### CubeSat Components: A Collection of Ideas from AFRL Space & Phillips Scholars

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#### ABSTRACT

CubeSats are fast becoming recognized as key elements of a satellite portfolio. Industry, academia, and government agencies are all participating in the development of these micro-satellite platforms for use as operational systems, testbeds, or as learning tools for young engineers.

The Air Force Research Laboratory (AFRL) Space Electronics Branch (RVSE) participates in the AFRL Space Scholar and Phillips Scholar programs which promotes mentoring young engineering students by AFRL/RVSE staff. As part of this program RVSE provides ideas for projects that the students will work on during their summer at the laboratory. This idea list includes the development of components that could be used for CubeSats and can range from the structure itself to individual modules that can be used across multiple missions. The primary goal was to provide solid engineering experience using real-world examples with useable hardware or designs as the output. This would give the students a quick emersion into the engineering process complete with reviews and documentation. A group of eighteen students ranging from juniors in high school to graduate students in engineering were assembled. The group developed several ideas that can be used for future CubeSat missions. In this paper we will describe a subset of the overall group of ideas.

#### **INTRODUCTION**

CubeSats are becoming increasingly popular to use as experimental devices and as training tools for young engineering students. In this vein the Air Force Research Laboratory (AFRL) regularly hosts students under two programs, the Space Scholars and Phillips These two programs team high school, Scholars. undergraduate, and post graduate students with AFRL scientists and engineers to provide the opportunity to develop their skills and learn the engineering process. Using the CubeSat model as a training tool the students were provided the opportunity to develop CubeSat items which we referred to as 'widgets'. These simple items would be used to teach the engineering process and help the students gain experience in creating and implementing ideas. The hope was that it would also spawn a collection of widgets that could be used in future CubeSat missions.

Students were given the opportunity to choose different items that might be used for a CubeSat. These included items such as a modular structure, novel propulsion, power modules and regulators, sensors, de-orbit modules, and the communications backbone based on the Space Plug-and-Play Architecture. In all there were 18 students working either individually or in teams based on experience and the project selected. Each project would go through the design process with presentations to the group and the mentors at key points along the way much like that done in a true engineering environment. The first review looked at the project idea. Could the student 'sell' the mentor on their idea and get it approved to proceed? This equated to a preliminary design review. This was followed by some design work and another review, or something similar to a critical design review. The final output for the summer was a presentation to the Space and Phillips Scholar programs and all the mentors as well as some of the AFRL Space Vehicles and Directed Energy leadership. We would also collect whatever hardware they fabricated over the course of the summer. In most cases these were engineering prototypes that proved the efficacy of the design.

This paper highlights four of the efforts that came out of the summer program. These four represent the most difficult endeavors from the students and ones that could have long term impact on small satellite designs. The following sections will describe the efforts, the end of summer status, and any follow on efforts expected.

#### **3-AXIS REACTION WHEELS**

The first effort to be highlighted started with the idea that if we were going to use CubeSats for taking serious missions we would need some sort of stabilization and pointing of the satellite. At the time there weren't many quality options for small spacecraft and especially CubeSats. After some discussion Sylvia Reiser, a student at Michigan State University, proposed the idea of a three-axis set of reaction wheels that would use a maximum of a single CubeSat unit. The concept may be scaleable based on the size of the satellite.

The system is a set of three rings, one spinning about each of the main axes of the satellite. The spinning motion of the ring creates a gyroscopic effect, preventing the axis about which it spins from tilting. The combination of all three rings rotating and producing counterbalancing torques will keep the satellite stable, or differences in torques can produce a net torque for the purpose of reorienting the satellite.

The three rings nest inside each other to reduce the amount of space taken up by the system, seen in Figure 1. The nesting also keeps the center of mass and the geometric center of the system coincident. This coincidence has two benefits. First, the CubeSat standards [1] put forward by California Polytechnic State University mandate that the center of mass of the satellite must be within two centimeters of the geometric center. Second, the coincidence of the system of reaction wheels simplifies the controls algorithms necessary to point the satellite, as no ring has to overcome a torque caused by the off-center placement of another ring.



Figure 1: Nested rings

To allow for the nesting, the rings have different radii. Changing the radius of the ring has a great effect on its moment of inertia, as seen in the following formula

$$I_{ring} = \frac{1}{2}m_{ring}(r_{outer}^2 + r_{inner}^2)$$

The difference in moments caused by varying radii is offset by changing the densities of the materials for each ring. The outer ring, since it is the largest, is made out of lightweight 6061 space-grade aluminum. The middle ring is made of stainless steel, and the inner ring is made of tungsten carbide.

The difference in torque stemming from the difference in moments of inertia can be compensated for with the rotational speed of the rings. The moment of inertia of a satellite with height h, width w, and depth d, is calculated about a given axis with the equation

$$I_h = \frac{1}{12}mass \times (w^2 + d^2)$$

and the variables can be switched to obtain the other values.

The mechanism for propelling the rings is based on the same principal that runs an electric motor. Each ring has four magnets embedded in it at evenly spaced intervals. Placed about each of the casings are four coils of wire. The current flowing through the coils interacts with the permanent magnetic field of each magnet, generating the force necessary to spin the rings. This force is governed by the equation [2]

$$\vec{F} = I \times B$$
 (3)

The magnets maintain a steady level of magnetic flux (B) since the distance between the coils and the magnets does not change. The rings then accelerate or decelerate based on the amount of current (I) flowing through the coils. These accelerations provide the means by which torque is generated for pointing the satellite or resisting external torques. Each ring will be limited to using no more than one watt of power at maximum. There is also a possibility of reclaiming some of the power when the rings are slowed down with the process known as regenerative braking [3], by using the motor as a generator. By stopping the current flow, the magnetic field from the magnets embedded in the rings will induce a collectable current in the coils and slow the rings down. This also removes the need for magnetic torquers for momentum dumping.

This effort has resulted in an application for a patent through AFRL. A 3D model was fabricated using an AFRL 3D printer and prominently displayed within the operations office. Ms Reiser will return for another summer through the Phillips Scholars program and will continue to refine the design and perform more simulations and begin to manufacture the components of the design to determine if it is truly manufactureable. She will also begin formal documentation of the assembly methods so that the item can be reproduced and used in future efforts. We will also begin to work with our controls experts to create a complete design.

#### SOLAR ENERGY CONCENTRATOR

As expected, the small volume of a CubeSat limits the energy available using conventional methods. Some newer designs use large deployable solar arrays to increase total power. Solar energy in space is almost exclusively harnessed for spacecraft power using photovoltaics. There is a significant untapped potential in also harnessing and utilizing heat from both solar radiation and spacecraft waste energy to produce electrical power.

One of the ideas was to look at innovative methods for generating power on a CubeSat that was fundamentally different. To that end this next highlighted effort from Matt Robertson of the University of Michigan looked at using a solar concentrator focused on the end of a Stirling engine to produce a temperature differential large enough to drive the Stirling engine and create power for the satellite.

Heat engines are driven by a thermal gradient to produce mechanical and in turn electrical power. Satellites often see large thermal gradients when exposed to the sun between their light- and dark-sides. Solar radiation thus seems an appropriate mechanism for driving a heat engine in space.

Unfortunately on its own there isn't enough of a thermal gradient to efficiently run one of these heart engines. A solar concentrator is necessary to collect and focus solar radiation onto the engine. The input power available from the sun is proportional to the incident area of the solar collector. The power available to the spacecraft is a function of engine efficiency.

If we make the assumption that the heat engine efficiency at most 32% [4], this means that we must collect solar power at least 3 times the desired engine output power. So to generate 35W of output power from a 32% efficient heat engine requires about 100W of collected solar power. This translates into the need, ideally, for a collection area of about 0.1 m<sup>2</sup>.

The requirement to collect 100W of solar power which is available in LEO at 1366 Wm<sub>2</sub> yields an area requirement for the solar concentrator of A =0:0732m<sub>2</sub>. For a simple parabolic trough reflector design with a width of about 1.5in to exclusively over the hot end of the Stirling engine, this area requirement yields a reflector length of roughly 75in. For parabolic reflector designs, the maximum diameter of the projection of the parabolic dish (the incident area, facing the sun) was found to be optimally about 14.75in, with an 8.5in hole in the center. The result of this design gives a parabolic ring rather than a full dish. This was chosen so that the "cold" segment of the Stirling engine could be isolated entirely from sunlight, while still placing the focal point of the paraboloid on the hot end of the engine.

The consideration of the STG stowed configuration requirement leads to an approximated volumetric limit of 2in x 2in x 2U1 as a target for the stowed FPSE and concentrator combination. As the Stirling Engine itself is nearly 1.88in on one end, this initially implores a lightweight and minimalist design, which coincides with the target of simplicity for the sake of dependable deployment. More specifically, the odd shape of the engine leaves little more than roughly 3in of length along the 1in diameter small section of its body around which to retract or fold in the deployable concentrator hardware.

A parabolic reflector ring of roughly 14" outer diameter and 7" inner diameter made from mylar would provide a suitable first attempt at creating the structure. Several versions were created with the final version created based on the shape in Figure 2.



Figure 2: Solar collector with stirling engine

For the given realistic conditions and design limitations set forth, the Torus concept solar concentrator holds the strongest appeal as a design choice for a CubeSat solar thermal generator system. This design features no moving parts, minimal material, and a high degree of stowability within a CubeSat, which also lends to a large degree of scalability as the compact nature allows for larger systems. Given the apparent feasibility of building a deployable solar radiation concentrator, and the parallel development by Sunpower, Inc. [5] of a small-scale Stirling Engine for space applications, utilizing the power of the sun to run a heat engine in space may prove to be a viable power supply option for CubeSat satellites, as well as for any small-scale vehicle situated in low earth orbit.

Unfortunately Matt wasn't able to return. The work has been preserved and will be transferred to the power and structures groups within AFRL so that they can evaluate the efficacy of the design.

#### INEXPENSIVE COLD GAS PROPULSION

Recent directives state that all vehicles must have a 25 year de-orbit life. There are many ways to do this but to combine that feature with a reliable and accurate ADAC module would be quite unique. Eric Murray from Missouri S&T came up with the idea of a cheap and compact Cold Gas Propulsions System. Keeping the ideas of a cheap and compact system in mind the search began for components and propellants that could be easily purchased in any city, and though this hope was optimistic it generated a good starting point for development. The system would have to be very small and for that reason redundancies were not possible, so the system would need to consist of the propulsion tank, a pressure regulator, a series of isolation valves and their associated nozzles- all of which would have to be sub-miniature components. With the proper nozzle configuration the system could provide the desired six degrees of freedom giving the satellite the ability to maintain orbit and/or orient itself to the specific needs of the payload. With these decisions made, the next step was to choose a propellant that was not only cheap but easily accessible and the resulting choice was CO<sub>2</sub> since it can be found in canisters at most any superstore, and when compared to custom tanks, is magnitudes cheaper.

The design matured over the course of the summer and included versions that ranged from a single canister to two sets of four canisters. Calculations were performed to determine the level of propulsion necessary to perform a nominal mission. There are concerns over the stability of the gas over temperature and if the overall design would be stable for longer duration missions.

CAD models were developed and a 3D printed version of the design was generated. The basic components were identified and a bill of materials created. Actual methods for puncturing the canisters were still be worked out by the end of the summer and there is still some work to be done with the implementation. Figure 3 shows the final version currently under investigation.



Figure 3: A four canister propulsion system

As mentioned, this effort still needs some refinement. Unfortunately Eric won't be returning but has used this propulsion experience for their University NanoSat program. However, an in-house effort has developed through one of the Lieutenants to take this idea forward. His area of work at the Air Force Academy focused on propulsion and he has become enamored with this concept.

### CUBESAT STRUCTURE

The AFRL CubeSat program is currently in the process of developing application boards for deployment on future CubeSat missions. With the advances being made in the internal electronics, a need arises for a standardized external structure for the CubeSat, one that will safely house the sensitive electronics and fit all of the specifications of commercial launch providers. Another internally imposed condition is that the CubeSat should be hinged and modular.

Currently, the AFRL CubeSat structure is bulky, and wastes both space and mass, which can be costly to the mission, and may not be suitable for launch in the P-Pod. Also, current structures available in the market do not provide the modularity sought by AFRL missions. This effort will redesign the CubeSat structure to be as efficient as possible while staying inside the launch parameters and keeping the structure hinged and modular. Using three-dimensional modeling software, a new structure; it is ready to be manufactured should my design be accepted.

California Polytechnic University is currently the leader in the CubeSat industry. The P-POD is their design and the current standard for CubeSat deployment. Because the AFRL has not developed their own CubeSat deployment method, any CubeSat they design must meet the standards that Cal-Poly sets out. The mechanical standards that the CubeSat must meet are:

- Material- 6061 or 7075 Aluminum
- Size- 10cm x 10cm x 11.35cm, 22.7cm, 34.05cm
- Rails- Must be a minimum of 6.5mm x 6.5mm
- Cover at least 75% of the overall structure length

The AFRL's current design only meets some of the requirements for launch in the P-POD. It is made of the correct material; however, it is not the correct height and it does not have rails, and has not left room for rails of the correct size to be added. Other than the elements of the CubeSat that don't meet the P-POD standards the design is too bulky and the hinges simply waste too much space for the design to be as efficient as possible.



Figure 4: Proposed CubeSat modular structure

The proposed design from Deryk Harder, a student at New Mexico State University, not only meets all of the mechanical requirements for the P-POD but it is also more efficient in its use of both volume and mass. Designers of widgets and the planners of missions need to know the structure on which their parts will be launched. This will allow them to make their products specifically for use on the CubeSat they will be launched on.

There is currently a prototype of the new design, which was machined at a shop on the University of New Mexico campus. The planned work for this design is to create a full set of technical drawings that can be used at any machine shop to begin final manufacturing of this design should it be accepted for use by the AFRL.

Deryk will return for another summer and will continue to refine the drawing set and AFRL will continue to vet this new structure. Hopefully it will become the new default structure for future AFRL CubeSat designs.

## SUMMARY

AFRL is involved with teaching young engineers the methods and processes involve in engineering. Through two programs, the Space Scholars program and the Phillips Scholars program, AFRL hosts high school, undergraduate, and graduate engineering students and provides them with ideas and mentors to work on problems of interest to AFRL. During one such summer session a collection of students provided an exceptional set of concepts and designs relating to CubeSats. We have shown that implementing good engineering practices and providing young engineering students with quality mentors and guidance, these next generation engineers can create some superb concepts and implement them over the course of a summer. The four highlighted developments shown in this paper are representative of the high quality of work we can expect from the next breed of engineers. This goes to show that we should energetically foster these relationships and develop these students so that they can take the reins as the current engineering workforce begins to retire.

If these students are representative of the future of engineering, we are in good hands.

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# REFERENCES

- The CubeSat Program, *CubeSat Design Specification*, Cal Poly San Luis Obispo, 2009. [Online]. Available: http://cubesat.org/images/developers/cds\_rev12.pdf [Accessed: Jun. 2, 2010].
- [2] W. Bauer and G.D. Westfall, *University Physics*, Dubuque, Iowa: McGraw-Hill, 2010.
- [3] J. Gordon, "Regenerative Braking Charges Ahead," *Motor Age*, Sep. 1, 2003. [Online]. Available: http://www.searchautoparts.com/searchautoparts/article/articleDetail.jsp?id=68244 [Accessed Aug. 10, 2010].
- [4] <u>https://share.sandia.gov/news/resources/releases/2008/solargrid.</u> <u>html</u>
- [5] http://www.sunpower.com/lib/sitefiles/pdf/publications/Doc008 3.pdf