A DRAGSAIL DE-ORBIT SUBSYSTEM FOR SMALL SATELLITES

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ABSTRACT

The continued growth of the number of launched satellites in recent years, driven primarily by small satellites, will aggravate the space debris situation in the already congested low Earth orbit regimes. Therefore, reliable end-of-life de-orbiting solutions for small satellites are needed to ensure the sustainability of space applications. We present the design and implementation of a robust, standardized de-orbit subsystem for small satellites. The de-orbit subsystem is a passive drag sail device that increases the area-to-mass ratio of the satellite at mission end. The entire subsystem fits into a 1U CubeSat form factor and weighs less than 1 kg, with a deployed sail area of $2.5m^2$. The system is highly scalable and intended for satellites weighing less than 50 kg. The system, developed as a collaboration between Fraunhofer EMI and High Performance Space Structure Systems (HPS GmbH), will be tested in November 2018 on the second stage of a Rocket Lab Electron rocket.

1. INTRODUCTION

The recent proliferation of small satellites drives the continued growth of launch traffic into Low Earth Orbit (LEO) protected regions [1]. The new launch record set in 2017 was due in large part to the mass launch of CubeSats for Planet's remote sensing constellation. The growth will continue with commercial Earth observation and telecommunication constellations planned for the next decade, which are expected to employ thousands of satellites [2]. This rapid progression will only exacerbate the problem of space debris, which poses a risk to operational satellites and manned missions alike. Collisions are predicted to be the dominant source of space debris in the future. To mitigate the growing problem of space debris, reliable end-of-life de-orbiting solutions are needed, particularly for small and nanosatellites.

Nanosatellite missions traditionally establish low cost, mass and volume requirements. The focus is on simplicity, a reduction to the bare minimum of components needed to support mission and payload requirements. The addition of a system that reduces available mass and volume, and increases overall system complexity, for post-mission operations, could be detrimental to many nanosat missions. Thus, the lack of commercially available de-orbit systems specific to the CubeSat form factor poses a potential risk to the future of the Nanosat community, a sector with a market value expected to surpass $30 billion in the next decade [3].

Fraunhofer EMI and High Performance Space Structure Systems (HPS GmbH) have collaborated to design a passive drag sail de-orbit subsystem for small satellites. A development model, EDOS, was developed within the scope of a Masters Thesis [4] as the de-orbit solution for ERNST, a 12U CubeSat currently under development at Fraunhofer EMI. Intended for a Sun synchronous LEO, ERNST will carry out an Earth observation mission leveraging an advanced MWIR imaging payload. ERNST provides an opportunity to test cutting edge hardware and evaluate the utility of the CubeSat platform for high performance, low-cost missions.

Fig. 1. Artist impression of ERNST 12U CubeSat with planar drag sail de-orbit system

A proto-flight-model of the de-orbit system will also be flown on the first commercial launch of a Rocket Lab Electron rocket. Building on knowledge gained from the development of the development model, the proto-flight-model, NABEO, was rapidly designed, built, and tested, culminating in delivery in June 2018. The launch is expected for the end of November 2018. This paper details the design and testing of NABEO, aided tremendously by digital design tools and additive manufacturing for quick design, review, and modification cycles. The ability to rapidly test design concepts in real-world test environments was instrumental in mitigating failures during a time critical delivery scenario.

2. BACKGROUND AND DESIGN REQUIREMENTS

The Inter-Agency Space Debris Coordination Committee (IADC), an international forum of space agencies has published Space Debris Mitigation Guidelines, which proposes a post-mission orbital lifetime limit of 25 years to be "reasonable and appropriate" [5]. These IADC guidelines are being adopted by an increasing number of regulatory agencies, with some requiring debris mitigation plans as a prerequisite for operation licenses [6].

The preliminary prototype design study included a literature review of state-of-the-art drag sail and solar sail systems. Simulations were carried out in STK to establish a minimum drag sail area of 1.6m^2 in order to de-orbit the ERNST nanosatellite within 25 years of mission end. The system must be compatible with the CubeSat form factor, a maximum size of 1U, and mass of 1kg, in order to be appropriate for small and nanosatellites.

2.1. Passive versus active system

Various active and passive technologies were considered, such as propulsion, electrodynamic tethers, and inflatable balloons, but the mechanically deployed drag sail was ultimately selected [4]. Active technologies require a functioning control system, making them unsuitable for the many nanosatellite missions. The orbit inclination planned for ERNST precludes the use of the electrodynamic tether, and an inflatable device requires pressurized system that adds significant complexity. The main advantage of a passive drag sail augmentation is its applicability for non-operational spacecraft. Small satellites are historically less reliable, with a significant number failing to operate in orbit. A passive drag sail that is triggered by a watchdog timer does not require ground control, nor does it rely on a functioning attitude control system.

The only electric energy needed for the system to operate is for pin puller actuation. The system must be stowed for the duration of the mission and requires spring-driven mechanisms for deployment. To keep the system separate from the structure of the satellite bus, a two-step actuation is required. First, the sail deployment subsystem is driven out of the satellite bus, via a telescopic motion. The second step requires the aluminized polyimide sail to be stretched into its final configuration.

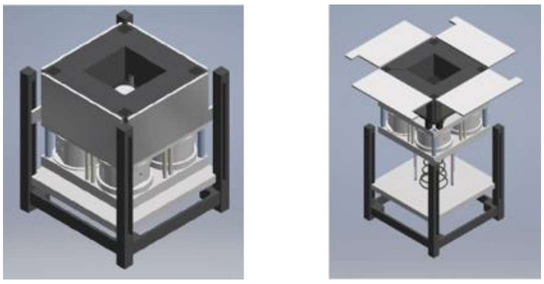

Fig. 2. First stage of deployment: telescopic motion out of 1U housing [4]

3. NABEO DESIGN DEVELOPMENT

3.1. Structure and deployment mechanism

To pull the sail into its stretched configuration and provide structure in the deployed position, the majority of drag sail systems surveyed employ coiled booms which rely on stored mechanical energy to unroll [4]. The booms can be made of various materials and have a variety of cross sections. Due to their low-cost, chemical inertness, low toxicity, commercial availability and flight heritage, stainless steel bi-stable tape spring booms with a C-cross section were selected. Four booms are needed for complete sail deployment.

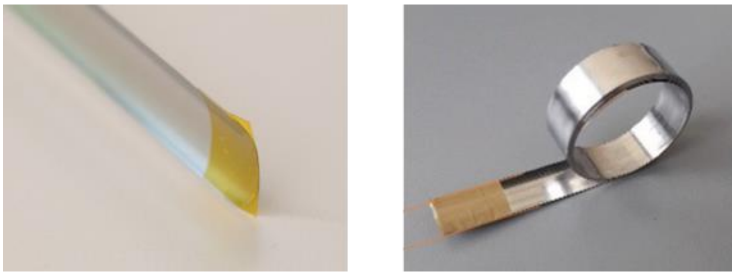

Fig. 3. Stainless steel tape spring booms are bi-stable, in rolled and unrolled configurations

For the development model EDOS, four booms were rolled onto individual spools to eliminate a single point of failure, i.e. one central spool, and therefore increase system reliability. However, this separation increased the number of system components, especially rotating components, leading to increased system complexity and more opportunities for failure. The four spools cannot be treated as isolated systems. There is the risk of individual failure, as well as failure as a result of spool interaction. Deployment testing revealed the issues associated with a four spool system [7].

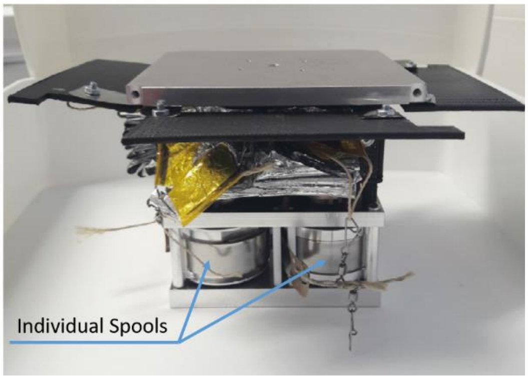

Fig. 4. EDOS breadboard prototype with four boom spools and sail cartridges [4]

First, the axial counter-force from the sail pull-out caused the coiled booms to "bloom" radially. Second, the boom attachment method led to a rotational instability that also caused rubbing between each of the booms, ultimately leading to an incomplete deployment, and thus system failure. While roller guides between the spools may have helped prevent rubbing and blooming, size constraints precluded the use of guides for all four spools.

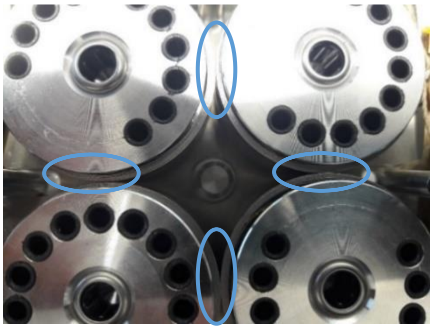

Fig. 5. Radial blooming and rotational instability lead to rubbing and prevent complete deployment

For NABEO, the decision was made to transition to a single central spool system, avoiding the spool interaction issues and allowing for larger, more powerful tape spring booms. A single spool system also decreased the number of rotating components, reducing cost and complexity. The larger central spool enabled the use of a redundant power spring housed within the spool body.

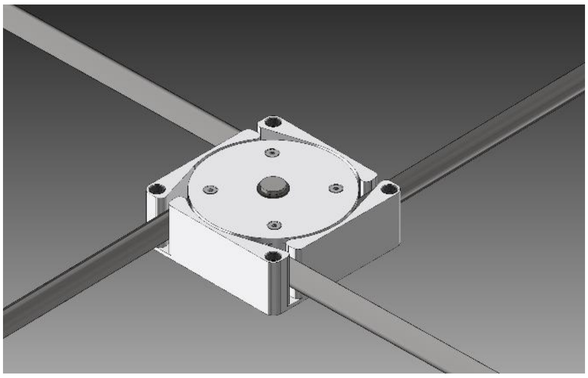

Fig. 6. Transition to single boom-spool to reduce number of moving parts and prevent boom interactions

With the larger cross section booms, the drag sail surface area could be increased. The sail area is dictated by the length of the booms. With the current center spool dimensions, there is space for four 1600 mm long coiled booms. This corresponds to a sail area of 5 m^2. However, the theoretical Euler critical load, the maximum load that the boom can experience before buckling, decreases quadratically with the boom length. Thus, for a 10 percent increase in boom length, the theoretical critical load decreases by nearly 20 percent. Also, manufacturing and assembly becomes increasingly difficult with a larger sail. A sail size of 2.5 m^2 was chosen to provide sufficient projected area in the case of a tumbling spacecraft while keeping assembly manageable and buckling propensity acceptably low for the booms we use.

The strict timeline for design, manufacturing, testing and delivery required rapid prototyping to screen preliminary design concepts. Functional mechanisms could be printed and tested in a matter of hours or days, not weeks, as with traditional manufacturing methods. The physical realization gave insight that would be impossible to deduce with computer aided design tools alone. It also provided a testing environment for the sail folding and deployment, the dynamics of which are very difficult to accurately predict with current simulation tools. Sail folding proved to be one of the most challenging aspects of drag sail system design. Initial concepts and prototypes were mocked up with paper. The preliminary prototype, EDOS, used four individual sail segments stored in cartridges, and a modified frog-leg folding pattern [4]. To eliminate gaps between sails, thus increasing the effective sail area, the transition was made to a square, single-piece sail. Thus the four sail cartridges could also be eliminated. A literature review confirmed that single-piece sails are quite rare in previous missions: of 13 missions surveyed, none used a single-piece sail [4]. Various folding patterns were explored. Two patterns were selected for additional testing [8].

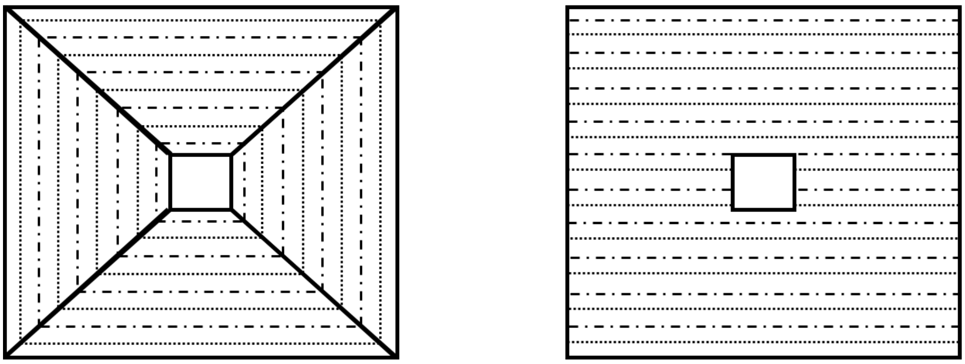

Fig. 7. Two folding pattern options for single piece sail; dashed lines represent mountain-valley folds.

Two methods of sail storage were also tested. In one scenario, the sail is first folded and then wrapped around an additional sail spool, housed above the boom spool. The second option requires only folding, with the folded sail stored freely above the boom spool, sandwiched between a separation plate and the top plate of the housing. The sail spool offers greater packing efficiency and a more controlled deployment, but also requires additional rotating components and a locking mechanism. Folding and storage without a dedicated enclosure or cartridge provides greater simplicity, but deployment is less controlled. Due to time constraints, the latter option was selected for the test with the protoflight model on the Electron rocket. Continued development will test the sail spool concept, to determine the most effective solution for a reliable de-orbit subsystem product, which we will use for the ERNST mission.

3.2. Sail membrane and interfaces to structure

The sail is made from a thin, aluminized polyimide membrane, which has been used in a number of previous sail missions [4]. The membrane material is sold in a maximum width of 1 m. The edge length of a 2.5 m^2 square sail is 1.6 m. Hence, the material was joined in house at HPS, using knowledge gained from the ADEO project [9]. Great care must be taken to avoid exposing the inner polyimide foil along any edges, as atomic oxygen in Low Earth Orbit can cause rapid degradation through material erosion [10]. Folding is performed in a clean room environment to avoid particle exposure. A pattern-specific process must be developed to ensure consistency and efficiency when sail folding. During preliminary deployment tests, mylar emergency blankets were used as a low-cost proxy for testing different cutting and folding processes. A large, flat magnetic surface in combination with long magnetic strips and blunt-edged clips proved to be useful tools when folding and handling the sail.

Proper interfaces between the sail and booms are important to prevent entanglement, puncture, and tearing. A number of interface methods were reviewed and screened during development of EDOS. To reduce the likelihood of entanglement, it is important to keep interfaces as short as possible. Asymmetric cutting and tensioning of the membrane can lead to failed deployment. Sharp edges of the metal booms were rounded and covered to prevent inadvertent cutting and tearing of the membrane. One effective method directly mates the membrane corners to the booms using Kapton tape, thus avoiding any entanglement issues. However, this does not allow for any fine adjustments to account for asymmetry of the sail or booms. A second method uses small loops of Kevlar string at each of the four corners. The loops are mated to the membrane using Kapton tape and threaded through a 3 mm hole punched in the end of each boom. The advantage is that the size of the loops can be easily adjusted to account for asymmetries, but care must be taken to keep the loops as short as possible to prevent entanglement.

Fig. 8. Kevlar loop allows for fine adjustments when tensioning sail.

4. TESTING AND QUALIFICATION

Functional and vibrational tests were performed on the final protoflight model. The rapid development timeline did not allow time for thermal vacuum testing, nor were the effects of long term stowage assessed. It is difficult to accurately characterize a gossamer structure in a simulated environment on ground. The two-stage deployment was tested in a laboratory environment, without gravity compensation. The development timeline did not allow any testing of the first stage mechanism, which involves a spring-driven telescoping of the boom-sail assembly out of its 1U housing, during the rapid prototyping phase. After the protoflight model was manufactured, initial testing of the first stage highlighted issues with the catch and lock mechanism at the end of the telescopic motion. Adjustments were made to improve reliability of the catch and lock mechanism before final delivery, however, this issue highlights the importance of "test early, test often" when designing dynamic systems. The first stage functioned successfully in a normal gravity environment.

Testing the second stage of deployment, when the tape spring booms pull the sail membrane into the final stretched configuration, is especially difficult in a normal gravity environment. The booms are long and slender, and tend to sag under their own weight as they reach the end of their deployment, a behaviour that would not be exhibited in the microgravity environment of LEO. This behaviour induces friction which can prevent complete deployment. To reduce these effects, a testing table was constructed with a low-friction gliding surface to support the boom tips while trying to minimize influence on torsional buckling as much as possible. However, the influence of the table on buckling is known to prevent complete deployment of gossamer structures during laboratory testing [11].

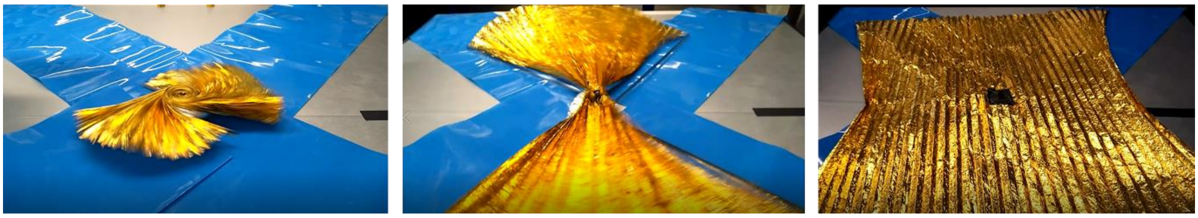

Fig. 9. Deployment tests carried out on table with low-friction polymer tracks.

Two protoflight models, one used as a flight spare, were qualified to the vibration standards in [12]. Tests were performed for Eigenfrequency determination, random vibration and quasi-static limit load. The protoflight model was qualified without significant structural damage.

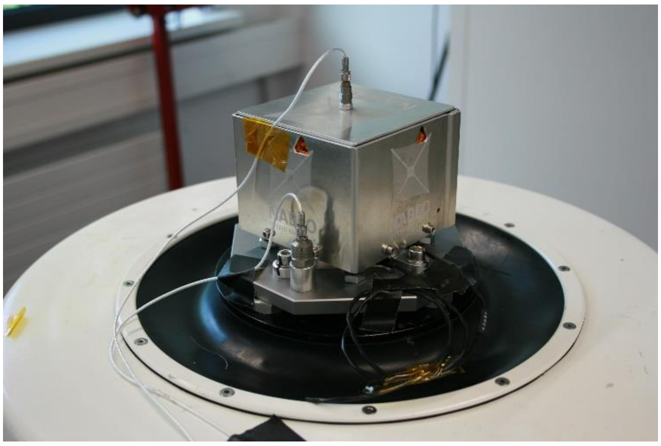

Fig. 10. NABEO mounted to vibration test platform at Fraunhofer EMI

5. CONCLUSIONS AND FUTURE WORK

We are developing a de-orbit subsystem for nanosatellites and small microsatellites. The system relies on a deployable dragsail that is stored inside a 1U-CubeSat volume. It working principle is to passively increasing the effective drag area for faster decay from low earth orbit. The design goal was a highly reliable and robust system. After comprehensive testing of different development models, we changed our design to a system deploying four coiled booms from one spool to unfold a 2.5 m^2 square dragsail. This design was implemented with a rapid prototyping approach for launch and demonstration on the Electron rocket kick stage.

The protoflight model NABEO was delivered to the Rocket Lab launch facility in Auckland, New Zealand in late May 2018, with team members from HPS participating in the integration campaign. The launch, originally scheduled for the end of June 2018, was ultimately delayed until November 2018, due to both weather and technical issues. The deployment test aboard the Electron rocket will be live-streamed via an on-board camera.

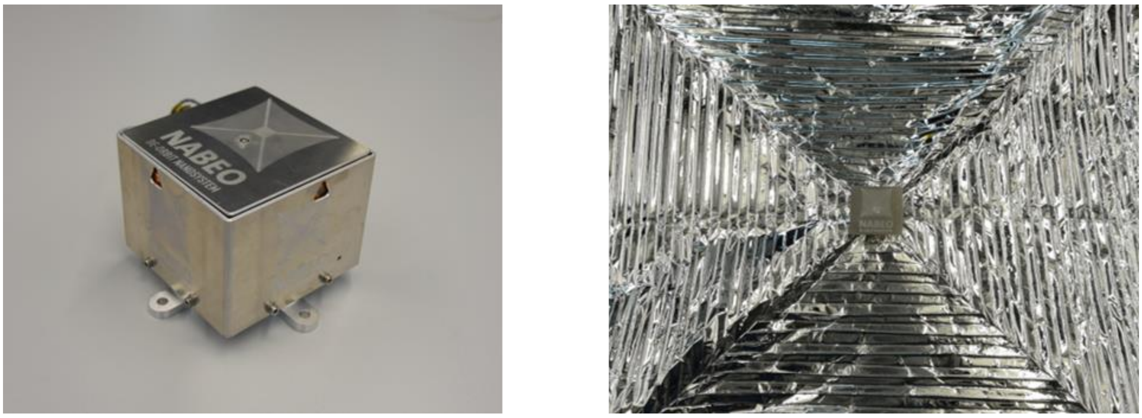

Fig. 11. NABEO in stored and deployed configurations.

A number of design enhancements were identified during manufacturing and testing of the protoflight model. Design work and testing is ongoing to improve system performance and reliability. Opportunities for improvement include increasing the power of the spring-driven first stage of deployment, modifying the existing catch and lock mechanism, designing a new attachment method for the redundant spool power spring to make assembly easier, and performing a trade-off study of the existing sail storage methods.

Additional tests will be performed to qualify the engineering model for the ERNST mission. Thermal vacuum tests will study the effects of thermal cycling, outgassing and identify any issues with cold welding. An investigation into the effects of long term stowage will be performed. The primary concern is the effect of stress relaxation of the various mechanical springs. In addition, a reliable control system will be integrated, capable of actuating the de-orbit system even if the satellite becomes inoperable. These development and verification activities will lead to a robust stand-alone de-orbit subsystem for small satellites.

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