# Smart Rockets: A Hands-on Introduction to Interdisciplinary Engineering

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## Abstract

Model rockets have inspired generations of students to pursue careers in engineering and science. Indeed, many current engineering educators have probably gone through a rocket phase in their formative years. Model rockets are popular with young aspiring engineers for good reason, they are exciting, fun to build and launch and they offer a number of significant engineering challenges that can be tackled with simple tools and small budgets. We have created a Freshman seminar subject at MIT in which the students build and modify a kit-based model rocket. In parallel we discuss the elements of rocket physics and guide them in creating their own predictions of the what the acceleration curve should look like for the rockets. Their goal for the term is to collect the data needed to test their predictions. To accomplish it, they build a compact microcontroller circuit that can log acceleration at 1,000 samples per second. During the term, the students learn the basics of programming the microcontroller and explore its uses in the laboratory. At the end of the term, the class goes to a large open area, launches the rockets, and returns with data. The subject concludes with the students comparing their observations to their predictions, complete with a discussion of possible error sources and analysis, and recommendations for future work.

## Rationale and Goals

Students at MIT do not declare a major during their first year at the Institute. Instead, they take a standard set of eight subjects over two semesters and have the option of taking one seminar subject (graded on a pass/fail basis) each semester. None of the core first-year subjects include a laboratory component (with the exception of an optional physics section). There are many reasons why the Institute chose this approach, but its drawbacks include:

- The material from core subjects (particularly physics) remains theoretical and disconnected from practical engineering.
- Students who want to learn what a particular field is like must wait another year before experiencing the joys (and challenges) of a particular discipline.
- Students get no sense of what is involved in working on a multidisciplinary problem.
- Students do not get the hands-on experience that comes from building a project.

Our approach is to use seminars as a channel for offering hands-on, multidisciplinary subjects for students with such interests. Our first offering was "Smart Rockets," in which students:

- Analyzed the physics of a small model rocket and predicted the accelerations the system would experience.
- Built and modified a standard model rocket kit.
- Learned how to use simple electronics equipment.
- Built and characterized simple LED and op-amp circuits.
- Built a microcontroller-based accelerometer log from a kit and learned how to program it.
- Launched their rockets, collecting acceleration data with their kit that allowed them to test their predictions from the start of the term.

The subject meets once per week for three hours. The time is generally broken into a lecture period of 45 minutes and a 2-hour-long lab period (except for the first class meeting, which is described in the next section).We presume that the entering students have been exposed to mechanics in their high-school physics classes and have a passing familiarity with the notions of differentiation and integration from calculus (this is typical for our entering classes). To date, the subject has been offered twice, with eight students enrolled each time.

The goals of the subject are:

- To build excitement for engineering among first-year students by engaging them in an interesting hands-on project.
- To introduce a few fundamental concepts from electronics to the students.
- To illustrate the utility of their core subjects in the context of a hands-on project.

In the balance of this paper, we first present the acceleration-logging system we devised and describe how it works. We then discuss the structure of the subject and close with the results of the two times it has been offered and our conclusions to date. In this paper, abbreviations for SI units are in roman font, whereas mathematical symbols including the acceleration due to gravity ($g$) are italicized.

## The System

A block diagram of the electronics system is shown in Figure 1, and a photo of the prototype board (front and back) is shown in Figure 2a and b. The circuit is powered by a 3-V, high-discharge-rate lithium cell and incorporates four integrated circuits (ICs):

1) The $\pm 50$-$g$ accelerometer, with on-chip signal amplifier (Analog Devices ADXL50)
2) The microcontroller (Microchip PIC16C73)
3) The serial flash EEPROM memory device (Xicor 25F128)

This system exploits the amplifier integrated within the accelerometer package. In particular, the gain of the amplifier can be set by the external resistors, allowing us to scale the output to match our anticipated signal strength. Not shown on the block diagram is the switching DC-DC converter (MAX631A) that raised the 3-V battery output to the 5 V required by the ICs. A detailed description of the circuit and software has been published elsewhere.[1]

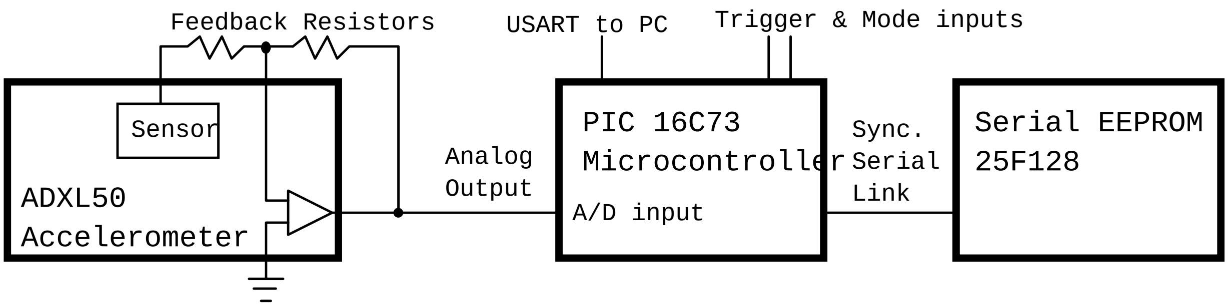
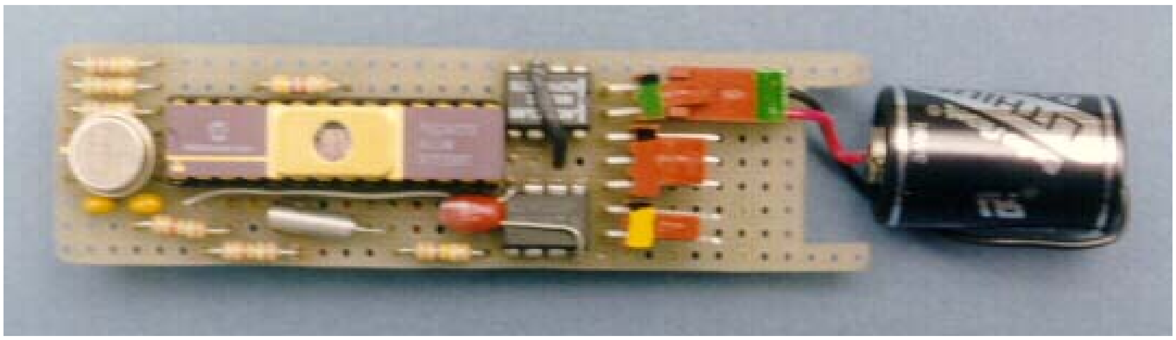



Figure 1. Block diagram of the system. The accelerometer generates a signal proportional to the acceleration the rocket sees. This signal is read by the PIC microcontroller. The PIC writes the data to the serial EEPROM, where it can reside even when powered down. After recovery, the data is sent via the USART to a laptop.



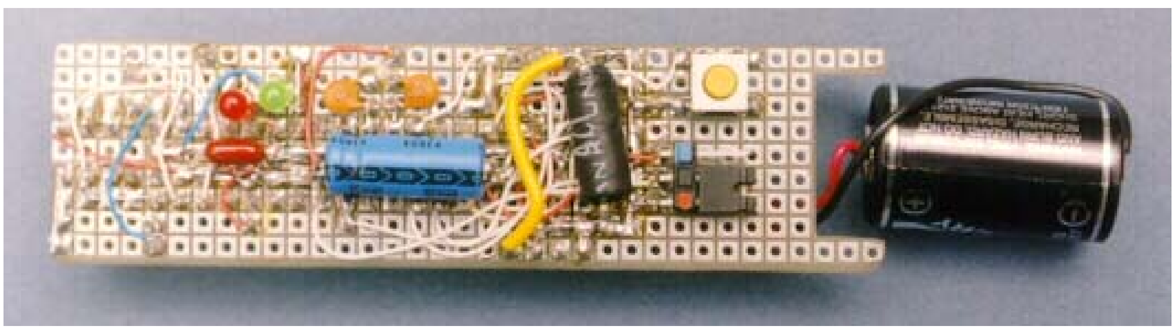


Figure 2. Photographs of the top (upper) and bottom (lower) sides of our hand-wired prototype. To simplify the construction of the circuit by the students, printed circuit boards were fabricated. The accelerometer is in the TO-100 can at the forward end of the board. Its axis of sensitivity is along the diameter of the can that crosses the tab. The color-coded connectors on the component side are for the trigger signal, serial communication (central 3-pin connector), and power, which is shown connected to the lithium battery. The red and green status LEDs, large black inductor, mode jumper, and the reset button are visible on the bottom of the board.

The system works as follows. The microcontroller detects the switch closure that ignites the rocket engine, at which point the microcontroller begins to measure and log the amplified output from the accelerometer. Shortly thereafter the engine ignites, swiftly accelerating the rocket into the air. When the propellant is consumed, the rocket continues to coast. During this stage, the rocket is in free fall and the accelerometer registers 0 *g*. After a set delay, the engine fires the ejection charge (to open the recovery parachute), which is recorded by the system as a short, intense impulse. The system continues to record acceleration as the rocket returns to Earth, until the serial EEPROM is full, at which point the program stops.

Upon recovering the rocket, the students remove the circuit board and attach it to the serial port of a laptop computer (through an intermediary level-shifting circuit). They then move a jumper on the board, which tells the microcontroller that it is to transmit the data from the serial EEPROM out of its serial port, and press the microcontroller reset. The data streams to the laptop, where it is captured and saved to a file (the program Hyperterminal bundled with Windows 9x is adequate for this task).

**Course Structure**

The subject was structured in five phases: Predicting the Acceleration, Introduction to Electronics and Microcontrollers, Assembling the Rocket, Launch and Data Collection, and Analysis and Reflection.

The initial phase occurred during our first meeting, where we skipped the usual introductory discussion of grading, etc. in favor of immersing the students in the physics of rocket flight. The students were grouped into pairs, and the pairs were instructed to consider a series of questions that walked them through the analysis of the acceleration that the rocket would experience during its flight. This analysis occurred instead of a laboratory exercise. The pairs of students were given the relevant physical principals, a reminder of the acceleration as the time-derivative of velocity, and the thrust curve for the engine we would be using (Figure 3). A set of questions were posed, the pairs were allowed to work on them (with the staff available for consultation), and then we had the pairs report back. A group consensus was reached and a second set of questions set forth and the process repeated. By the end of the session, the entire class had agreed on their prediction of what the acceleration curve should look like for the rocket.

The second phase, Introduction to Electronics and Microcontrollers, occupied the bulk of the subject. In this phase, students were (re)introduced to the concepts of current, voltage, and resistance, as well as Ohm's law. They learned how to use simple tools such as the digital multimeter (DMM) and the protoboard. They were introduced to LEDs and op-amps as a prelude to learning about the accelerometer we used (Analog Devices ADXL50). After the students performed a two-point calibration of the accelerometer, we moved on to an overview of microcontrollers.

The third phase, Assembling the Rocket, was carried out in parallel with the introduction to electronics. This was possible because the process of building the model rockets (Estes Nova Payloader) has several steps that are relatively quick to carry out but then require waiting for glues to set. We found that this helped break up the 3-hour-long class period into more manageable chunks, and some students said that they appreciated taking a break from the intense review of electronics. The last two phases (Launch and Data Collection, and Analysis and Reflection) occurred at the end of the term. We arranged one day in the field (and a rain date) each term the subject was taught.

In the next sections, we address each phase in turn and close with a summary of the results from the two times the subject has been offered to date.

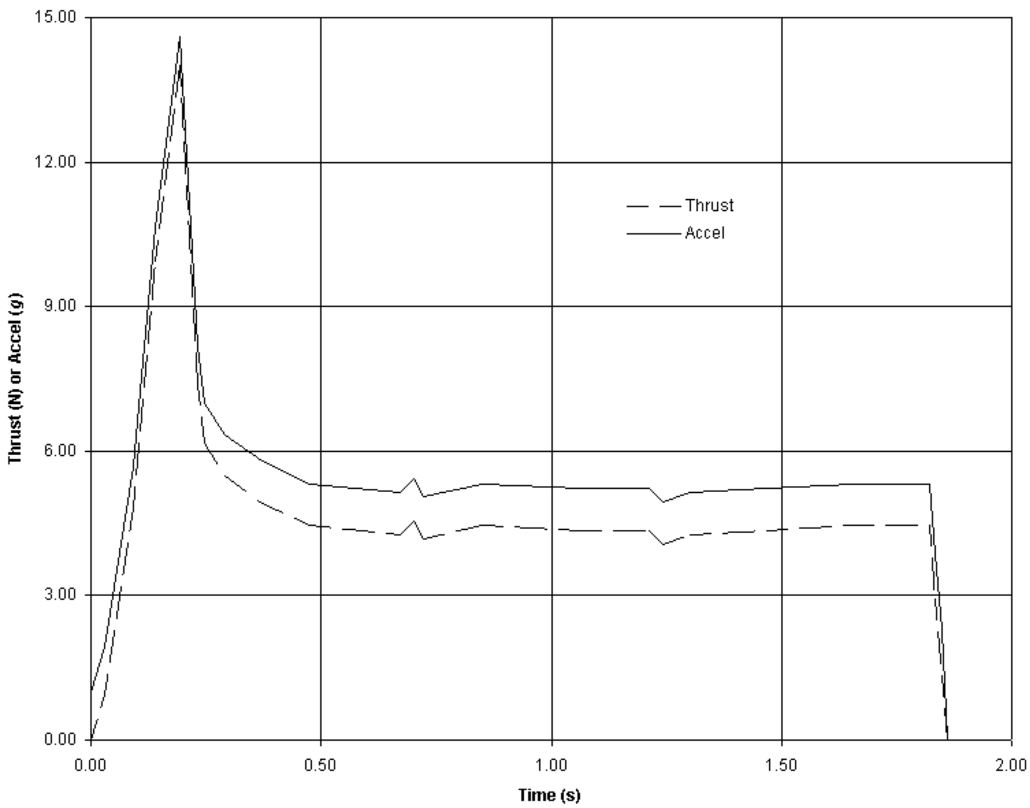



Figure 3. Predicted performance of the rocket. The thrust data was extracted from a performance curve of the Estes C6-5 engine provided by the National Association of Rocketry (NAR).[2] The acceleration curve for the rocket is calculated from the NAR thrust data. Note that at $t$ = 0, the system experiences Earth's gravity, which is equivalent to a rocket accelerating upward at 1 $g$ in free space.

### *Predicting the Acceleration*

We started by reminding the students that Newton's Second Law, $F = ma$, contains all the physics needed to predict the accelerations that the system will record. We gave them the mass ($m$) of our prototype rocket. The applied force ($F$) exerted by a rocket engine is not constant as can be seen in the thrust vs. time curve for an Estes C6-5 engine (the dashed line in Figure 3). We assume that the rocket moves straight up while the thrust is applied, so the total force is the engine thrust corrected for the gravitational force ($m \times g$, $g = 9.807$ m/s$^2$), where $m$ is the 105-gram take-off mass of the rocket, engine, and payload.

If the mass of the rocket were fixed, then the acceleration would just be the dashed line divided by the mass. However, as the propellant burns, the mass of the rocket decreases. We asked the students to decide if this effect were critical for our system (we noted that 85% of the space shuttle's take-off weight is fuel). In our case only 12 grams of the 120-gram take-off weight is fuel (10%), and the students decided that for their first-order analysis they could treat the mass of our rocket as a constant. They generated the expected acceleration curve shown as the solid line in Figure 3. Their task for the remainder of the semester was to determine—by direct measurement—if Figure 3 was correct.

### *Introduction to Electronics and Microcontrollers*

Initially, students were (re)introduced to the concepts of current, voltage, and resistance as well as Ohm's law. They learned how to use a DMM to measure voltage, current and resistance. We had them build and study resistive voltage dividers as an exercise that also consolidated their skills with the DMM. Next we presented the LED and its operating characteristics. The students built LED drivers and then measured the voltages at each node with the DMM.

Because the accelerometer we used (Analog Devices ADXL50) has an integral amplifier on chip, we selected the op-amp as the next device to present to the class. For this subject, we treated the op-amp as a black box whose inputs draw no current and whose output acts to keep the inputs at the same voltage. The students built a simple op-amp circuit on the breadboard and explored its operation. Then we used the same circuit to introduce them to soldering on a printed circuit board.

At this stage we introduced the accelerometer to the class. We had them select the resistor network for the accelerometer's op-amp to scale the expected output from the accelerometer to the 0–5-V range of the A/D converter on our microcontroller (PIC16C73). The students then wired up the accelerometer on a small protoboard and measured its output for ±1 $g$ by holding the board upright and then inverting it. From their results, the students performed a simple calibration of the sensor.

Next we embarked on a compressed overview of assembly-language programming and interfacing techniques for our microcontroller. We had the students review selected code fragments from the final program. Next, they modified those fragments into small programs that they downloaded into the microcontroller and debugged. In this way, we were able to give the students an overview of each major section of the code in the microcontroller and give them the chance to create their own working programs.

### *Assembling the Rocket*

The prototype data-acquisition system was point-to-point wired on a 15/16″ by 3 1/2″ piece of pad-per-hole perforated board (students built their circuits on printed circuit boards manufactured for the subject). The PIC chip was socketed so it could be removed for reprogramming. All other components were soldered directly to the board. Three connectors were mounted on the board (Figure 2)—two 2-pin connectors to the battery and to the trigger lines to the rocket body, and a 3-pin connector for the USART connection. The major challenge in the board layout was minimizing the component heights at the edges to accommodate the cylindrical shape of the payload compartment. Thus the PIC chip, accelerometer, and the large capacitor and inductor of the power supply were mounted centrally on the board. We also mounted components on both sides of the board, which had the added bonus of balancing the weight of the payload.

(a) (b)

Figure 4. (a) The 21-inch-long rocket on the launch pad. Note the data-acquisition system in the clear payload section and the copper contacts beneath the fins. The brown streak down the right side of the rocket is one of two lines of conductive paint bringing the trigger signal to the payload. (b) The data-acquisition system. The modifications made to the payload compartment are visible. The brown patch on the rear bulkhead connector is conductive paint that forms a sliding electrical connection with the rocket body. An engine is shown to the left.

Figure 4a shows the assembled rocket, and Figure 4b provides a close-up view of the disassembled payload section. A slot was cut in the rear end of the plastic nose cone that acts as a guide to hold the circuit board in the payload section (Figure 4b). Some material was removed from the plastic bulkhead that forms the bottom of the payload compartment to make a crude battery holder. Small pieces of foam wedged between the battery and the wall of the payload compartment helped hold everything in place. Both the nose cone and the rear bulkhead had to be taped to the payload tube to prevent the electronics from falling out of the compartment during recovery. For safety, the course staff attached wires onto the solder tabs of the battery and brought them out to a connector that mated with battery header on the circuit board.

One of the more difficult aspects of the design was bringing the trigger lines out of the payload compartment, down the rocket body, and out onto the wing tips. For this we used conductive paint, the kind used to repair windshield defrosters. An electrical connection was established between the payload compartment and the rocket body by applying two patches of paint on the outside surface of the payload bulkhead connector where it slips into the rocket body and two corresponding patches of paint inside of the forward end of the body (Figure 4b). Conductive lines were painted from these forward patches around the edge of the tube, down the exterior of the rocket, to patches of paint at the very tips of two of the three fins. These patches contact copper plates on the launch pad that connect to the launch control box (Figure 4a).

The paint patches on the bulkhead connector and the rocket body provide electrical continuity between the payload and the rocket while the model is on the launch pad. This connection is easily broken by the ejection charge. The trigger lines are brought from the circuit board to the paint spots on the bulkhead connector. Since it was not possible to solder the wires to the conductive paint, we essentially pasted the stripped end of each wire to its patch with a thick coating of the conductive paint. For strain relief, we glued the insulated portion of the wires to the bulkhead connector with model cement. Still, these connections proved to be very delicate.

### *Launch and Data Collection*

Before we ever left the lab, we went through every step in the sequence of the setup, launch (with no engine), data recovery, and data visualization. We had the students shake the rocket up and down a few times after pressing the launch key, generating acceleration data. Once we had perfected this procedure, we were ready to move outside.

In the field, students downloaded the raw data into a laptop after each launch and plotted it (Figure 5). The acceleration appears to be negative, but that is because the on-chip buffer of the ADXL50 is an inverting amplifier. The initial kick and the sustained thrust are easily seen. Although the accelerometer output has not yet been converted into acceleration, this plot still demonstrates to the students that their system was working as planned.

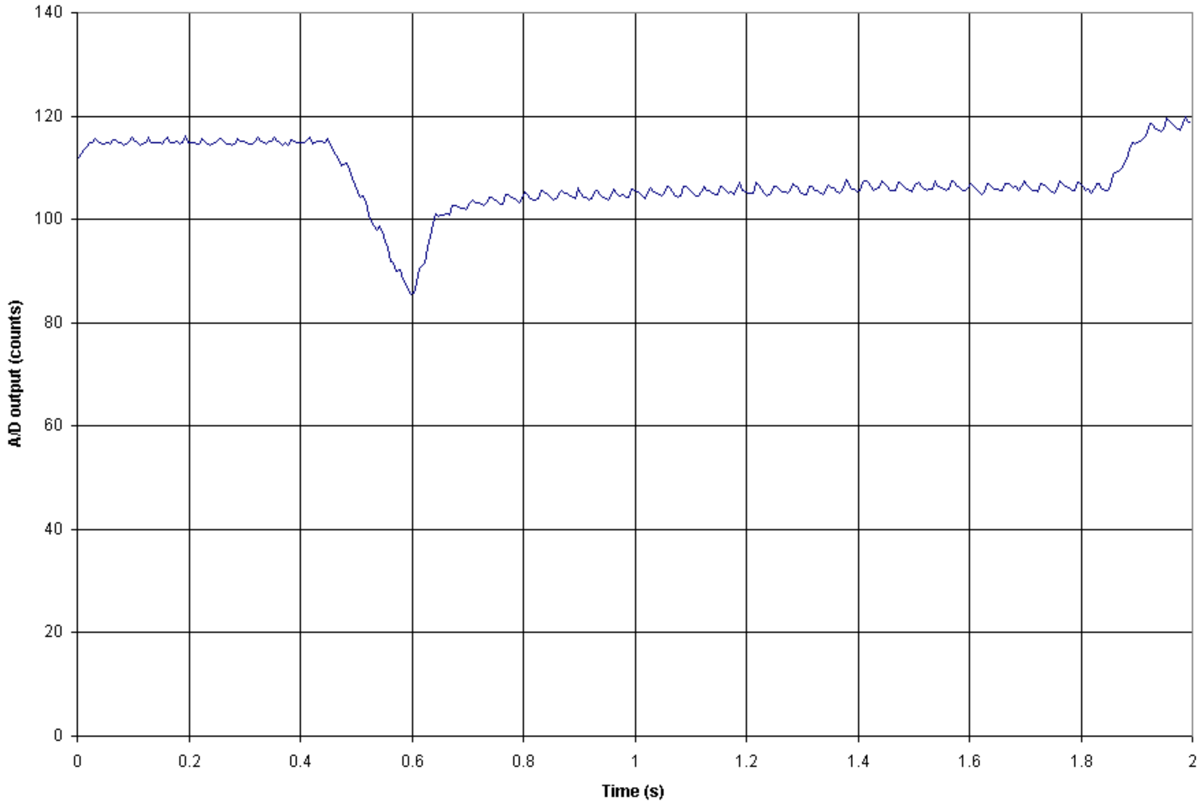



Figure 5. Raw data from an actual rocket mission using a C6-5 engine. As this is the output of an inverting amplifier, upward acceleration causes decreased output voltage. This curve was readily plotted in the field and shows that the system functioned correctly. The ripple is the switching frequency of the power supply, aliased by the sub-Nyquist sampling rate.

### *Analysis and Reflection*

We led the student through the following analysis to transform Figure 5 into the desired acceleration plot:

1) Remove any spurious data points,
2) Convert the 0-255 A/D readings to 0–5 V, and
3) Convert the voltage to acceleration, exploiting the fact that the system saw 1 *g* just before ignition.

Figure 6 is a typical result and is to be compared to the solid line in Figure 3. The general shape of the curves agree, although the measured curve is compressed in time. Additionally, the maximum measured acceleration was 17 *g*, whereas the maximum acceleration predicted from the mass of the rocket and the characteristics of the C6-5 engine used was 13 *g*.

For the third step, our students used the published sensitivity of the sensor and the calculated transfer function for the amplifier given the values of the gain-setting resistors. We had them apply a simple DC offset so that while the rocket is sitting on the pad, just before ignition, they obtain an acceleration of 1 *g*. As the measured acceleration goes negative when the engine stops firing (not zero), this calibration should be considered preliminary but sufficient for our purposes.

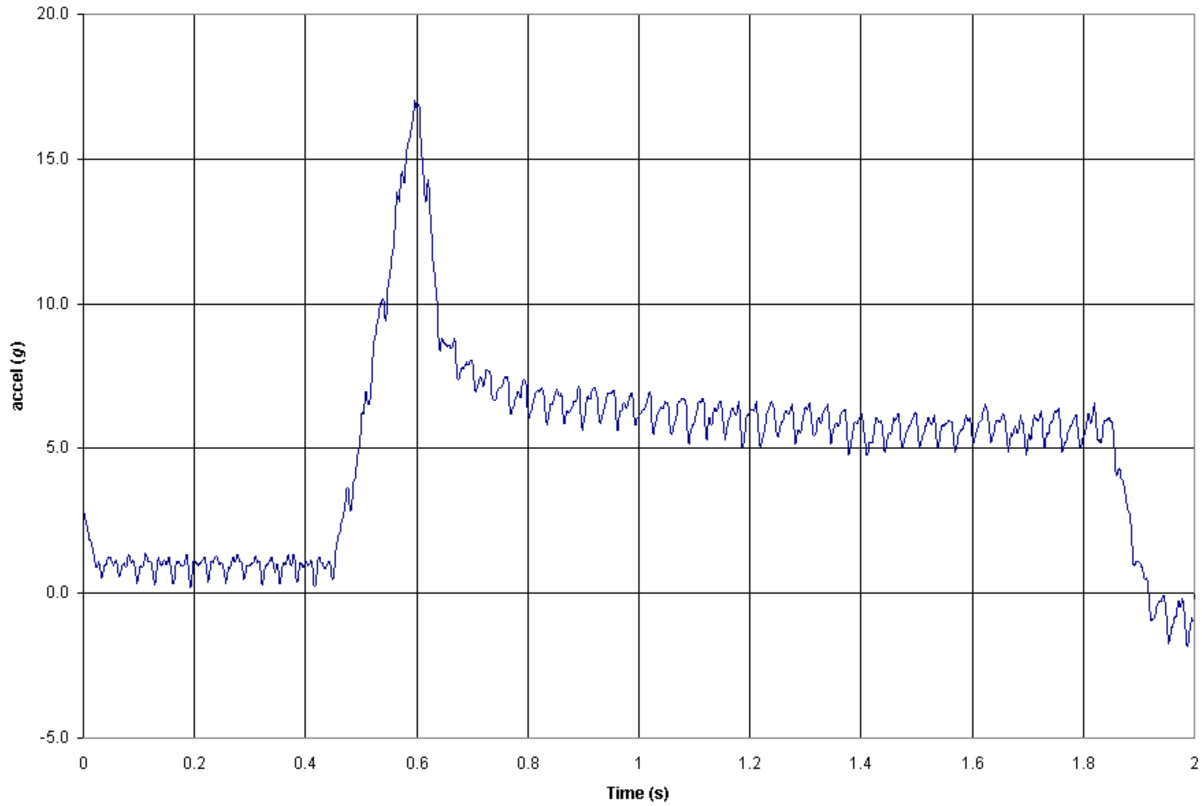



Figure 6. Processed acceleration data for the launch shown in Figure 5. The shape compares favorably to the predicted acceleration curve in Figure 3. As the measured acceleration goes negative when the engine stops firing (not zero), this calibration should be considered preliminary but sufficient for our purposes.

We closed the subject with a class expedition to the local ice cream shop (even during a New England winter), where we had an informal discussion to review and reflect on the subject. In particular, we encouraged students to talk about the lessons learned over the term and the potential enhancements that we missed in creating the subjects. These discussions (and similar interactions throughout the term), as well as a short, anonymous, survey form for the second time the subject was offered, formed the basis for our conclusions presented in the next section.

## Results to Date and Conclusions

The course has been taught twice, to date, with eight students enrolled each time. Clearly, the number of students who have taken the subject is too small for significant statistical analysis, but we found that informal surveys and anecdotes do present a consistent story.

At the start of the term we asked the students to tell why they signed up for this seminar. Most of their answers fell into three groups (many students listed more than one):

1) The hands-on nature of the subject,
2) The chance to learn some electronics in a small class setting, and
3) It appealed to a preexisting interest in model rocketry.

We were somewhat surprised that most entering students had little electronics experience. However, the homogeneity of their electronics skills (i.e., quite limited) was an aid in teaching the subject.

When we asked the students at the end of the term for the strengths and weaknesses of the subject, they generally noted that it had met their expectations and given them the hands-on experience and skill-building they sought. They also felt that this was one of the more demanding subjects for the amount of credit received, but they did not recommend cutting back on the material covered or the pace.

The second time the subject was offered, it was a freshman advising seminar—that is, a seminar where the instructor (Dr. Bales) was also the academic advisor for the eight freshmen in the class. The preceding summer, all entering students had been sent a list of all of the freshman advising seminars. Students listed their top choices (up to eight), and this seminar was listed more than any other. (The entering class was slightly over 1,000 students, of whom 60% go on to major in engineering.) We note that all freshman advising seminars with a hands-on component are generally oversubscribed at MIT and that their numbers are limited (typically enough to handle only 5–10% of the freshman class).

We believe that the strengths of the subject include that it:

- Has a strong appeal to freshmen considering engineering as a major,
- Gets students working with their hands, building the rocket and circuits, giving them tangible results rapidly (as opposed to the highly theoretical freshman curriculum),
- Gives students experience with the non-idealities of real-world engineering (e.g., electrical noise, mechanical tolerances) early in their careers,
- Appears to have students complete the subject with a positive impression of engineering as a field of study, and
- Can be readily taught by a graduate student or an advanced undergraduate, enabling large numbers of students to take the subject without taxing a limited (and overworked) faculty and staff.

Its weaknesses include that it:

- Is somewhat more time consuming than typical for the amount of credit received (one half that of a typical subject such as first-term calculus, physics, or chemistry),
- Appeals most to those students predisposed toward electrical and aerospace engineering, and
- Requires a space large enough to safely launch the model rockets (not always easy for an urban school such as MIT).

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## Bibliographic Information

1. "Smart Rockets: Data Acquisition in Model Rocketry," Tom Consi and Jim Bales, *Circuit Cellar INK*, Issue 98, pp. 12–23, 1998, Circuit Cellar Inc., Vernon, CT

2. National Association of Rocketry, Altoona, Wisconsin, http://www.nar.org/SandT/NARenglist.shtml

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