operational at the 1999 event.

The main vehicle is based on a Bergen Industrial Twin model helicopter with a two-cylinder gasoline engine and a five-foot diameter rotor. The vehicle weighs about 20 pounds and has a payload capacity of about 20 pounds. The electronics package designed by the club weighs about 15 pounds. The 1997 vehicle used three video cameras, a wide angle, a zoom, and an infrared setup, multiplexed to the single channel video transmitter using a custom video multiplexer, which can be controlled from the on-board computer. The 1998 vehicle will use a combination of these sensors and a new high resolution, auto-focus, variable-zoom camera.

The on-board computer is an Ampro Little Board 486DX100 with an add-on timer board for reading and controlling the servo settings. The on-board computer runs a single executable under DOS, booted from a solid state disk. The vehicle's orientation is determined from the Watson Industries Attitude and Heading Reference System (AHRS), which uses rate gyroscopes, inclinometers, and a magnetic compass to determine orientation and rotation rates in three axes. The AHRS communicates with the on-board computer via a serial port.

A Novatel differential GPS receiver determines the vehicle's position to within 2 cm in all three axes. The differential GPS system requires correction signals from a stationary reference receiver. The corrections are sent via a radio modem from the ground station. A second radio modem allows the ground computer to send navigation commands to the on-board computer and sends the vehicle's position, orientation, and other flight data to the ground station. The entire system is powered by a 50 W nickel-metal hydride battery and a custom power board, which does DC-DC conversion for the required 12V, 5V and -12V supplies. A custom engine speed sensor allows the on-board computer to maintain a constant engine speed.

A custom control multiplexer allows the safety pilot to switch control from the computer to manual, and individual servos can be switched or kept on manual control. A safety feature of the vehicle required by the competition rules is that a separate receiver and power supply operate an engine kill mechanism (ignition grounding), so that if control is lost the vehicle can be shut down.

The on-board computer runs the flight control algorithm, reading the orientation and position from the AHRS and GPS and adjusting servos to maintain stable flight in the correct position as determined by the ground station. The flight system can also be configured to monitor a manual flight and transmit all servo positions and position data back to the ground station for verifying helicopter simulation models.

The ground station has two main purposes: image processing (recognition of victims and hazards), and path planning. Images transmitted from the vehicle are digitized at the ground station and recognition algorithms attempt to locate the victims and hazards defined in the competition rules. Whenever a victim or hazard is located, its location can be determined using the vehicle's position and image location, and the result reported to the judges for points. Image processing is done on the ground mainly because the large amount of computing power required would result in unreasonable power and weight demands on the flight vehicle.

The ground station also is responsible for path planning. The field is predefined with boundaries and known obstacles (street lights), but the locations of victims and hazards are unknown, so the ground station must determine where to search, where to avoid (40 foot flames, street lights, and field boundaries), and where to hover for a better look. Because the flames are detected by the processing of the infrared images, and difficult identification problems may get improved results by hovering and looking at multiple frames of video, the ground station, which already has the image information, is responsible for planning the path of the vehicle. This arrangement also allows the more convenient entry of the field boundaries and known obstacles on the ground computer.

1997 Results

In 1997, nine club members traveled to the competition at Epcot Center. Because the field size at Epcot was smaller than the current competition field, their design was based on a much smaller Kyosho Concept 60 helicopter, which is about half the size of the Bergen. In test flights before the competition the team had several systems working independently. The tail rotor had been controlled autonomously, the image recognition successfully recognized toxic waste barrels, and the GPS system could report the vehicle's location to the ground station. On the strength of their design and technical paper, the team achieved fifth place among ten teams.

The competition rules in 1997 required that the vehicle autonomously move the sample disk in order to receive any flight points, and no team received flight points that year. However, each team did take their allotted flight time to demonstrate the working components of their system. Carnegie Mellon's team brought an extremely nice (and expensive) vehicle that demonstrated autonomous flight and barrel recognition, but it failed to retrieve the disk as required. The Rose-Hulman team however, learned a few hard lessons about operation in the Orlando summer sun. They were able to demonstrate their image recognition and a few other operations, but several on-board components failed due to heat problems. The system had to be exposed to full sun for 10 to 20 minutes to get a good GPS reading started, and this exposure heated the on-board computer and the radio modems beyond their limits. The heat failures prevented the team from demonstrating the partially autonomous flight and the GPS location reporting. Since this was the club's first appearance at the competition, we felt that it was a strong showing.

1998 Results

Because Carnegie Mellon nearly completed the mission, and because the organizers wanted to do something special for the year 2000, the rules were substantially changed for 1998. The site was moved to the Department of Energy's Hammer facility. The Hammer facility is a hazardous waste cleanup training ground, and mockups of disaster scenes are available, including a burning fuel truck, an overturned railcar, and a smoke-filled building. Because these props were available and because the site is in a remote location, the competition field size was increased to about 1 acre. The 1997 vehicle was only capable of about 10-15 minutes of flight time, which is not enough to search the new larger field. To allow increased payload for more fuel and batteries, the team moved to the Bergen vehicle instead. Many of the same electronics were employed with some upgrades to the video system, the power system, etc. Four team members drove to Richland, Washington for the 1998 competition.

The new vehicle is substantially more elegant than the 1997 vehicle. It has a more modular design, with an electronics rack that can be completely removed from the vehicle using just two screws. However, because of the substantial changes to the helicopter platform, the competition rules, and club personnel (two important members graduated), some ground had been lost in functioning systems. For the 1997 competition, the flight control scheme had been based on manually tweaking gain constants in independent PID controller loops. For the 1998 competition, the flight control system used a more systematic approach. To get an accurate simulation model of the vehicle, a telemetry system was designed to record manual control inputs and vehicle responses at the ground station. Although the flight telemetry worked nicely, the control system was not completed and tested in time for the competition. Similarly, the new video system with three cameras instead of one gave the team better images to work with, but these required more sophisticated imaging algorithms take advantage of the extra detail. With a new team member in charge of imaging, some of the previous year's capability was lost despite the improved system hardware.

The improved design won third place among ten teams, and again no team received flight points in 1998. Rose-Hulman was able to demonstrate their flight telemetry system and record valuable video data of the flame and barrel hazards. Their precautions against heat were quite successful at protecting the on-board electronics. New cooling fans on the computer and power boards kept them operating smoothly, and reflecting foil on the modems and effective use of shady areas kept the other electronics in working order despite 105 Fahrenheit temperatures.

Unfortunately, last minute component failures are a hallmark of this competition, and 1998 was no exception. The hard drive used to develop the on-board computer code failed the day before flight day and had to be rebuilt from backups. The helicopter's clutch failed during a test flight at 3 am before the flight day and no spare part was available. Since the clutch failed to disengage entirely, the vehicle could be flown, but not at full power due to engine tuning problems. The result was that the vehicle could take off, but could not achieve any significant altitude. Another concern was that the high temperatures may have reduced both engine efficiency and lift. The temperature on the asphalt of the competition area was measured at 146 Fahrenheit during the competition. It is safe to say that no team had tested under these conditions.

1999 and 2000 Competitions

The 1998 and 1999 competitions are designed to be qualifiers for the 2000 competition, so that in order to participate in the 2000 competition a team must have accumulated 2000 points. Rose-Hulman accumulated 393 points in the 1998 competition and must therefore earn the remainder in 1999. Fortunately, the rules of the competition for 1999 will be very similar, so that major changes to the vehicle will not be needed. Ground vehicles and multiple air vehicles will be allowed, but not required, and so incremental improvements should be possible.

Educational Value of the Competition

There are a number of ways to deliver design education in the undergraduate curriculum. Two important components of design education are design methodology and practical experience. Either one without the other is hollow and does not prepare engineering students adequately. Ideally, these two components will be included in labs, courses and projects throughout the engineering curriculum. In reality, there is a competition between theoretical content and practical application that often compresses the design component of a course or lab into a very small portion of the work.

Students are hungry for the practical experience and applications of the theoretical concepts presented in class. In the days of discrete electronic components and repairable appliances many students came to engineering school with a strong background in practical problem solving, repair, and often design. Today, consumer appliances tend to be modular, integrated, and disposable. Students rarely have experience building a simple electronic or mechanical device at home, and so they lack the framework on which to place the theoretical background we present. Informal surveys in my courses indicate that almost every student wants to see more practical applications of the material. This is a large part of their motivation for grinding through the work of engineering school.

One of the highest goals we can have as engineering professors is not only to help the students learn the material, but to enjoy learning it. The design component of their education not only helps them be better engineers by managing their creativity, but in the application it allows them to build concrete links to the material they are studying. Short design problems can be integrated into most courses, but they usually don't incorporate the entire design process because of the time requirements. Longer projects tend to take up larger portions of a course and only fit in to courses designed to accommodate them. A few of the popular methods of incorporating significant project/design work in a curriculum are discussed below.

Senior Project

Rose-Hulman operates senior project courses in most majors, including my own Electrical and Computer Engineering department. A three term sequence (one full academic year) allows teams of ECE seniors to work on an industry sponsored project. The student teams manage a budget, create a schedule, and deal directly with the sponsoring company. Faculty mentors support the team and some class time and several previous courses provide for design methodology education. During the last term, the team produces a final report and presents their work at a symposium including the sponsoring companies.

This approach has a number of advantages in providing a long-term project on a real problem. The students get a good look at typical industry practices including the darker side such as having to work for resources and attention from supervisors. The teams have the opportunity to see a large part of the total design process including documentation, but generally don't get involved in the mass manufacturing and revision stages because of time limitations.

The senior project approach is the best coursework method for dealing with time limitations because it makes sense to dedicate a large block of time at this level of the students' development. Use of outside sponsors also encourages interaction between the students and potential employers and gives an opportunity for exchange of ideas between the school and industry. Senior projects have the disadvantage of tending to concentrate the design and practical experience at the end of the educational process. Because graduation requirements may differ among majors, it is difficult to coordinate interdisciplinary projects.

Major Course Projects

Major course projects are extremely useful for tying together the concepts presented in a meaningful way. They allow the students to apply the material in a practical and motivational way, and are usually fairly popular with students. Although a course project may push some of the practical material to the end of the course, it does allow the students access to project work much earlier than their senior year, perhaps even in their first few terms.

A course project is substantially limited in the length of time available. If it is only a portion of a term, much smaller projects, and therefore less of the whole design process can be considered. Course projects tend to be time-consuming both for the student and the professor. If every course had a major project, the load would be overwhelming for everybody. Because of the load, and because senior projects tend to compete for time, space and money, a tradeoff has to be made over the total amount of design experience to which students can be exposed.

Design Methodology Course

A design methodology course can be a valuable addition to the curriculum, especially for delivering well-known methods and practices for planning and managing projects. Like most technical material, design methods are hard to absorb without practice, so design courses beg for a parallel project. If the project is too small, the methods seem like overkill, and if it is too large, it leaves no time in the course for teaching the methods. The ECE department at Rose-Hulman deals with this paradox by delivering design, project management, teaming and professional development material in a series of courses using small projects. The courses lead up to the senior design project. This is a compromise, but a workable one.

Competitive Design Teams

An alternative method of delivering design education is the competitive design team. The Aerial Robotics Club at Rose-Hulman is an opportunity for students to participate in a long-term (several years), iterative project, where they are required not only to specify, design, manufacture, test, and document the components, but also to manage the organization details of assigning responsibilities, running meetings, raising money, and getting publicity. Operating the Aerial Robotics Club is more like running a business than any other experience the students could choose in their college years, except running a business themselves.

The Aerial Robotics Club provides its members with practically all of the desirable elements of design education. The problem and the team are interdisciplinary. Students from a variety of majors work together on problems that fall across all disciplinary boundaries, including aerodynamics, structural integrity, vibration, controls, sensors and instrumentation, optics, microprocessor interfacing, radio frequency communication, electromagnetic interference, programming, image processing, and pattern recognition, etc. Usually, the students are confronted with problems for which there is no clear answer, and they have to seek external sources for help, including research literature, various faculty and staff, and the internet. Since "life-long learning skills" are a major goal for any good educational program, it is pleasing to see the students using the same kinds of resources for help that they will depend on once they graduate. In essence, they practice their life-long learning skills continuously in the Aerial Robotics Club.

Unlike a course project where an instructor grades the results, the results of the Aerial Robotics Club are evaluated by comparison with the best efforts of other student teams from schools like Georgia Tech, Carnegie Mellon, and Stanford. Although not a topic for this paper, competition and awards in the classroom can also be a useful motivator when used appropriately. The fact that they are presenting their work to a national audience and competing with sharp teams from other schools has a powerful effect on their willingness to devote time and effort to the project.

Perhaps the most powerful effect of the project on the participants is the motivational boost they get from working on a truly fascinating and challenging problem and actually implementing their solution. Because students from all levels, freshmen to graduate students, can and do participate, they don't have to wait for a senior project to do some real applied engineering on a challenging problem. The availability of sponsorship makes it possible for them to begin working with expensive and complex equipment immediately, including systems too expensive to provide in most labs. Just the differential GPS system and the inertial navigation systems, both loaned by their manufacturers, bring the vehicle cost to over $40,000. The opportunity to work with real hardware goes way beyond the excitement of most "toys." I believe the project satisfies a deep need for these students to explore the limits of their abilities, and to express a practical application of the education they are receiving. I know that they get a great deal of satisfaction from designing the required components and seeing the working result.

Educational Outcomes for the Aerial Robotics Club

Although the Aerial Robotics Club is a tremendous educational tool, there are obviously some things a competitive student design team cannot do. A student design team cannot provide opportunities for every student. Team sizes, resources, and the interest levels of some students prevent the use of design teams as a required part of the curriculum. Design competitions are most appealing to students looking for a technical challenge, and might not be useful for students with poor self-confidence, or a desire to "just get by." Voluntary participation seems to be a necessary component of competitive design teams.

As voluntary groups, design teams are not easily conformed to a set of requirements for process, documentation, or a particular set of conceptual material. It can be argued that even trying to push a design team toward a particular solution or method defeats the purpose of developing their open-ended problem solving skills. In any case, design teams do not lend themselves to satisfying a set of curricular requirements. On the other hand, arrangements may be made for students to meet academic requirements using the design team's activities. The Aerial Robotics Club has spawned a number of course projects and independent projects. In a number of cases, students who had no connection with the Aerial Robotics Club worked on a project initiated by the team.

There are two things the Aerial Robotics Club does exceptionally well: give students a reason to aggressively pursue new knowledge, and challenge excellent students. Just a couple of anecdotes will serve to illustrate just how educationally effective the club can be. In one case a freshman electrical engineer was working on conditioning a noisy sensor signal. He came by my office to ask a few questions about how to reduce the noise, but was struggling with the concepts of filtering and frequency since he had not yet taken any courses remotely preparing him for the problem. After some discussion, we determined that a simple RC filter would be adequate and we turned to choosing the R and C values. I explained a little about time constants and loading the sensor, and showed him a basic circuits textbook explaining RC filters. This student looked at me and asked, "Could I take this book home and read more about RC filters?" He took the book home as if I had given him a present, and brought back a reasonable design for the filter he needed. I was overjoyed. It was one of my best moments as an educator. When was the last time you heard of a student in one of your courses asking to borrow a book to read more about the current topic? This rarely happens unless the student is working on a project.

Another example of the educational effectiveness of the Aerial Robotics Club involves another freshman student who had taken responsibility for the power supply board on the helicopter. As a freshman he did not know how to measure the energy capacity of the batteries he needed, much less how to do the required voltage conversion to obtain the needed supply voltages. Over three months, I had two or three conversations with him explaining amp hours as a battery specification, and basic solid state regulation. At the end of the year this student had determined the power requirements of the on-board systems, specified and purchased adequate batteries for the required flight time, and designed a supply system using two regulators and a voltage inverter circuit. I was surprised to find that he had also designed, etched, built and tested a printed circuit board for the power system. The entire system worked correctly, and yet he had not had a single circuits course, and had little to no previous experience. If the average student in the average course had such motivation, I wouldn't be able to meet the demand for more homework problems.

Admittedly, the Aerial Robotics Club attracts strong students with great self-confidence. Why else would they want to spend their spare time trying to solve a problem that hasn't been perfectly solved in nine years? Clearly, the Aerial Robotics Club is not just motivational for the students; it is also motivational for me. The mix of very good students, a fascinating problem, and nice equipment regularly recharges my enthusiasm for teaching engineering.

Clear Advantages

The Aerial Robotics Club offers a design experience superior to the senior project course in the length of the project, in multidisciplinary experience, and in the level of responsibility assumed by the students. Several students in the Aerial Robotics Club have had opportunity to take a design to the competition one year, evaluate its weaknesses, and then iterate the design for the next competition.

The Aerial Robotics Club provides a challenging open-ended problem with real budget constraints and other unrelenting specifications like total payload weight. The problem involves a wide range of disciplines and encourages students to work with teammates outside their major on problems, which are often outside their major specialization.

The Aerial Robotics Club gives good students a challenge and the motivation to aggressively learn new skills and concepts. No assigned work can give students the inward desire to learn, but a truly fascinating problem can motivate students to devote evenings and weekends to learning what they need to know.

Ways to Improve

The fact that team members have to choose between work on their courses and work on the Aerial Robotics Club has always been a stumbling block. Much better ways of giving academic credit for all the learning that occurs in the club need to be found. Although the club does initiate some academic projects, most of the work occurs outside the coursework/academic circle, so the students receive no credit. The solar car team has successfully run a design course around the club's activities, giving members the opportunity to receive credit for their efforts.

This approach acts to correct one of the main shortcomings of the club's educational benefits. Team members are not strongly inclined to document their work, and so the process of communicating specifications between technical groups, and from members who graduate to their successors, is often inadequate. Building a design course around the club would allow the imposition of some formal design process procedures onto the work, including a requirement for complete documentation. This approach would resolve one of the main difficulties with assigning academic credit for club work. It is difficult to give academic credit without the documentation, and since other members may contribute to work handed in by a student receiving credit, it is difficult to assign credit for some projects to an individual. Requiring documentation assures that contribution by others is minimized, since they are unlikely to document their work, and it also produces a record that can be used as evidence of the learning experience.

Conclusions

Members of the Aerial Robotics Club have the opportunity to learn things that they could learn few other places. With the exception of a few other design clubs on campus like the solar car team and the human powered submarine team, the Aerial Robotics Club offers the only opportunity for underclassmen to dirty their hands with real applications. The motivational aspects of the club are powerful, and the benefits to the educational experience of active members are significant. Several past members have related to me how their experience in the club aided their job search and enhanced their careers. Several corporate recruiters have also mentioned how impressed they were with the students who could tell about their design work for the Aerial Robotics Club.

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