UNIVERSITY OF FLORIDA
UF JUR
JOURNAL OF UNDERGRADUATE RESEARCH ISSN: 2683-0668

Controlled Spacecraft Re-Entry of a Drag De-Orbit Device (D3)

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Abstract

The University of Florida Advanced Autonomous Multiple Spacecraft (ADAMUS) lab is developing a drag de-orbit device (D3) for CubeSats (small spacecraft intended for university and research group use). By modulating the D3 drag area, decaying orbital maneuvering and partial attitude control can be performed, and the host satellite can be made to de-orbit in a desired location. This paper details the design, manufacturing, and testing of the D3. Four retractable deployers are used to vary the drag area from 0.01 m^2 to 0.5 m^2. Each deployer is actuated independently using a brushed DC motor to drive the boom. An encoder affixed to the deployer measures the distance that the boom travels and the number of rotations it takes to reach that distance, and is used to stop the rotation after a preset distance. All manufacturing of the D3 device is performed in-house using a Computer Numerical Control (CNC) milling machine and manual lathe. Testing of the D3 consisted of thermal testing, fatigue testing, and vacuum testing. After initial testing of the D3, it was determined that another iteration will need to be made with slight adjustments to the design.

*Keywords:*D3, de-orbit, satellite

Introduction

As the number of space vehicles being launched increases, there is an increasing concern for orbital debris mitigation. NASA requires that all Low-Earth Orbit (LEO) spacecraft must de-orbit within 25 years [1], which means that there is a need to investigate methods of expediting the re-entry of spacecraft so they do not remain in orbit too long. Aerodynamic drag is one method to control re-entry location and de-orbit a LEO spacecraft without using thrusters. Several teams have developed drag devices such as single-use drag sails that cannot be retracted [2,3] or are limited in their capabilities by how far they can retract [4]. To date, there has not been a successful targeted de-orbit of a small spacecraft using entirely aerodynamic drag..

To fill this need, the University of Florida Advanced Autonomous Multiple Spacecraft (ADAMUS) Lab is developing a drag de-orbit device (D3) for CubeSats and other similarly sized spacecraft. By modulating the D3 drag area, orbital maneuvering can be performed, and the host satellite can be made to de-orbit in a desired location. The drag de-orbiting device consists of four retractable tape-spring booms and was designed and manufactured to validate the targeted re-entry of a CubeSat in LEO in addition to orbital maneuvering, reducing orbit lifetime, and avoiding collision [5].

Methodology

Drag De-Orbit Device (D3) Overview

The D3 consists of four retractable deployers, each containing a brushed DC motor. Each motor controls the drag area of a steel tape boom inclined at 20 degrees relative to the baseplate of the satellite to which the D3 is attached (Figure 1). This dart-like configuration allows the satellite to aerodynamically stabilize up to an altitude of 700 km. Each boom is actuated independently so that a clear minimum moment of intertia axis and an arbitrary drag torque configuration can be created. Attached to the shell of each deployer is an encoder that maps the boom deployment to the motor rotation in order to control the drag area. The deployment of each boom rotates a urethane roller, and this rotation is captured by the encoders. The D3 also contains five magnetorquers (solenoids) that will damp attitude oscillations.

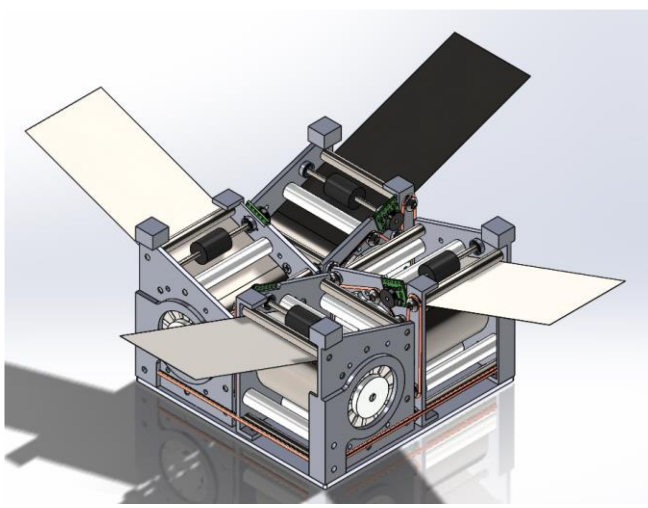


Figure 1. Four deployers are attached to a base plate to make the drag device.

As seen in Figure 2, each deployer consists of a male (1) and a female (2) outer shell held together by screws (12), which also acts as axles for PTFE (Teflon®) rollers (11). These rollers guide the 3.7 m long boom as it moves in and out of the deployer. The boom (17) is rolled up and attached to a drum (7) that encloses the motor (16), which is held to the drum with a set screw (14). Covering the drum is a sleeve (6) that attaches the drum and boom subassembly to the female shell. Bearings (3) on the inside of the male and female shells are held in place by the drum and sleeve to aid rotation. Below is an expanded view of the entire D3 deployer assembly.

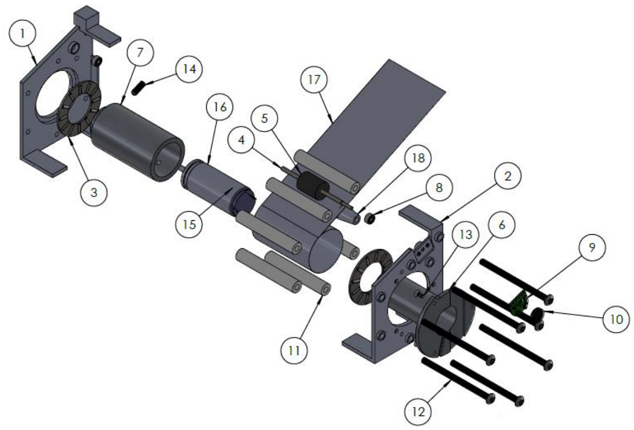
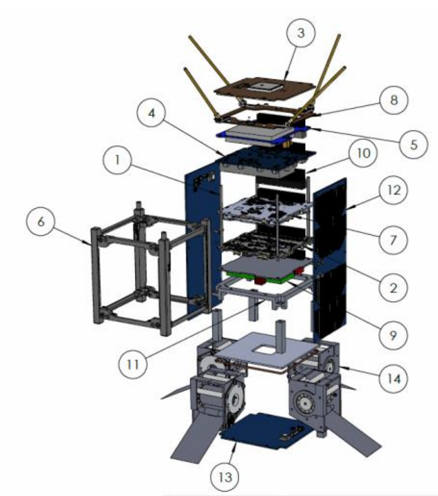


Figure 2. Expanded view of the D3 deployer.

CubeSat Design

The D3 system is mounted in a host satellite, a 2U CubeSat that is designed to perform testing of the D3 device and demonstrate point targeting algorithms required to de-orbit the satellite (Figure 3). It hosts five avionics boards and contains a custom-made adapter stage and base plate that will attach the D3 device to the rest of the CubeSat. The faces of the satellite contain custom-made solar panels (Figure 4).



ITEM NO.	PART NUMBER	QTY.
1	Post	4
2	Clyde_Space_EPS	1
3	piPATCH-L1_Integration_Model	1
4	Clyde_Space_Radio	1
5	piNAVi-L1 Integration Model	1
6	ISIS CubeSat STS PC104 Skeleton1	1
7	Clyde_Space_Bat_20whr	1
8	nanocom-ant430-deployed	1
9	Complete_D3_Board	1
10	Pin_Header	2
11	D3_Adapter	1
12	Side_Panel	2
13	Top_Panel2	1
14	Quad D3 with Magnetorquers	1

Figure 3. Expanded view of entire satellite assembly, including D3 device, avionics boards, and adapter stage.

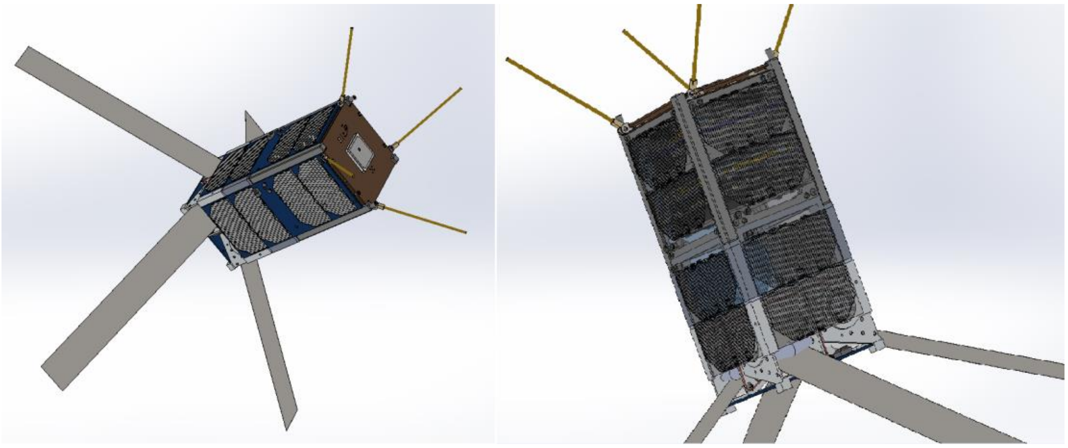


Figure 4. D3 device integrated into host CubeSat.

Manufacturing, Assembly, and Ground Tests

manufacturing and assembly plan. The D3 is designed so that each part could be either purchased off the shelf or manufactured in-house. Each deployer is manufactured from aluminum, steel, Teflon®, and silicon stock using a CNC router (Figure 5) and manual lathe (Figure 6).

Figure 5. The in-house computer numerical control (CNC) milling machine, the STEPCRAFT-2/D.300.

Figure 6. The benchtop manual lathe, produced by Grizzly Industrial.

test plan and procedures. After manufacturing the latest iteration of the D3 deployer, the deployer required vibration, shock, and thermal vacuum (TVAC) testing. Preliminary structural analysis was performed to ensure that the spacecraft can withstand the required shock and vibration levels.

Concerning thermal testing, the major area of concern is the deployed booms. If untreated, the booms will be unacceptably hot and may warp or overheat the deployment electronics. To potentially solve this issue, the booms will be treated with Insta-Blak SS-370 coating to achieve an absorptivity to emissivity (A/E) ratio of 1, which will result in an acceptable boom temperature.

Results

A total of twelve iterations of the deployer have been manufactured and assembled over the course of about two years. Each iteration required slight adjustments to various aspects of the design such as roller dimensions, roller shape, shell shape, and shell dimensions. The encoder was implemented only in the latest edition. A side-by-side comparison of the design model in SolidWorks and the manufactured design is shown below (Figure 7).

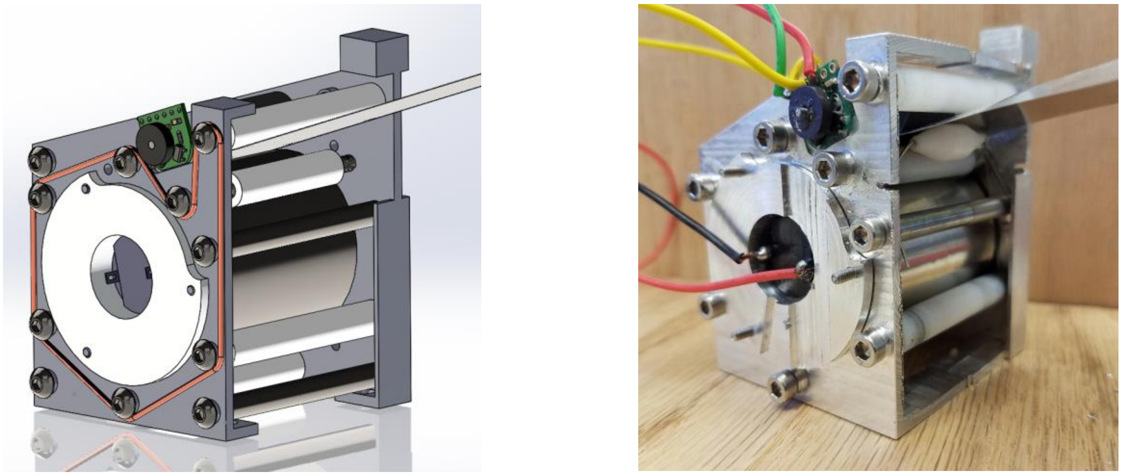


Figure 7. Design of deployer in SolidWorks (left) and manufactured and assembled deployer (right).

Fatigue and thermal vacuum testing was performed for the deployer above. The goal of this testing was to verify that the system could deploy and retract properly while in orbit. A total of 502 fatigue cycles were performed on the deployer. A screw fell out of the drum and jammed the boom, which was mitigated by redrilling and tapping the drum. Prior to adding the encoder, a stepper was used in an attempt to move the boom a specified distance. However, this type of motor was susceptible to overheating when left energized, so the deployment software was modified to include an auto-shutoff procedure. Later revisions used a DC motor, which are not susceptible to overheating unless stalled. Figure 8 below shows wear particles on the deployer after deployment testing, which are partially from the drum screws wearing on the sleeve. The remaining wear is mainly from the boom contacting the shells.

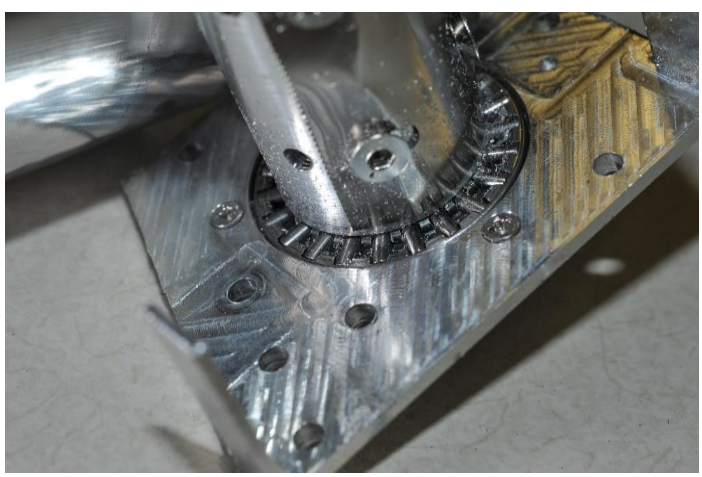
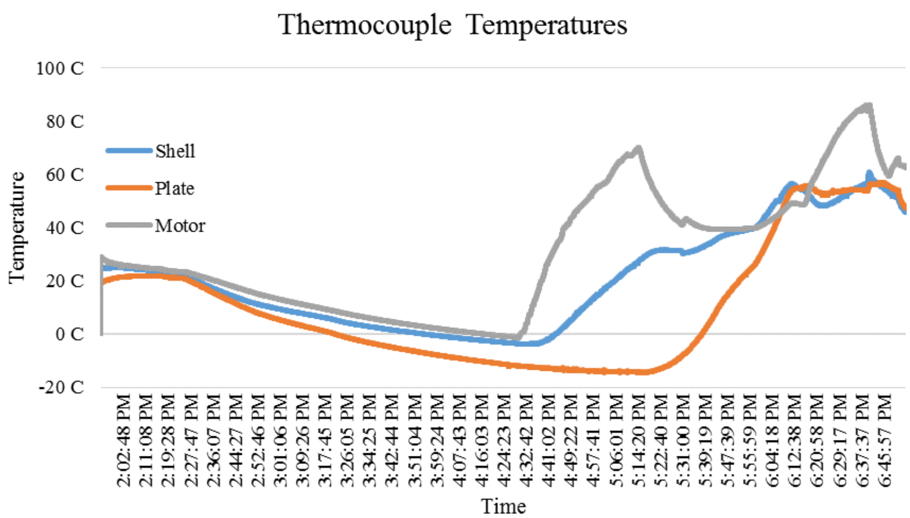


Figure 8. Wear particles on the drum base.

For the thermal testing, two thermocouples were used on the deployer shells and baseplate: one placed on what was expected to be the coldest part, the male shell, and one placed on what was expected to be the hottest part, the stepper. Forty partial cycles were performed to verify that the deployer was able to operate in the expected temperature range between -94 and 68 °C. After testing, the stepper motor was verified to be the major temperature driver in vacuum testing and it has been shown to work in both hot and cold conditions, with the boom deploying properly in all expected temperatures (Table 1).

Table 1. Thermocouple temperatures experienced during vacuum test.



Discussion

From the experimental results, it was seen that various improvements to the D3 deployer need to be made. To ensure that the deployer screws are fastened at a consistent amount of torque, four corner posts need to be added as spacers between the male and female shells. To prevent the boom from pulling in to the deployer all the way, a stopper needs to be added to the end of the boom, similar to the hook at the end of a tape measure. The location of the encoder steel shaft and the screws directly left and right of it need to be adjusted in order to achieve a 20-degree boom angle from the horizontal. Other possible adjustments include adding a roller that keeps the boom taut via a spring so that backlash (mismatch between the motor rotation and deployment length) on the boom can be reduced.

Conclusion

The results from testing the deployer determined that another iteration will need to be made with slight adjustments to design. Provided that funding is still available for the project, the boards could be purchased and and integrated with the D3 device. After assembly and launch, the spacecraft will demonstrate the operation of the drag device, orbital maneuvering using aerodynamic drag, and controlled re-entry using aerodynamic drag. Then after a successful mission, the D3 device and control algorithms will hopefully become standard tools for spacecraft attitude, orbit, and de-orbit control.

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