Team 18: CanSat

EML 4551C – Senior Design

Final Design Report

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Table of Contents

Abstract

The senior design project for Team 18 is the annual AIAA Cansat Competition that is being held this year in Burkett, Texas on June 8th, 2013. The competition is a "design, build, fly" styled competition that requires the registered teams to design and build a container with deployable payload. The primary objective of the Cansat is to deliver, safely, to the ground a sensitive payload. The secondary objective is to collect and telemeter sensor data.

The goal of this project is for the container/payload, Cansat, to be delivered to the competition for integration into competition-supplied rocket. At time of the competition, the rocket launches and deploys the Cansat at approximately 670m. At deployment, the Cansat begins its initial descent and begins telemetry of a specific set of data acquired by onboard sensors. The Cansat telemeters the sensor data for the duration of the flight. On-board Flight Software autonomously controls all operations of the Cansat. Ground control software maintains communication with the Cansat and monitors the descent. The CanSat was constructed using these guidelines and tested in laboratory settings to demonstrate successful execution of each mechanical and electrical task.

Introduction

Mission Overview

The CanSat competition is a design-build-launch competition held by the American Institute of Aeronautics and Astronautics (AIAA). The competition provides teams with an opportunity to experience the design life cycle of an aerospace system. The CanSat competition is designed to reflect a typical aerospace program on a small-scale implementation. The competition includes almost all aspects of an aerospace program from the preliminary design review to post mission review. The mission and its requirements are designed to reflect various aspects of real world missions including telemetry requirements, communications, and autonomous operation. The competition for 2013 will be held June 7th through the 9th in Burkett, Texas. Each team is scored throughout the competition on real-world deliverables such as schedules, design reviews, and demonstration flights. The goal of the CanSat project is to design and manufacture a container/payload system to be launched via rocket and develop an autonomous descent control strategy to safely land the CanSat. The primary objective is to deliver the payload safely to the ground, while the secondary objective is to collect telemetry data & impact force calculation.

The motivation behind this project is to simulate how a satellite entering the atmosphere of an Earth-like planet gathers flight data and safely delivers a sensor payload to the planet's surface. The two main components of the CanSat are the payload that secures the sensor (a hen egg) and the container that encloses the payload from ascent to initial descent. The rocket, provided by the competition, will launch the CanSat, then deploy it at an altitude of 670 m, at which point a parachute or streamer will decrease its descent velocity to 20 m/s. At 400 m, the container will release the payload and an aero-braking system will be employed in the safe landing of the payload. In addition to controlling the descent autonomously, the flight software will transmit telemetry data during the flight to the ground control station. This includes altitude, temperature, GPS data and battery voltage. The force of impact will be transmitted upon landing of the lander-payload. The impact force calculation is one of two "selectable objectives" that were required to be selected and implemented in the CanSat design. The other selectable objective is a video camera that would record the descent. The force of impact calculation was selected based on the relative ease of implementation of the impact force calculation and transmission. Figures 1 and 2 on the following page illustrate the mission sequence of operation.

A post-flight review will be conducted and taken into account to evaluate the success of the design at the competition. Since the competition will not be held until a month after the end of the semester, the results of the competition design reviews and demonstration flights are taken into account for the purposes of evaluation of this project.

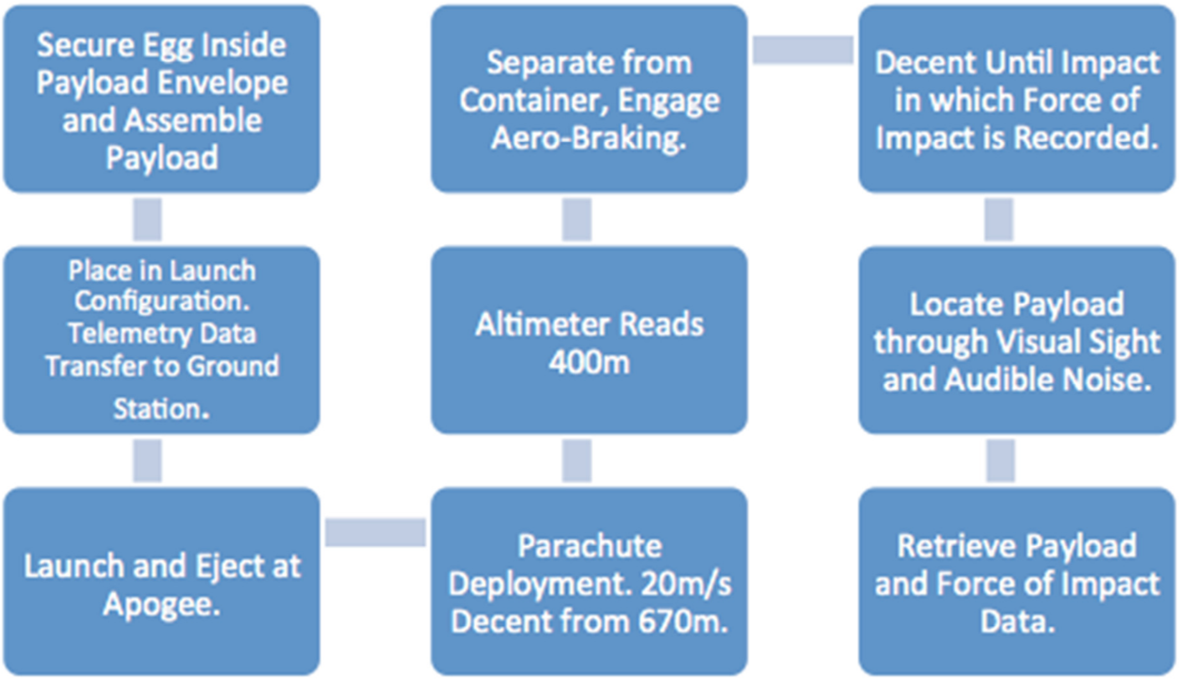


Figure 1, Flow Chart of Mission sequence

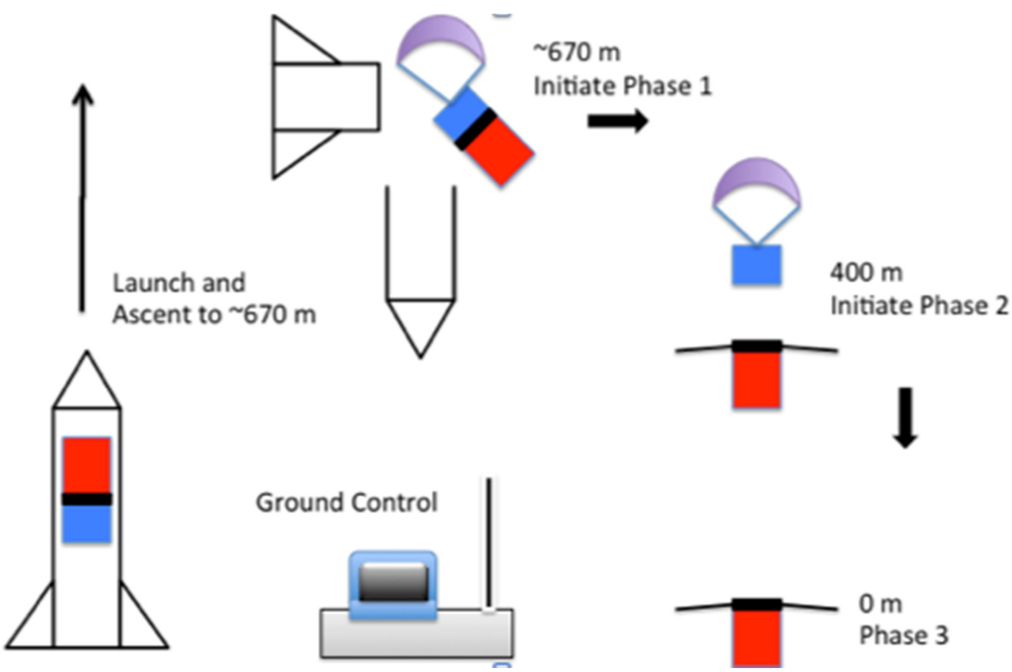


Figure 2, Pictorial overview of Flight Sequence

Goal Statement

The end goal of this project is for the container/payload, Cansat, to be delivered to the competition for integration into competition-supplied rocket. Intermediate goals that have been met are the Preliminary Design Review (PDR) and the Critical Design Review (CDR) as specified by the competition. The PDR has been delivered and the CDR is on-schedule to be delivered.

Objectives

Primary

The primary objective of the project was to deliver the PDR and CDR and initiate fabrication of the Cansat prototype. This includes complete design and fabrication of the telemetry sensor subsystem.

Secondary

The secondary objectives of the project were the design and fabrication of descent control mechanism and the mechanical support structure. This includes integration of the telemetry sensor subsystem.

Tertiary

Tertiary objectives include preparing the AIAA members who will be participating in the competition. This includes confirmation of the team members and providing them with clear instructions and a tutorial on the operation of the Cansat.

It should be noted that the primary and secondary objectives of this project have been completed and the operations manual has been prepared for the competition team.

List of Constraints

The CanSat design requirements are dictated by the 2013 CanSat competition rules. Below is a list of the relevant constraints and parameters.

- The container must protect the sensor load (egg).
- The telemetry requirements are transmitted in the radio frequency required and all telemetry is accomplished via the XBEE radios series 1 or 2.

- The audible location device is activated and emits a tone of at least 80 decibels and maintains power until found.

- The power delivery system is sufficient to provide electrical power to all relevant components.

- The ground station antenna is at least at a height of 3.5 meters and powered by ground station circuitry.

- The CanSat's total mass must be 700 grams ± 10 grams before the egg is placed inside.

- The CanSat must fit inside a cylinder that is 130mm in diameter and 250mm in length.

- When initially released the satellite may use any passive decent control device to reduce its speed to 20 m/s ±1m/s.

- When the container is below 400 m it cannot free fall or use a parachute or similar device.

- The container cannot have any sharp edges or protrusions that go beyond the envelope.

- No flammable substances may be used.

- All decent control devices, attachments and mechanisms must be able to survive a 30 G shock.

- The Canister must have an external power control.

- The CanSat cannot use lithium polymer batteries.

- No electronics can be exposed except sensors.

- The CanSat flight hardware must cost less than 1000 U.S. dollars excluding ground support and analysis tools.

- Mechanisms that produce heat must be ventilated.

These are the primary design constraints, however the comprehensive list can be found at the competition website[1]. In addition to building a physical prototype, AIAA competition rules state a Preliminary Design Review, Critical Design Review, and a Post-Flight Review must be presented to a panel of judges for evaluation.

[1] http://www.cansatcompetition.com

Concept Generation

Phase 1 Descent Control System

Phase 1 is the portion of the descent from apogee, about 670m, to 400 m. During this time the CanSat will use a passive breaking system to limit its descent velocity to 20 m/s. There are many types of parachutes and streamers available. In order to decide which option is the best for the project, some of the important characteristics of each choice were compared. These characteristics are drag coefficient, size and weight, how much a crosswind will cause the CanSat to drift (wind drift), complexity and cost. The drag coefficient is important because it affects the amount of material that we have to use to get the correct amount of drag force as well as the cost. The next characteristic to consider is the overall size and weight of each choice. Since there is a limited amount of space and a limit on the mass of the CanSat, it is imperative that the passive breaking system be light and small.

Another potentially important consideration is wind drift. This parameter's importance is based on the area where the competition takes place because average wind speed varies depending on what part of the country you are in. If the wind speed is high then the CanSat could be carried off by the wind and move out of range of the ground station. Figure 3 shows a map of the average wind speed across the U.S. The black dot on the map is where the competition will be held, Burkett Texas. This map shows that the wind speed in the area averages between seven and nine meters per second. Since the average wind speed is high in the area, wind drift could be a significant problem.

Complexity of the system is to be taken into account as well. If the system is more complex, then it could take more time and resources to design and produce as well as have more room for error and thus failure. The last parameter to take into account is cost. There is a limit put on the total cost of the CanSat, so having a low cost option is preferred. This is the motivation for the design from simplicity, rather than an overly complex design that may provide more control and stability during the descent. The cost versus constraints argument was employed throughout the concept generation and final design.

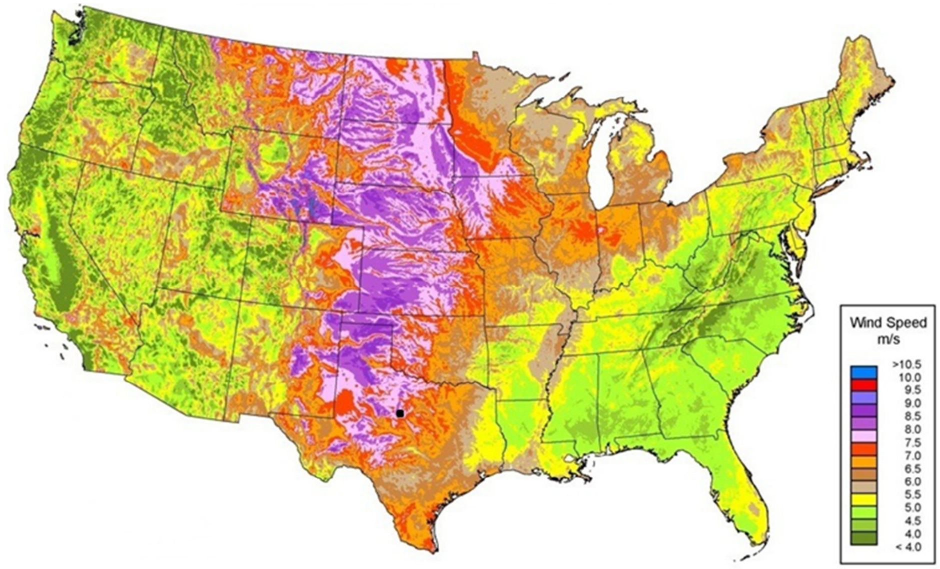


Figure 3 shows a map of the average wind velocity in the U.S. with Burkett Texas marked on the map.

Figure 4 shows a true dome shape round parachute on the left and a flat round parasheet on the right.

One of the most well-known types of parachutes is the round parachute shown on the left of the above figure. A round parachute with a true dome shape has a high coefficient of drag and will require less material to make. This type of parachute is somewhat difficult to make but is one of the best options for situations were a slow and stable fall rate is desired. However, this type of parachute is susceptible to wind drift. A round parasheet, shown on the right of the above figure, is similar to a round parachute but, instead of having a true dome shape, it is flat. This type of braking system has a lower drag coefficient then a true dome shape parachute but, is much simpler to produce. It is, also, susceptible to wind drift. These types of passive braking systems are used when the payload must fall at low speed and when wind drift is not a problem.

Figure 5 shows a rocket using a streamer to slow its decent.

A streamer is a simple passive breaking system for model rockets. This option tends to have a much lower coefficient of drag than the other options. The coefficient of drag can be increased by using paper or other material that holds it shape when folded and folding it in a zigzag pattern. This type of passive brake is used when there is a high cross wind to reduce wind drift because a parachute tends to carry the payload off. However, streamers tend to allow objects to fall faster and require more material to make then a round parachute.

Separation Mechanism

When the CanSat reaches the 400m mark, the payload needs to detach from the container so that the phase 2 aero-braking system can engage. In order for this detachment to happen a mechanism is necessary to physically separate the container from the payload. Out of three design concepts, the one of optimal design was chosen.

Option 1: Trap door

This concept is essentially what the name implies, a trap door mechanism. The payload sits inside the container sealed on all sides. Upon release, a mechanism opens the floor to the container in order for the payload to simply slip out. The bottom portion of the container will be in two separate pieces, attached to the container via spring loaded hinges. A locking mechanism, comprised of a an electronically actuated device, most likely a solenoid, will hold the doors closed and keep the payload safe inside of the container. Upon the electronic signal and the locking mechanism actuation, the spring loaded hinges will open the doors and the payload will slip out using its own weight.

This design, along with its benefits, has some drawbacks. There will be a possibility of malfunction which would likely result in failure. The rules stipulate that the outermost shell of the CanSat, the one which will be in direct contact with the rocket, may not have any protrusions that may hinder the safe release of the CanSat. This being said, any geometry associated with the trap doors must be on the interior of the container which will therefore limit the diameter of the payload. This constraint will have a larger effect on the payload volume than if the geometry was shortened length wise. And while the CanSat may easily release from the rocket, the payload may have trouble releasing from the container.

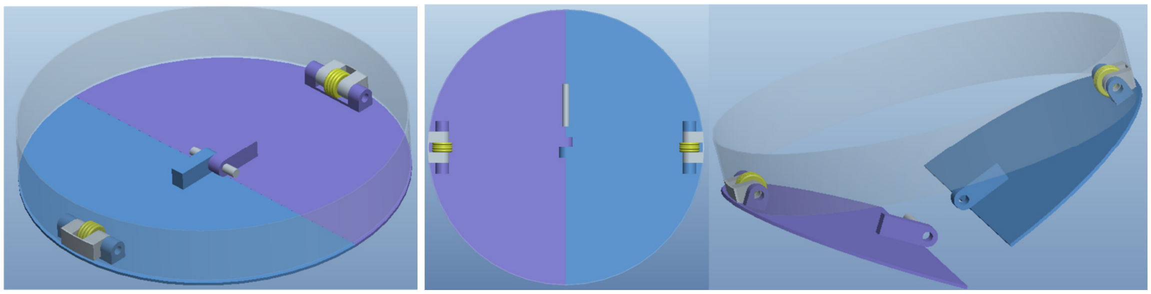


Figure 6: (left) Trap door isometric view, (center) Trap door top view, (right) Trap door opening

Option 2: Solenoid quick release

This design utilizes a simplistic, pin release mechanism. A pull type, electronic solenoid will be the source of actuation. Upon electronic signal, the solenoid will move the pin in an axial direction. This pin is initially situated through a three piece sandwich comprised of two brackets with holes connected to the payload, and an eyebolt connected to the container. The movement of the pin disconnects the ring from the outer brackets and allows the payload to release under its own weight.

An issue that is associated with using this method is within the solenoid. Solenoids do not offer feedback control. Meaning within flight, under autonomous control, the electronics won't have a way to tell if separation was successful. This could potentially be an ultimate failing point for the project.

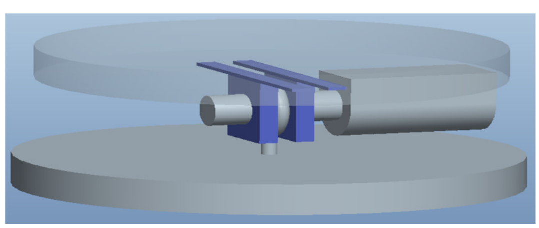


Figure 7: Solenoid quick release mechanical drawing

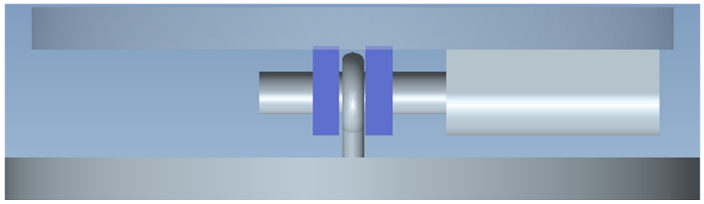


Figure 8: Solenoid quick release pin fully extended

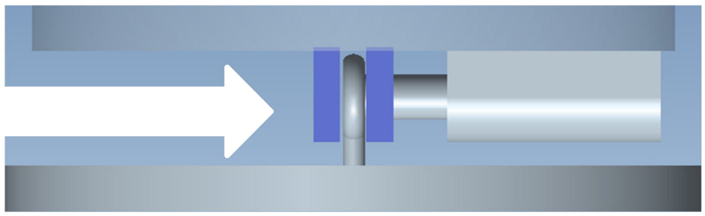


Figure 9: Solenoid quick release pin retracting

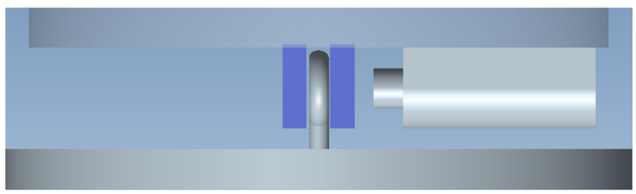


Figure 10: Solenoid quick release pin fully retracted

Option 3: Ring Release

This design is very similar to the solenoid mechanism, however, it uses a DC motor rather than a solenoid. The other primary difference between the two is instead of using a pin to separate the eyebolt from the brackets, this uses an un-closed ring that the motor spins, rather than pulls. The main reason for this idea, since it very closely resembles the solenoid method, is that the electronics needed to implement it are simpler than those needed for a solenoid. Another benefit of this method is that if frictional forces are too great, the problem can be easily fixed by increasing the diameter of the ring, raising the mechanical advantage. This solution is simpler in comparison to sourcing a stronger motor that would change size, weight, and electronic constraints. Implementation of a feedback system will be simple as well along with adding to the success rate.

The ability for this method to fail lies within the payload coming out of the container. As long as the motor is supplied with enough power, the feedback control will ensure that the open ring is no longer in contact with the eyebolt. So the only failure point should be from the payload becoming stuck in the container.

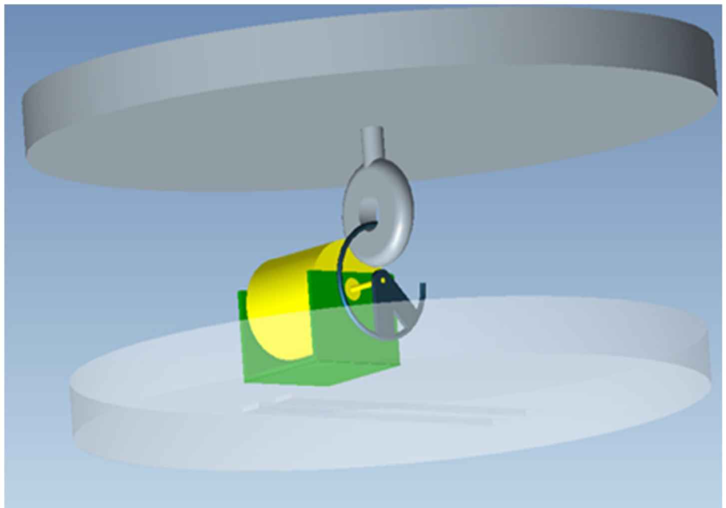


Figure 11: Ring release drawing

Table 1: Release mechanisms pros and cons

	Pros	Cons
Trap Door	Solenoid offers instant Release Container Completely encloses Payload	Solenoid requires additional voltage supply Multiple moving parts, more fail points Solenoid does not offer feedback control Comparatively heavier More parts, more money Payload has potential to get stuck
Solenoid Quick Release	Solenoid offers instant release Container bottom open, safe release Small amount of parts	Solenoid requires additional voltage supply Solenoid does not offer feedback control
DC Motor Quick Release	Inexpensive Used with existing voltage supply Container bottom open, safe release Small amount of parts Offers feedback control	Slower actuation Open ring is hard to manufacture

Phase 2 Descent Control System

After container-payload separation, which occurs at 400 m, the CanSat will deploy an aero-braking structure to reduce the descent rate. The following designs were developed to meet competition requirements and limitations regarding the use of certain chemicals and pyrotechnics, structural material properties, geometry, weight, and size. Details of the design constraints can be seen in the competition manual and the Needs Assessment provided on the team website.

In a NASA technical brief, an aero-braking structure is defined as a method of increasing the drag of a spacecraft by increasing the effective area by at least 5 times without significantly contributing to the structure's mass. Since parachutes, streamers, para-foils, and similar devices were unacceptable methods to use for the Phase 2 descent, the following designs were developed.

Option 1: Spring-loaded Rods

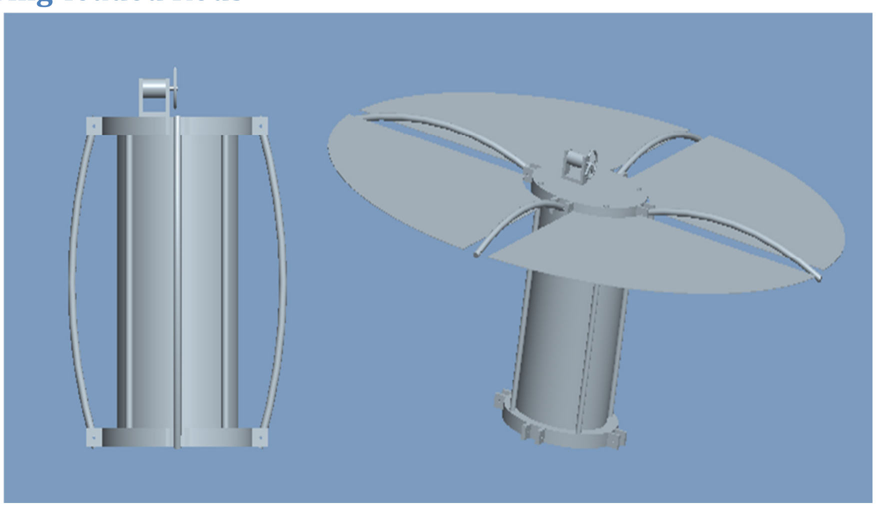


Figure 12: Spring loaded rods mechanical drawing, left closed, right open

This schematic shows an enclosure containing the payload. Support rods are used to secure the payload to the aero-braking structure and provide the rigidity necessary to withstand the specified impact. Essentially, the aero-braking structure is composed of rods with fabric in between, which deploy at 400 m to increase the effective area. Though not modeled in figure 17 above, durable fabric (such as a kite textile) is secured at the top portion of the structure and the bottom ends of each rod. The motor on the top of the design is used as the separation mechanism, mentioned previously. Torsional springs located at the top inner portion of the rods are held in compression at the bottom of the enclosure. A release mechanism, such as a contractible pin, a heating element to release a wire, or other similar concept may be used to release the stored mechanical energy in the springs.

Option 2: Deployable Exterior Panels

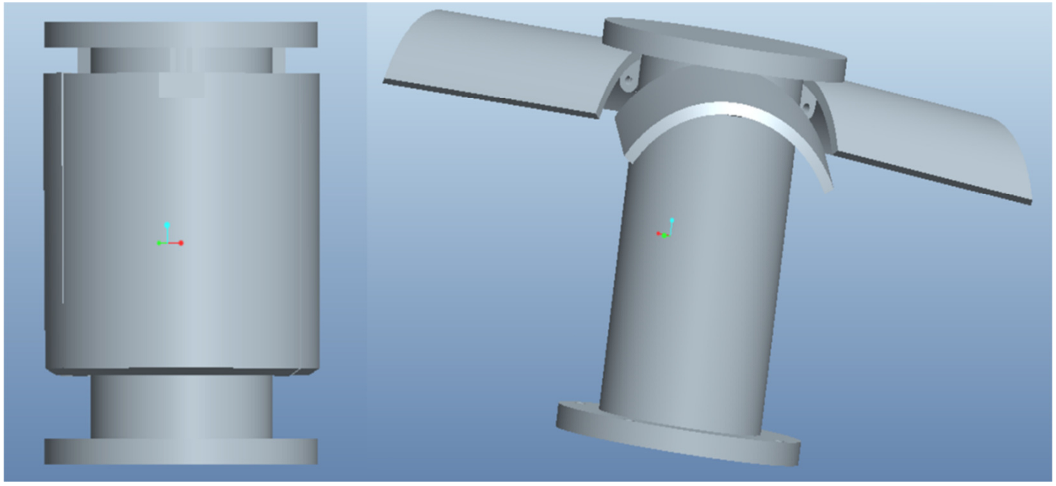


Figure 13: Deployable exterior panels mechanical drawing, left closed, right open

This second concept operates by having rigid panels on the payload open to create needed drag during the descent. The panels are geometrically constrained at the top of the enclosure, limiting the maximum angle they can open. The advantage of having rigid panels is a more durable aero-braking structure, at the expense of power needed to open the panels. Though a motor would be an effective method of deployment, it would be costly both for a mass and a power budget.

Option 3: Telescoping Arms

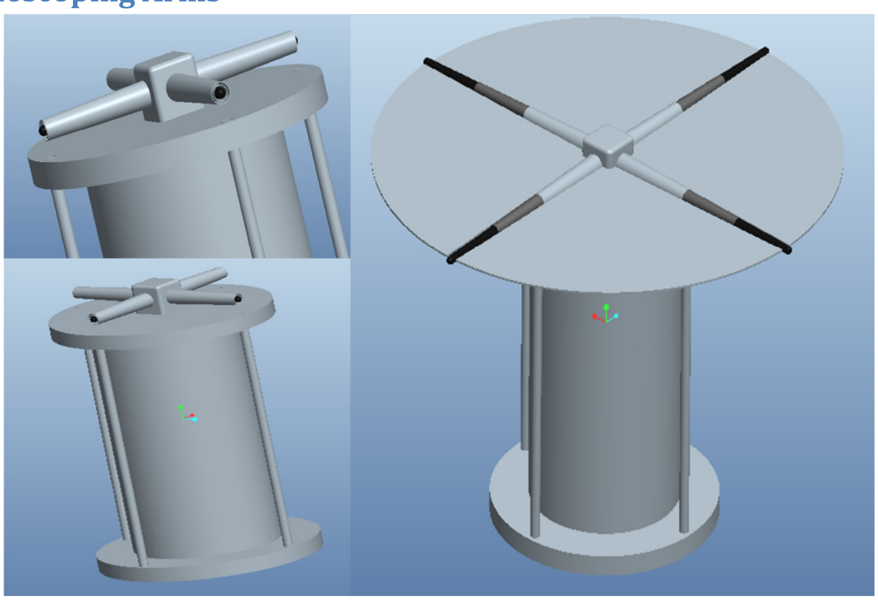


Figure 14: Telescoping arms mechanical drawing, left retracted, right extended

Fabric, not seen in the two left images, is folded in between arms, attached at the center point and the tips of the last arm. As the telescoping arms extend, the fabric does as well. This design is easily customized to fit larger effective area ratios by adding longer arms. However, as the arms decrease in diameter, strength needed to withstand the drag force also decreases. The complexity of this design is in the method of extending the arms. A linear actuator can accomplish the task, but the time it would take to reach the fully extended position may be too far into the payload's descent to be effective.

The rules specify that the design must be able to withstand 30 gees of shock, which is denoted by the strength category. Mass, cost, and size restrictions are explicitly given. Simplicity incorporates ease of manufacturing, implementation, and deployment. Based on these parameters, the final design chosen is Option 1.

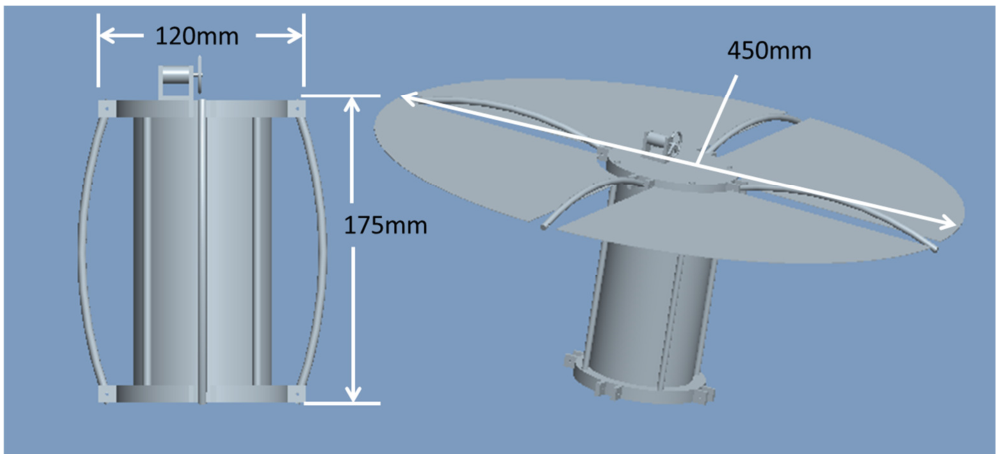


Figure 15: Spring loaded rods drawing with measurements

As seen above, the specified dimensions are well within the allotted diameter and height of the container, which is constrained by the competition guidelines. Further development of the design is in progress, including the deployment method, materials, purchasing, and fabrication.

Egg Protection

In order to simulate a sensor or other sensitive device that would be placed inside of a satellite, a raw hen egg will be placed inside the payload of the CanSat. In order to protect the egg, it is necessary to find a substance that will adequately absorb any sudden forces on the payload.

Option 1: Dough

Figure 16: Dough

Dough could be used to do dampen the blow of an impact. The gluten molecules in the dough can act as springs to help absorb the force the egg will experience during landing. Completely enclosing the egg in dough allows it to be protected from all directions. Bread dough is very cost effective and can be experimentally tested prior to implementation in the design. This could have a significant weight contribution due to its density.

Option 2: Memory Foam

Figure 17: Memory Foam

Memory foam, developed for commercial retail bedding, has properties that can conform to odd shapes as well as off a soft, yet firm feeling. This material could be used in order to safely deliver the payload to the ground while absorbing every bump along the way. This could be implemented by simply taking a cube of the material, slightly larger than most large hen eggs, and cutting a core out from the center. The “payload” could then be fitted inside of the empty core region for a nice, snug fit. This method would also offer a nearly entire enclosure surrounding the egg, due to its form fitting nature, making it a very effective method of protection. This material also has a very low density making it ideal for our lightweight CanSat. A drawback however, is that depending on the properties we calculate our memory foam to need, some sources could be at quite some expense.

Option 3: Polystyrene Beads

Figure 18: Polystyrene Beads

Polystyrene beads are a low density option that is capable of absorbing an impact. Since the beads are loose, they are can conform to shape of the payload to maximize the amount of material that is protecting the egg. They are extremely inexpensive costing only $12.00 for 100L. A drawback of the polystyrene beads is that the egg may push some of the beads out of the way rather than letting them absorb the shock.

Telemetry, Data Handling, Electrical Systems

Sensory Subsystem

The sensory subsystem shall take all the required measurements per the competition Telemetry requirements. (COMP_REQ-3.3) The data will be processed and transmitted in the proper format to the Ground Control Station. The Sensory Subsystem is composed of the Altitude, Temperature, Force sensor, and GPS module. All sensors must be able to be sampled at a rate no less than 0.5 Hz; i.e. every 2 s. All sensors must be able to interface with the microprocessor using standard protocols. Examples of protocols are serial TTL, UART, I^2C, SPI, and analog voltage. All electronic components were researched using distributors and manufacturer websites to obtain data-sheets and other resources related to the device.

Microcontroller

The microcontroller will run the flight software and interface with all of the sensors, the radio, the separation mechanism, and the stage 2 aero braking mechanism. The microcontroller was selected using the following criteria.

- Low cost
- Small Size
- Able to interface with all needed components
- Sufficient memory to run program
- Easy development

Table 2: Microcontroller comparison

Microcontroller	Clock Speed [MHz]	Memory	Communication Interfaces	Operating Voltage [V]	Size	Cost [$US]
Arduino Pro Mini 328	16	32k	Serial, I^2C, SPI, A2D	5	0.7 x 1.3 in	25
Arduino Uno	16	32k	Serial, SPI, I^2C, A2D	5	2.7 x 2.1 in	10
FEZ Cerberus	168	300k	SPI, I^2C, UART, A2D	5	2.25 x 1.85 in	30

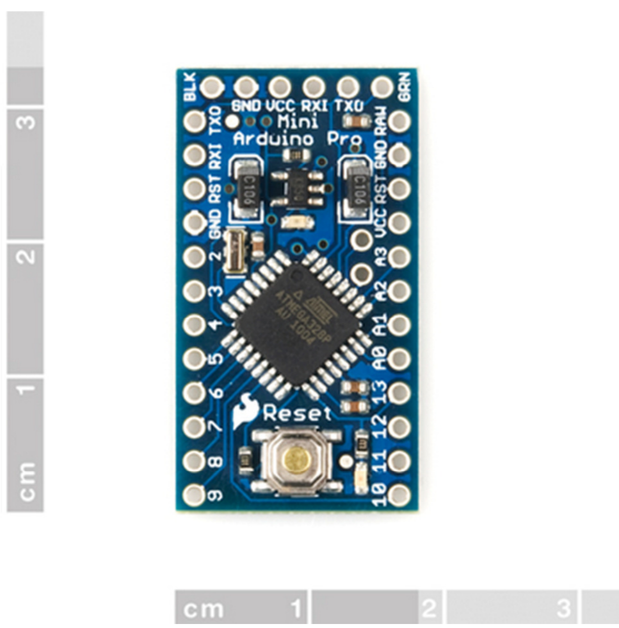


Figure 19. Arduino Pro Mini

Communications

Concept generation for Telemetry was restricted by the competition to a specific transceiver set and specific sensor data. The competition stated specifically that an XBEE Series 1 or 2-transceiver module be used, no other communications system is allowed. Since the geometry of the competition environment is such that the deployed Cansat will maintain a clear, radio frequency line-of-sight (LOS) with the ground control station (GCS), it was determined by reasons of simplicity to design the telemetry system with the XBEE-Pro Series 1 transceiver module shown in the following figures.

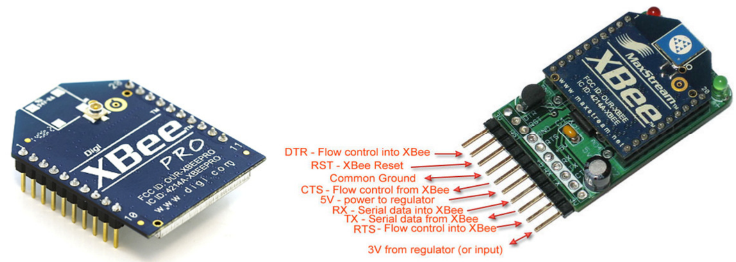


Figure 20. (left) XBEE Pro Series 1 , (right) XBEE integrated onto breadboard Adapter with pin-out shown

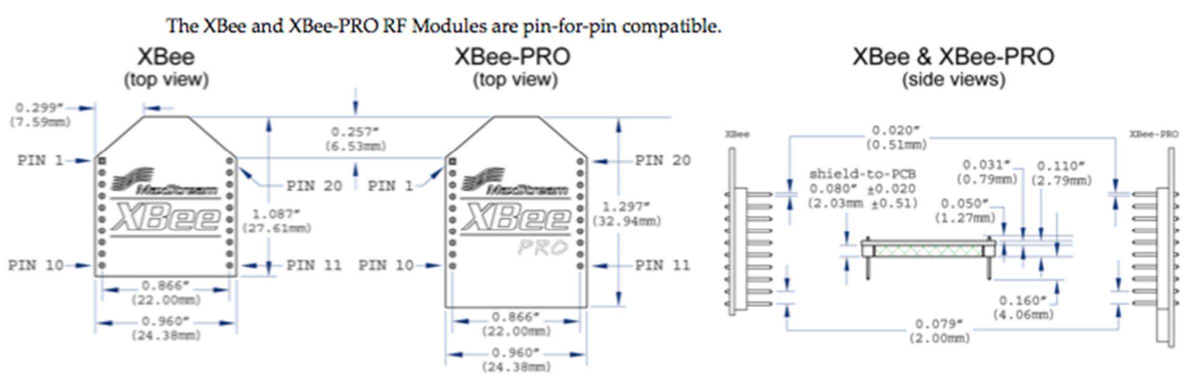


Figure 21. XBEE Mechanical Drawings

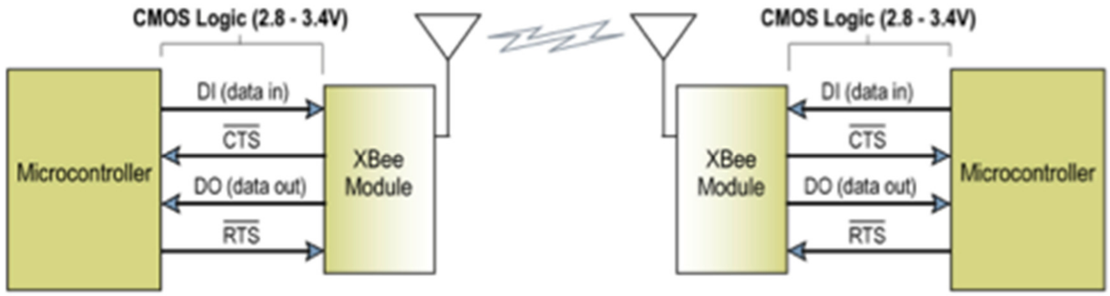
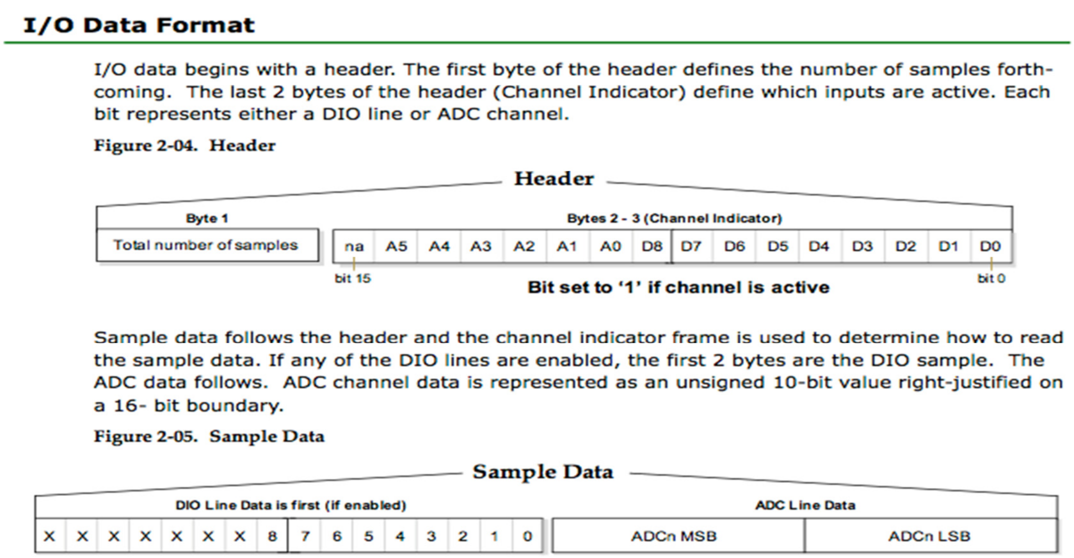


Figure 22. XBEE Data Flow Diagram in a UART interfaced environment

The main reason for the selection of the XBEE-Pro was that the Series 1 communications protocol is IEEE 802.15.4 standard. This standard is ideal for simple point-to-point communications.



I/O Data Format

I/O data begins with a header. The first byte of the header defines the number of samples forth-coming. The last 2 bytes of the header (Channel Indicator) define which inputs are active. Each bit represents either a DIO line or ADC channel.

Figure 2-04. Header

Sample data follows the header and the channel indicator frame is used to determine how to read the sample data. If any of the DIO lines are enabled, the first 2 bytes are the DIO sample. The ADC data follows. ADC channel data is represented as an unsigned 10-bit value right-justified on a 16- bit boundary.

Figure 2-05. Sample Data

Figure 23. I/O Data Format

The telemetry sensor requirements are listed as follows:

- Barometric Air Pressure
- Ambient Air Temperature
- Non-GPS Altitude
- NMEA GPS Data
- Voltage of the Battery
- Impact Force Sensor

The format of the telemetry data that is transmitted shall be in packets of comma-separated fields followed by a carriage return character in the following format. The telemetry data shall be transmitted every 2 seconds.

```
CANSAT,<TEAM_ID>,<MISSION_TIME>,<GPS_TIME>,<GPS_LAT>,<GPS_L
ONG>,<GPS_ALT>,<GPS_SAT>,<ALT_SENSOR>,<TEMP>,<BAT_V>,<STATE
>[,<CUSTOM>[,<CUSTOM>]]
```

Pressure/Temperature Sensor

The competition guidelines require that data from a non-GPS altitude sensor be included in the telemetry. The barometric pressure and temperature sensor is a commonly used method for measuring height above sea level. The components shown in the following table were obtained by using the following criteria:

- Output resolution of 0.1 m
- Sample rate of at least 0.5 Hz
- Operate on I^2C, SPI, or serial LV TTL protocol
- Nominal operating voltage no higher than 5 V
- Low weight, low cost
- Preferably connected with breakout board

Table 3: Altitude Sensor Comparison

MFG P/N	Sample Rate [Hz]	Resolution [m]	Interface / Protocol	Operating Voltage [V]	Weight [g]	Cost of Component [$US]
BMP085	1	0.1	I^2C	3.3	5	19
SCP-1000	1 to 9	0.15	SPI, I^2C	3.3	5	30
MS5607	10	0.1	SPI, I^2C	5	5	30

Based on the criteria above, the BMP085 was found to be the most desirable for the purposes of non-GPS altitude sensor. The BMP085 has been used successfully in similar projects. This is made very clear when reviewing past competition documents and performance reviews, as well as rocket hobbyist and design/build shops that implement these devices regularly and can verify the validity of the output data. The BMP085 is shown in the following image.

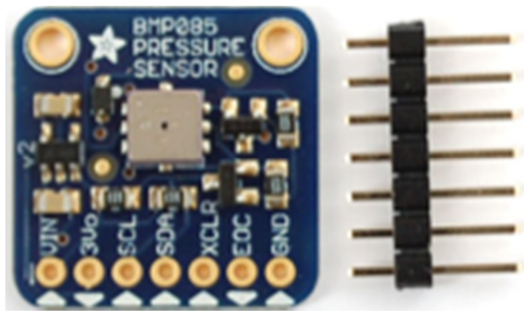


Figure 24: BMP-085, Pressure/Temperature sensor with breakout board

The output of this sensor includes a temperature measurement with a resolution of 0.1 degrees C. It is a low noise (0.1 m), low power device that has a current drawn of only 5 µA at 1 sample/sec and operates at 3.3 V.

Using the I^2C interface, only 4 pins are required for connection to the microcontroller: V_{CC}, GND, SDA, and SCL. It is available, as shown; with a breakout board that allows for quick integration to the main processing board or the device itself can be integrated into a custom PCB. The decision to implement the telemetry devices via breakout or a custom PCB has not been made as of this time.

This device requires calibration on start-up. The data is stored on the BMP085 on-chip, so it is a calibrated device.

The altitude is determined by the equation (obtained from the data sheet)

$$altitude = 4430 * \left[1 - \left(\frac{p}{p_0}\right)^{\frac{1}{5.255}}\right]$$

Where p is the measured pressure and p_0 is the pressure at sea level. A range of about 0 to 1000 m corresponds to a change in p of about 100 hPa. A pressure change of 1 hPa corresponds to 8.43 m at sea level. Typical application of the BMP085 is shown in the following figure

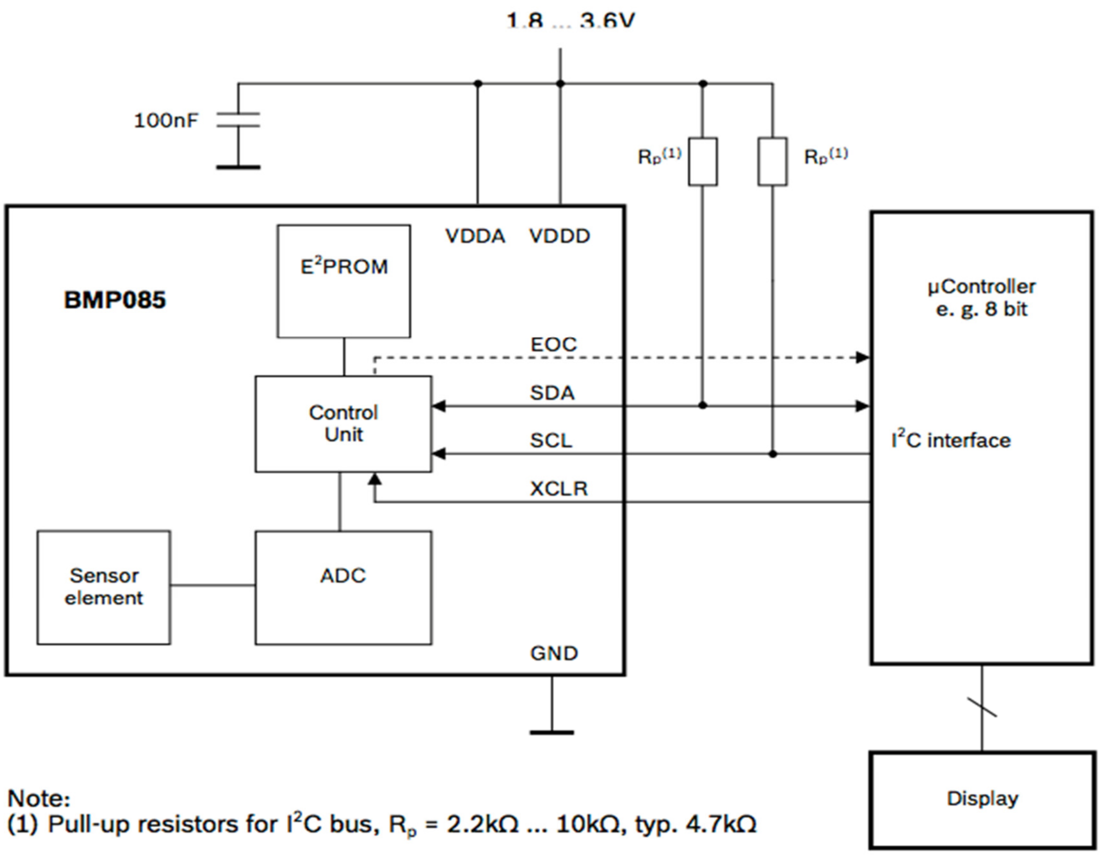


Figure 25. BMP085 Application Diagram

Impact Force Sensor

For the force of impact selectable objective the competition requires that the force of the CanSat's impact with the ground be measured and recorded. To accomplish this we will use an accelerometer to measure the deceleration on impact and multiply that by the known mass of the CanSat.

The components shown in the following table were obtained by using the following criteria:

- Sample rate of at least 100 samples/second
- Operate on I^2C, SPI, or serial LV TTL protocol
- Nominal operating voltage no higher than 5 V
- Low weight, low cost
- Preferably connected with breakout board

Table 4:Accelerometer comparison

MFG P/N	Sample Rate [Hz]	Resolution	Interface / Protocol	Operating Voltage [V]	Weight [g]	Cost of Component [$US]
ADXL 345	3200	16g	I^2C, SPI	3.3	2	19
LSM303-DLHC	2400	8g	SPI, I^2C	3.3	2	30
BMA180	2400	16g	SPI, I^2C	5	2	25

Based on the criteria above obtained from the manufacturer datasheets, the ADXL326 was found to be the most desirable for the purposes of the obtaining an acceleration to be input to the impact force calculation. The ADXL326 has a proven track record for reliability and has been used successfully in similar projects. This is made very clear when reviewing past competition documents and performance reviews, as well as rocket hobbyist and design/build shops that implement these devices regularly and can verify the validity of the output data. The ADXL326 and breakout board is shown in the following image.

Figure 26. ADXL326 Breakout PCB

The ADXL326 is a complete 3-axis acceleration measurement system with a selectable measurement range of ±2 *g, ±4 g, ±8 g,* or ±16 *g.* It measures both dynamic acceleration resulting from motion or shock and static acceleration, such as gravity, which allows the device to be used as a tilt sensor. The nonlinearity of the device is, as a percentage of full scale, ±0.1%. This should be a negligible concern for the output to our force of impact calculations.

The sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces.

Deflection of the structure is measured using differential capacitors that consist of independent fixed plates and plates attached to the moving mass. Acceleration deflects the beam and unbalances the differential capacitor, resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation is used to determine the magnitude and polarity of the acceleration.

The output resolution is 10-bit for each axis (x,y,z) with a typical sensitivity of 32 LSB/g and a scale factor of 31.2 mg/LSB. The sensitivity due to temperature is ±0.01 %/degree C. The noise performance for a data rate of 100 Hz at 10-bit full resolution is less than 1.5 LSB_{RMS} for the z-axis. The bandwidth is user selectable from 6.25 to 3200 Hz.

GPS Module

The competition requires information from a GPS be included in the telemetry transmission, specifically, data from the the NMEA GGA sentence shown below.

```
$GPGGA,123519,4807.038,N,01131.000,E,1,08,0.9,545.4,M,46.9,M,,*4
7

Where:
     GGA          Global Positioning System Fix Data
     123519       Fix taken at 12:35:19 UTC
     4807.038,N   Latitude 48 deg 07.038' N
     01131.000,E  Longitude 11 deg 31.000' E
     1            Fix quality: 0 = invalid
                               1 = GPS fix (SPS)
                               2 = DGPS fix
                               3 = PPS fix
                           4 = Real Time Kinematic
                           5 = Float RTK
                               6 = estimated (dead reckoning)
(2.3 feature)
                           7 = Manual input mode
```

```
                         8 = Simulation mode
08           Number of satellites being tracked
0.9          Horizontal dilution of position
545.4,M      Altitude, Meters, above mean sea level
46.9,M       Height of geoid (mean sea level) above WGS84
                 ellipsoid
(empty field) time in seconds since last DGPS update
(empty field) DGPS station ID number
*47          the checksum data, always begins with *
```

The components shown in the following table were obtained by using the following criteria:

- Sample rate of at least 1 Hz
- Operate on I^2C, SPI, or serial LV TTL protocol
- Output NMEA GGA Sentence
- Low weight, low cost

Table 5: GPS comparison

MFG P/N	Sample Rate [Hz]	Accuracy	Interface / Protocol	Operating Voltage [V]	Cost of Component [$US]
LS20031	5	3m	Serial	3.3	60
Copernicus II	1	<4m	Serial	3.3	45
Linx RXM-GPS-SR-B	1	5	Serial	3 - 4.3	44

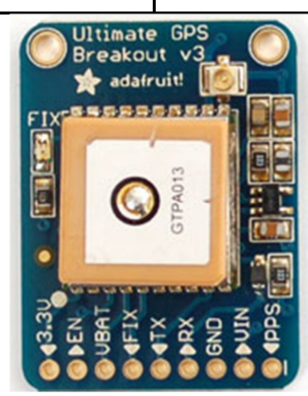


Figure 27. GlobalTop GPS Module, Adafruit Insudtries

Final Design

Descent Phase 1

When choosing the best option for this portion of phase 1 portion of the descent, a MATLAB model was made to determine the area required for each option to limit the descent velocity to 20m/s per the competition guidelines. The MATLAB model takes into account various factors including the drag coefficient of the respective braking device, the drag created by the CanSat itself, and the change in density of the air as the CanSat's altitude decreases. When the drag coefficients for each option are put into the MATLAB model, the area required for the parachute, parasheet, and streamer are 28.2in^2, 42.8in^2, and 229in^2 respectively. A parachute with this area would have a diameter 6in. This is very small and the smallest parachute available in rocketry has a diameter of 9in. Since most parachutes in rocketry are actually parasheets and the parachute necessary is so small, making one is not an option because a small error in in the fabrication process could have a significant effect on the descent rate of the CanSat. The diameter of the parasheet necessary to limit the descent velocity to 20m/s is 7.4 in. This makes a parasheet a much more viable option then parachute since it is easier to modify and is more available. The stream that is necessary to limit the descent velocity to 20m/s is very large, if it is 3in wide then it must be over 6ft long. Since it takes much more fabric to use a streamer and it is somewhat harder to predict the drag coefficient, a modified parasheet, like the one below will be used.

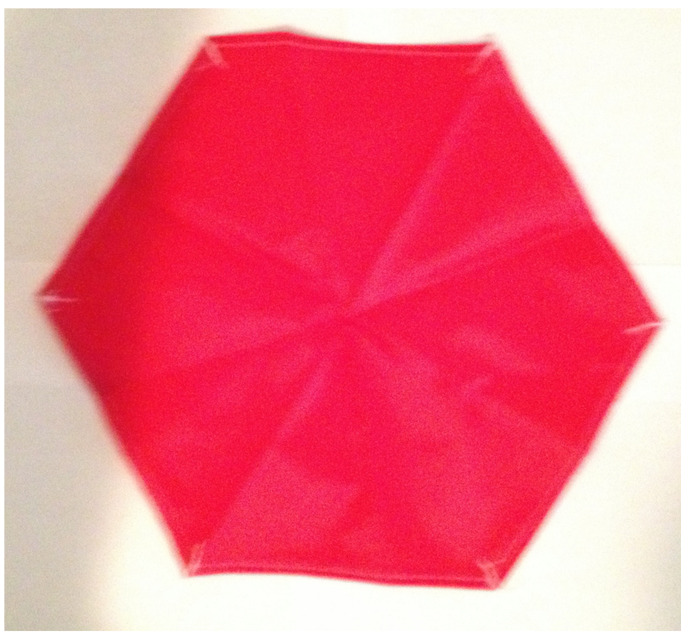


Figure 28. Parachute for Phase 1

The smallest available parasheet is 9 inches in diameter so, one could be made or modified to meet the specified requirements. If a circular hole is cut into the center to make the parasheet have the proper effective area it could increase the stability of fall. Since this parasheet is so small and the falling velocity so high, wind drift will not be a large problem.

Separation Mechanism

Recalling from the concept generation, the method of operation chosen for the CanSat separation is the ring release mechanism. This method was chosen mainly due to its simplicity, ease of implementation, and low rate of failure. There are three main components for this system. The tertiary component of this design is an eyebolt that is affixed to the container of the CanSat and that the ring hooks on to. This part was chosen from a commonly available, relatively strong Nylon part from McMaster Carr. The secondary component of this design is a small, high torque motor that requires the same voltage that the electronic system works on. The main component of focus for this design is the open ring of the mechanism. This is because of the inherent difficulty to manufacture such a part given size, weight and strength constraints. The size of the final part was to be minimalized as much as possible in order to leave as much room as possible for every other component of the CanSat.

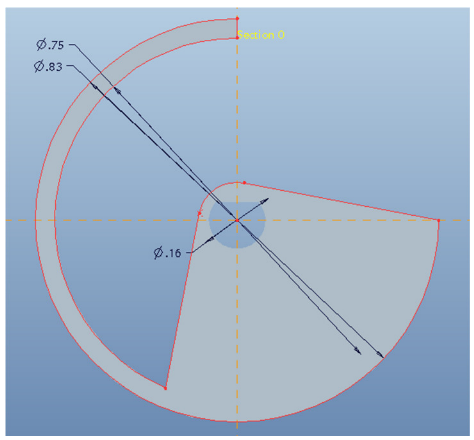


Figure 29. Ring Component 1

As can be seen from the figure, the overall size of the part is less than 7/8" with a very thin lip. The initial design had a cylindrical profile that would be extremely difficult to machine at such a small size. The use of a 3-D printer was then thought to be the simplest way of creating the part, however it came with a complication. The strength of the part would be of big concern. The majority of the 700g weight of the CanSat would be resting on the thin lip of the ring and a failure at that point could be catastrophic. At that point, the material and method of fabrication was changed such that it would be made from aluminum using a water jet. This gave the benefit of strength and ease of manufacturability. The drawbacks were that the possibility of radio interference due to the use of metals was increased and that the part had to be two-dimensional. The final product was created and then tested to ensure proper operation. The ring was coupled to a compact, high torque motor that was able to surpass the force of friction between the ring and eyebolt and the eyebolt was then attached to the container that would resemble the weight of the loaded CanSat. The test was proven successful through multiple trials and no complications from failure arose.

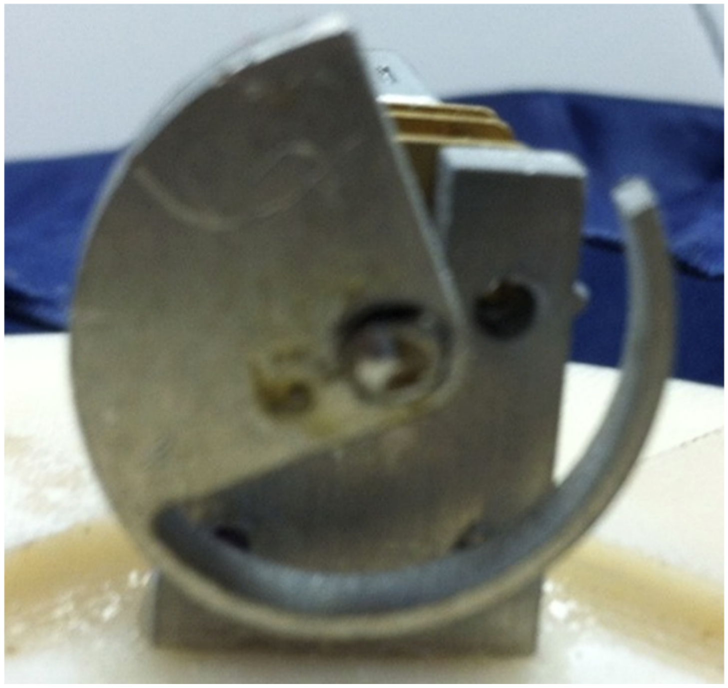


Figure 30. Ring with Motor

The final product was created and then tested to ensure proper operation. The ring was coupled to a compact, high torque motor that was able to surpass the force of friction between the ring and eyebolt and the eyebolt was then attached to the container that would resemble the weight of the loaded CanSat. The test was proven successful through multiple trials and no complications from failure arose.

Descent Phase 2

Through the concept generation, the phase 2 design that was chosen was the spring loaded rods method. This method uses rods that are affixed to the Payload's main structure with a fabric material that upon deployment will increase the effective area of drag by definition of Aero-Braking. The rods are held in tension so that when released, they will spring open. During the refinement of this idea, the structure was first addressed. The structure would help to protect the electronic components and sensitive sensory payload while simultaneously being the connection to the aero-braking system. Due to the weight, price, and radio interference constraints, metals and composites were deemed to be out of the design constraints and other materials were sought to fit the bill. The main use of plastics and wood was then investigated to see if they would be a viable solution to the constraints.

Figure 31. Support Rods for Payload

Due to the complexities of the top and bottom parts of the aero-braking structure, these parts were chosen to be made from plastic using the method of 3-D printing. Though this method is expensive for large parts of this size, it would be the cheapest and quickest way to prototype such intricate parts as compared to other methods. The structural supports between the top and the bottom were made from wooden dowel rods that were easily purchased from McMaster and slightly modified in order to form a tight fit. Using wooden dowel rods gave a great strength to weight ratio as well as helped to steer clear of the use of metals. Given the properties of the rods, it was also beneficial to use them for other components such as the aero-braking arms as well as the supports for tension springs in which these will be discussed further.

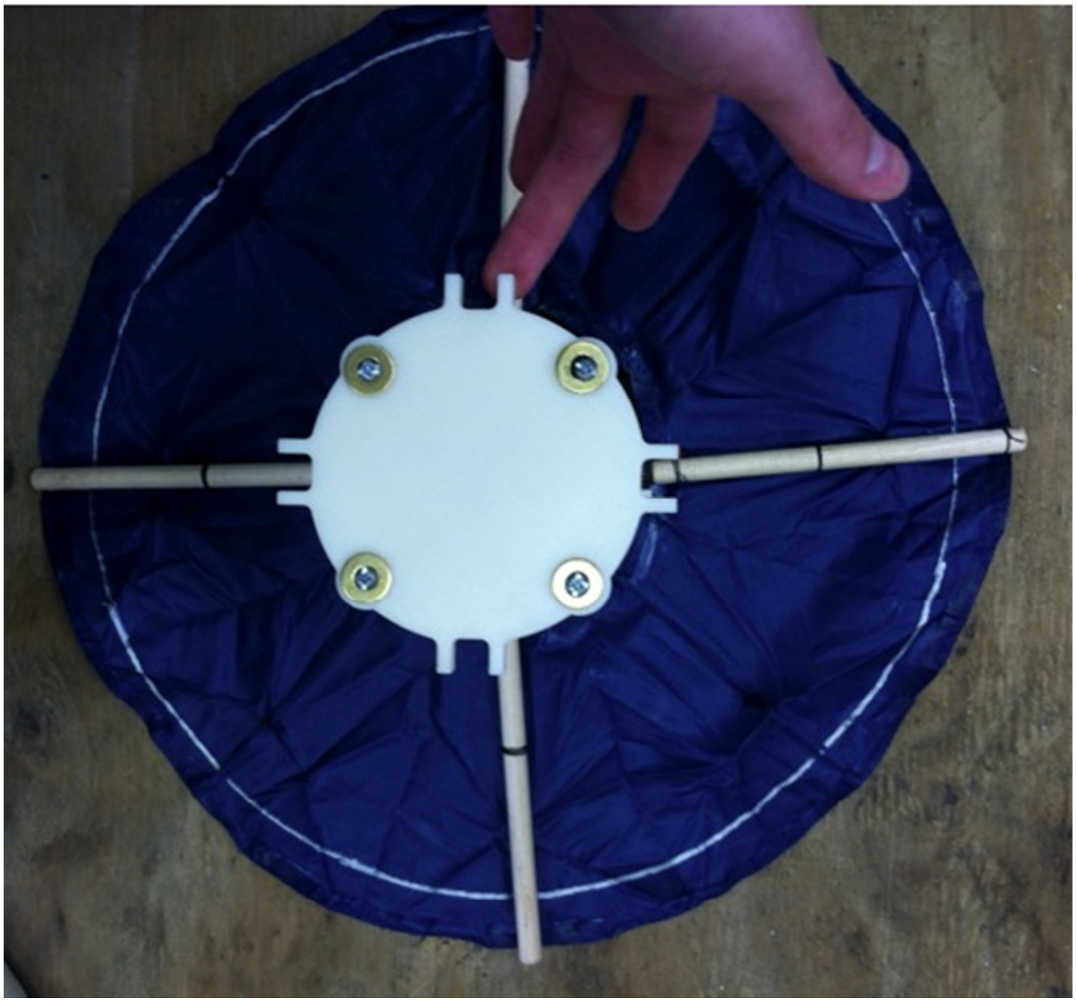


Figure 32. Bottom view of Aero-braking device

As can be seen from the figure, the aero-braking arms are made from the wooden dowel rods and affixed to the top structure using the torsion springs. Torsion springs were used due to their compactness, simplicity, and availability. They also were purchased through McMaster Carr but in a large quantity and with different sizes, shapes, and tensions in order to experiment with the optimum design. The final outcome was two opposite wound torsion springs with one end into the plastic top structure, and the other inside the aero-braking arms. A wooden dowel and alignment pin were used to hold the spring upright and on center of its pivot. The final outcome gave a compact profile and a very reliable operation. The last component of the Aero-braking system was the fabric material used for the actual aero-braking. Multiple materials were purchased inexpensively from McMaster however, the best material that was used in the final construction was from an ordinary umbrella. The umbrella material was cut into the correct shape and then sown to the aero-braking arms. The final manufactured assembly gave a very light weight yet strong, reliable, and easy to manufacture product.

Payload Layout

In order to properly situate the electronics and sensitive sensory payload, simple organization needed to be done. Through the use of a plastic container, an organized payload envelope was created. The plastic container was purchased through McMaster Carr and was modified by removing the top portion to give access to its interior space. The bottom portion was used for the sensitive payload, a hen's egg and the protective material, and the top was for the electronics. All of the electronics were placed on acrylics "shelves" that were laser cut to dimension.

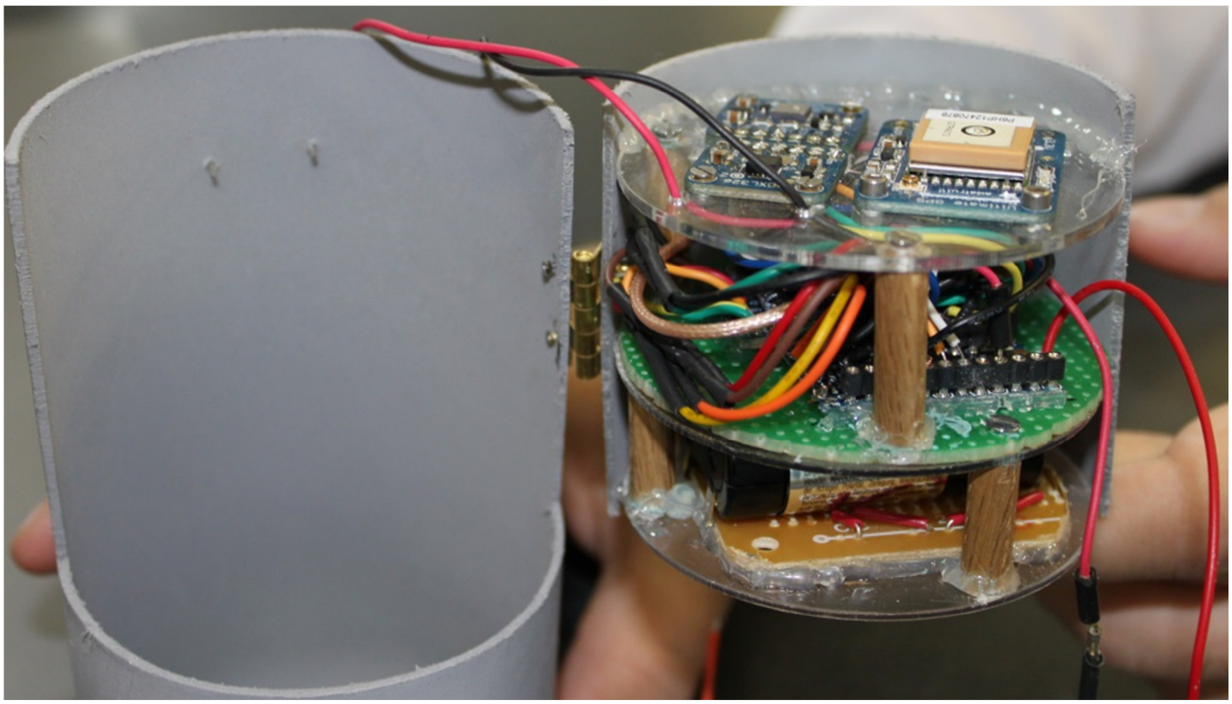


Figure 33. Electronics Bay Shelves

The acrylic gave a lightweight solution that would make mounting the electronic components. Cutting a half moon portion the length of the electronics out of the plastic and using a hinge in order to create easy access to the components then modified the plastic container for the payload envelope. The payload envelope was then also modified in order to give a mount for the ON button, antennae, and audible buzzer.

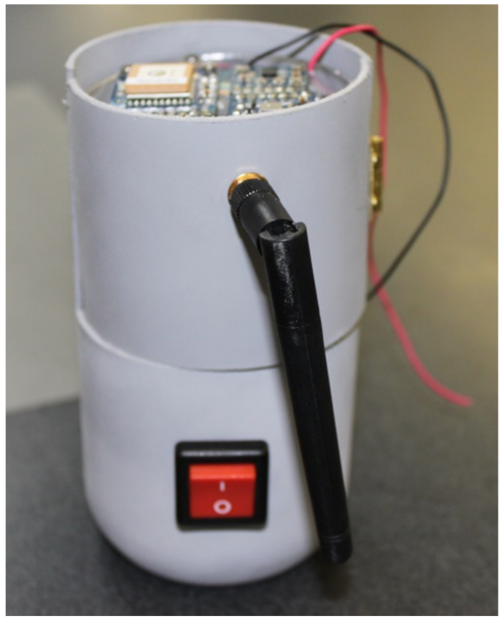


Figure 34. Completed Payload

Egg Protection

An experiment was performed to determine the best material to protect they egg. A raw hen egg the same size as the one provided at competition was placed inside of a container with the protection material and then dropped from a height of thirty feet. Multiple iterations were performed to ensure accurate results. Memory foam failed multiple times the experiment and it was decided not to use it. The egg placed inside the dough survived but the dough was much heavier than the other substances and it was decided that dough would not be used for that reason. The egg survived when placed inside the polystyrene beads as well. Since the polystyrene beads were light and inexpensive. In order to compensate for the fact that the egg might move through the beads, saran wrap can be used to make pouches of the beads that can be placed on the top and bottom of the egg and beads can be poured around the egg to protected it around the sides. A pouch made with saran wrap is shown below.

Figure 3, Egg Protection Material

Telemetry Subsystem

The telemetry subsystem was built using the components selected from the research done in the Fall semester and finalized during the first few weeks of the Spring semester. The following shows a recap of the component selection.

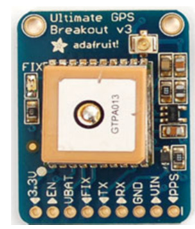
Sensors

Bosch™ BMP085, Pressure/Temperature Sensor

Selection criterion:

- Precision: ± 0.25m, ± 2.0 ºC
- Reliability: vetted by many users
- Cost: $20

GlobalTop™ FGPMMOPA6C, NMEA GPS Module



Selection criterion:

- Reliability: -165 dBi sensitivity
- Low power: 20 mA current draw
- Cost: $40

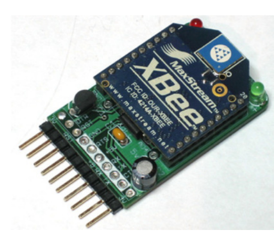
Analog Devices™ ADXL-326, Accelerometer

Selection criterion:

- Range of measurement: ±16g
- 5v logic ready, via onboard regulator
- cost: $18

Communicaitons

Xbee Pro™ Series 1, 802.15.4 (Digi Int'l)



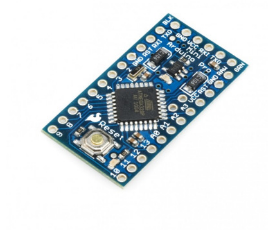
Selection criterion:

- Selection restricted by competition
- Series 1 point-to-point communication
- Compatible with Adafruit™ breakout kit
- Advantageous for breadboard proto-typing

Microcontroller

Arduino Pro Mini™ Microcontroller

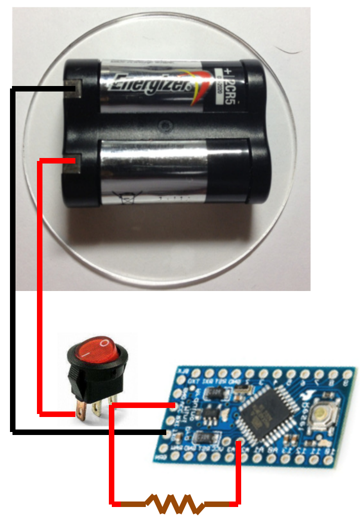
Selection criterion:



- Size: 18x33mm, essential due to size limits
- Handles power demand and protocols: ADC, I2C, Serial, Analog, Digital
- Open source platform
- Code is easily migrated from other Arduino environments (Uno, Duo, etc)

Electrical Power System

Energizer 2CR5, 5v, Li/MnO2



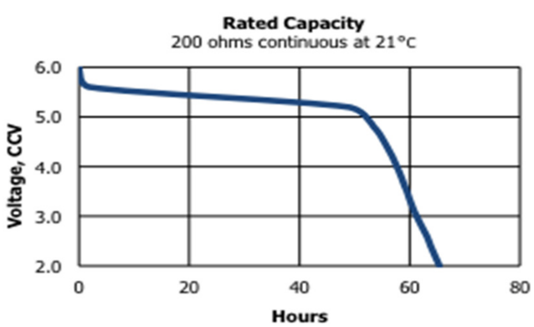
Selection criterion:

High energy density, low weight

High discharge current current (1500 mA)

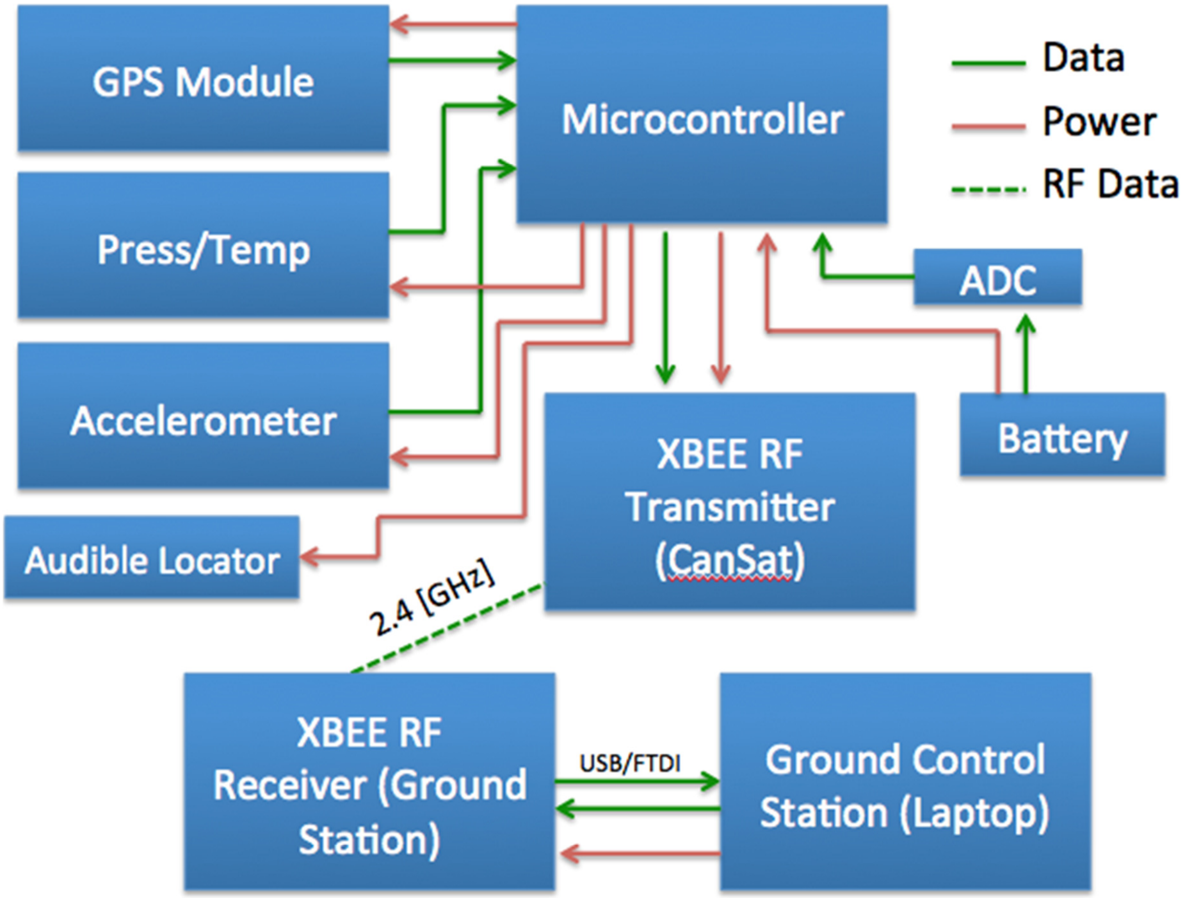
Capacity exceeds need by factor of 3

Rated voltage output ensures power delivery



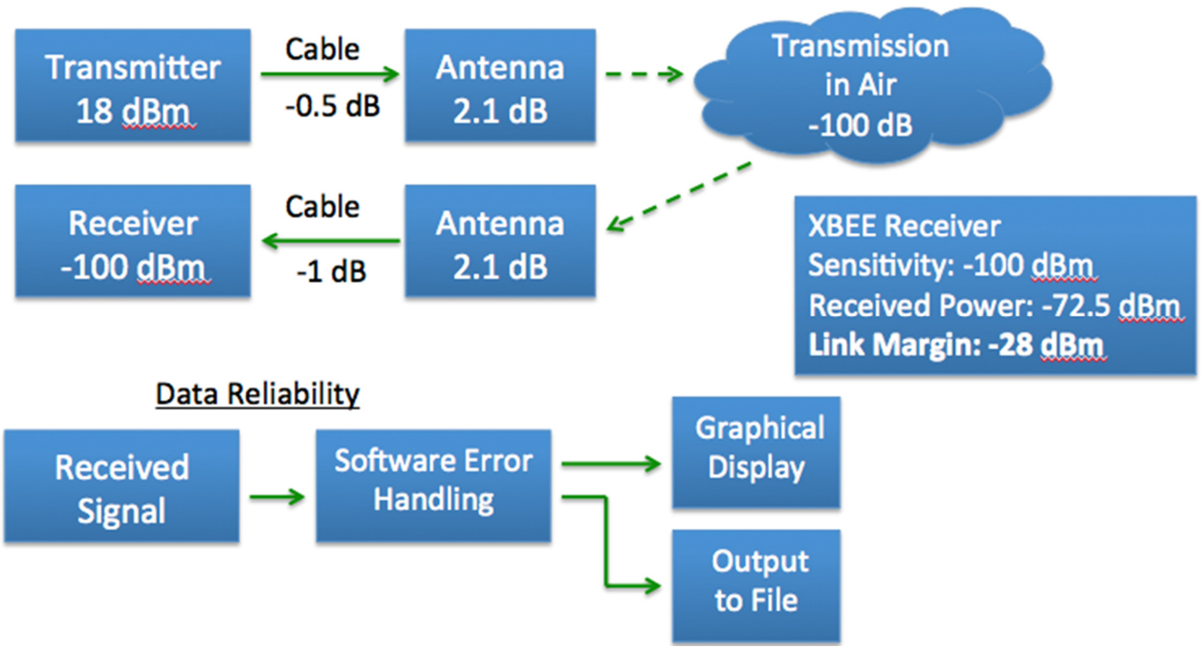
The components were integrated into a system via the Arduino Pro Mini microcontroller. The following flow diagram shows the flow of data and the flow control of the electrical power system.

Telemetery Subsystem Flow Diagram



Note that the dotted lines represent the wireless transmission of data from the Cansat to the Ground Control Station. The telemetry subsystem was bench tested before fabrication. Due to the nature of the competition, a proper test of the data transmission range was difficult and proved to be nearly impossible to perform with any degree of reliability. For this reason a link margin was calculated and this information was relayed to RF test engineers from Digi International, the manufacturers of the XBEE radios. The engineers reassured that with the link margin of the design and the geometry of the competition layout, they would nearly guarantee the effective communication of our telemetry vector. The following figure shows the link margin graphically and how the values were calculated.

Reliability: Link Margin



Comparing the receiver sensitivity to the received power uses the Link Margin calculation. This is calculated by converting all values to deciBels using the formula

$$deciBels = 10\log(power\ in\ mW)$$

then summing all the values taking note of the sign convention of a power loss having a negative decibel value. As is shown in the following figure, Lfs refers to the intrinsic power transmission losses due to "free space", which is a good approximation for the RF power loss in open air. Lfs is calculated by the following equation, the distance and wavelength are both in meters.

$$Lfs = 20\log\left(\frac{4\,\pi\,(distance)}{wavelength}\right)$$

XBEE Rcvr Sensitivity [dBm]:	-100
Received Power [dBm]:	-79.35
Link Margin:	**-20.65**

Prx	Ptx	Gtx	Ltx	Lfs	Lm	Grx	Lrx
-79.35	18	2.1	0.5	100.045997	0	2.1	1

Note: Ltx, Lrx are estimations based on reported use of similar cables/connections (IPHX/u.Fl)

Lfs	distance	wavelength	frequency	GHz
100.045997	1000	0.125	2.4	1000000000
			speed of light	
			300000000	

Prx	Power received
Ptx	Power transmitted
Gtx	Gain of transmission antenna
Ltx	Intrinsic losses of Transmitter (cable, etc)
Lfs	Loss due to free space
Lm	miscellaneous losses
Grx	Gain of receiving antenna
Lrx	Intrinsic losses of Receiver (cable, etc)

Figure 36. Link Margin Calculation (Excel)

Flight Software

The flight software runs on the Aruduino Pro Mini microcontroller and controls the reading of sensors, transmission of telemetry, deployment of the stage 2 aero braking system, impact force calculation, and starting the locator beeper on landing. The software is written in the Arduino programming language, a simplified version of C/C++ and ultimately required around 250 lines of code. According to the competition rules the software must wait for a signal from the ground station before beginning telemetry transmission, it will receive this signal while on the launch pad. After that it must gather information from the sensors and transmit the telemetry every two seconds. It must also keep track of what state it should be in even in the case of a processor reset. Because the software state is determined both by the altitude and direction of motion of the CanSat this will be accomplished by checking the current altitude and comparing it to the last taken altitude measurement. If it is higher the CanSat is ascending, if it is lower the CanSat is descending, if they are the same the CanSat has landed. The software was developed by keeping all of these requirements in mind and creating a basic framework that would satisfy all of them. After writing the basic outline of the code it was integrated with the sensors and other electronic components it needed to control. Because of the Arduino's open source nature and its popularity libraries and example code existed for many of the components, which made interfacing with them much easier.

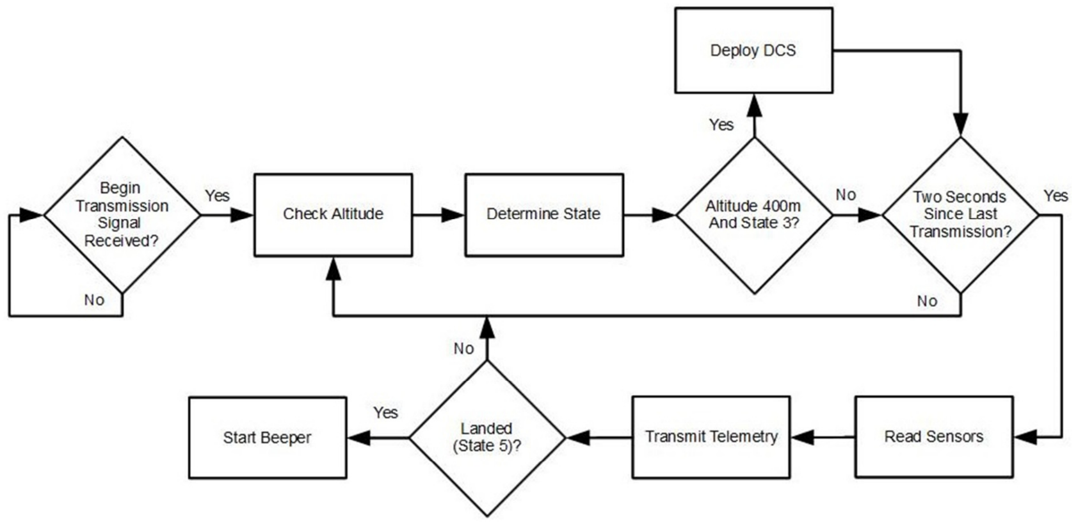


Figure 37. Flight Software Flow Diagram

Ground Control Software

The ground control software was designed to run on a laptop and communicate with the CanSat through an XBEE radio. It sends a signal to the CanSat telling it to begin telemetry transmission, receives telemetry, displays and plots the telemetry data in real time, and saves the data to a .csv file. Python was chosen to write the ground control software in because it is simple to code in, creates a program that will run on many kinds of machines, and is open source. It was written using libraries such as tkinter, for creating the graphical user interface (GUI), and matplotlib, for creating the real-time graphs. This software went through several iterations, from a simple proof of concept GUI to the final version. Each iteration added functionality until the the final version fulfilled all the requirements. Using a utility called cx_Freeze an executable was created from the Python code so that the program can be run on any computer, even if it doesn't have Python installed.

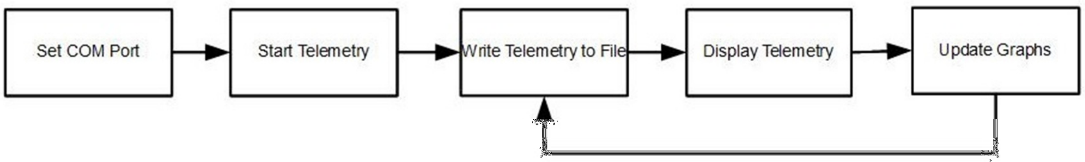


Figure 38. Ground Control Station Software Flow Diagram

Software Testing and Results

The software was “beta tested” by uploading the flight software and running the ground control software on a PC running Windows 7. The software ran for over an hour without any error in the data handling. It was presumed that their was no error in the flight software since, inspection of the data in the “csv” file showed no deviations from the expected result.

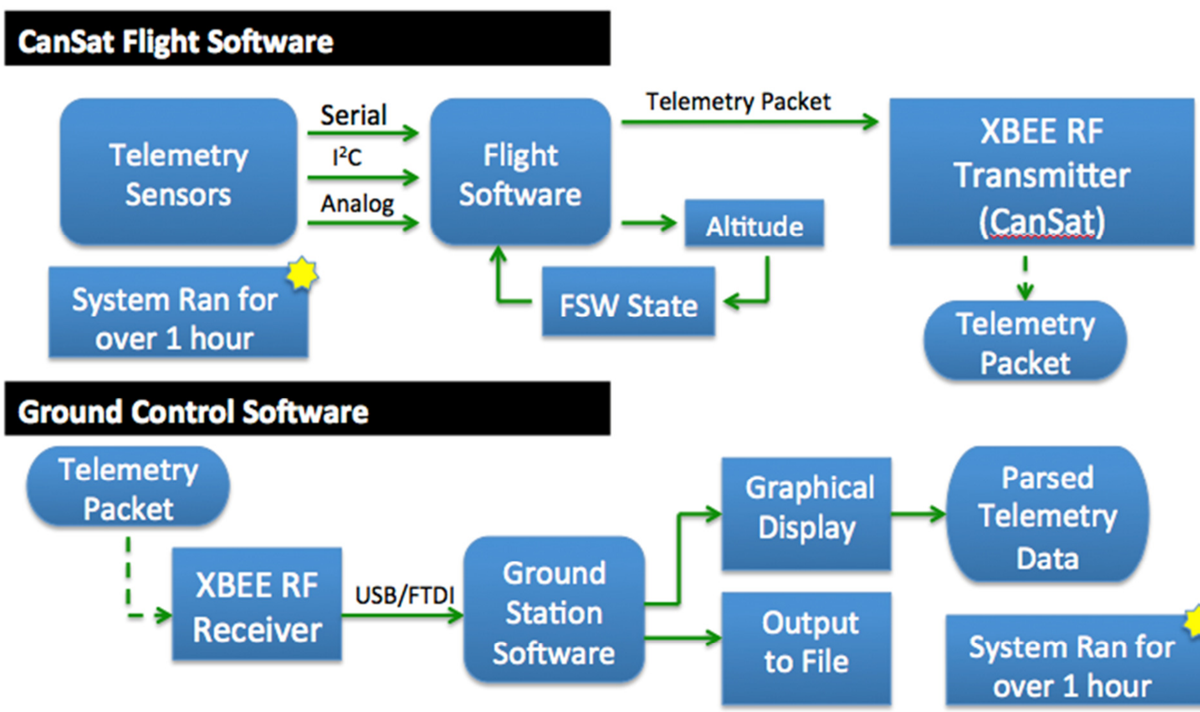


Figure 39. Complete Software Flow Diagram

Electrical Power System

The Electrical Power System (EPS) was designed to be a 5 V regulated system with a 6 V battery source. The reason for the 5 V system voltage was to accommodate the different sensors. The sensors were soldered to an individual "break-out" printed circuit board (PCB). Each of the PCB's have a voltage regulator on them, in addition to the voltage regulation provided by the Arduino Pro Mini.

The battery management will be accomplished using a simple voltage divider and an analog to digital converter (ADC). The voltage divider is used to limit the current flow to the ADC and also to provide a known voltage to base the measurements from. The following figure shows a simple schematic the configuration.

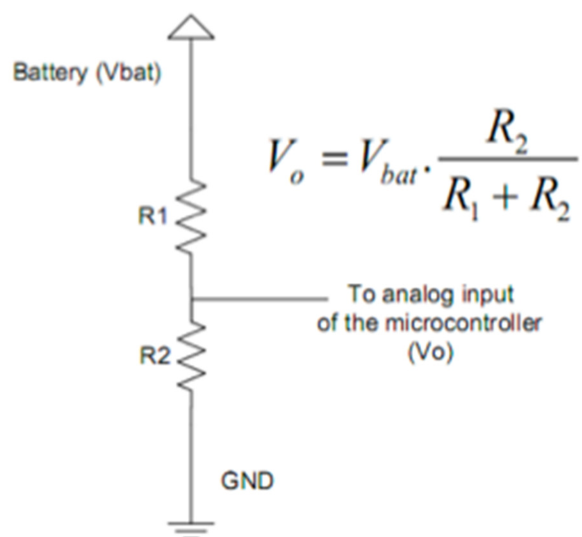


Figure 40. Voltage divider

Where R_1 = 660 kΩ and R_2 = 540 kΩ

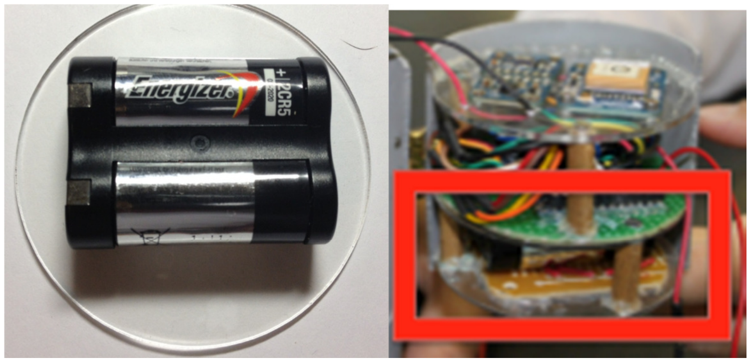


Figure 41. (left) Energizer 2CR5, (right) Batter in electronics bay

The following table shows a power budget based on the current design and interpretation of the competition requirements.

Table 6: CanSat power budget

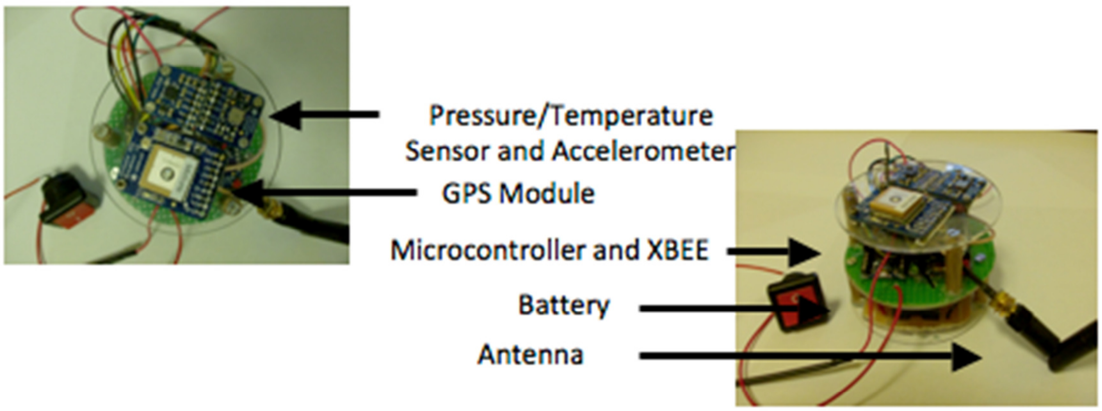
Component	Current [mA]	Voltage [V]	Power [mW]	Expected duration [min]	Total energy [mWh]
Microprocessor	50	5	250	10	41.7
I/O Pins	40	5	200	10	33.4
GPS	41	3.3	136	10	11.8
BMP085	0.01	3.3	0.2	10	n/a
XBEE Tx	250	3.3	825	10	137.8
XBEE Rx	55	3.3	181.5	0.1	18.2
Motor	600	3.3	1980	0.1	198.0
Buzzer	8	3.3	26.4	180	79.2
Total					520.1

Based on the required energy from the power budget in the previous table a minimum of 520.1 mWh would be needed for the operation of the CanSat under normal conditions.

The battery selected for the design is the Energizer model 2CR5. This battery is one that comes with a package that is ideal for compact implementation. The battery is a Lithium/Manganese Dioxide composition that is rated for a continuous output capacity of 1500 mAh for up to 40 hours of operation. The battery package contains a "positive temperature coefficient" safety device to limit current during short circuit conditions. The following shows the rated capacity of the battery. Further information is provided in the Appendix.

Completed Telemetry subsystem and Electonics Bay

The following pictures and figures show the completed telemetry subsystem and electronics bay including the electrical power compenents. The XBEE-Adapter, microcontroller and battery were attached to the acrylic shelves by using customized perforated PCB. This allowed for custom circuitry to be implemented. This is advantageous given the manufacturing process we used for this prototype.



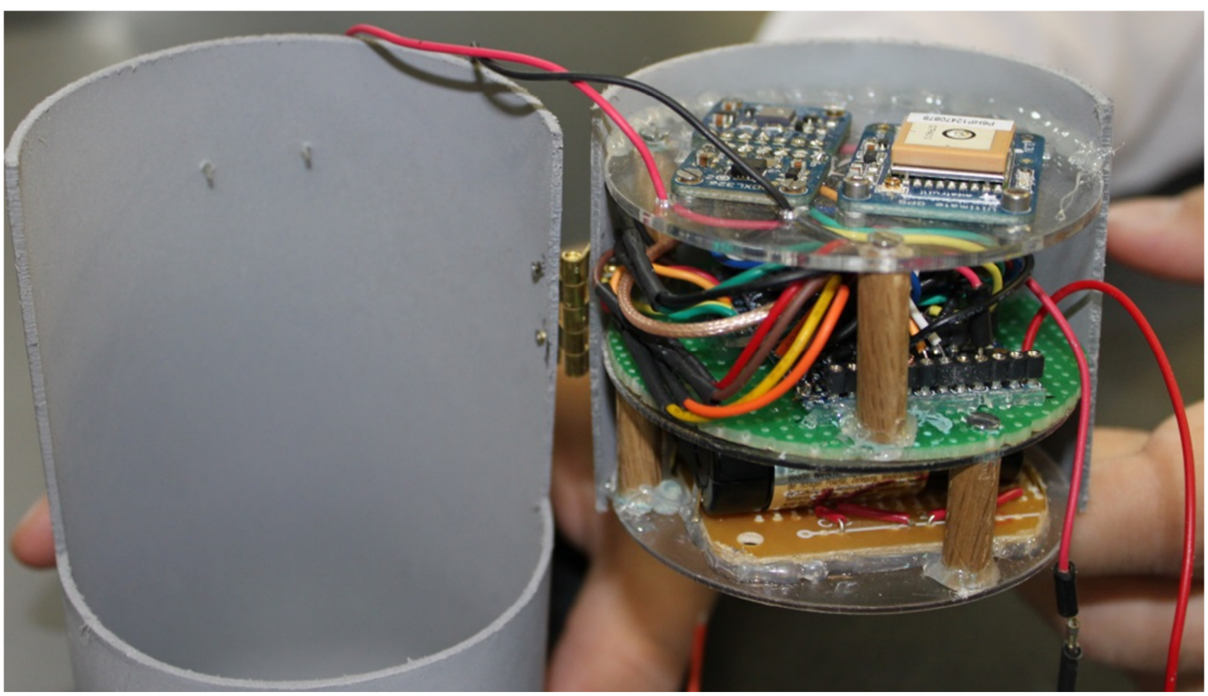


Figure 42. Completed Electronics Subsystem fabrication

Engineering Economics

In order to fund our project we had to gather money from various resources. Our contributors include the ECE department, Dr. Shih, State farm, Mr. and Mrs. Grant and Mr. and Mrs. Shafer. The donations from all the contributors make the projects total funding $2,200. The table below shows the various sources of income and the money spent on the various components. The cost analysis is shown below.

Revenue		Expenses	
Funding Source	Funds Received	Procured	Expense Amount
ECE Department	$200.00	ECE Components (Telemetry)	$300.00
Private Donation	$750.00	Mechanical & Structural	$175.00
Dr. Shih	$1000.00	Shipping	$25.00
State Farm	$250.00		
Total Funds Generated	**$2200.00**	**Total Procurement Expenditures**	**$500.00**
Total Available Funds Remaining	**$1700.00**		

Figure 43. Budget Information

According to the competition rules, the final product is not allowed to cost more than $1000 to build. The amount spent on the raw materials is allowed to be higher than that as long as the material put into the CanSat itself is less. To determine if the CanSat fits this competition regulation the cost analysis below was performed.

Total Component Cost			
Component	Quantity	Unit Price	Total Cost
Xbee Series 1 Pro	2	$32.00	$64
Antennae	2	$5.16	$10.32
BMP085 Barometric Pressure Sensor	1	$20.00	$20
ADXL345 Accelerometer	1	$20.00	$20
Adafruit Ultimate GPS	1	$40.00	$40
Arduino Pro Mini	1	$10.00	$10
Battery	1	$12.00	$12
Motor	1	$16.00	$16
Wires, solder, pins, screws	1	$8.00	$8
PCB perfboard, Misc	1	$15.00	$15
Torsion Springs	2	$7.44	$14.88
Slot Pins	1	$5.29	$5.29
Nylon Eyebolt	1	$5.67	$5.67
Semi-Clear Plastic Bottle	1	$5.95	$5.95
Semi-Clear Plastic Bottle	1	$13.87	$13.87
Tyvec Fabric	15	$1.13	$16.95
Plastic Rod	2	$1.60	$3.20
Glue	1	$35.77	$35.77
Primer	1	$5.70	$5.70
Fluorescent Paint	1	$5.70	$5.70
3D Printed Parts	79.67 cm^3	$2.00	$318.68
Maple rod	2	$1.60	$3.20
Assembly	2 hours	$20.00	$40.00
Total			$690.18

Since the total cost including assembly was approximate $690.18, the CanSat developed by our team is in the acceptable cost range for the competition. With the overall costs being within 30% of the total allowable expenditure on the final design, it should be noted that future designs could possibly benefit from more funds being allocated to research and development.

Health and Safety

Competition guidelines stipulate that the Cansat cannot have any sharp edges and no object or part of the Cansat shall protrude the exterior of the Cansat outer container. No pyrotechnic or highly resistive heat elements are allowed on the Cansat. The Cansat is fairly safe since it's not meant to be used in any direct human interaction.

Although the Cansat is meant to be operated autonomously, the ground station software on a laptop screen monitors it. The GCS operator shouldn't stare at the screen too long, adverse affects may follow like blindness or possibly chronic boredom. Also, the Cansat does utilize electromagnetic radiation to transmit data. Electromagnetic radiation has been known to scare some people, notably mechanical, civil, and industrial engineers.

The Cansat electronics are soldered with a soldering compound composed of 2 % silver, 60 % tin, and 38% lead. Lead poisoning is a serious health concern, though it is mostly a hazard during the fabrication process as solder fumes are able to be inhaled. Some of the components on the Cansat are RHoS compliant, isn't that nice.

Conclusion

The primary and secondary objectives that were communicated to our technical advisors at the beginning of the semester have been met and were demonstrated at the open house hosted by the FAMU-FSU Mechanical Engineering Dept. Team 18 also won "honorable mention" for their presentation and poster. It should be noted that the telemetry and software of the Cansat are fully operational and that the Cansat physically exists. These were the literally expectations communicated by the team leader to the technical advisor at the beginning of the semester.

Given that the operation conditions could not be replicated, several lab tests and experiments were conducted to model the launch environment and simulate the CanSat's behavior for each individual stage of the launch. Tests for the separation mechanism, both descent control strategies, and the communications portions proved to be successful and meet competition requirements.

References

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Team Member Biographies

Samuel Rustan

I'm an Electrical Engineering student of the FAMU-FSU college of Engineering. I will be graduating from FSU this spring. Originally from Minnesota, I began my university studies after spending several years as an electronics technician and IT administrator. I'm involved in several projects on and off campus including an online educational initiative (FSU), a sustainability group (SES), and recently participated in NASA's International Space Apps Challenge –winning our local competition and moving on to the next level.

Max Sandler

My name is Maxwell Sandler and I am senior in Mechanical Engineering at Florida State University. I have very strong interests in anything automotive, aerospace, or energy related. My goal is to attend graduate school and expand my knowledge towards aerodynamics. One of my ideal dream jobs would be to work for a Formula1 team and design some of the most technologically advanced machines anyone has ever seen.

Andrew Guerr

I am a senior in Computer Engineering at Florida State University. I am interested in programming and computers.

Andrew Grant

I am Andrew Grant. I am a senior in Mechanical Engineering with a specialization in thermal Fluids. I have been involved in The Society of Automotive Engineers for the past 2 years. We are currently constructing an off road vehicle for the SAE Mini-Baja competition this summer. I am also involved in Pi Tau Sigma, The International Mechanical Engineering Honor Society.

Yasmin Belhaj

I study Mechanical Engineering at Florida State University. I am currently the president of the American Institute of Aeronautics and Astronautics-- FAMU-FSU Student Branch. With the help of the AIAA student executive board, I oversee design/build competitions, coordinate outreach events, and create a networking tool to integrate motivated students into the professional industry. I participated in a research program at the Florida Center for Advanced Aero-Propulsion and currently work as a teaching assistant for an experimental fluids lab. In addition, I coach a group of competitive gymnasts.

Appendix

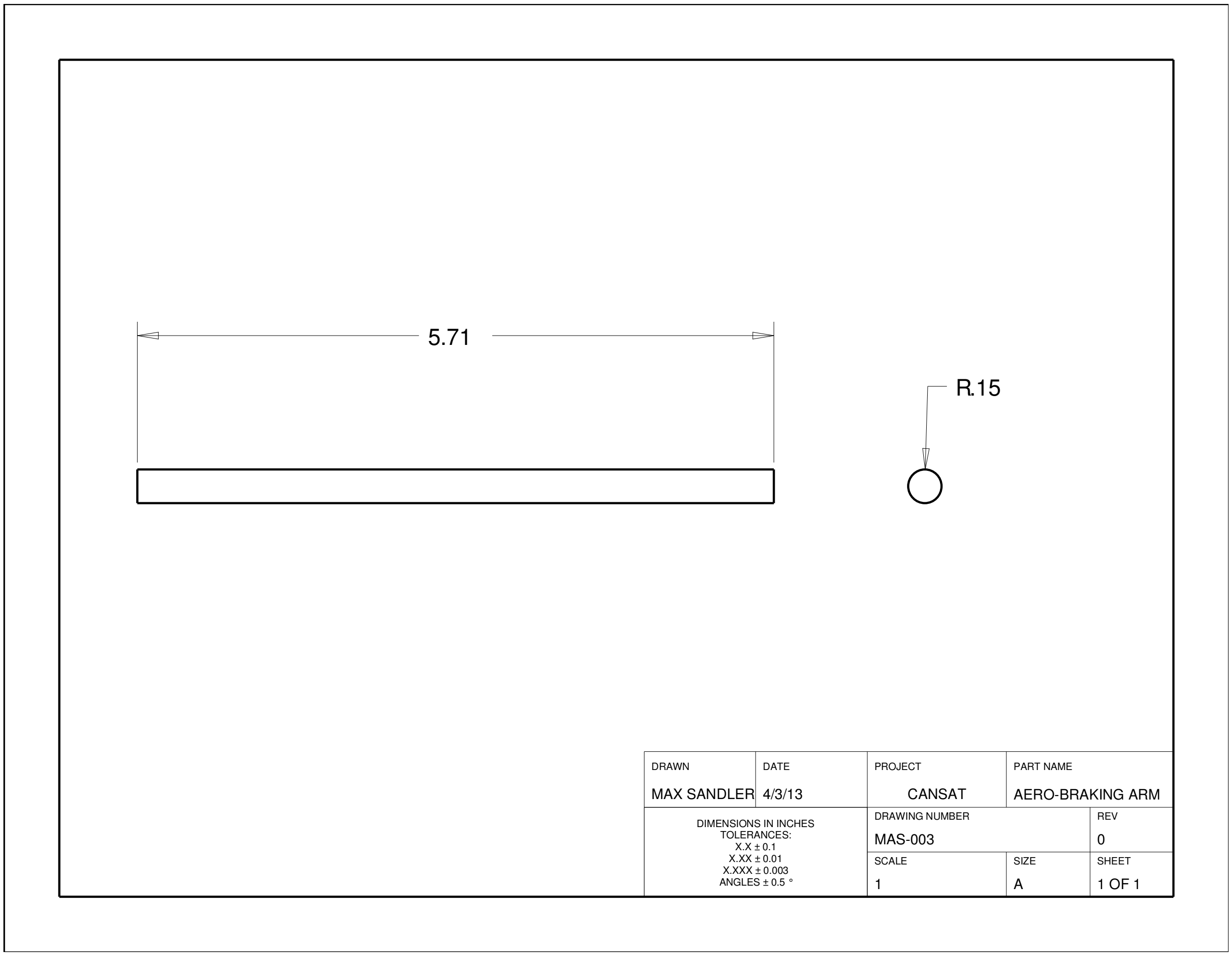

Figure 44. Aerobraking Arms

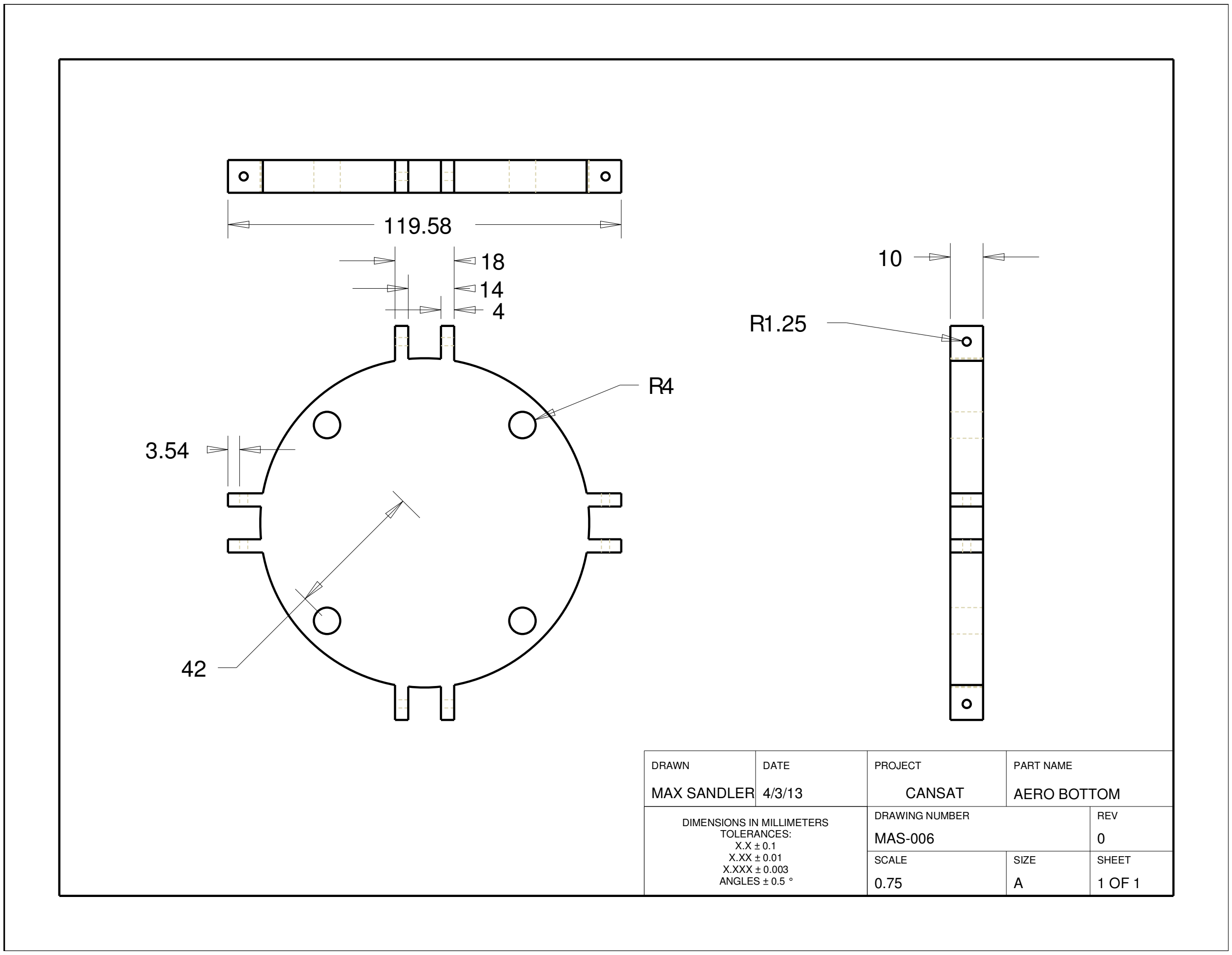

Figure 45. Aerobraking structure bottom plate

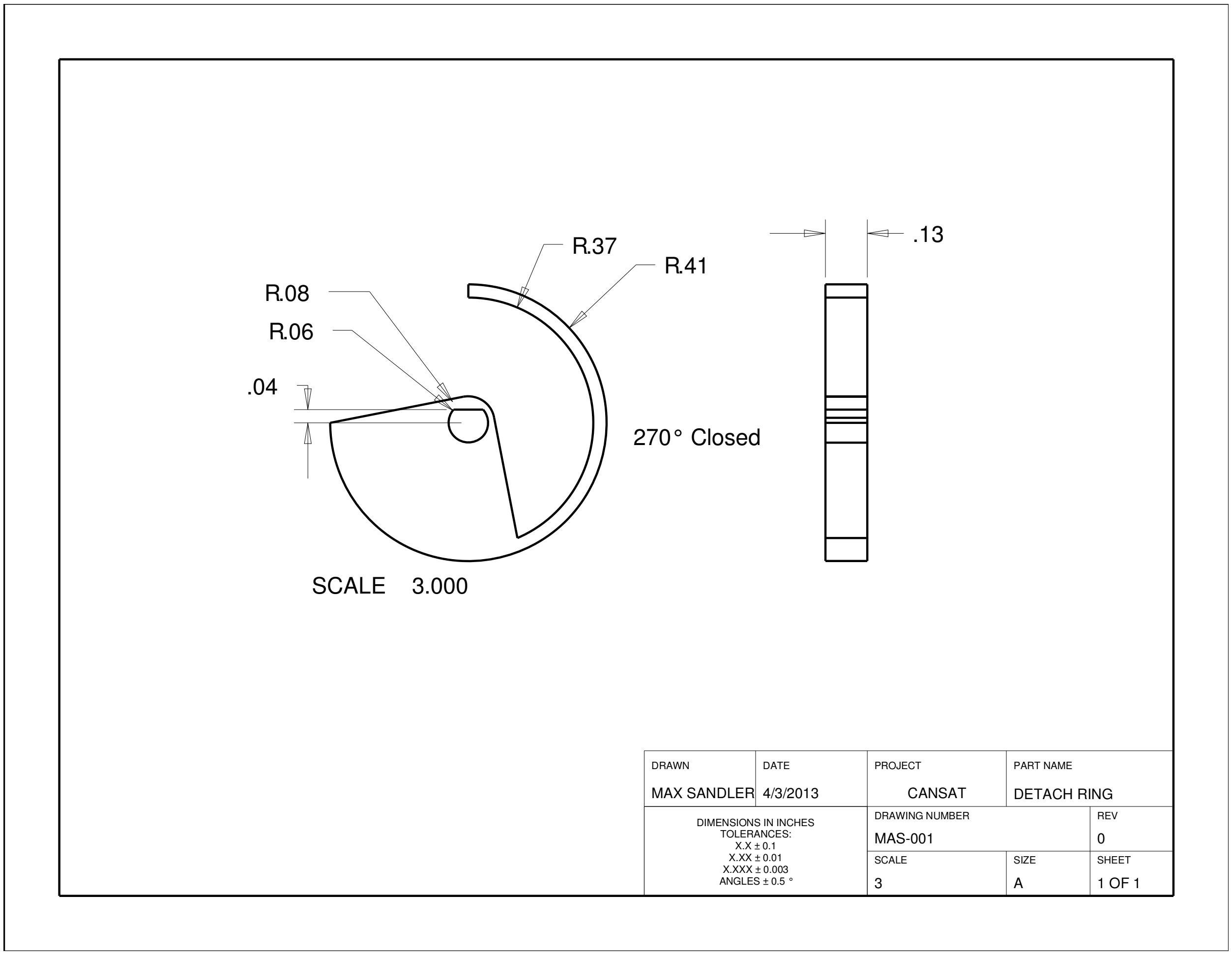

Figure 46. Release Mechanism Ring

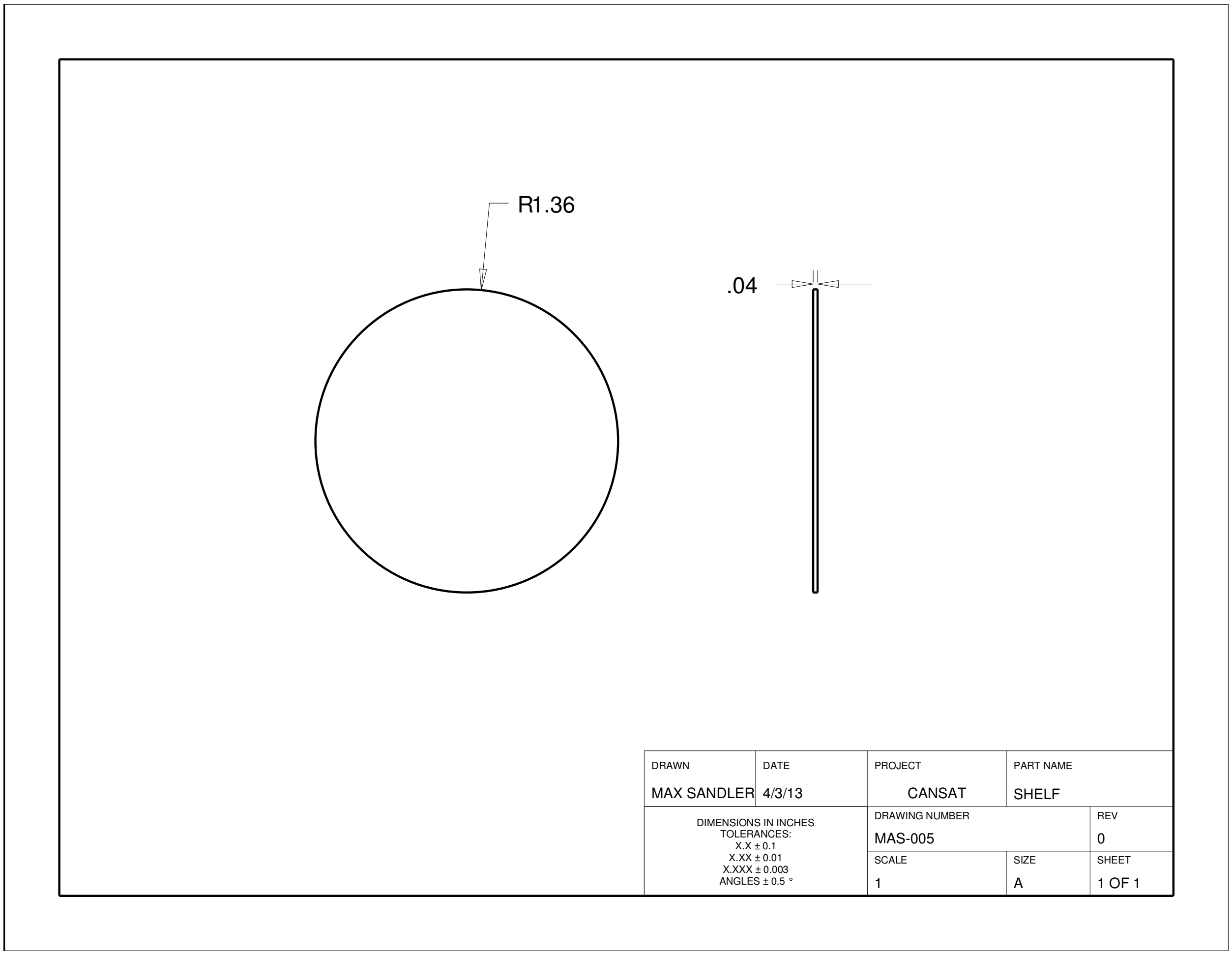

Figure 47. Support Shelves

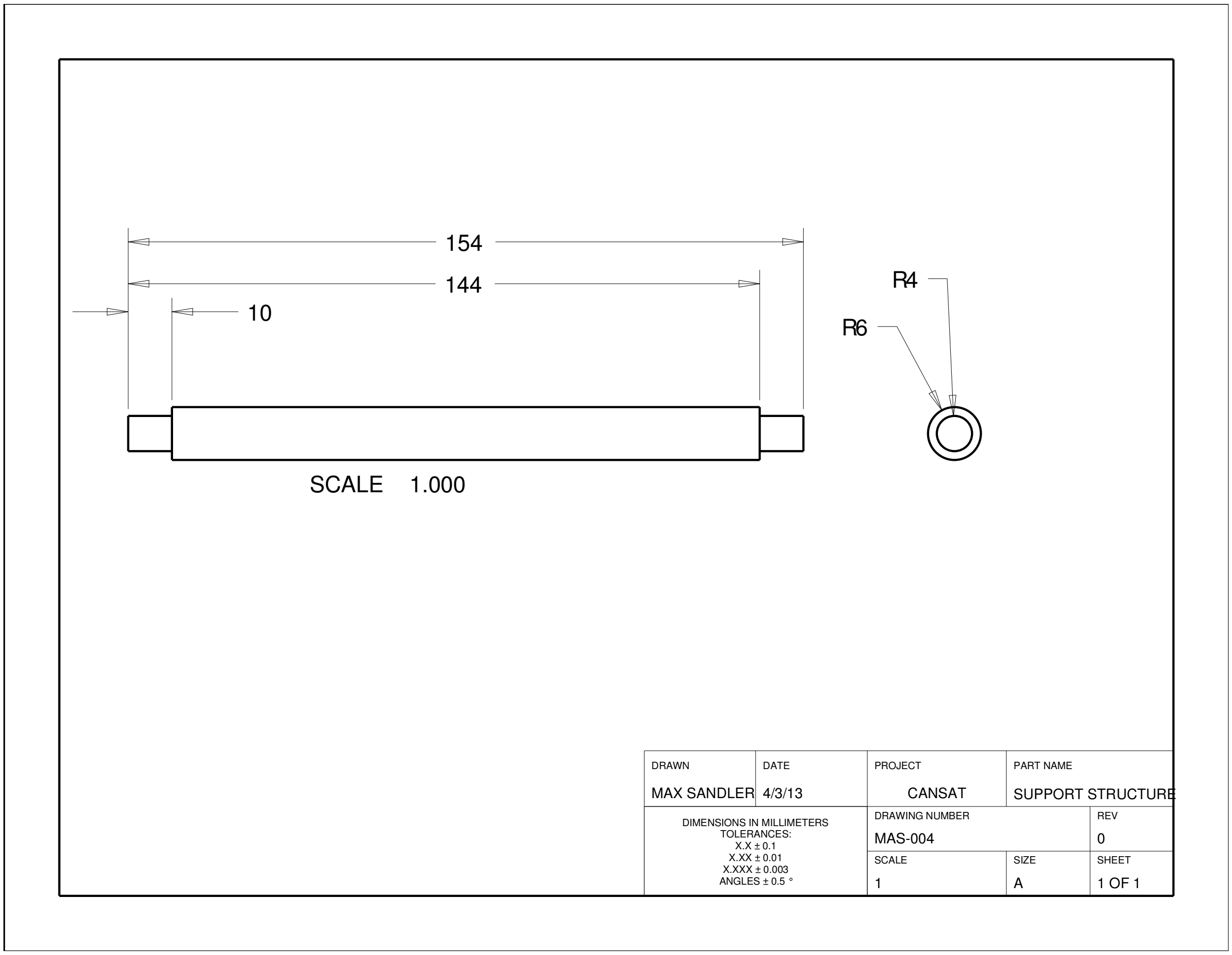

Figure 48. Support Structure