

# **A Gossamer Structures Technology Demonstrator for De-Orbiting Pico-Satellites**

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## Abstract

Design of an engineering model for the Inflate-A-Brake system is proposed. The device is intended to mitigate the contribution to orbital debris from small satellites by reducing their orbital lifetime after a mission. It takes the form of an add-on module consisting of a passively deployed ballute. The basic design and preliminary test results for the development of an engineering model are presented.

## Introduction

With the current interest in pico-satellite class vehicles and the potential proliferation of these vehicles in orbit, the issue of space debris mitigation becomes critical. In fact, the Federal Communications Commission (FCC) has recently issued a ruling that requires all future applications for spacecraft licensing to submit “an orbital debris mitigation plan” along with the license application [3]. A petition has been filed to the FCC on behalf of the Radio Amateur Satellite Corporation (AMSAT) requiring exemption from the FCC ruling [4]. Specifically stated on page six of the petition is the following: “However, we know of no presently available, proven technology for de-orbiting a satellite that is capable of being implemented in spacecraft such as AMSAT-OSCAR 51, Cubesats, and most other spacecraft designs that are within the financial reach of owners of spacecraft carrying amateur space stations.” The Inflate-A-Brake is a potential solution to this problem using gossamer structures. It employs a passively inflated ballute and generates more drag due to the larger area, thus *decreasing the post-mission lifetime of small satellites in LEO*. The reduction in orbital lifetime due to the chute has shown to be significant in orbital propagation simulations. The device is designed to be unobtrusive to small satellites in that it requires minimal power, mass, and volume for deployment. The Inflate-A-Brake is a project being developed by an undergraduate student team at the University of Florida for the 2004-2005 Florida University Satellite (FUNSAT) Competition. The goal of the competition is for university teams around the state of Florida to produce a pico-satellite design which is innovative and practical. This paper presents the engineering model design of the Inflate-A-Brake and preliminary test results.

## Orbital Lifetime

The performance of the Inflate-A-Brake system is measured in the decrease in orbital lifetime due to a change in the ballistic coefficient. The ballistic coefficient ( $B$ ) is a function of the satellite’s mass

( $m$ ), cross-sectional area ( $A$ ), and drag coefficient ( $C_d$ ) as shown below:

$$B = m / C_d A$$

The effect of ballistic coefficient on orbital lifetime can be analyzed with orbital propagation software; e.g., *SatLife* is an orbital analysis tool made by Microcosm Inc. which predicts orbital lifetime given initial orbital and spacecraft parameters. The input parameters consist of the start date, orbital altitude, and spacecraft cross-sectional area and mass. Historical and projected solar cycle data is used to predict atmospheric drag. The resulting lifetime from initial orbit through reentry is then computed using variable step size Euler integration [1].

The orbital lifetime for a CubeSat in LEO was analyzed using *SatLife*. The input parameters and corresponding results for four simulations are summarized in Table 1. Columns one and two show the reduction in orbital lifetime due to a change in ballistic coefficient for a given orbit and start date. Columns three and four show how the magnitude of this reduction is dependent on the start date of the orbit, i.e. on the solar cycle. A broader range of ballistic coefficients and their corresponding effects on the orbital lifetime are shown in Figure 1. The data was taken for a circular orbit at an altitude of 650 km starting July 1<sup>st</sup>, 2005.

## PAYLOAD

This section describes the design and testing of the Inflate-A-Brake payload. The payload consists of an inflatable ballute, a storage bin, and a release mechanism.

The Inflate-A-Brake payload is designed for integration with a standard CubeSat structure as set forth by Pumpkin Inc. in their CubeSatKit [2]. This structure is in the shape of a cube 10 cm on edge. The ballute is packaged tightly inside a non-intrusive structure doubling as the storage bin and one face of the satellite. The ballute is released from this storage bin and passively inflates using residual atmospheric air and potentially will have phase-change chemicals as well. The combination of the internal air – at sea level atmospheric pressure – and the near-vacuum environment of space create a pressure gradient that causes full deployment of the ballute with a minimal amount of air. The use of chemical phase change for sustaining necessary pressure is also being investigated.

## Ballute

The increase in cross-sectional area, and hence the decrease in ballistic coefficient, is accomplished by inflation of a stowed ballute. An inflatable ballute is packaged and stowed, and after completion of the spacecraft's mission it is deployed using a passive inflation mechanism.

A chute shape was chosen due to its passive control ability and a favorable ratio of increased area to material volume. A drawing of a fully deployed ballute is shown in Figure 2. Four inflated struts attach an inflated outer ring, or torus, to the storage bin. The torus will have a flat lenticular in the middle which will fill in the area. The imparted drag on the chute will eventually settle the satellite's attitude such that the plane of the inflatable is normal to the satellite's velocity vector. In order to show that passive attitude control using the ballute is possible, an analysis tool is presently being developed which can give a time history of the orientation given a particular chute shape. The equations of motion along with atmospheric data are used to find a shape which will dampen out initial oscillations after deployment. Then, this shape can be scaled to adjust the total de-orbiting time.

Kapton and mylar were investigated for use as a ballute material. They both exhibit favorable mechanical and chemical properties over a wide range of temperatures [5]. The kapton available required adhesive for sealing, while available mylar could be sealed using a heat sealer thus producing more tightly sealed seams. Mylar was chosen for this reason and also due to its widespread use in inflatable structures for space applications, as well as its availability. Using mylar also simplified fabrication of test inflatables. Some of the structural characteristics of both materials are shown in Table 2.

## Ballute Testing

Tests were performed to assess residual air inflation of a mylar ballute in a vacuum environment. The tests assessed the ability of a mylar inflatable to fully inflate using a minimal amount of residual air. Also, the resulting pressure of the residual air in the expanded inflatable was characterized. The inflatables were constructed using a 12 inch heat sealer, which simplified fabrication but limited the degree of detail in the design, and then placed in a vacuum chamber. As the pressure in the vacuum chamber was decreased, the internal residual air trapped in the mylar caused its inflation.

For the inflation tests, inflatables were constructed with the intention of characterizing the effects of the

residual air trapped inside. In test one, a square pouch was fabricated that roughly resembled a single large strut when fully inflated. The pouch was attached to a face of the satellite structure as it is constructed in the standard CubeSatKit offered by Pumpkin Inc. This standard structure is pictured in Figure CUBE PIC. Images of the pouch before and after inflation are shown in Figure 3.

The tests showed repeatedly that full inflation was achievable using minimal residual air. They also indicated that the pressure exerted was sufficient to lift the weight of the face. This is significant because the pushing of the ballute on the face starts the deployment. And, since the gravitational acceleration in LEO is a fraction of that at sea level, this indicates that the residual air offers enough force to initiate deployment on orbit.

Test two was conducted to study the ability of smaller inflatables, which more closely resembled a strut shape, to fully inflate with residual air. Figure 4 shows four such mylar struts before inflation and the resulting full deployment once in the vacuum chamber.

A third test involved investigation of a fabricated mylar structure that resembled the design size and shape of the ballute. Six strut-shaped mylar pouches were fabricated with Methanol inside. They were all individually tested in the vacuum chamber and found to inflate. These six pouches were attached with epoxy in a hexagonal shape, as shown in Figure 5. A single sheet of Mylar was fabricated in the hexagonal shape and attached with epoxy to these six strut-shaped pouches, as also shown in Figure 5. Struts for the hexagonal ballute were fabricated, tested and then also attached. The structure had an area of 1,040 cm<sup>2</sup>, which was able to be folded and packaged into a prototype storage bin. The prototype bin had dimensions of 6x8x1 cm<sup>3</sup>, thus proving that the assumption of folding our ballute into the volume of the storage bin is reasonable. The prototype bin with the stowed hexagonal ballute is depicted in Figure 5.

A fourth type of testing was conducted to study chemical phase change via evaporation for ballute inflation. Several simple alcohols were tested: methanol, ethanol, and t-butanol. These chemicals were chosen for their high vapor pressures and their ease of use and availability. The liquids were placed inside the ballute and evaporated into their gaseous state once a critical pressure was reached.

Heat-sealed Mylar struts, 75cm<sup>2</sup> when flat, were constructed with 0.5g of each chemical and as much of the residual air removed as possible. A similar bag was left with just the residual air for comparison.

Each bag was folded and placed within an aluminum bin inside the vacuum chamber. Different weights were put on top of the bin to see how much each chemical could lift. The tests showed that the alcohol-filled struts inflated sooner and more vigorously than the struts with solely residual air. Methanol was chosen as the inflation mechanism because of its apparent better performance in the tests and its lower vapor pressure.

### Ballute Pressure

As the satellite leaves the atmosphere, the ballute will begin to expand due to the pressure gradient. It will exert a pressure on the inside of the storage bin. This pressure can be estimated by assuming the air behaves as a perfect gas. As such the perfect gas law may be applied:

$$PV = nRT$$

Here, “P” is the pressure (kPa), “V” is the volume of fluid (m<sup>3</sup>), “n” is the amount of air (moles), “R” is the universal gas constant (8314.3 J/kg mol K), and “T” is the temperature (K). Assuming negligible losses due to permeability, the amount of air inside the ballute before launch and after orbit insertion is identical. By solving the perfect gas law for “n” for each state, equating, and solving for the final pressure, we get the following result:

$$P_2 = P_1 * (V_R) * (T_R)$$

Here, “V<sub>R</sub>” refers to the volume ratio V<sub>1</sub>/V<sub>2</sub>. It is a measure of the initial volume of the ballute inside the bin pre-launch to the final volume of the ballute inside the bin on orbit. “T<sub>R</sub>” refers to the temperature ratio T<sub>2</sub>/T<sub>1</sub>. It is a measure of the temperature change between states 1 and 2.

Table 3 shows results for five different volume ratios given an initial pressure and a temperature ratio. Conservative assumptions for the volume and temperature ratios result in a maximum possible pressure around 104 kPa.

### Storage Bin

The ballute is stored in a packed, folded state inside of the Inflate-A-Brake’s storage bin. The bin houses the ballute and serves as part of the satellite structure. It is pictured without the top (lid) or the release mechanism in Figure 6. The lid will be secured to the bin and also attached to the top of the ballute. Deployment consists of detaching this lid from the satellite structure while staying attached to the lid, thus allowing the ballute to deploy and inflate without creating any debris. A depiction of a closed storage bin attached to Pumpkin Inc.’s standard CubeSat is shown in Figure 7.

The bin is designed to save space and weight by having multiple functions. Besides housing and deploying the inflatable, the bin provides structural support as one of the faces of the satellite, i.e. the bin will replace one of the standard faces which comes in the standard CubeSat. The width of the bin is the same, i.e. 10cm, thus the guide rails are replaced by rounded edges of the storage bin. The Inflate-A-Brake system is meant to be non-intrusive to the satellite’s internal volume by taking advantage of space normally *unused* on a CubeSat – the region just outside the face between the guide rails (see Figure 8). This region has a depth of 6.5 mm, and the bin is designed for a total depth of 10 mm. This means a depth of only 3.5 mm, or about 3.5% of normally available internal volume, will be taken up by the Inflate-A-Brake.

The bin is to be fabricated from the same material as the CubeSat structure so that the coefficients of thermal expansion match. This material is Aluminum 5052 H-32. Using the same thickness as the structure, 1.5mm, the mass of the bin with the dimensions mentioned above comes to approximately 120 g. The total mass allowed for launch of a CubeSat is 1kg, so the mass of the Inflate-A-Brake system is 12% of the total. With further design and optimization, the mass should be further improved. A composite design is also being investigated for mass savings. A prototype composite bin has been fabricated which had a mass of 27 g. Testing is in progress of this bin, shown in Figure 9.

### Release Mechanism

Deployment of the ballute consists of releasing the lid of the storage bin, as previously mentioned. The release of the lid needs to have simultaneous disconnect of connection points. Thus, an actuated cable and plug release mechanism has been designed toward this end. It is shown in Figure 10.

Four connection points will be released with simultaneous movement of four plugs attached to a cable. At each connection point, a pin attached to the lid will fit inside a pin attached to the storage bin. A plug is inserted inside each connection point to secure the pins together. The lid pins are designed to allow the cable to slip through it so that when the plugs are pulled, the pins are free to separate. These plugs are all pulled simultaneously by movement of a cable to which they are all connected. The cable will move using a spring-loaded actuator, development of which is still in progress. The cable runs along a channel on the perimeter of the storage bin to prevent interference from the ballute. A close-up of a pin-plug connection point is shown in Figure 11 and the lid along with its pins is shown in Figure 12.

The actuator to move the cable will be comprised of a burn wire and torsional spring. The spring will be loaded and held in place by fishing tackle. Wrapped around the fishing tackle is the Nichrome burn wire. When a small current is sent to the burn wire, it heats up. The heat is sufficient to break the fishing tackle and thus release the spring. The rotation of the spring will then move the cable, and thus the plugs, allowing the ballute to deploy. Tests of the Nichrome burn wire have shown a nominal power of 2.7 mW is needed to break the fishing line in about 2 seconds.

The design details for stresses incurred on the pins, the friction force on the cable and plugs, and development of the actuator are all in progress. The engineering model and test results are to be delivered at a FUNSAT workshop May 27. It is anticipated that the final design of the release mechanism will be finished by this date and thus by the date of the Small Satellite Conference.

### **Bus Design**

To ensure that the ballute is released and data/communications subsystems function correctly, a power source must be supplied on the satellite. Due to the constricting area and mass constraints, efficiency is a priority. Power must supply the burn wire with enough current to detach the face. It must also supply our GPS and TNC with enough power to communicate with the satellite to carry out its vital functions.

### **POWER**

Subsystems requiring power for the CubeSat are the payload and the data/comm. The payload requires 2.73 mW of power (3 V and 0.91 mA) to burn the wire for the detachable face. The voltage and current provided by 4 solar cells was enough to run the data/comm subsystem which requires 250 mW for the terminal node controller and 350 mW for the transceiver.

The power subsystem is comprised of three components necessary to power the satellite. Emcore dual junction solar cells are used to convert the solar radiation into usable voltage and current. A Maxim 745 battery charger uses the power from the solar cells to charge a Panasonic Lithium-Ion Rechargeable Battery.

Two Emcore dual junction solar cells will be connected in series on each of the six faces of the satellite (to complete one "string"). At 2.3 Volts per cell, 4.6 Volts will be produced per face in the sun. Each face will be connected in parallel, thus the total voltage produced from three faces will have a

theoretical maximum value of 6.9 Volts. Connecting the faces in parallel allows for an increase in current produced while keeping the voltage constant.

Once the satellite is in orbit, there will be two conditions from which power can be generated. On the sunlit side of the orbit, power will be generated directly from the solar cells. This power will be used to charge the battery and to power the satellite. On the dark side of the orbit, the battery will be used to power the satellite. The use of Maxim 1561 and Maxim 770 voltage regulators is integral to the voltage distribution within the pre and post charge phase of the power subsystem. A standard photo-diode will be the means for detection for which side of the Earth the satellite is on. The photo-diode is connected in series between the solar cells and the subsystems in need of charging. When the photo-diode is in the shade, the line between the solar cells and the subsystems will be broken and the only source of power will be the battery. In the sun, the photo-diode will permit this line to be completed for a closed circuit between solar cells and subsystems. This system should be completely self-sustainable. Minimal interaction from the communications system will be needed to monitor this procedure. Included in this loop of subsystems are the data and communications and burn wire control.

The power is regulated on a need by need basis. Power levels will be checked by the data/comm. System. Subsystems will command how much power they will need. The Maxim 770 and Maxim 1561 voltage regulators will control both the voltage into the battery charger and the voltage out of the battery. Both the battery and the solar cells are capable of powering the data/comm system alone, however, certain regulation must be incorporated to ensure that the battery and battery charger are not violated.

Various tests were performed using the Emcore dual junction solar cells. These tests were performed in direct sunlight with a cloudless sky. A 3.3 k $\Omega$  resistor was connected between the two faces in parallel to check the measured voltage across the system. A photo-diode was connected in series with the resistor to confirm that when the diode was covered, the series was broken. This would simulate the dark side of the orbit.

Results in Table 4 confirm that the wiring used to connect the faces in parallel was indeed accurate. Voltage remained constant while the number of strings connected in parallel increased. Power generated from a standard two face configuration, two cells in series per face and both faces connected in parallel, was enough to power the data/comm

system. With the addition of the burn wire, the aforementioned voltage regulators will be implemented. In testing the photo-diode, the series was broken with the covering of the diode. This confirmed that we could use such a device to switch between solar cell generated power and battery generated power.

Figure 13 shows a schematic of the power subsystem incorporated into the other systems of the satellite.

## **DATA AND COMMUNICATIONS**

The data/comm. subsystem provides communication between the satellite and a ground station for system checks, as well as to initiate deployment by sending a signal for current to be sent to the burn wire. The subsystem is made up of two key components: the processor board and the radio/TNC (Terminal Node Controller).

The processor is the main component in charge of the CubeSat's data handling system. Data from the power subsystem and GPS coordinate data will be transmitted as the CubeSat is within range. By doing this, it saves the processor from having to store the desired data in onboard memory.

When the satellite is deployed from the launch vehicle, a switch is tripped which will turn on the electronics of the CubeSat. When all electronics are running, the TNC and transceiver will be broadcasting a GPS beacon, and it will be also be broadcasting a beacon containing a specific string for verification of the ground station. Once the ground station receives this beacon string, it will begin tracking the CubeSat along its orbit with a directional antenna. After this, the ground station will send up a string containing a command for the processor to begin sending the relevant data. Different commands can be sent to the CubeSat via the storage string, such as to activate a burnwire, or to send only power system or GPS data.

The components used for communication are a commercially available radio and TNC. The radio is a Yaesu VX-2R and a Paccomm PicoPacket with GPS, both of which are ideal due to their compact design and ease of use. The VX-2R will be running on a frequency of 433 MHz, which falls in the frequency range originally suggested by the FUNSAT competition.

The antenna system has been chosen as a dipole arrangement that will be located on the face opposite of the ballute/bin assembly to minimize any possible interference between the two.

The processor will be pre-programmed with the commands needed to access the TNC and send the data from the power and GPS systems. To activate the burnwires, a command will be sent to the processor, which will then send current through the desired pin to begin heating the nichrome wire.

The processor is a PIC16F876. This processor has three separate input registers, a built-in analog to digital converter (ADC), and an onboard universal asynchronous receiver-transmitter (UART). The input registers will be used to supply power to the burn wire, and to interface with any data handling components that may be added, such as photodiodes for orientation, or temperature sensors. The ADC will be used to check the battery and turn the processor off if power is too low. It may be necessary to use a separate battery gas gauge, such as a BQ2050, to monitor battery charge. We are attempting to handle this with the processor for ease of implementation and simplicity of design.

The burn wire will be driven by an FET connected to power. The gate will be controlled by the processor, which will be turned on for a short amount of time when the proper deploy command is received. This will provide enough current to heat the nichrome, melting the fishing line used to hold the actuator's spring in place.

## **STRUCTURES**

The structural shell is provided by Pumpkin Inc.'s CubeSatKit, as mentioned previously. The structure (chassis, cover plate and base plate) is made from 5052 H-32 sheet aluminum. All captive and loose fasteners and the Remove-before-Flight Pin are made from stainless steel. The storage bin is integrated with the top face of CubeSatKit structure as mentioned above as well. The structure is shown in Figure 8.

## **CONCLUSION**

An engineering model of the Inflate-A-Brake, a device for ballute deployment from small satellites to reduce their orbital lifetime, is close to completion. Simulations have shown the device will drastically reduce the orbital lifetime. Basic design and testing of the device has been done for the ballute and deployment mechanisms as well as for the supporting bus system. It is anticipated to have the ability to be used on small satellites other than the pico-satellite class as well. The engineering model of the Inflate-A-Brake system integrated with the CubeSatKit structure will be demonstrated at a workshop for the FUNSAT competition on May 27.

## **REFERENCES**

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3. "Mitigation of Orbital Debris" Federal Register: Rules and Regulations, Vol. 69, No. 174, 9 September 2004, pp 54581-54589
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5. <http://www.dupont.com/kapton/general/spgeneral.html>

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Jim Pearson, SRS Technologies

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## Tables

Table 1. Orbital lifetime results of four simulations done with orbit propagation analysis tool *SatLife*.

<b>Simulation</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>
Start Date	7/1/2005	7/1/2005	7/1/2013	7/1/2013
Altitude (km)	700	700	700	700
Drag Coefficient	2.2	2.2	2.2	2.2
Mass (kg)	1	1	1	1
Area (sq m)	0.01	0.06	0.01	0.06
Ballistic Coefficient (kg/sq m)	45.45	7.58	45.45	7.58
Lifetime (yrs)	32.4	8.5	33	2.2

Table 2. Material property comparison between kapton and mylar.

	Kapton	Mylar
Tensile Strength	16 kpsi	14 kpsi
Tear Strength (Graves)	1.6 lb	5.3 lb
Yield Strength	8 kpsi	6.7 kpsi
Stiffness	330 kpsi	250 kpsi

Table 3. Resulting pressure of the ballute given various initial volumes for a fixed temperature ratio.

$V_1$ (cm <sup>3</sup> )	$V_2$ (cm <sup>3</sup> )	$T_1$ (K)	$T_2$ (K)	$P_1$ (kPa)	<b><math>P_2</math> (kPa)</b>
0.0048	0.096	300	323	101.325	<b>5.455</b>
0.024	0.096	300	323	101.325	<b>27.273</b>
0.048	0.096	300	323	101.325	<b>54.547</b>
0.072	0.096	300	323	101.325	<b>81.820</b>
0.0912	0.096	300	323	101.325	<b>103.639</b>

Table 4. Voltage and current produced from two solar cell configurations.

<b># of Solar Cells</b>	<b>Voltage Produced (V) / Current Produced (mA)</b>
2 (in series)	4.6 / 0.7
4 (2 series strings in parallel)	4.6 / 1.4

## Figures

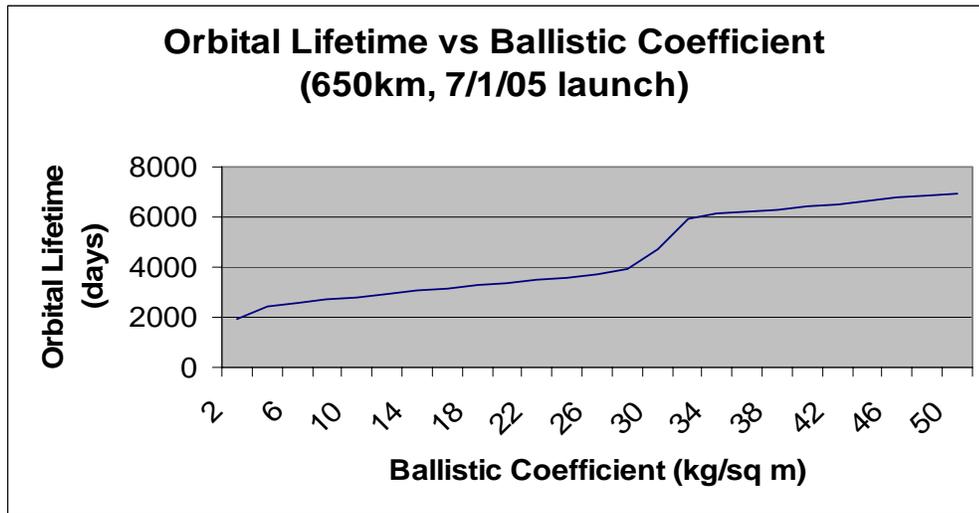


Figure 1. Effect of ballistic coefficient on orbital lifetime for a given altitude and date, as given by *SatLife*.

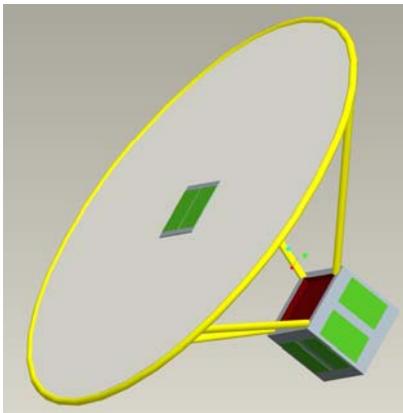


Figure 2. Conceptual drawing of fully deployed ballute attached to satellite.

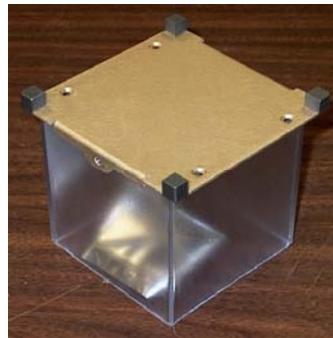


Figure 3. Mylar pouch shown attached to one face of satellite before inflation (left), and after achieving full inflation and lifting of face in vacuum chamber (right).



Figure 4. Mylar inflatables with closer resemblance to design strut size and shape; shown after fabrication (left) and after successful inflation in vacuum chamber (right).



Figure 5. Replica ballute outer torus ring: Six strut-shaped mylar pouches attached with epoxy (left); Hexagonal ballute attached with epoxy to these pouches (center); Stowed hexagonal ballute in prototype storage bin (right).

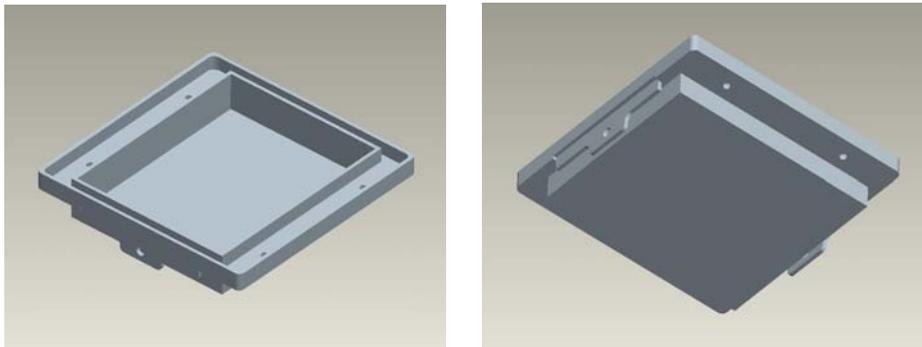


Figure 6. Inflate-A-Brake storage bin top and bottom views (shown without top or release mechanism).

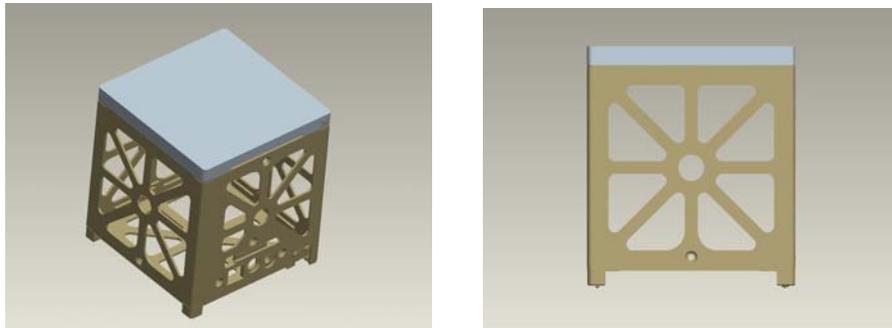


Figure 7. Inflate-A-Brake mated to Pumpkin Inc.'s CubeSatKit structure (shown closed).



Figure 8. The standard CubeSat structure offered by Pumpkin Inc.'s CubeSatKit (The Inflate-A-Brake would be attached to the bottom as it is shown here).



Figure 9. Prototype composite bin (without lid).

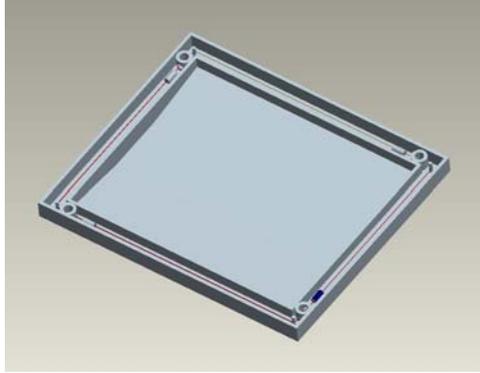


Figure 10. The plug and cable release mechanism.

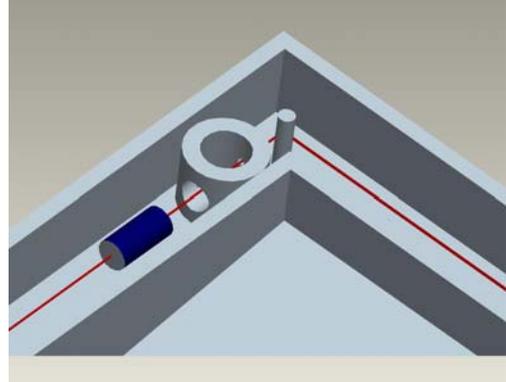


Figure 11. Close-up of the plug and pin connection point and guide rail.

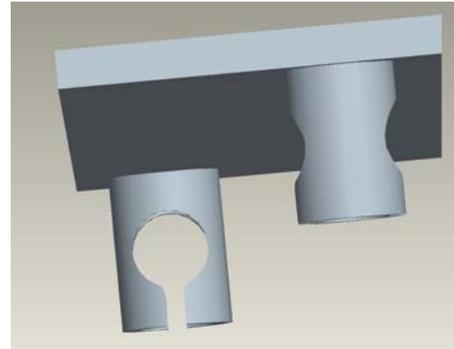


Figure 12. The lid to the storage bin (left) and a close-up of the pins attached to the lid (right). (Note: storage bin pictured is from an early design iteration, but the concept is the same)

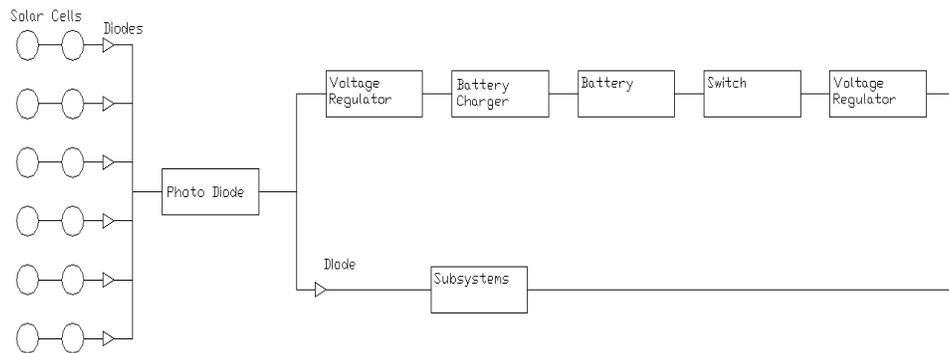


Figure 13. Schematic of the power subsystem incorporated into the other systems of the satellite.