

Rapid Build and Space Qualification of CubeSats

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ABSTRACT

CubeSats, a type of nano-satellite, have the potential to provide a relatively low cost platform to conduct on-orbit research. While CubeSat form factor and mass are well-defined, defining clear processes for designing, building, testing, and qualifying will assist in delivering satellites on schedule with a high probability of mission success. This paper describes best practices and lessons learned for a CubeSat program intended to launch a satellite every 18 months. Good systems engineering practices were followed and the described method includes recommendations for defining the mission, designing the satellite subsystems, and testing procedures and equipment.

INTRODUCTION

The Air Force Institute of Technology (AFIT) intends to design, build, qualify, and launch CubeSats in 18 months. The program goal is to use CubeSats for the dual purpose of low-cost advanced technology experiments and student hands-on space experience. Using a commercial CubeSat bus reduces the risk involved with testing new technology on-orbit because they are inherently low-cost due to their size and low complexity. The launch costs are reduced through ride sharing.

Standard commercial CubeSat kits include: structure, flight processor, battery and charging system, solar arrays, attitude determination and control system, and a 1.5U (10x10x15 cm) payload section. While newer models come with radios, antennas, and flight software, older versions do not and require these to be designed, built, tested, and integrated into the bus along with the payload.

To achieve an 18 month program timeline, it is critical to choose a technology for the payload that has been tested previously to lower the integration risk.

Several customizations were implemented to achieve the ambitious timeline and will be discussed here. These include ground testing procedures, specialized equipment, and a reliable low out-gassing deployment mechanism. Implementation of these customizations enable a rapid timeline from concept to launch as well as a program capable of sustained satellite production.

CubeSats

The CubeSat standard was started by California Polytechnic Institute and Stanford University (Cal-Poly) in 1999. CubeSats were originally 100 mm cubes that had a mass no greater than 1.33 kg. This original size of CubeSat is called a 1U CubeSat. There are now 1U, 2U, 3U, 5U and 6U CubeSats depending on the size needed to complete the mission. During launch the CubeSats are placed into a Poly Picosatellite Orbital Deployer or P-POD. The P-POD ejects the CubeSat using a spring with a targeted exit velocity of 1 m/s. The standard P-POD can hold three 1U CubeSats or one 3U CubeSat. Each 100 mm cube has 7 mm feet on each end that provide a stand-off between the CubeSats in the P-POD. Because of these feet the 2U is actually 220 mm long and the 3U is 340 mm long.

The 100 mm profile is based on the PC-104 printed circuit board (PCB) card size. The 100 mm profile will accommodate PC-104 cards to be stacked vertically in the CubeSat. Because the CubeSat was designed around the PC-104 developers have been able to use existing Commercial-Off-The-Self (COTS) PC-104 systems in their designs.

CubeSat developers must follow the CubeSat Design Specifications provided by Cal-Poly.¹ This document lists the requirements for a CubeSat to launch. The requirements cover the following areas; mechanical, electrical, operational and testing. The CubeSat must have a width of 100 ± 0.1 mm and a height for a 3U CubeSat of 340.5 ± 0.3 mm. The center of gravity (CG) of the CubeSat must be within 20 mm of the geometric center of the CubeSat in the stowed position. The CubeSat mass can be no more than 1.33 kg per U. The

structure of the CubeSat should be either; 6061 or 7075 aluminum. The CubeSat must have at least one deployment switch to turn the power off the entire satellite when in the P-POD. All deployables have to wait 30 minutes after P-POD separation to deploy. RF transmissions over 1mW must wait 30 minutes after P-POD separation to begin. The only space qualification tests required by the CubeSat Design Specifications are random vibration and thermal vacuum. The random vibration testing levels are provided by the launch integrator or use NASA GSFC-STD-7000 acceptance levels.² The thermal vacuum testing for CubeSats usually consists of five hot-cold cycles.

CUBESAT DEVELOPMENT

Methodology

The timeline of CubeSat development is important. A CubeSat can be completed in as little as 18 months using the procedure described here. The following is a recommendation of the order of the major tasks (keeping in mind that some rearrangement is possible but could cause problems or delays later). The CubeSat development timeline is based on the systems engineering Vee model shown in Fig. 1. The Vee model basically states the system requirements should drive the design decisions. Once the system is designed it should be verified and tested to insure that it achieves the original requirements.

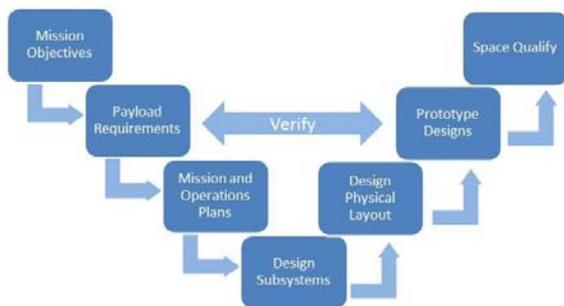


Figure 1: CubeSat Development Flow Chart

Using this Vee model based development process will help give a CubeSat program structure and will provide a developer a starting point. The development process used the requirements to drive design decisions and used testing to verify the design meet the original requirements. The process went through: defining mission objectives into threshold and goal; determining the payload requirements of the bus subsystems; designing the communications system given the payload requirements; determining mission phases and operations plans; deciding what subsystems are needed to support the payload; designing the layout of the

CubeSat to meet the mechanical requirements; discussing the prototyping of in-house designed subsystems along with the testing of all subsystems and the integrated CubeSat; and finally the space qualification of the flight CubeSat.

When starting a new CubeSat program it must first be determined if using a CubeSat is a viable option. As previously discussed, the CubeSat standard has a number of constraints associated with it.¹ A general rule of thumb is about half of the volume in any given CubeSat will be available for the payload, with the exception of the larger 5U and 6U CubeSats which will have more than half of the volume available for the payload. The CubeSat standard does allow for deployables if in the stowed configuration the deployables do not extend past six mm from the CubeSat body. Many CubeSats have deployable solar arrays to increase the power generation.

Defining Mission Objectives

If the planned payload can operate within the constraints of a CubeSat then the mission objectives must be determined. It is important to determine the mission objectives and purposes early as they will help bound the project. The mission objectives should have both CubeSat bus and payload objectives. It is useful to break the objectives up to at least two categories: threshold and goal. Thresholds are the minimum tasks that allow for a successful mission. These could be as basic as simply communicating with the satellite while the satellite is on orbit or only getting part of the payload data. Goals are the tasks that allow for a mission that achieves beyond what was expected, for example the CubeSat bus functions for the duration of the mission and all payload experiments are conducted successfully.

Determining Payload Requirements

The payload requirements will drive many design decisions of the CubeSat. The primary requirements to discuss are: power consumption, data rates, pointing requirements, volume, and mass. The power consumption of the payload will determine if deployable solar arrays are required, battery capacity, operations tempo, and heat generation. While it is unlikely that the exact power consumption is known, an estimate is sufficient. The amount of data produced by the payload experiment will determine what data rate the CubeSat radio will have to operate and at what frequencies it will transmit and receive. Most CubeSats will have five or six passes a day with eight to ten minutes of communication time with the ground station each pass, though this will vary some depending on orbit. Most CubeSats can use the UHF band for

downlink, but S band is needed for higher data rates. Most S band antennas have a narrow beam width and therefore require the ability to accurately point to communicate with the ground. Depending on the payload or antenna, the CubeSat may need to be always pointed in a direction (sun, nadir, etc.). A passive or active attitude control system can be used. The payload will have to fit into the given volume of one of the standard CubeSat sizes. The payload will also have to adhere to the mass and center of mass requirements stated in the CubeSat standards.¹ If the payload has a high density it is advised to place it as close as possible to the geometric center of the CubeSat.

Designing Communication Subsystem

The communication subsystem of a CubeSat and its corresponding ground station require the coordination of the either the installation communications office or the FCC. The ground station will fall under the amateur radio operators (Ham Radio) rules. If the ground station will be located on federal government property then the local communications office will coordinate. The recommended time frame to complete the process is 12 to 18 months. Data rate and frequency selection is driven by the payload requirements previously discussed.

Defining Mission and Operation Plans

Mission and operations planning need to be discussed at this point to help determine what subsystems will be required on the CubeSat. The Mission should be broken up into at least three phases: checkout, normal ops, and safety. The checkout phase is used to verify functionality of the CubeSat. This phase should also be used to verify any analysis that was conducted. Normal operations phase is the phase used to execute the main mission of the CubeSat. The CubeSat is placed into the safety phase whenever anomalies occur. Operations plans are detailed scripts of what happens during each phase and each orbit. At the beginning of the project these might not be very detailed and may only be a list of tasks to be conducted. Both the mission and operations plans will increase in detail during the program to better reflect the actual hardware and software designs. The final operations plans should include the actual commands the operator sends to fly the CubeSat.

Determine Subsystems

With the preliminary mission and operations plans and the payload requirements decided, the specific subsystems can now be determined. The CubeSat must have a few basic systems to function as a satellite but some subsystems are optional. Each CubeSat requires: chassis, flight computer or flight processor, solar arrays,

charging system, batteries, and radio. An optional subsystem is the ADACS. While designing each subsystem the pseudo code for its software needs to be developed. Pseudo code will help with the coding process when the hardware is built.

Chassis

The chassis type should be decided first as this will impact the integration of the subsystems. Two main types are available: folded aluminum sheet metal and a rail system. CubeSats were originally designed to use PC 104 PCB's for all the electrical hardware which allows for easy integration with each other because of the capability to stack the cards. A spacer is placed at each corner of the PC-104 card to provide support. The folded aluminum chassis is easy to manufacture and allows the PC-104 stack to be attached to a base plate and then the rest of the chassis can slide on afterwards for easy integration. The folded chassis also allows the developer to easily attach additional hardware to the sides of the CubeSat. While the fold chassis is the most common chassis design, some have started using four aluminum rails with cross members. The rail design uses the PC 104 stack as additional structural support. The rail design weighs less than the folded chassis but is harder to integrate. Figure 2 shows examples of the different types of CubeSat chassis. If weight is a major concern use the rail system, if a subsystem needs to be attached to the chassis or ease of assembly is needed then use the folded configuration.



Figure 2: Folded (Left) and Rail (Right) Chassis Examples

Flight Computer

The decision between a flight computer or a flight processor depends on how much computing power is required. A flight processor is a microprocessor that has limited computing power with no operating system and needs to be programmed directly, similar to firmware. A flight computer is similar to a standard desktop

computer in functionality but smaller and slower. If some computing tasks are delegated out to subsystem processors, a flight processor can be used to control the CubeSat. If an operating system is needed then a flight computer will be required. A flight computer will handle most if not all of the computing tasks.

There are advantages and disadvantages to both configurations. The flight processor uses substantially less power than a flight computer, but microprocessors are more difficult to program and often use a machine language. Flight computers often use a stripped down version of Linux or Unix, which allows for easier programming but requires more power, which increases the load on the power system and produces more heat that must be dissipated.

Solar Arrays

Solar arrays can be body mounted, deployed or both depending on the estimated power requirements. It is good practice to add an additional 20% to the estimated satellite power requirement, and then size the solar arrays. If the required area is greater than what body mounted solar arrays can provide, either the operations tempo of the CubeSat can be reduced or deployable solar arrays can be used. Deployable solar arrays can be designed such that the CubeSat will generate the same amount of power no matter which side is sun facing (basically doubling the power produce vs. body mounted solar arrays) and allow for a less complicated ADACS. Or the deployable solar arrays can be designed to have all the solar arrays face one direction and always keep that side sun facing (basically quadrupling power production vs. body mounted solar arrays). This configuration requires a more complicated ADACS system that will have to run all the time.

Batteries

The charging system and batteries need to be designed together. Often these systems can be purchased together if COTS equipment is used. For most CubeSats lithium ion or lithium polymer batteries are the best option. Nickel metal hydride batteries are also an option but have a much lower power density than the lithium based batteries. The only reason to consider NMH is if the mission duration is longer than a year and a half because lithium based batteries are only rated for 10,000 charge-discharge cycles.

Communication System

Multiple CubeSat COTS radios can be found with a range of functionality, prices and size. Often integrating the antenna can be more challenging than the radio. The antenna can range from a simple mono-pole whip antenna for UHF to a patch antenna for S-band. A UHF

mono-pole or di-pole can be designed to effectively be omni-directional. An S-band typically has a narrow beam width and requires a high pointing accuracy. Any deployable antenna must be constrained during launch and ejection from the P-Pod, so a deployment mechanism must be used. If the CubeSat will have low pointing accuracy use an omni-directional antenna design, if high data rates are required use a S-band system with a patch antenna.

ADACS

The only truly optional subsystem is the ADACS. The control of the CubeSat can be from an active or passive system. Examples of passive systems are: gravity gradient systems (uses a deployable boom to obtain the required torque), aero-stable systems (space dart), magnetically aligned systems (passive magnet aligns itself with earth's magnetic field), and passive momentum biased wheels do not require any control system (wheels spinning at a constant speed to prevent movement about the spinning axis). Examples of active systems are: reaction wheels (often 3 wheels aligned with the body axes of the CubeSat to provide 3 axis control and movement), control moment gyros, magnetic torque rods (electro-magnets that push against earth's magnetic field to provide torque) and thrusters (mostly compressed cold gas thrusters). CubeSats primarily use a combination of a magnetometer and some form of sun sensing for attitude control. The CubeSat can have a dedicated sun sensor system for more accurate attitude determination (5^0 accuracy or less) or it can use the charging data from the solar arrays (10^0 - 15^0 accuracy). The complexity of the ADACS will depend on the pointing accuracy requirements of the other subsystems. A high pointing accuracy system (5^0) will require at least 3-axis control authority and a sun sensor system. A medium pointing accuracy system (10^0 - 15^0) will require at least 3-axis control authority and can use the solar array data to determine its orientation. If the CubeSat needs minimal pointing then a magnetically aligned system will prevent the CubeSat from tumbling.

Designing Physical Layout and Structure

Once all the subsystems are determined and preliminary designs complete, the layout of the CubeSat subsystems can begin. Some subsystems work better in specific locations. For example, the attitude control system works best at the geometric center of the satellite for ease of control laws and helps keep the CubeSat near the center of gravity requirements. The attitude determination system may require special placement depending on which method is used. The payload should be placed in an easily integrated area if possible since the payload is often the last piece of hardware

manufactured. The batteries and charging system should be co-located for ease of operation. The rest of the hardware can be placed where needed to meet the center of gravity CubeSat requirements.

Prototyping Designs

With the preliminary design of the hardware and layout complete, prototypes need to be completed, integrated and tested. Each subsystem that was designed in-house should be prototyped. The CubeSat software should be transitioning from pseudo code to actual code and tested on the prototypes. All subsystems will need to be tested by themselves and integrated into the CubeSat. By testing the subsystems in this manner, design or manufacturing errors can be found early. The prototyped CubeSat should go through complete functionality testing. The prototype should also be tested using the mission and operations plans to verify the design meet the original requirements. After the prototype is fully functional it is subjected to the space qualification process detailed in the next section. Once the prototype completes all the testing and any design changes are documented, the space hardware can be manufactured

Space Qualification Testing

The space qualification process is the final phase of the CubeSat development. The flight hardware should be manufactured and assembled. The flight hardware should be checked for full functionality before integration and space qualification. The space qualification is detailed in the next section. After the CubeSat passes space qualification it cannot be modified. If a modification is required the CubeSat will have to complete the space qualification again.

This section assumes each subsystem is functional and is going to discuss the suggested tests of the integrated CubeSat. NASA GSFC-STD-7000 standards² go in detail the tests required for large satellite systems, but for CubeSats the launch provider only wants to know if the CubeSat will survive launch and P-Pod ejection, therefore only random vibration testing is required. The functionality after ejection is not their concern. Thermal vacuum testing is suggested to give the CubeSat the best chance of success. Additional tests, that will not be discussed but may need to be conducted are EMI, acoustic, and shock.

Random vibe testing is conducted before thermal vacuum to allow the thermal cycling to stress any failures or cracks created by the random vibe tests. The CubeSat is placed in a P-Pod or Test-Pod for all random vibe tests. It then undergoes random vibe testing in all three axes. Before and after each random vibe test a sine sweep is performed to determine the modal

response profile and a functional verification test is run to test all systems on the CubeSat. The results of the sine sweep will be compared to a base profile to determine if the natural frequencies are different indicating something broke loose. The random vibe profile should be provided by the launch provider if it is not, use the NASA GSFC-STD-7000 standard for acceptance testing.²

By conducting thermal vacuum testing it will be verified that the CubeSat can function in a vacuum, will not overheat, and can survive launch. Thermal vacuum testing starts by taking the vacuum chamber down to a pressure of at least 10^{-4} torr and then conducting a functional verification test. The thermal cycling is then started. It is suggested to conduct five temperature cycles with at least an hour hold at each extreme to soak the CubeSat at that temperature. After the satellite reaches equilibrium at each temperature, a functional verification test is conducted. Temperature cycles should be selected to simulate the conditions on orbit. If the exact temperatures are not known, a range of -10^0 C to 40^0 C is recommended for the flight hardware. After the CubeSat has successfully completed both random vibe and thermal vacuum testing it will be ready to deliver to the launch provider for integration. Typically the launch provider will require a Missile System Prelaunch Safety Package (MSPSP). The process of delivering and integrating the CubeSat onto the launch vehicle is not discussed because the process varies widely depending on the launch provider.

Summary

This section covered: the Vee model based development method that flows the mission objectives and requirements to the subsystem designs and then are verified through prototyping and testing; it covered all the major design during a CubeSat development; and the space qualification process was discussed with emphasis on random vibration and thermal vacuum testing. The discussed development method will provide a developer the best opportunity to keep to an 18 to 24 month schedule.

TEST FIXTURES

To complete the space qualification and prototyping processes three test fixtures were designed: a test pod, a PC-104 vibe block, and a Mechanical Aerospace Ground Equipment (MAGE). All test fixtures were machined by the AFIT Machine Shop.

Test Pod

The test pod is based on the standard P-POD dimension to make any vibration tests as realistic as possible. The

test pod can hold one 3U CubeSat or multiple smaller CubeSats. All interior dimensions are the same as the P-POD, but the walls of the test pod are thicker than the P-POD so it can be used for more than one test series. The thicker walls do not affect the test results, but do increase the mass over the P-POD. The test pod is mounted to an adapter plate which mates to AFIT's vibration testing equipment. The test pod is made from 6061 aluminum. Each side has alignment pins to ensure that tolerances are met. The sides are then screwed in place. The front face is designed to be removed allowing the CubeSat slide in and has an adjustable plate with four adjustment screws that holds the CubeSat in place. Figure 3 shows the test pod, each side has access ports to allow easy access to during testing.

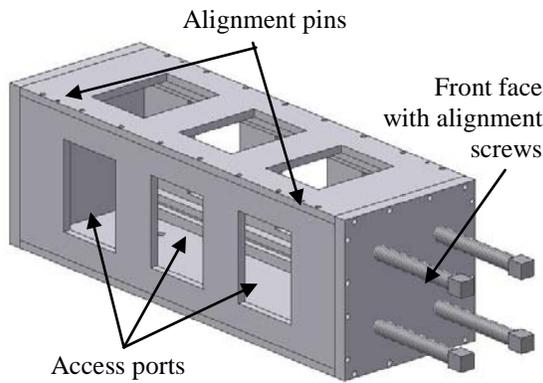


Figure 3: Test Pod

After the test pod was built, sine sweep and random vibrate tests were performed to baseline the test pod without a CubeSat. It was discovered when the tests were performed on the slip table exiting the x - and y -axes the motion of the table amplified the natural modes of the test pod and caused the test to shut down. A finite element analysis was conducted and confirmed the rocking mode shown in Fig. 4. To dampen this response, a stiffener was added. The stiffener was successfully decreased the response of the rocking mode. Figure 5 shows the final test pod configuration.

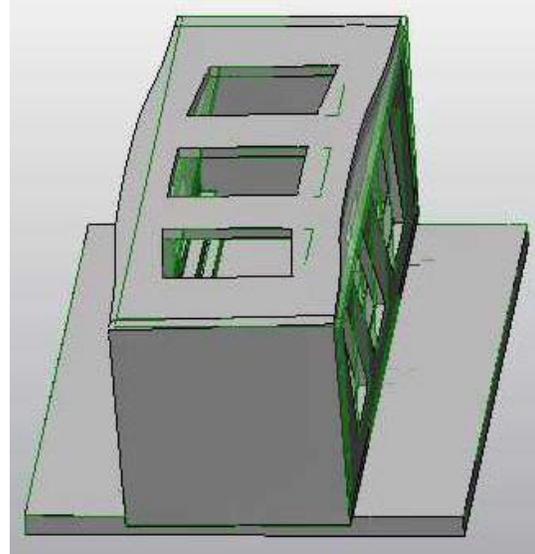


Figure 4: FEA Illustrating the Rocking Mode

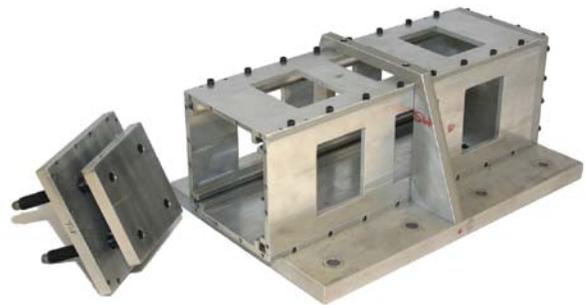


Figure 5: Final Test Pod Configuration

Vibe Block

The PC-104 vibe block was designed to vibration test individual PC-104 cards to verify their ability to survive launch loads. The vibe block has threaded holes with the same pattern as a PC-104 card so they can be structurally tested in all three axes. The vibe block is attached to an adapter plate which mates to AFIT's vibration testing equipment. Figure 6 shows the as built PC-104 vibe block with a custom payload interface board attached, ready for testing.

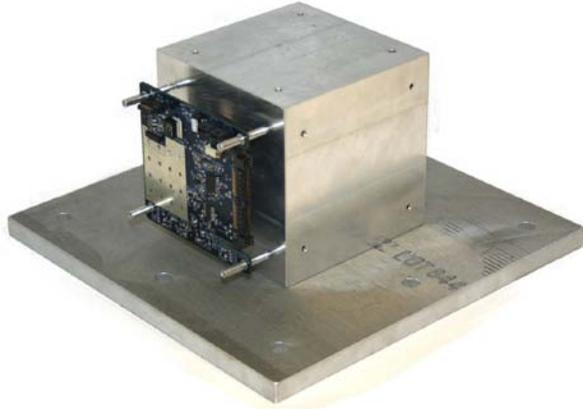


Figure 6: Vibe Block

MAGE

The MAGE was designed to accommodate the CubeSat during full system testing. The MAGE holds the CubeSat on the four corners of the rails, allowing for deployment testing of the solar arrays and antennas; it is also used for all thermal vacuum testing. The MAGE rails are made from 6061 aluminum and the stand is made from 80/20 pieces. The MAGE rotates about the center axis to allow for ease of access to all sides of ALICE. Figure 7 shows the deployed CubeSat in the MAGE.



Figure 7: Deployed ALICE in MAGE

DEPLOYMENT MECHANISM

The CubeSat standard requires that all deployables be restrained for 30 minutes after P-POD ejection.¹ Most CubeSats use fishing line to secure the deployables and a nichrome hot-wire cutter to release them – a very simple low power and low volume method. The drawback is that when the fishing line is melted it

outgasses. The CubeSat mission here was sensitive to outgassing, so a different method was required.

A guillotine-type cutter was determined to be the best solution to deploy the restrained solar arrays. With this design, fishing line is still used to secure the arrays but the line is cut instead of melted and therefore no outgassing occurs. The cutter uses a shaped memory alloy based pin-puller that is space-rated and has two redundant triggering mechanisms. The only negative to this design is that the pin-puller is large by CubeSat standards, taking up about 20 cm³. The deployment mechanism was tested under vacuum at both temperature extremes and functioned perfectly. Figure 8 shows the assembled deployment mechanism. The fishing line is thread through the hole on the extended post; when the pin-puller is actuated it retracts, cutting the fishing line against the cutting surface.

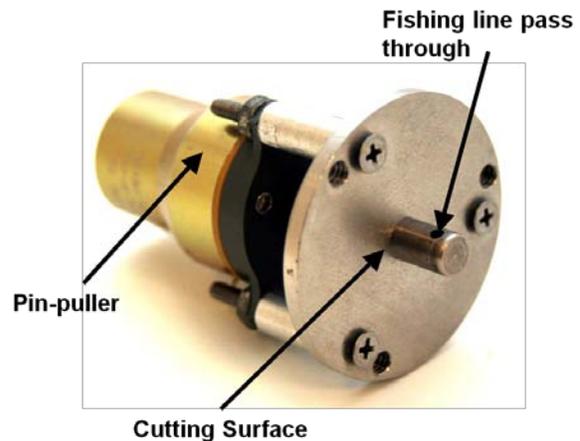


Figure 8: Assembled Deployment Mechanism

The routing of the fishing line was chosen to eliminate the possibility of any knots passing through the guillotine cutter. To secure the arrays the fishing line was tied to one of the outside holes on the -Y deployable array. The thread was then passed through the hole on the guillotine cutter. Then the fishing line was loop around the +Y array and tied to the -Y array. Another piece of fishing line was tied to the outside hole of the +X array and loop it around the string attaching the Y panels before tying the fishing line to the opposite hole on +X array. The same was done for the -X array. Figure 9 shows the routing of the fishing line so no knots are passed through the cutter.

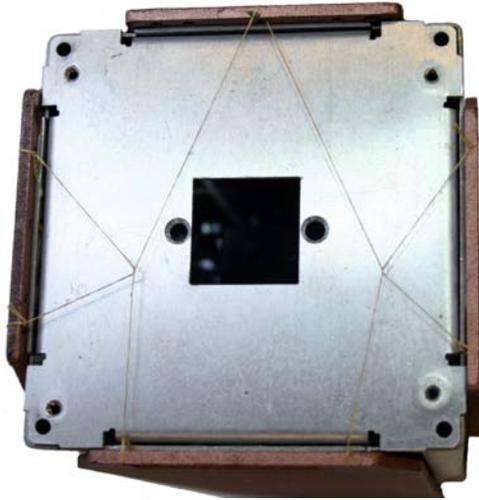


Figure 9: Routing of Retention Fishing Line

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CONCLUSIONS

CubeSats promise to be low-cost test-beds for new and emerging space technologies as long as they can operate within the imposed constraints. With testing and qualification standardization, the custom equipment described here, and sufficient workforce it is possible to design, build, qualify, and deliver a CubeSat for launch in 18 months with high mission assurance.

Many capabilities were added to AFIT's infrastructure to yield a successful program. These include CubeSat manufacture at the machine shop, ground station, and custom testing equipment. AFIT will be able to leverage the experiences gained by the technicians, professors, and students to design and integrate more complicated technologies into CubeSats for future cutting-edge science and technology missions.

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