Rocket Systems Engineering Education at the Undergraduate Level

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Abstract

Cadets and faculty at the U.S. Air Force Academy are designing and building a sounding rocket powered by advanced hybrid propulsion. The eventual goal of the program is to launch a vehicle carrying a small payload to an altitude greater than 50 miles thereby achieving "space." Senior-level cadets are developing a prototype rocket to meet these objectives as part of their engineering curriculum. The primary objective of this capstone design project is to allow the cadets to synthesize what they have learned in the classroom and apply it to a challenging project within their field of study. We have found that this program significantly enhances the ability of our students to tackle ill-defined problems within a dynamic team environment.

By its very nature developing a rocket system is a multi-disciplinary endeavor. Although the participating cadets are primarily Astronautics majors, the project requires them to apply expertise from many technical disciplines including aerodynamics, mechanics, electrical engineering, computer science, and astronautics. Through the development process the students learn the value of systems engineering to pull together the diverse subsystem disciplines into a well-integrated vehicle system.

Advancements in aerospace technology are exciting and beneficial spin-offs from this effort. Cadets are performing leading-edge research and development in hybrid rocket propulsion systems that use solid fuels and liquid oxidizers for propellants. A small piston oxidizer pump is being developed to negate the need for highly pressurized vessels. The rocket system will employ lightweight composite propellant tanks, integral to the structure, to reduce mass and enhance the overall system performance. A peripheral interface controller (PIC) chip will be used to store sensor data and to initiate key flight events.

As with any significant curriculum effort, developing a rocket system with undergraduate students can be a formidable task. In particular, our program requires a substantial commitment of faculty expertise, laboratory resources, and funding. Nonetheless, overcoming these inherent challenges enables substantial student learning to occur. Our experience is that both group learning and independent thinking are enhanced, and that the curriculum provides first-hand experience in the development of aerospace technology.

Introduction

An ongoing challenge in engineering education is to provide students with meaningful design projects that help them synthesize what they have learned in the classroom and to better prepare them for their future careers. The United States Air Force Academy (USAFA) faces the same challenges despite its uniqueness as a military institution. The mission of the Academy is to "inspire and develop outstanding young men and women to become Air Force officers." Many USAFA “grads” will enter scientific and engineering career fields after commissioning. They will be assigned to laboratories, system program offices, test agencies, and operational air and space units. The nature of the technology-driven Air Force requires that these new officers be able to understand the key concepts and issues to allow them to resolve ill-defined technical problems. “Capstone” design courses in the engineering curriculum at the Academy allow senior-level cadets to hone their skills at attacking such problems.

A challenge we face within the Astronautics Department is how to give our cadets relevant “hands-on” experience within the space arena. We want cadets majoring in astronautics to have the opportunity to “learn space by doing space.” So what can space engineers design, build, test, and operate to provide them with practical experience in their chosen field of study? The obvious answers are satellites and rockets! This short answer has some very non-trivial implications as one might suspect. Such systems are typically complex and can be costly. Nonetheless, the Air Force Academy has aggressively pursued programs in which cadets can build small spacecraft and rocket systems. This paper will focus on our rocket development effort; our small satellite program was presented at the 1999 ASEE conference.[1]

Rocket Program Background

Our rocket development program is implemented totally within the context of the Academy’s undergraduate curriculum. Engr 433z, Rocket Systems Engineering, is a 4-credit hour course taught in a two-course sequence. It is one of three courses that fulfill the senior-level capstone design requirement for the astronautics major. It is the “big brother” of another course, Astro 433, in which cadets design and build much smaller scale rockets (about 4 ft tall) that fly to a maximum altitude of 2000 ft. The third course of the trio is Engr 433, our small satellite design course. Two of the courses carry the “Engr” moniker to emphasize their multi-disciplinary nature and to help attract cadets from various technical disciplines.

As one would expect, cadets take a variety of majors and core engineering courses to prepare them for their design courses. The prep curriculum includes courses in astronautics, rocket propulsion, space vehicle systems design, control theory, aeronautics, thermodynamics, fluid dynamics, electrical engineering, computer science, and aerospace structures. While this is an impressive resume, nothing fully prepares them for the “real world” challenges they will face as they design and build a rocket-powered vehicle. They must learn to work as a technical team and deal with issues such as task scheduling, safety practices, cost control, the government procurement system, external agency coordination, vendor delivery delays, hardware manufacturability, configuration control, and intra-team communication - to name a few. The team environment also provides an excellent setting for our officer candidates to gain first-hand experience with technical management and leadership – exactly what many will be doing a few short months in their new jobs as 2nd Lieutenants.

Research on hybrid rocket propulsion dates back to the 1930’s in Germany. For the next 50 years or so, hybrid research continued sporadically in the United States and Europe. In recent years more organization and focus has been placed on this propulsion technology. The largest hybrid rockets to date were built by AMROC in the late ‘80s and early ‘90s. This work is continues today under a group of companies organized under the umbrella of NASA. The USAFA started doing basic work on hybrid rockets in 1990. This led to the flight of a GOx/HTPB (gaseous oxygen/hydroxyl-terminated polybutidiene) sounding rocket in 1991. Further work, using liquid oxygen and HTPB as propellants, resulted in the flight of a 350 lb. sounding rocket, “Chiron,” in 1994. Powered by a 1000 lb thrust hybrid rocket engine, Chiron flew to an altitude above 15,000 ft. More recently, we have been concentrating on the use of hydrogen peroxide and nitrous oxide as oxidizers in combination with a variety of solid fuels including HTPB and polyethylene. This work has involved hundreds of static test firings and dozens of sounding rocket flights.

Our Educational Approach

Though there are a number of learning objectives for our Rocket Systems Engineering course, we can narrow them down to two overarching objectives:

- Understand the basic engineering design process
- Understand the design of rocket-propelled vehicles.

Of these objectives, the first one is the most important, by far.

We have been “engineering things” now for millennia and have been engineering aerospace-like things for about the last century or so. This vast amount of “cultural experience” has led us to, some would argue, a somewhat rigid and burdensome process. This process includes such things as design reviews, work-breakdown structures, detailed schedules and the myriad of administrivia that can cause the most stout-hearted program manager to cringe, if he or she is really intent on “getting the job done.”

The advent of all of these “aids” stems from our need to tackle complex problems. The definition we like best for a complex problem is one that “a single person cannot keep in his head.” By contrast, a simple problem is one that a single individual CAN keep in his head. Of course, this very definition implies a subjective nature to the whole design process, as it should. To overcome the limitation of not being able to keep everything in a single manager’s head, industry developed a variety of tools to give technical managers some control over the complex problem. These tools include the usual things such as schedules, work-breakdown structures (WBS - a hierarchical list of work tasks), etc. All of these various aids can be very useful if you know why you are using them. However, if you do not know why you are developing a WBS, for example, then creating it can be counterproductive, or even detrimental, because you create the illusion that you know what you are doing.

Now, there are two ways to approach the problem of teaching the basic engineering design process. The first way is to have the students create all of the tools needed for a typical engineering project. The students will dutifully generate schedules, WBS’s, design documents, design reviews, etc. as required by the syllabus. We require these products knowing how difficult it is to create a truly complex system over the period of a semester or two. This could lead the student to conclude that implementing the tools is a waste of time and effort. But worse, the student may not really understand the need for all of these tools. Of course, there is value in this approach in exposing the student to the process so that he at least recognizes it when he sees it.

We take a different approach in our rocket engineering course. We start out by generating a list of only the broadest of objectives (e.g. mission-level objectives). We then leave the development, and the structure of the development, completely up to the students. Inevitably, an individual, a sub-group, or the entire group will reach a point where they are struggling. This point is highly subjective and is dependent on the particular talents of those in the class. However, “the point” is usually pretty easy to identify. Now, the instructor has to only ask some very simple questions, such as: “what things do you need to do between now and the end of the project to get everything done?” After the student(s) have compiled this list, a second question can be posed: “when do these tasks need to be completed so that we can get everything completed by the end of the project?” This will encourage them to look at the schedule and to figure out the sequence of events that must be done to “get there.” Only later is value added by pointing out that they have created a WBS, a schedule, and have done a critical-path analysis. Of course, in any project, there are other issues such as design reviews and verification activities to name just two. Each of these can be handled in a similar manner.

One interesting effect of this approach, that we have noticed, is almost a complete lack of understanding, initially, of how long it takes to get a particular job accomplished. Invariably, we find that any particular class believes that they can build a large, complex rocket-vehicle system in just a month or so. When you get these estimates, the most difficult thing to do is not to smile. The second most difficult thing is not to criticize. They really believe that they are capable of doing what they propose. Being critical at this point adds no value to learning. However, once they are clearly and hopelessly behind schedule, a gentle reminder adds a world of value, and experience.

Our second objective, designing rocket-propelled vehicles, is less important that the first but is, nonetheless, significant. The main “draw” of this choice of topic is its exciting nature: generating tremendous power (burning stuff), high risk and consequence of a failure (blowing stuff up), and flying the resulting vehicle.

There are three basic rules that we try to follow as we implement the course:

- Let the students have ownership
- Almost nothing is a “dumb idea”
- Failure IS a viable option

Ownership in a project is an absolutely KEY attribute of this or any other project. In fact, if you examine the myriad of engineering failures throughout history, the underlying cause is rarely a calculation error. Instead it almost inevitably comes from the fact that a given individual did not have enough ownership or responsibility to motivate him to properly tackle the problem. Student ownership of this project flows from the very approach of not dictating the concept, the schedule, or anything else. Allowing the students to develop all of these things naturally engenders ownership.

At times it can be difficult to not criticize a “dumb idea.” Although it is important to steer the project in a direction that is appropriate and that will hopefully lead to successful completion, learning is the ultimate goal. Arbitrarily rejecting ideas, which at first glance, seem ludicrous, is destructive to the learning process. If the idea works, the instructor learns something. If the idea does not work, the student has learned infinitely more. Of course, the exception to this “rule” is an idea that is inherently dangerous. Safety is always the key concern.

Failure must always be a viable option. Historically, we have been focused on successful ventures. Success always appears to be better than failure, at least upon cursory examination. The problem is that when we focus on “no-failure” we tend to be conservative and sometimes excessively so. Without aggressive ideas, there is no overall progress. What would have happened in the 1950’s and 1960’s if failure were not a option? We lost a large number of launch vehicles and spacecraft, most of which added to our collective body of knowledge. However, a tremendous quantity of learning happened. Today in the aerospace industry failure is rarely tolerated, even in the R&D realm, because of the extremely high costs of aerospace systems. Fortunately, in a learning environment, we have the flexibility to accept failure, and often, it is for the good.

It is interesting to stand back and observe the results of failure. At first, it is quite exciting; an engine is damaged or a vehicle crashes. Then the student has to rebuild his system again, usually from scratch. It does not take long for the student to realize that he is expending a lot of unnecessary effort as a result. The student would have been better off to think through the problem more thoroughly ahead of time so as to avoid the failure and the resulting extra effort to redo everything. No success can EVER replace this learning experience!

We believe that the key components of our philosophy are:

- Learning is paramount
- People learn MUCH MORE from experience

We can lecture until we are blue in the face, yet we know that a very small percentage of the content we lecture on will be retained. This is tremendously frustrating for the “teacher.” On the other hand, just creating an environment that allows the student to learn on his own, seems to enhance retention tremendously and is ultimately easier and more rewarding to the teacher. On the other hand, it can be exceedingly difficult to stand back and just let things happen.

Student Sounding Rocket Design

Fifteen cadets in the Air Force Academy Class of 2000 have aggressively been working on a sounding rocket concept capable of meeting the design goal to deliver a 22 lb payload to an altitude of over 50 miles. The following description of the system is a summary of information provided by the cadets themselves. This information is intended to provide the reader with an appreciation of the level of learning taking place within the project by describing the cadets’ progress and accomplishments as well as the issues and challenges they have faced.

System Overview (C1C Chris Gentile)

To achieve our design altitude, a total change in velocity (or ΔV) of about 8000 ft/sec is required. After preliminary design analysis we chose to use a single-stage core vehicle powered by a "hybrid" propulsion system. Hybrid engines typically use a solid fuel grain and a liquid or gaseous oxidizer. A drawing of the 13' tall (4.0 m) core vehicle configuration is shown in Fig 1. Two solid "strap-ons," each providing about 150 lbs of thrust, will help accelerate the vehicle off the pad to obtain a velocity suitable for fin-stabilized flight. The 500 lb thrust hybrid engine will use hydroxl-terminated polybutidiene (HTPB, a rubber-like compound) as fuel and hydrogen peroxide (H_2O_2) as the oxidizer. This system will generate a sea-level specific impulse (I_{sp}) of about 225 seconds. This level of performance means that, for a payload mass allocation of 10%, over 70% of the rocket at lift-off must be comprised of propellant. This leaves only 20% available for the "inert mass" which must accommodate such subsystems as the engine, structure, oxidizer tanks, and propellant feed system.[2] To meet this challenge, several innovative technologies are being attempted.

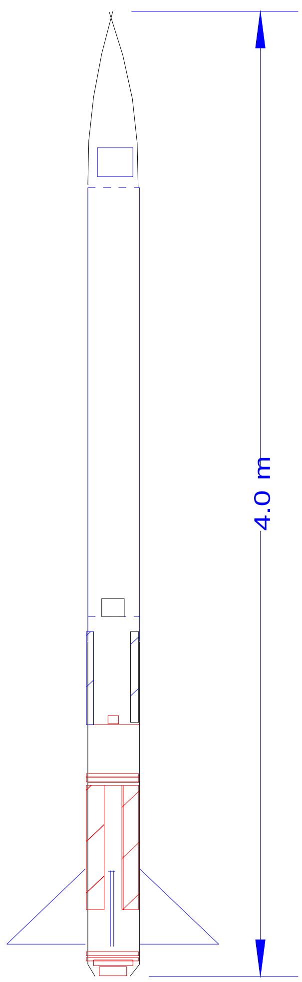


Figure 1. The Rocket

When first evaluating our system, it quickly became apparent that a tank-pressure fed system, traditionally used at the Academy, would not be acceptable. The tank mass and pressurant system alone would have exceeded our total inert-mass budget. From this point, the decision was made to design a pump-pressure fed system, leading to the piston pump currently in production. Next, we searched for ways to reduce the structure mass while still allowing ease of assembly, testing, and adjustment, leading to a composite structure that integrates the tank seamlessly with the main structure of the rocket. Finally, in an effort to reduce the mass of the engine and thrust chamber, energetic chemicals were added to the HTPB fuel to increase the regression, or burn, rate and allow a smaller thrust chamber.

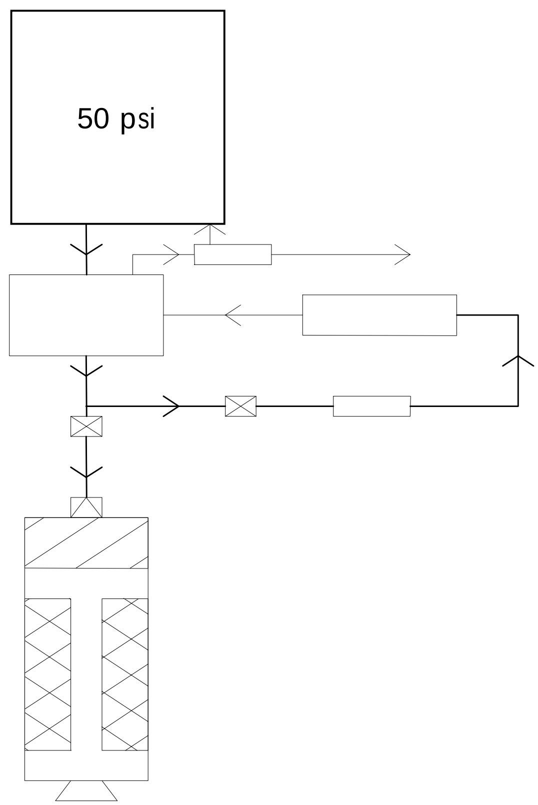
Although the vehicle engineering is currently our main focus, cadets in the course are also developing the rocket's primary payload - a telemetry, tracking, and control system (TT&C). This microcontroller-based flight computer unit is capable of reading and storing information from a GPS receiver, pressure altimeter, accelerometers, and several other housekeeping sensors. This data is then transmitted via packet radio to a ground station, which also provides a control uplink for such events as an emergency engine shutdown.

Technology Thrusts

As alluded to above, the mission requirements and associated constraints forced us to consider alternatives to some conventional technologies. These "thrusts" include hybrid propulsion, small piston propellant pumps, integral composite tanks, and the application of PIC (peripheral interface controller) technology. Though our efforts may not be considered hardcore research, the applied R&D work we are doing adds to the knowledge base in the field.

Hybrid Propulsion (C1C Andy Martin)

We chose to use a hybrid propulsion system over solid and liquid alternatives because of its inherent safety characteristics, acceptable performance, and relative simplicity. Because both the fuel and oxidizer are stable and easily handled, it is much easier for students to build and test engines without extreme safety precautions and restrictions. Hybrid rocket propulsion exhibits better performance than comparable solid rocket motors, while being much simpler to construct than liquid bi-propellant systems. The safety considerations, in particular, make hybrids very attractive for use at an academic institution like the Air Force Academy.



A schematic of the engine system is shown in Figure 2. The engine consists of all plumbing required to transfer the oxidizer from its tank to the combustion chamber at a flow rate of about 0.5 lb/sec. The H_2O_2 is stored in the tank at a relatively low pressure of 50 psi. The pump increases the oxidizer pressure to about 1000 psi, to ensure a chamber pressure of about 500 psi throughout the burn. Bleed gas from the pump is used to maintain a nearly constant ullage pressure in the oxidizer tank as H_2O_2 is drawn out. The pump forces the H_2O_2 into the combustion chamber through an injector where it then passes through a catalyst bed which causes the H_2O_2 to catalytically decompose into hot O_2, H_2O, and H_2O_2. Once ignited, the oxidizer gases and the HTPB combust forming reaction products of H_2O and CO_2. These hot gasses will then travel down through the central fuel port, pass through the aft mixing chamber, and be exhausted out of the nozzle. The engine will produce an estimated thrust of over 500 lbs during a nominal 60 second burn duration.

The combustion chamber is currently sized with an inner diameter of 7” and a length of 28”. The fuel port will have a 3” diameter and the fuel core will be 20.5”. long. The remaining combustion chamber length will be used for premixing and aft mixing chambers.

Several challenging issues have arisen during the design process of the engine. The most important hurdle is to maximize the fuel burn rate. The current regression rate for H_2O_2/HTPB dictates a fuel core about one meter long, which is about twice as long as is practical. The fuel core must be made this long to ensure that the optimum oxidizer/fuel mixture ratio is achieved during the burn. By increasing the regression rate, the fuel core can be made shorter, which aids in body tube design, as well as helping with structural concerns resulting from a long slender frame. This problem is being attacked by testing sub-scale fuel cores with different amounts of potassium perchlorate mixed into the rubber base. This chemical adds a pressure dependency to the fuel regression, which should result in a much higher burn rate. Another challenge that must be addressed is the use of a catalyst bed for oxidizer decomposition. The proposed design has never been tested at the required oxidizer flow rate of 0.5 lb/sec. The possibility of auto ignition using only the catalyst bed is also being considered. To allow reuse of the combustion chambers, each fuel core is wrapped with silicon rubber, which will allow the spent core to be removed after each burn and replaced with a new fuel core, while protecting the chamber walls from heat damage.

Oxidizer Piston Pump (C1Cs Chris Gentile, Nick Hamilton, Kevin Lee)

After deciding that our propulsion system design needed to be pump-fed, we began exploring different pump technologies. The first option, using turbopumps, was dismissed because of the small size requirement of our pump and the corresponding low turbine and impeller efficiencies. In addition, the complex machining necessary for the rotors is beyond our in-house capability. With these factors in mind, we chose a piston pump, designed by Dr. John Whitehead of Lawrence Livermore National Laboratory. This pump design is simpler to construct and is not affected by the inefficiencies of small-scale turbomachinery.

The pump operation is relatively simple. High-pressure liquid H_2O_2 is bled off the propellant line and fed to a gas generator where it is catalytically decomposed. The hot, high-pressure gas is then delivered to the pump (see Fig. 2). The pump houses a series of valves to deliver the gas to the cylinders. The main pistons operate on the principle of differential area; a plug reduces the effective area on the liquid side of the piston. This results in the liquid exiting the pump at a higher pressure than the drive gas entering the pump. This allows the pump to ‘bootstrap’ itself up to its operating pressure from an initial pressure as low as 50 psi. The pump is being designed for a flow rate of 0.5 lb/sec at 1000 psi. To accommodate the high temperatures of the pump drive gas (about 1800^{o} F) the pump will be immersed in the liquid H_2O_2, mounted in the bottom of the tank.

Figure 3. Piston Pump Housings

Cadets in the course are fabricating the most of the components for the pump themselves. As design sketches and instructions arrive from Dr. Whitehead, we generate engineering drawings, assist in analysis, and begin construction. The first section of the pump to be completed was the gas drive/cylinder housing, shown in Figure 3. These parts, the main housing (on the right) and the spare, were constructed on the mill and lathe from 6061-T6 aluminum.

The main challenges that we have faced to date have primarily dealt with fabrication (we have yet to get to the integration and test phase). Early errors, such as a broken drill bit inside the cylinder housing, taught all the cadets involved some lessons about the practical aspects of engineering work.

Vehicle Structure (C1Cs Joe Bemis, Jason Goldberg, Nick Hamilton, Ben Wolf)

To minimize overall system mass we are developing of an integral tank structure, i.e. one in which the exterior of the oxidizer tank forms the outer skin of the rocket itself. In our design approach we divided the rocket structure into three major sections: the H_2O_2 tank liner, the composite overwrap, and the aeroshell with support beams. The oxidizer tank liner is an 8" diameter tube of 0.02" thick aluminum rolled into shape. It is about 70" long to provide enough volume for the hydrogen peroxide and the pump. The aluminum was chosen for its good strength-to-weight properties and because it does not react with the oxidizer over our relatively short storage durations.

The composite overwrap is made of carbon fibers and epoxy. The material was donated by Vanguard Composites Group of San Diego, CA. The overwrap runs the length of the tank liner, with some extension on the top and bottom for connections to the nosecone and aft aeroshell, respectively. The primary purpose of the composite overwrap is to hold the shape of the tank and to seal the mating edge of the tank liner. Three to five layers of composite material will be sufficient to fabricate a tank strong enough to handle the expected loads and tank pressure. The appeal of the composite construction is that it is relatively lightweight compared to an all aluminum tank. The weight of the composite will be about 4 lbs, about half the weight than the necessary amount of aluminum.

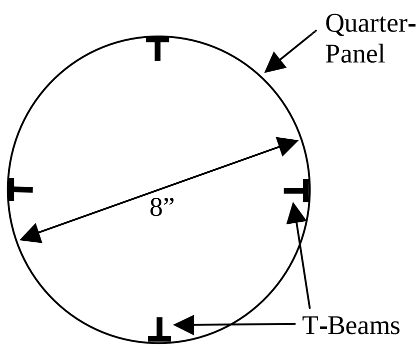


Figure 4. Cross-Section of AeroShell

The third part of the structure is the aeroshell that covers the propellant feed system plumbing and the combustion chamber near the aft end of the rocket. The composite aeroshell is supported by four aluminum T-beams that run the length of the shell. The beams are bolted to the inside of the composite overwrap at the top and onto the motor case at the bottom. The beams are 1.5" by 1.5" with a 0.25" thickness and are spaced at 90^o intervals within the structure (see Fig. 4). The beams are designed to support all expected loads on the rocket, to include buckling; the aeroshell is intended to serve only as an aerodynamic shroud covering the internal hardware. It is sectioned into four quarter panels to allow access to the plumbing.

Payload (C1Cs Brian Marbach, Joe Roe)

For this demonstration mission the “brains” of the system are considered as the payload to be carried by the rocket. The function of this system is to monitor and track the launch of the rocket and recovery of its payload. To do this, we are using a GPS receiver to acquire position data and a radio to relay this data to a ground station. The rocket also has an on-board memory storage capability in case the radio does not send all of the data. Besides position, other data includes the current status of our deployment system, ambient pressure, temperature, and other miscellaneous engine performance data (See Fig. 5).

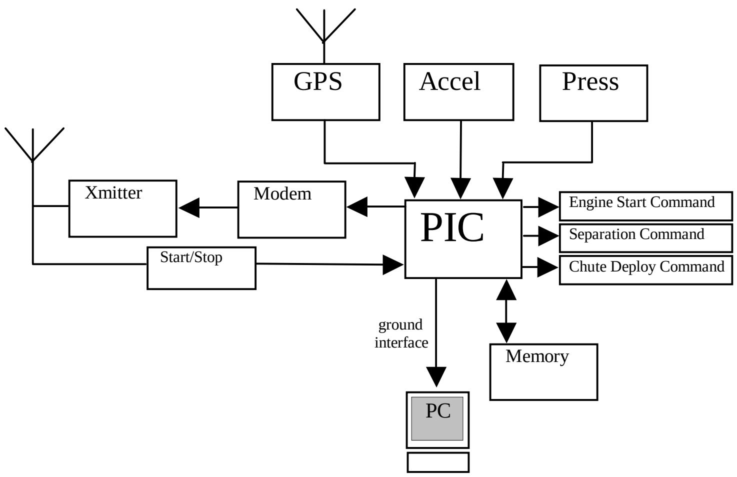


Figure 5. Payload Block Diagram

To perform this function, we are using a peripheral interface controller (PIC) as the central processor. The PIC is a small CMOS chip made by Microchip that is coded in assembly language. We are using a PIC 16C773 8 bit micro controller with 4 built-in 12-bit analog-to-digital converters, 22 input/output ports, 8K program memory and 256 bytes of data memory. The GPS altitude is used to trigger separation of the rocket nose cone and opening of the drogue and main parachute. It sends the data through a Mixed Signal modem chip in AX.25 packet radio protocol to a ground station so that we may track where it lands to recover the nose of the rocket. It also stores all of the data on 2 Xicor 128K EPROMs that can later be downloaded onto a laptop compute after recovery.

We chose to use PICs because they are expendable and we have prior experience in using them. The controllers cost about $5.00 each and work at about 1 million instructions per second. This provides us with a platform that can handle the data rate at a fraction of the cost of other controllers. Also, the whole PIC circuitry is compact and lightweight - ideal for our purposes. PICs are an emerging technology. They are commonly found in terrestrial devices like printers, copiers, and digital clocks. We are putting them to the test by using them in a rigorous aerospace application.

Two design issues we are tackling are the recovery system development and the transmit-antenna design. We need to make sure that the components of our recovery system survive the harsh environments experienced during the mission. It can get extremely hot on the ascent as well as during initial descent. We must have a system that can deploy parachutes large enough to slow the payload to an acceptable impact speed, while not letting it drift too far. For aeroheating reasons, we do not want to have external fittings on the nose cone, so we must have a means to attach everything to the base of the cone. The major problem with antenna design is knowledge of the radiation patterns to get a strong enough signal to the ground station throughout the entire duration of the flight. Our solution is to switch between two antennae during the different phases (launch and recovery). If we have enough time and weight allowance, we can install a camera near the base of the nose cone to give us a real-time view of the rocket's environment.

Program Challenges

A project as ambitious as rocket system development and operation generates a number of challenges. Some of the challenges faced at the Air Force Academy include funding, launch facilities, safety considerations, and undergraduate curriculum.

Funding. For the last few years the rocket project has lived on a shoe-string budget, so we must stretch every dollar as far as possible. The program receives very little institutional funding except for its pro-rata share of department funding for course support. We rely heavily on funding from outside agencies and benefactors including the Academy's Association of Graduates (AOG), the NASA Colorado Space Grant Consortium, and the Air Force Office of Scientific Research (AFOSR). The program budget for this current academic year is about $15,000. In our academic environment this is sufficient funding to build a rocket system, perform numerous engine test firings, and execute a test flight of the vehicle. A large share of the budget is allocated for propellants, particularly for high-concentration (90%) hydrogen peroxide (about $4,000). Other "big" ticket items include assorted chemicals and compounds, plumbing parts for the propulsion feed system, electronic components for the flight avionics system, and specialized test equipment. The program saves a lot of money not having to pay for skilled labor. Most of the cadets in the program are very adept at using available machine shop equipment and can fabricate most of the components themselves. Only in rare instances are jobs "out-sourced" to the Academy's professionally-staffed machine shop.

Launch Facilities. Although the Air Force Academy owns thousands of acres of open space, the base is not large enough to provide a range for the launch and recovery of high-altitude rockets. In addition, because the Academy operates a very busy airstrip for airmanship training, rocket launches are restricted to a maximum altitude of 2000 ft AGL. Consequently any launches of our rocket development effort must take place from sites away from the Academy. We have used the artillery range at Ft Carson Army Post in Colorado Springs for two previous missions, one of which achieved an altitude of over 15,000 ft. Our next test flight, scheduled for May 2000, will also launch out of Ft Carson. Because of an imposed 5-mile impact radius constraint, however, the maximum altitude allowed is 20,000 ft. To assure that the rocket will not fly higher than this limit it will only carry less than 20% of its oxidizer load capacity. It will thrust for just 10 seconds and then coast to its apogee altitude before starting its descent and recovery. For missions into near space we will have to use established rocket test ranges at locations such as Poker Flats, AK or Wallops Island, VA. Using sites like these brings with it the obvious logistics challenges of transport and remote operations as well as significant additional cost.

Safety Considerations. By its very nature rocket system development is a hazardous business. We must be extra careful because inexperienced students are involved. Even though we use relatively benign propellants, the hydrogen peroxide requires proper storage, handling, and disposal. It is a corrosive oxidizer that can cause burns to exposed skin. Mixing of the solid fuel also requires proper ventilation and handling. Static test firings of the rocket engines are performed at a site on the Academy grounds. Because failure is a real possibility special precautions must be taken. Base Safety reviews and approves the test procedures and periodically observes the test firings. The operation is conducted remotely, and personnel are kept a safe distance from the outdoor test stand behind a blast shield. Abort procedures are implemented in case of misfire or abnormal engine performance (e.g. burn-throughs). The stakes are even higher when test launches are conducted. The rocket can become a high-energy projectile if its recovery system fails potentially causing damage to property or injury to personnel. As such spotters must be used to track the vehicle throughout its trajectory. We also learned first hand that a failed rocket can start a small brush fire and that recovered pieces of the rocket may be quite hot to the touch!

Undergraduate Curriculum. As in our small satellite program a challenge we face in our rocket development program is the lack of graduate researchers. Unlike research institutions that have graduate students available to work such projects essentially full time, we must rely on undergraduates to execute the program. Although the Academy attracts some of the best students in the country, the reality is that time is a limited commodity here. Cadets in engineering majors often take more than 20 credit hours of course work a semester. In addition, cadets have military duties to perform as well as required physical training. Many cadets are also involved in various aviation programs like flight or jump training. From the cadet perspective, the rocket design course is just one of six or seven courses that they may have in a given semester. Fortunately, most cadets are motivated by the project to put in the necessary time to get the job done.

Conclusion

Our experiences with implementing a rocket systems engineering course illustrate some of the unique opportunities and challenges of undertaking such an ambitious program. Our approach is non-traditional in that we do not force the "classic" systems development process on the cadet team. We give them the broadest of program objectives and empower them to tackle the complex, ill-defined problem on their own. We allow cadets to think "out-of-the-box" and try new ideas; we have the luxury to accept failure as a viable outcome. Through their first-hand experiences these fledgling engineers learn the value of the tools used to manage the development of real-world aerospace systems. These experiences will better prepare the cadets for their future profession as Air Force officers in the technologically advanced realm of air and space combat. The learning achieved in the rocket systems course can be summed up by the comment of one cadet: "I've learned more from this course than from any other at the Academy." While we would like to think this is true, it does reflect the effectiveness of the "learning space by doing space" approach to undergraduate engineering education.

Bibliography

1. Chesley, Bruce C. and Caylor, Michael J. "Developing an Integrated Curriculum for Small Satellite Engineering," ASEE Conference, Session 2302, Charlotte, NC, 1999.

2. Humble, Ronald W., Henry, Gary N., and Larson, Wiley J. *Space Propulsion Analysis and Design*, New York: McGraw-Hill Companies, (1995), Ch. 1.

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