Origami-based Drag Sail for CubeSat Propellant-free Maneuvering

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This paper presents a self-contained 1/2U drag sail subsystem for integration into CubeSats. Traditionally, sails have been used for propulsion or de-orbiting, and the goal of the research is to introduce a deployable sail that can open and close to change the cross-wind drag area, while meeting the CubeSat design standards. The drag sail subsystem was based on an existing origami model and is intended to control a CubeSat while in orbit by varying the drag. This is intended to be used for relative maneuvering in Low Earth Orbit (LEO) with the use of differential drag. The sail subsystem has been shown to successfully work in prototype testing, and will be integrated into the upcoming Propellant-less Atmospheric Differential Drag LEO Spacecraft (PADDLES) CubeSat developed at Rensselaer Polytechnic Institute. The system is currently patent pending.

Key Words: CubeSat, Differential Drag, Maneuver, Formation, Sail

1. Introduction

1.1. CubeSat Background and Utility

CubeSats are nano and pico-satellites used for space research, generally in Low Earth Orbit (LEO). CubeSat size varies between 0.5U and 6U, with each U representing a 10 x 10 x 10cm volume of no more than 1.33 kg. The majority of CubeSats are made from primarily commercial off-the-shelf (COTS) components, which allow them to be built relatively cheaply and reduce the cost of space access. Generally, CubeSats are added as a secondary payload using the Cal Poly P-POD (Poly-PicoSatellite Orbital Deployer) on planned launches, reducing the cost of access to space [1]. CubeSats are stacked inside the P-POD launcher both for protection during launch and to prevent interference with the primary payload.

1.2. Previous Work in Space Sails

Solar and drag sails have been implemented in similar applications. Successful demonstrations in 1999 were conducted by the The Space Research Center of the Federal Republic of Germany (DLR), European Space Agency, and NASA Jet Propulsion Lab to test the seams and folding of solar sails aluminized to increase reflectivity. Single-aluminized Mylar, and dual-aluminized Kapton and polyethylene-naphthalate (PEN) were all considered [2].

A two-part ground test was conducted to determine the feasibility of the design. First, four remote-controlled booms were tested for proper deployment and operation. Then, a rope subsystem was used to deploy four sail segments in a simulated zero-gravity and reduced friction environment. Preliminary testing demonstrations were successful [2].

Solar sails are also being developed for small satellite propulsion, such as the NanoSail-D (NS-D), in order to minimize the payload mass of the satellite while maximizing acceleration. The NS-D was launched on the Falcon Rocket in 2008, but failed to reach orbit. The NS-D was initially designed with a modular sail system: one module for the sail assembly and another module for the mechanical boom assembly. The NASA Marshall Space Flight Center is awaiting the launch of a NS-D flight spare [3]. Solar sail propulsion will allow for prolonged operation and the ability to reach new orbits. Sails will be made of aluminized Mylar or CP-1, both of which have been used in space, and are undergoing tests in mission simulated conditions. NASA Glenn facilities were used to successfully complete vacuum and ambient testing. Suggested improvements to space sails include more complex model development based on computational modeling and analytical simulations [4] and carbon fiber reinforcement.

The Surrey Space Centre has been designing and building the CubeSail, a 5m x 5m nano-solar sail designed to fit in a 3U CubeSat. Towards the end of the mission, the 3kg solar sail will be used as a drag sail for end of life de-orbiting using active attitude control. Such sails are a low cost solution to de-orbit a satellite and could potentially be used to capture and reduce the amount of space debris left in orbit [5]. The CubeSail has led to testing of composite booms rather than the commonly used metallic booms, for improved strength. The composite structure allows for the ability to scale to the compact size of a CubeSat. A 2.2m x 2.2m sail was designed in which the sail membrane was divided into multiple strips, proving to be easily scalable and extremely lightweight with low density composite booms. This design will be scaled up to a 5m x 5m sail to be implemented in the CubeSail mission [6].

1.3. CubeSats and the Proposed Drag Sail Subsystem

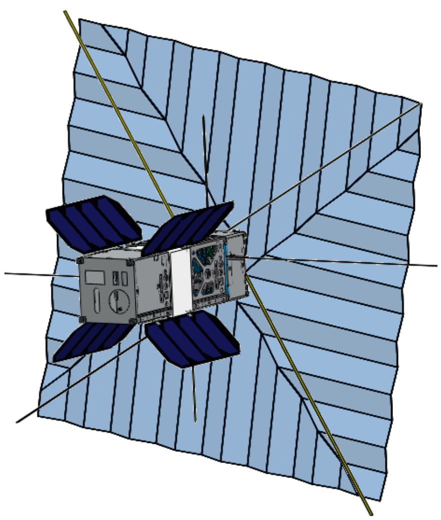

Fig. 1. PADDLES 3U CubeSat

The purpose of the sail subsystem proposed herein is to be a self-contained 1/2U off the shelf (OTS) component for custom CubeSats. It is intended to be integrated into a standardized CubeSat with little to no modification, as in Figure 1. The system is designed around the constraints of the CubeSat architecture-e.g. low weight, standard size, and low power. Inspiration for the drag sail was taken from an existing origami pattern [7]. The drag sail subsystem is currently patent pending.

The drag sail subsystem is designed to be integrated into an upcoming CubeSat launch. PADDLES (Propellant-less Atmospheric Differential Drag LEO Spacecraft), developed at Rensselaer Polytechnic Institute, is expected to be launched in 2015, and will include the drag sail subsystem. PADDLES is intended to maneuver by varying the atmospheric drag on the CubeSat. The drag sail is able to open and close, allowing the atmospheric drag to change as necessary.

1.4. Advancements of the State of the Art

This research proposes several advancements to the current state of the art in CubeSat maneuvering.

- The drag sail subsystem has been adapted to meet the CubeSat design standards
- An origami-based design has been demonstrated to be viable for control of a CubeSat
- The drag sail has the ability to open and close repeatedly as necessary for drag control

2. Differential Drag Basics

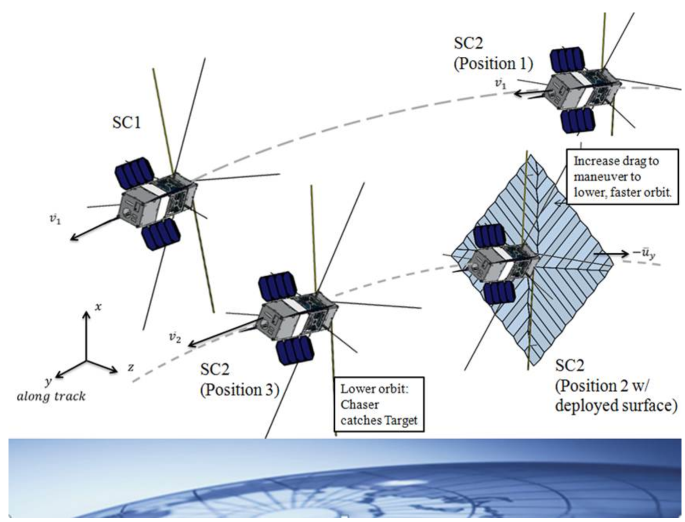

Fig. 2. Differential drag maneuvering

Differential drag techniques leverage the difference in drag between two bodies in LEO. PADDLES is able to vary its cross-wind area and change the atmospheric drag relative to another spacecraft as seen in Figure 2. Some previous work has been done in modeling differential drag and simulating maneuvers using Systems Tool Kit (STK)[8] [9] [10] [11].

2.1. Using Differential Drag for Relative Maneuvering

Many CubeSats and nanosats fly in formation, which requires frequent maneuvering and has a high propellant cost. Additionally, to minimize the risk to the primary payload, P-POD restrictions preclude the use of propellant or compressed gases [12]. Because of these, the use of propellant is not an option for CubeSat maneuvering. Varying the relative drag on CubeSats allows the use of relative maneuvering without the storage or use of propellant. The drag sail used opens and closes perpendicular to the ram direction, so very little energy is used to open and close the sail, but the result is a proportionally larger change in orbital energy. The tradeoff is that energy can only be removed from the CubeSat orbit, i.e. it can only maneuver 'down'.

3. Description of Technology

3.1. Design Requirements and Metrics

The system was designed to be completely enclosed in a 1/2U volume meeting the CubeSat design standards. It is intended to be mounted at the end of a CubeSat stack. Since one goal of the CubeSat standard is to reduce the cost of entry to space, minimizing the cost of the hardware was an explicit design requirement. The cost of materials of the system is approximately $600 including space-qualified materials, putting it within reach of many universities and research groups. Control of the drag sail must also be standardized. A serial bus was used to open and close the sail, allowing its use with various controllers. The decision of when to open and close the sail is determined by the mission profile and left to the designer. Because positive identification of the cross-sectional area of the sail is necessary for accurate control, an encoder is built into the motor assembly.

3.2. Sail Subsystem Description

The system is composed of the chassis, booms, deployment springs, and motor system. The chassis is a 1/2U aluminum casing designed to maintain rigidity of the subsystem. This bolts directly on to existing CubeSat hardware, as seen in Figure 1.

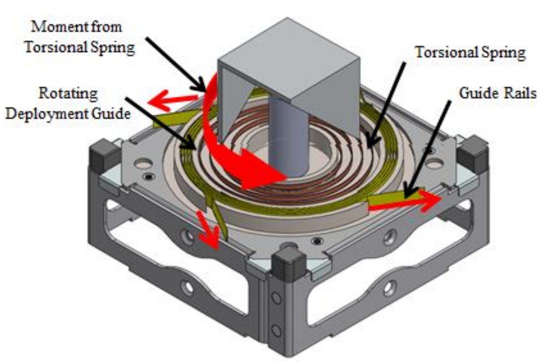

Fig. 3. Direction of rotation of the drag sail when opening

Figure 3 shows the components of the drag sail subsystem. An exploded view is visible in Figure 4. The booms are radially symmetric and are designed to act as guide rails for the sail. A spring is used to push the booms out of the chassis. Once the system is outside the 1/2U chassis, the booms uncoil and fully deploy.

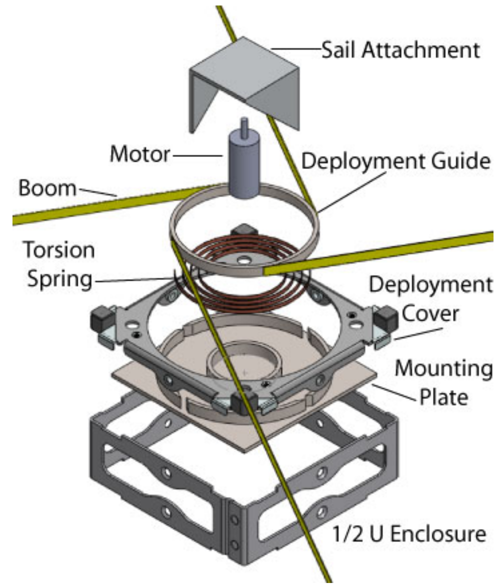

Fig. 4. Sail subsystem exploded view

Opening and closing of the sail is done with a space-qualified Faulhaber 1516SR Series 12V motor equipped with a reduction gearbox and encoder. The motor will produce 0.1 Nm after gear reduction at 4 rpm and 3A. As previously mentioned, the motor rotates the attachment in the center to open and close the sail. The direction of movement is indicated in Figure 3.

3.3. Sail Folding Pattern

The overall size and shape of the folded drag sail can be approximated by a cylinder. As the number of squares on the flasher increases, the aspect ratio will increase non-linearly. The dimensions of the cylindrical space are as follows:

$$d = \sqrt{2}\frac{L}{2N} + \frac{2Nt}{p_f};\ h = \frac{L}{2N}, \tag{1}$$

where d is the diameter of the cylinder, h is its height, 2N is the number of squares on the edge of the full sheet (as seen in Figure 5), L is the length of the sheet, and t is the thickness of the sheet. The packing factor p_f was experimentally determined to be approximately 0.25, and represents the ratio of the sail minimum theoretical stacked thickness to its actual stacked thickness. Some previous work has been done in determining the volume of spiral wrapped sheets based on similar folding patterns [13].

The volume of the packed drag sail is derived from the maximum diagonal dimension of the sail attachment in the center added to the thickness of the layers wrapped around it. This approximation allows the folded size to be found as a function of configuration and sheet dimensions. For a 0.2m x 0.2m sheet 0.5mm thick, the diameter reaches a minimum at 6 squares per half-edge, while the height monotonically decreases with increasing squares per half-edge.

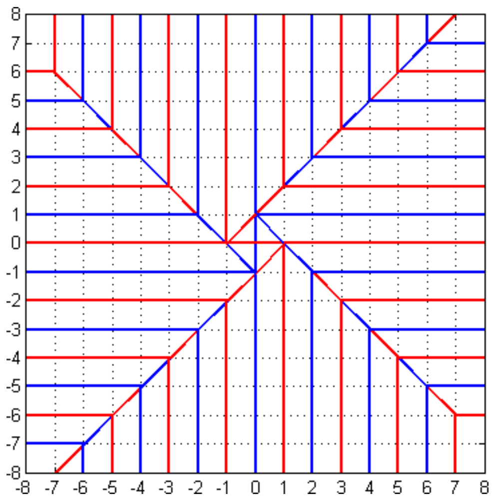

Fig. 5. Sail folding pattern, $N = 8$ squares. Red lines indicate mountain folds and blue lines indicate valley folds [7].

3.4. Estimating Sail Crosswind Area

The drag cross sectional area can be experimentally mapped to a rotation of the sail attachment, detailed in Table 1. The sail can be closed so that it is not visible to the wind, but the subsystem cannot be fully retracted into the CubeSat chassis.

Table 1. Cross-Sectional Area vs. Rotation from Completely Closed

Angle	0°	45°	90°	135°	180°	225°
Area (m^2)	0.01	0.017	0.029	0.044	0.063	0.084
Angle	270°	315°	360°	405°	450°	
Area (m^2)	0.12	0.14	0.18	0.21	0.25	

3.5. Sail Construction

Much of the system was made from COTS materials. The sail was folded from Mylar sheet [14]. Mylar was chosen to meet the outgassing and thermal requirements put forth by the Goddard Space Flight Center (GSFC) [12]. The folding pattern provides the necessary stiffness to maintain shape in flight.

The sail is attached using wire loops bonded to and encapsulated in the corners, shown in Figure 6. A second layer of the sail material is layered on top of the wire loop and the stack is bonded together.

Fig. 6. Encapsulated attachment of the wire loop in the corner of the sail

DAXX MicroCoat, a space qualified UV-cured adhesive from MicroCoat Technologies [15] is used to encapsulate the wire loops in the corners of the sail. To prevent shear, it is also applied to the material at the locations of high stress concentration, which occur primarily at the folds seen in Figure 5. A 100 W/cm^2 fiber optic UV curing unit is used to cure the adhesive.

4. Technology Testing and Verification

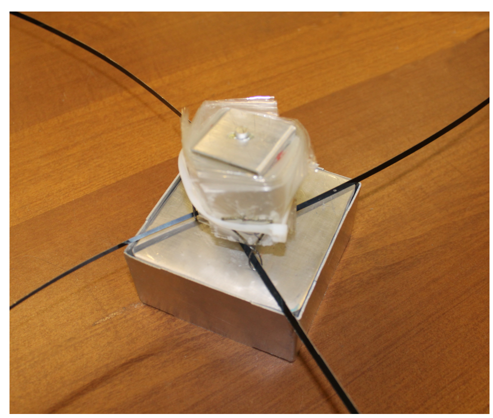

Fig. 7. Prototype of drag sail subsystem

The system is still in the prototyping phase and an image can be seen in Figure 7. Future tests include those necessary to meet the P-POD Launcher specifications [12]. Thermal, vacuum, and fatigue tests are among the most vital to ensure that the sail subsystem will survive in space. Preliminary fatigue testing has been successfully performed on the sail, and suggests that the sail will not fail due to fatigue.

The preliminary sail fatigue test was performed using a set of permanently deployed booms and an Arduino Uno as a controller. Each test cycle consisted of a complete open and close cycle with a pause in between. The opening and closing both consisted of 1.25 revolutions of the motor and were executed at 20rpm. After every 20 cycles a camera recorded an image of the opened sail to monitor any damage. The current draw of the motor was also recorded every 200 cycles by measuring the voltage across a known resistor.

In testing the first three sails, Sails A and C failed from encapsulation degradation and delamination (see Table 2). In these initial sails, the adhesive used to mount the sliding attachments shown in Figure 6 failed prematurely and allowed the sliding attachment to detach from the drag sail. These failures illustrated a weakness in the existing manufacturing process. The sail, guide ring, and encapsulating Mylar are now pressed with Styrofoam and clear acrylic sheet during the manufacturing process. This allows for even distribution of the adhesive and ensures a proper bond is achieved while the epoxy cures. After modifying the procedure, 3 sails, D, E, and F, have been tested and none have shown signs of failure. Each sail has passed 2000 cycles, with one surpassing 4000. This testing has shown the fatigue life of the sail is not the limiting factor for the subsystem mission life.

Table 2. Sail Fatigue Test Results

Sail	Successful Cycles	Comments
A	300	Encapsulation Failure
B	200	Incorrect command to motor
C	698	Encapsulation failure
D	2500	Successful
E	3000	Successful
F	4000	Successful

5. Discussion

Since the system is expected to remain in LEO for only a few weeks, the theoretical maximum number of open-close cycles is on the order of a few hundred. Because maneuvers last for hours or days, this number drops to the order of a few tens of cycles. Preliminary fatigue testing has shown that (excluding manufacturing defects and operator error), the sails last for thousands of open-close cycles without showing any fatigue-related damage. This suggests that sail fatigue will not be a problem, though further testing is necessary to confirm this.

Further extensive fatigue testing under anticipated in-flight conditions will be needed to verify the sail's functionality in space. This will be comprised of thermal-vacuum and radiation testing. Ideally, for thermal-vacuum testing the sail will be cycled through temperatures exceeding the extremes of the expected temperature range in orbit and opened and closed several times while exposed to these temperatures in a vacuum.

Radiation testing will occur separately to ensure exposure does not cause the sail material to weaken, become brittle, or become more susceptible to tearing on orbit. For this, the sail will be exposed to radiation levels similar to those that will be experienced on orbit in both closed and open positions and afterwards cycled through more fatigue tests to ensure acceptable fatigue life consistent with unexposed samples.

6. Conclusions

Drag sails have previously been used to propel or de-orbit spacecraft. The current research proposes the use of a drag sail that meets the CubeSat design standards. The drag sail subsystem is designed to fit in a $^1/_2$U subsystem and attach directly to existing CubeSat hardware.

Differential drag is used to maneuver the CubeSat and will be effected by the drag sail, allowing maneuvering without the use of propellant. Although the energy requirements are reduced compared to the use of thrusters, the tradeoff is that the CubeSat can only maneuver in ways that reduce orbital energy.

The drag sail system has been shown to work properly in prototype testing, and preliminary fatigue testing has been successful in showing that the sail will survive the open-close cycles necessary. After correcting the design errors that led to premature failure, all sails successfully endured at least 2000 open-close cycles, far more than would be encountered during a mission, without any signs of fatigue failure. Further testing is necessary to extend this to the conditions of space.

With accurate drag information and motor control, the sail subsystem can be used to maneuver a CubeSat without the use of propellant. This allows the use of lower-cost, propellant-free satellites, and reduces the barrier to entry for LEO spacecraft. This sail subsystem is able to be integrated into a CubeSat as a self-contained unit at the end of a stack.

Acknowledgments

This research was supported by the U.S. Office of Naval Research (ONR) Contract No. N00014-13-1-0536, and by Rensselaer Polytechnic Institute internal funding.

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