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A Passively Stable Pyramid Sail for the Deorbit of Small Satellite Constellations

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Abstract

Several commercial organizations are developing plans to launch thousands of small satellites into Low Earth Orbit at altitudes ranging from 1,000-1,350 km, with the goal of providing global internet service. There is a clear need to deorbit these satellites at the end of their operational lifetime, in order to preserve the utility of high-value orbit regimes. Without a system to accelerate deorbit, the 150 kg-class satellites would take over 100 years to reenter the atmosphere. A standardized, bolt-on system is being developed to address the deorbit problem for microsatellites. The Passively Stable Pyramid Sail ([PS]^2) is a thin-membrane drag sail with the geometry selected to establish aerodynamic stability. The system is capable of deorbiting small satellites from the planned constellation orbit altitudes within 25 years regardless of the operability of the host satellite. A design requirement of the drag device is that it will aerodynamically trim to a maximum drag attitude in the upper atmosphere, in order to accelerate the deorbit timeline. A stability analysis was conducted to evaluate possible geometries, and it was determined that the drag sail should have a square pyramid shape with an apex half-angle of 75°. For a 150 kg satellite at an altitude of 1,100 km, the system is designed to have a base area of 125 m^2, which requires 8 meter long booms. The mass and stowed volume of the device are designed to be consistent with the 6U CubeSat standard. A 1/10 scale prototype of the [PS]^2 system was selected for launch through the United Launch Alliance STEM CubeSat program. The mission, called the Aerodynamic Deorbit Experiment, will demonstrate the [PS]^2 design from a 1U CubeSat platform. The system will have four 0.8 m long composite booms, and four triangular sail quadrants made of transparent CP1 material. This paper will provide an overview of the [PS]^2 system, describe the design of the deployment system, and discuss the results of prototype testing.
Keywords: Orbital debris, deorbit system, drag sail, prototype

Nomenclature

φ – Apex half-angle
L – Boom Length

Acronyms/Abbreviations

Aerodynamics Deorbit Experiment, ADE
Passively Stable Pyramid Sail, [PS]^2
SHEAth-based Rollable Lenticular-Shaped and low-Stiction, SHEARLESS
Polylactide, PLA
Acrylonitrile butadiene styrene, ABS

1. Introduction

Orbital debris is a growing problem in low-Earth orbit; it has crossed a threshold of critical density where the number of debris objects will grow exponentially due to collisions unless actively mitigated [1]. Recent announcements of plans for commercial small satellite constellations indicate interest in deploying hundreds to thousands of micro-satellites into Low-Earth Orbit (LEO) at altitudes ranging from 1,000-1,200 km to provide global internet service[2-4]. The need to deorbit these microsatellites at the end of their operational lifetime is apparent since a 100 kg satellite with a 0.25 m^2 frontal area would take more than 100 years to deorbit naturally from a 1,100 km circular equatorial orbit. These constellations create a need for a standard system for deorbit to help mitigate the orbital debris problem. This research is focused on accelerating the orbit degradation of small satellites by using a deployable drag sail that is attached to the satellite before launch. Following the operation of the satellite, the drag sail will be deployed to passively decrease the orbit lifetime of the system. It will be stowed using a small footprint and a simple interface with the spacecraft. This research describes an aerodynamically stable drag sail comprised of four thin membranes that are supported with deployable booms in the shape of a square pyramid. Therefore, the sail is called the Passively Stable Pyramid Sail or [PS]^2.

2. [PS]^2 System Design Overview

One of the benefits of using a drag sail to deorbit is that it is capable of being deployed regardless of the operability of the host satellite. There are three possible procedures to initiate the deployment, and only one requires an active satellite. The first procedure is to deploy the sail via ground command from operators. This would be the nominal deployment method because it allows the operators to adjust the lifetime of the mission, based upon satellite functionality and propellant availability. The second option is to initiate the deployment via backup timer that will deploy the sail at a predefined time following completion of the mission. Ideally, this timer could be updated by the ground operator. The final procedure is a watchdog signal from the spacecraft, if it is interrupted, the sail is deployed autonomously. All three options may be incorporated in the design.

The square pyramid shape ensures that the sail will trim to close to a maximum drag attitude by creating torques when perturbed that restore it to the nominal attitude. The key components of the sail are shown in Fig. 1. The two variables that define the size and shape are the boom length, L, and the apex half-angle, φ. The apex half-angle is defined as the angle between one boom and the center axis, so the larger the value of φ, the flatter the sail. The nominal values of these variables were determined by Long and Spencer through a deorbit analysis and a stability analysis [5].

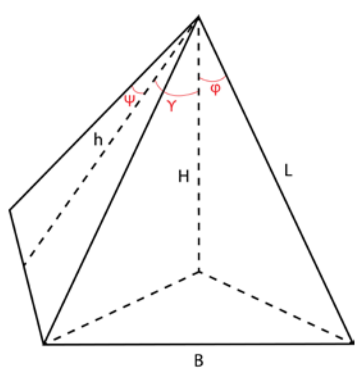

Fig. 1: Diagram of the square pyramid sail with variable definitions

2.1 Deorbit Analysis

The goal of the deorbit analysis was to determine the size of a drag sail that will deorbit a satellite within the 25 years required by international guidelines. This analysis used the General Mission Analysis Tool (GMAT), developed by NASA Goddard Space Flight Center [6]. It was assumed that the satellite drag area was the base area of the pyramid, then the orbit history was simulated starting from a 1,100 km circular orbit for different drag areas and different satellites masses. The results are shown in Fig. 2. It can be seen that a drag area of 125 m^2 is adequate to deorbit a 150 kg satellite within 25 years.

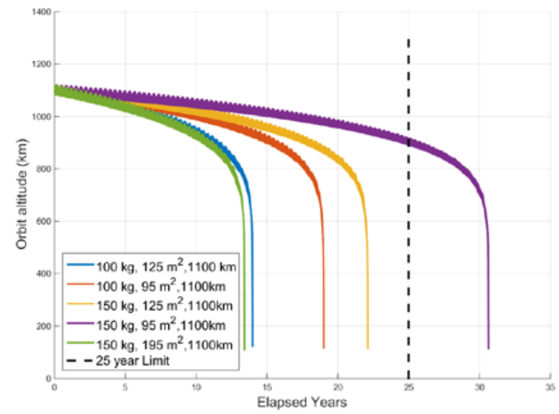

Fig. 2: GMAT simulation results starting at an altitude of 1,100 km [5]

2.2 Stability Analysis

An analysis to evaluate the stability of this design was conducted. This consisted of simulating the attitude over five orbits to show the sail will correct its orientation to maintain the nominal attitude that maximizes the drag of the sail. The attitude was simulated by integrating the non-linear equations of motion for an orbiting rigid body, including disturbance torques due to the aerodynamic pressure, the solar radiation pressure, and gravity gradient. This was investigated over a range of parameters such as apex half-angle, orbit altitude, and right ascension of the ascending node. Stability was defined as when the angle of attack and side slip angle of the system stayed within ±90°, as shown in Fig. 3. It was shown that if an aluminized sail membrane material is used, as is common for solar sails, the solar radiation pressure will disturb the stability of the system.

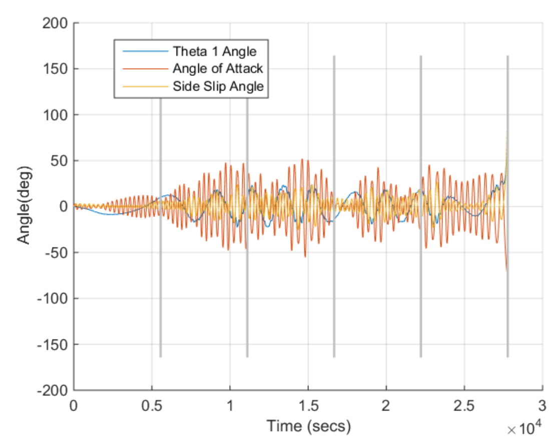

Fig. 3: Stability simulation results with a clear CP1 sail membrane, Φ = 70°, h = 400 km, Ω = 10° [5]

The conclusion drawn from the stability analysis was that a 70° apex half-angle with a clear CP1 sail should be marginally stable for altitudes of 500 km or lower, such that the angle of attack and side slip angle are both maintained to less than 60 deg by aerodynamic torques. In order to achieve the desired 125 m^2 drag area, 8 meter long booms are required to support the sail membrane [5]. It is estimated that this system will have a mass of 10 kg and a volume of 24 cm x 24 cm x 12 cm, similar to a 4U Cubesat.

3. Small Scale Test Flight Development

To demonstrate the stability of the $[PS]^2$ concept, a 1U CubeSat will be launched by Purdue University as part of United Launch Alliance's rideshare program, CubeCorp [7]. This mission is called the Aerodynamic Deorbit Experiment (ADE). A 1/10 scale version of $[PS]^2$ with 0.8 m long booms will be deployed by ADE. The drag sail assembly occupies 0.5U of the 1U CubeSat. The other 0.5U will contain avionics, including an inertial measurement unit to measure the CubeSat attitude during drag passes. The design of the drag sail subsystem is shown in Fig. 4. ADE will be deployed from a launch vehicle into a geosynchronous transfer orbit that has an apogee of 35,756 km and a perigee of 185 km. It is estimated that the spacecraft will deorbit within 11 days after deployment of the drag sail [8]. The strict volume constraints of the ADE mission created a number of design challenges. The design of this system, as well as the prototype testing using non-flight like materials are discussed in the following sections.

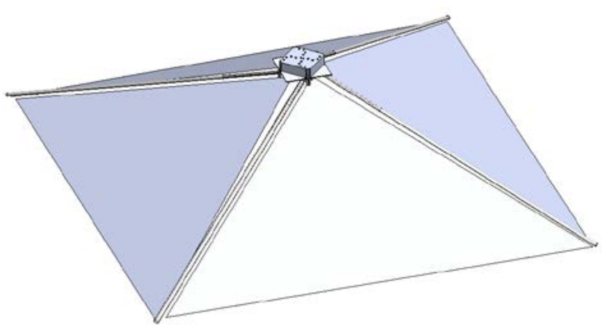

Fig. 4: Deployed drag sail subsystem for ADE.

3.1 Drag Sail Subsystem Design

One of the main challenges for fitting the sail assembly into the designated volume is that each of the four booms needs to be mounted on its own deployer in order to create the square pyramid shape. The drag sail assembly is self-contained, as shown in Fig. 5. The outer casing includes the feet required by the CubeSat standard [9], and will take the load during launch. The booms and sails will be contained by four doors that will open when deployment is initiated. Each sail quadrant will be folded separately and stored next to a boom deployer, shown in Fig. 6. The sail compartments are outlined with yellow and the boom deployers are outlined with red.

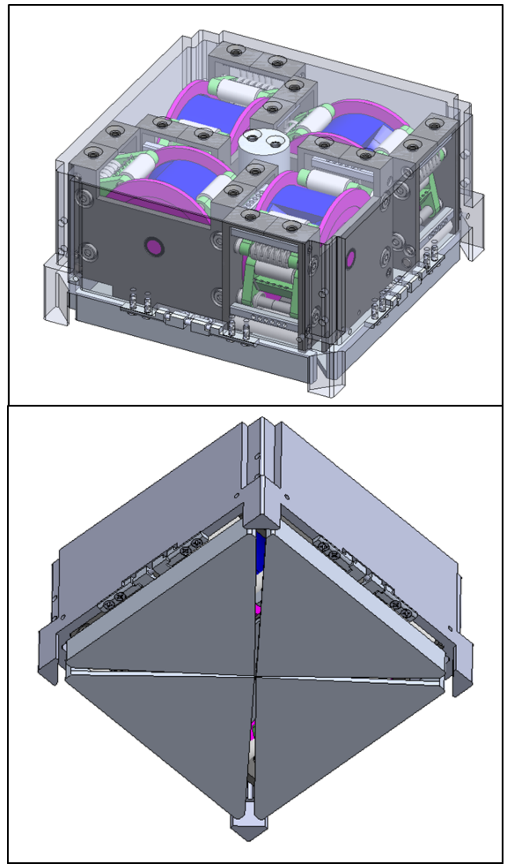

Fig. 5: Top view of contained drag sail system with transparent outer casing (top) and bottom view to show doors (bottom).

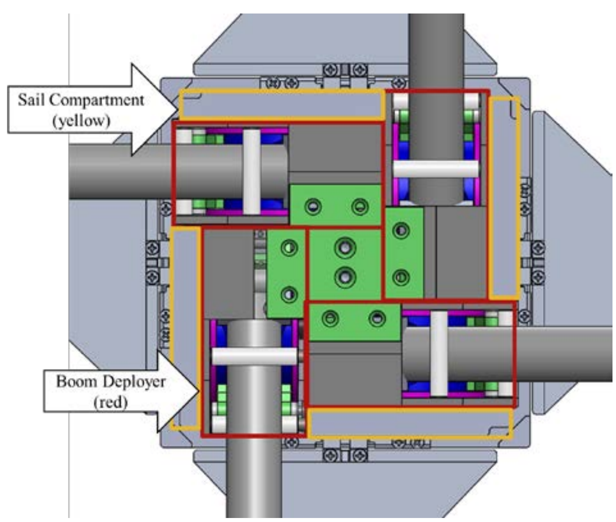

Fig. 6: Bottom view of deployed drag sail assembly with sail quadrants hidden.

3.2 Boom Deployer Design and Testing

The tight volume constraints on the boom deployer were a driving requirement for both the boom selection and the deployer design. This led to the requirement for the booms to be deployed using internal strain energy since there is not sufficient volume to include a deployment motor and gears. The selection of the type of strain deployed boom and the design of the boom deployer are described below.

3.2.1 Boom Selection

The two main dimensions of a strain deployed boom are the stowed height and the minimum wrap diameter. These are determined by the cross section design and the maximum allowable strain of the materials, respectively. The volume allotted to a single boom deployer is 57.2 mm in length, 47.5 mm in height, and 28.56 mm in width. This volume includes the stowed boom, the outer diameter of the wrapped boom, and the additional hardware needed to ensure the boom deploys smoothly in the correct direction. The outer diameter of the boom roll was estimated using the Archimedean spiral and the thickness of the stowed boom [10].

At the start of this project, none of the current designs were small enough to allow four deployers to fit in the allocated volume because most strain energy deployed booms have a much larger stowed height. This led to choosing the SHEARLESS booms made at NASA Langley Research Center. As shown in Fig. 7, these booms are comprised of two tape springs inside of a polymer sleeve. This allows them to slide alongside each other when they are stowed and allows a smaller hub to be used [10].

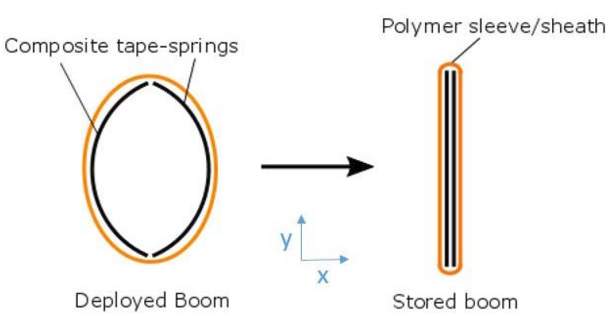

Fig. 7: SHEARLESS boom in the stored and deployed state [10].

The shell radius was chosen to maximize the moments of inertia in both x and y directions (as shown in Fig. 7) using the equations defined by Fernandez [10]. The final design of the tape springs is a shell radius of 7.94 mm and a stowed height of 20 mm. They are made from three-ply carbon fiber composites with a [45PW/0/45PW] layup. Four-ply layups were also investigated, but they were too thick to fit the full length of the boom in the deployer.

3.2.2 Boom Deployer Layout

The boom deployer is shown in Fig. 8. The boom is mounted to, then wrapped around, a central hub. The boom is mounted in a manner that allows the root to regain the full cross section once the boom is fully deployed to increase the strength. The central hub is able to spin freely with two guide rollers positioned to enforce the desired orientation of the boom. The design ensures the 70° apex half-angle for the square pyramid shape, and supports the boom inside the deployer. The other mechanisms in the deployer are there to prevent the phenomenon called blossoming, also known as blooming. Blossoming occurs when the coils of a boom do not rotate rigidly with the hub. Rather, the layers slide with respect to each other and expand to a lower energy state. Blossoming typically occurs partway through the deployment and causes the boom to jam inside the deployer, risking damage to the boom at the root. A common way to prevent this is by applying a normal force to the outside of the boom roll at regular intervals around the circumference [11]. This is accomplished by the anti-blossoming assemblies shown in Fig. 8. The force is applied by torsion springs that are restrained by the spring mount posts. Each assembly is able to hold six springs, but the number needed was determined in the prototype testing as described below.

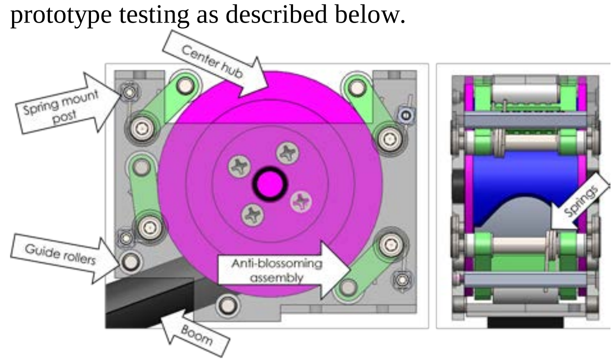

Fig. 8: Boom deployer front view with transparent structure (left) and side view (right)

3.2.3 Boom Deployer Prototype and Testing

The flight version of the boom deployer will be machined out of aluminium to provide strength and rigidity. Due to cost of machining, the initial prototype builds were created using non-flight like materials that were 3D printed. The first few versions were printed using PLA plastic on an Ultimaker 2+ machine to ensure that the parts would print well. Then, the version used for testing was printed using black nylon on a MarkForged MK-2 machine.

The disassembled deployer is shown in Fig. 9, and the assembled deployer with a fully spooled boom is shown in Fig. 10. Notice that when the boom is spooled the tape springs are no longer the same length. This requires more flexibility in the design for mounting the sails to the boom tips.

The testing of the boom deployer consisted of assembling it with first one spring per anti-blossoming assembly, rolling up the boom, and determining if the boom would freely deploy. The original design called for 1 m long booms, but it was determined that the full 1 m length only fits inside the deployer by making undesirable contact within the deployer, increasing the friction and losing its ability to free deploy, regardless of the number of springs. Fig. 11 shows the boom deployer with the boom being held stowed at the last point of free deployment. This extra length is about 20 mm, therefore the designed length of the boom was shortened from 1 m to 0.8 m to ensure it will deploy. The anti-blossoming only needed one spring to ensure the boom free deployed.

Fig. 9: Disassembled nylon boom deployer

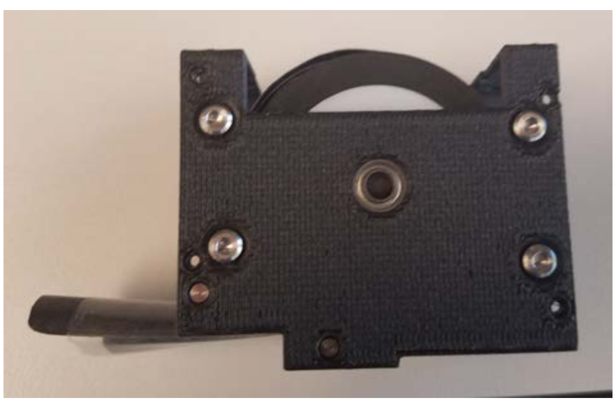

Fig. 10: Assembled boom deployer with fully stowed boom.

Fig. 11: Deployer held at the last point where it will free deploy

3.3 Sail Membrane Design

The sail is divided into four membrane quadrants for ease of packaging, deployment, and survivability. Each quadrant is an isosceles triangle with a base length of 0.85 meters, and a height of 0.5 meters, as shown in Fig. 12. The two primary risks associated with the sail membrane are proper stowing and extraction from the drag sail assembly, and degradation of the material following deployment due to the space environment.

3.3.1 Sail Design for Survivability

The membrane is most susceptible to atomic oxygen erosion and tears from micrometeorites. Surviving atomic oxygen erosion contributes to the selection of the material and thickness of the membrane. Thickness loss is determined by the erosion yield of the material, the altitude of the orbit, and the time spent in orbit [12]. One precaution is applying an aluminium coating, but this has the undesirable effect of making the membrane reflective. The other options are to make the membrane thicker (requiring additional storage volume), and/or use a more durable material. For the ADE mission, it was determined that 5 μm thick CP1 is adequate for the short mission duration and low altitude [13]. The full-scale system will most likely need to use a material like Corin that creates a protective layer of silicon dioxide as it is eroded [14].

Orbital debris and micrometeorites can rip through the thin material of the sail membrane. The tension in the membrane allows the tear to propagate through the sail, destroying the drag area it provides. This is mitigated by dividing the sail into four quadrants, so no more than ¼ of the drag area can be destroyed by a single piece of debris. The sail quadrants are further protected by adding ripstops. These are created by making a grid of kapton tape on the surface of the membrane. A tear is only able to propagate to the nearest line of kapton, assuming the initial hole is smaller than the grid sections. There is a design trade-off for the grid spacing because smaller grid sections reduce vulnerability to debris impacts, but locally increases the thickness of the membrane. It is also important that the ripstop lines are not perpendicular to the folds or else they will stack on top of each other. With that in mind, the ripstop pattern shown in Fig. 12 was designed. The ripstop lines are parallel to the hypotenuse edges and evenly spaced. If one of the squares is completely destroyed, only 12% of the quadrant area and 3% of the total membrane area will be lost.

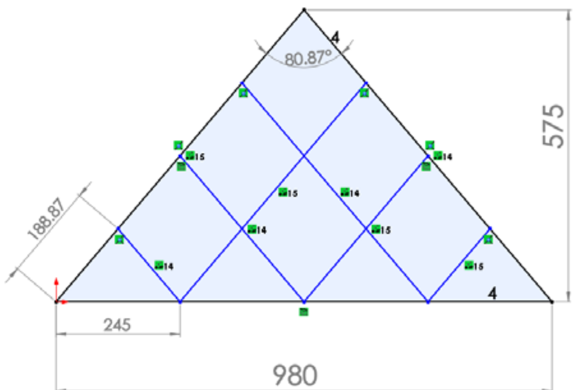

Fig. 12: Sail quadrant ripstop pattern, dimensions in mm.

3.3.2 Sail Design for Packaging

The more efficient design for folding a sail membrane is to z-fold it then wrap it around a spool, as was done for Nanosail-D and NEAScout [15, 16], and will be used for the full scale design, but the available volume for the ADE mission does not allow for that. Instead, the sail will be folded in the "Frog Legs" pattern, as proposed by Dalla Vedova, et al [17]. The concept is shown in Fig. 13. It consists of z-folding the sail into a strip, then z-folding the ends into the middle. This allows all three corners of the sail quadrant to be free for mounting and facilitates the booms pulling the sails out during deployment.

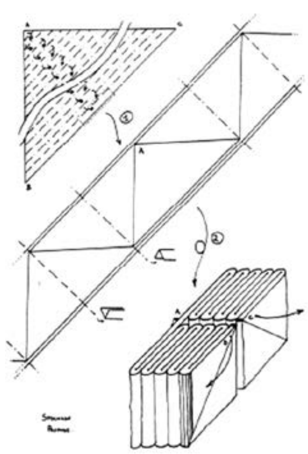
Fig. 13: Frog Legs sail folding concept proposed by Dalla Vedova, et al. [17]

3.3.3 Sail Prototype

The first sail prototype consists of the 5 μm thick CP1 with the design shown in Fig. 12. The prototype can be seen in Fig. 14. The edge reinforcements and the ripstops were taped using 12.7 mm wide kapton tape.


Fig. 14: CP1 sail prototype with kapton ripstops.

A teflon coated wire was used to create each fold by holding it tightly on top of the membrane while the unfolded membrane was passed over it. The wire was then pulled out of the fold and laid down on the other side. Fig. 15 shows the sail being folded with the many volunteers ensuring the folds stay in place. The green Teflon wire can be seen in the bottom right corner as it is being held under tension.


Fig. 15: Folding process. Note the green Teflon wire used to define the folds.

As more of the membrane was folded, new layers were not being added to the ends, so they were covered with thicker mylar, and secured with binder clips. The sail after the first phase of folding is shown in Fig. 16. Note that the rip stops did not stack on top of each other, reducing the thickness of the folded sail. The next phase was to fold both sides of the sail into the center.

In order to test if the folded sail will fit in the assigned volume, the outer casing and a few more deployer outer structures were printed out of ABS plastic on an Afinias machine. Fig. 17 shows the fully folded sail in the allocated volume of the 3D printed structure, proving that the volume requirements will be met.

Fig. 16: CP1 prototype after initial folding phase.

Fig. 17: Fully folded CP1 sail quadrant in the allocated volume of a 3D printed prototype

4. Conclusions

The [PS]² system is designed to deorbit small satellites within the 25 year guideline. To demonstrate the feasibility of the deorbit system, a 1/10 scale version will demonstrate deorbit from GTO by the Aerodynamic Deorbit Experiment. The component level prototype testing, using non-flight materials, demonstrates that the volume requirements will be met. The next steps are to refine the design of the sail membrane and to fully define how the sail membranes will be mounted to the boom tips and the satellite. Then, full system will be tested. Flight of the ADE mission is planned for 2018.

Acknowledgements

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References

[1] E. Levin, J. Pearson and J. Carroll, Wholesale debris removal from LEO, Acta Astronautica. 73 (2012) 100-108.
[2] S. Masunaga, Boeing applies for license to launch proposed satellite constellation, Jun 23, 2016, http://www.latimes.com/business/la-fi-boeing-satellites-20160623-snap-story.html, (accessed 26.07.16)
[3] OneWeb Satellites Company Given Birth By Airbus Defence and Space + OneWeb, 2016, http://www.satnews.com/story.php?number=214814180, (accessed 26.07.16)
[4] P. B. d. Selding, SpaceX To Build 4,000 Broadband Satellites in Seattle, Jan 15, 2015, http://spacenews.com/spacex-opening-seattle-plant-to-build-4000-broadband-satellites/, (accessed 26.07.16)
[5] A. C. Long and D. A. Spencer, Stability of a Deployable Drag Device for Small Satellite Deorbit, AIAA 2016-5676, AIAA/AAS Astrodynamics Specialist Conference, Long Beach, CA, 13 - 16 September, 2016.
[6] D. Chavali and S. Hughes, GMAT Wiki Home, Mar 29, 2016, http://gmatcentral.org/, (accessed 02.08.2016)

[7] B. L. Huchel, AAE CubeSat flight experiment picked for launch on ULA rocket, Oct 24, 2016, https://www.purdue.edu/newsroom/releases/2016/Q4/aae-cubesat-flight-experiment-picked-for-launch-on-ula-rocket.html, (accessed 05.01.2017)
[8] M. LaChance, Purdue wins a launch slot on Atlas V, Fall, 2016, https://engineering.purdue.edu/discovery/2016_3/purdue-wins-a-launch-slot-on-atlas-v, (accessed 31.08.2017)
[9] C. P. S. The CubeSat Program, CubeSat Design Specification, Rev 13, 2014.
[10] J. M. Fernandez, Advanced Deployable Shell-Based Composite Booms For Small Satellite Structural Applications Including Solar Sails, 4th International Solar Sailing Symposium, Kyoto, Japan, 17 January, 2017.
[11] J. M. Fernandez, M. Schenk, G. Prassinos, V. J. Lappas and S. O. Erb, Deployment Mechanisms of a Gossamer Satellite and Deorbiter, 15th European Space Mechanisms & Tribology Symposium, Noordwijk, The Netherlands, 25-27 September, 2013.
[12] R. C. Tennyson, Atomic oxygen effects on space inflatable materials, in: (Eds), Gossamer spacecraft: membrane and inflatable structures technology for space applications, 2001, 281-302.
[13] Nexolve, CP1 Polymide, http://www.nexolvematerials.com/low-cure-polyimides/cp1-polyimide, (accessed 01.09.2017)
[14] Nexolve, CORIN XLS Polymide, http://www.nexolvematerials.com/low-cure-polyimides/corin-xls-polyimide, (accessed 01.09.2017)
[15] D. C. Alhorn, J. P. Casas, E. F. Agasid, C. L. Adams, G. Laue, C. Kitts and S. O'Brien, NanoSail-D: The Small Satellite That Could!, 25th Annual AIAA/USU Conference on Small Satellites, 2011.
[16] L. McNutt, L. Johnson, D. Clardy, J. Castillo-Rogez, A. Frick and L. Jones, Near-Earth Asteroid Scout, AIAA 2014-4435, AIAA SPACE 2014, San Diego, CA, 2014.
[17] F. Dalla Vedova, H. Henrion, M. Leipold, T. Girot, R. Vaudemont, T. Belmonte, K. Fleury and O. Le Couls, The Solar Sail Materials (SSM) project - Status of activities, Advances in Space Research. 48 (2011) 1922-1926.