Mechanical Design and Deployment of a Quasi-Rhombic Pyramid Drag Sail for Safe De-Orbit of a 3U CubeSat

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Abstract

Orbital debris is rapidly becoming a more prevalent and alarming obstacle that, without immediate intervention, will undoubtedly become disastrous for human activity in space. The University of Glasgow's microsatellite society, GU Orbit, has taken action to equip its 3U CubeSat ASTRAEUS-01 with a drag sail de-orbit device. This payload represents a simple and low-cost solution for the mitigation of debris in Low Earth Orbit (LEO) and is expected de-orbit the CubeSat within 12 to 24 months, depending on solar activity. These aspects are deemed fundamental for the mission and align with GU Orbit's ethics of promoting space sustainability and accessibility. As a student society, the aim of this research is to demonstrate the viability of a drag sail technology in the absence of large monetary investment.a

In this article, the studies on the structure, material and Hold-Down and Release Mechanism (HDRM) of the drag sail system are evaluated and briefly discussed. The discussion starts by illustrating the 7m² quasi-rhombic drag sail that will deploy to increase the satellite's atmospheric drag and allow the spacecraft to lose altitude and re-enter the atmosphere. Various aspects of the geometry and folding technique used to fit the drag sail on the CubeSat are analysed. Phenomena of material degradation such as thermal and oxygen degradation have been accounted for in the design to mitigate their effect over the duration of the mission. Tape spring booms coiled around a spool will release the drag sail from its folded state maintained throughout the mission. These have been dimensioned through a mathematical model in order to provide optimum deployment dynamics for the drag sail. The paper describes also how a simple and economic nichrome burn-wire HDRM has been integrated with the drag sail design to trigger the release sequence of the cover doors and the drag sail itself.

Keywords

GU Orbit, CubeSat, ASTRAEUS-01, drag sail, deployable, gossamer, space debris, LEO, student society, HDRM, sustainability

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Nomenclature

A	*Area*
r	*Radius*
B	*Base length*
L	*Length*
L_b	*Boom Length*
t	*Thickness*
α	*Apex half-angle*
β	*Subtended Angle*
R_T	*Transverse Radius of Curvature*
R_L	*Longitudinal Radius of Curvature*
R_e	*Reaction Efficiency*
Δm	*Mass loss*
ρ	*Density*
φ	*Incident Atomic Oxygen Flux*
t_E	*Exposure time*
A_E	*Exposed Surface Area*

Acronyms/Abbreviations

AO	*Atomic Oxygen*
CoM	*Centre of Mass*
CoP	*Centre of Pressure*
GPU	*Graphics Processing Unit*
HDRM	*Hold-Down and Release Mechanism*
IADC	*Inter-Agency Space Debris Coordination Committee*
LEO	*Low Earth Orbit*
PCB	*Printed Circuit Board*
QRP	*Quasi-Rhombic Pyramid*
UV	*Ultraviolet*

1. Introduction

ASTRAEUS-01 is a 3U CubeSat mission currently being developed by GU Orbit, a student society at the University of Glasgow. The objective of the four-year-long mission is to gather Earth surface data. The payload for Earth observation is composed of a camera and a Graphics Processing Unit (GPU), which utilises on-board processing as a novel method of optimising data processing and transmission to Earth. The operational altitude of the satellite will be between 500 and 600 km in a Low Earth Orbit (LEO).

The drag sail is a secondary payload that will be included on board ASTRAEUS-01. It consists of a deployable thin-film membrane whose purpose is to increase the satellite's atmospheric drag, allowing the spacecraft to decay and re-enter the atmosphere within two years instead of five. This happens due to the interaction of the drag sail with the Atomic Oxygen (AO) present in LEO. For this reason, the material of the drag sail must be selected by considering the effects of its interaction with the space environment, namely the drag area lost due to degradation from AO interaction and thermal radiation. Sail erosion can manifest within a matter of days post-deployment, culminating in a thickness loss of approximately 3.15 μm per year [1]. The sail is of quasi-rhombic pyramid (QRP) [2] shape and will be folded and stored within cartridges until the de-orbit phase commences.

The main purpose of equipping ASTRAEUS-01 with this payload is to make the mission as sustainable as possible. At the end of its life, the CubeSat will deploy its drag sail to begin the de-orbit phase of the mission. This will prevent the creation of additional orbital debris that it is well known to be an alarming obstacle to current and future human activity in space. Indeed, this debris poses a catastrophic threat to active space missions, hence leaving ASTRAEUS-01 in orbit would only contribute to accelerating the phenomenon of Kessler Syndrome.

2. Drag Sail Membrane

2.1. Material Selection and Stowage

The primary requirements of the drag sail membrane material are twofold. Firstly, it is required to be sufficiently resistant to AO and UV radiation degradation such that its area will not reduce by an amount that would compromise the de-orbit timeline. Secondly, the sail material should be transparent to minimise disturbance torques from solar radiation pressure that, in sun-synchronous polar orbits, perturb the spacecraft's attitude in such a way that lessens the sail's effective area [3]. Kapton film meets this latter requirement, however, it is susceptible to degradation. For this reason, it is proposed to employ a 12.7 μm Kapton film with a 300 Å aluminium protective coating as the sail material. Stowage of the sail is achieved by utilising a folding pattern with high packing efficiency – in this case, the Miura-Ori fold (see Figure 1).

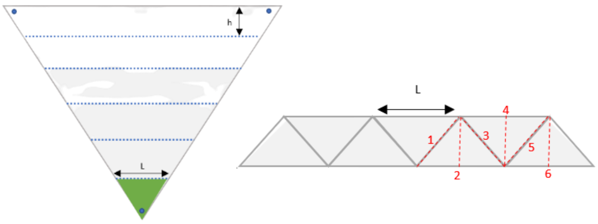


Figure 1: Drag sail folding pattern.

2.2. Dimensions

The effective drag area of the sail will heavily influence the de-orbit duration of the CubeSat. The size of sail required is itself highly dependent on the mass, altitude, and orbital inclination of the host satellite. Various studies have shown that, for a 3U CubeSat, a drag area of 4m² is sufficient to fall well within the IADC's 25-year de-orbit requirement [4]. In fact, a preliminary analysis by GU Orbit estimates a de-orbit time of slightly under two years for a 6kg 3U CubeSat with a 4m² drag area.

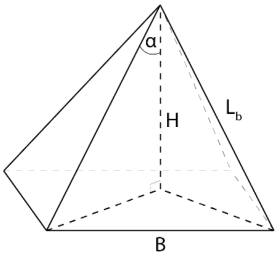
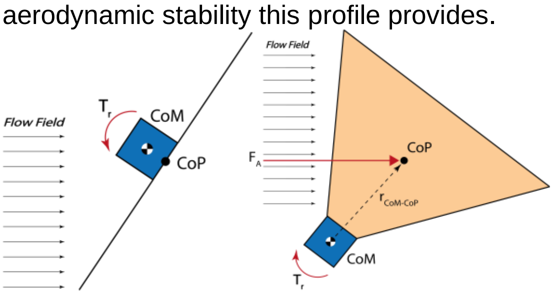


Figure 2: Geometry of a QRP drag sail with important dimensions labelled.

Figure 2 shows the geometry of a QRP sail, as proposed by Ceriotti et al [2]. Taking the base to be square, B is 2m for a 4m² sail (frontal drag area). The boom length L_b is determined by the apex half-angle α. Ideally, the booms should be as long as the CubeSat's volume and mass constraints permit in order to maximise the principal moments of inertia about the y- and z-axes, thus increasing the perturbation torque required to generate undesirable angular accelerations [5]. An apex half-angle of 30° gives the CubeSat an aero-stable profile and, to retain a 4m² frontal drag area, requires booms of length 1.87m, resulting in a 7m² sail area when projected onto a flat plane.

2.3. Aerodynamic Characteristics

When compared to a flat sail, the CoM and CoP of a pyramidal sail are significantly further offset from one another, as illustrated in Figure 3. This results in a far greater restoring torque T_r for the same applied force F_A. Moreover, the sail's QRP shape increases the effective drag area exposed to the flow field on the side of the angular offset, further augmenting the restoring torque [6]. The nominal reduction in frontal area is deemed a worth sacrifice for the additional aerodynamic stability this profile provides.



(a) Flat sail (b) Pyramid sail

Figure 3: Aero-stability comparison between a flat sail and a pyramid sail

3. Booms and Deployment Dynamics

To successfully deploy the drag sail, there must exist a deployable structure to which it can attach. A typical low-cost and relatively simple solution is the implementation of tape spring booms. Tape springs are thin strips of material with an initially curved cross-section and are of increasing interest for nanosatellite applications. To design a safe and reliable drag sail deployment mechanism, it is vital to have a firm understanding of tape spring deployment dynamics.

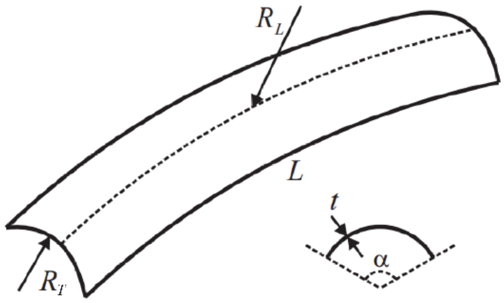


Figure 4: Geometric characteristics of a typical tape spring, adapted from [7].

The standard geometric parameters of a tape spring have been defined in Figure 4. These, in tandem with material properties, can be used to study tape spring dynamics (Beryllium Copper has been selected for testing purposes). The transversal radius of curvature R_T corresponds to the radius of the spool around which the boom is coiled. This radius of the spool around which the boom is coiled will determine how energetic the deployment is, with a smaller radius resulting in more violent deployment and vice versa. A balance must be struck to ensure the deployment is sufficiently energetic to full deploy the sail without risking tearing or detachment. Another important consideration is that the spool radius should be approximately equal to the boom's transverse radius of curvature R_T to avoid buckling during deployment. A mathematical model was developed to study boom deployment dynamics and optimise the geometry accordingly.

4. Deployment Mechanisms

4.1. Spool and Boom Mechanism

While in their stowed states, each tape spring boom will be coiled around a spool (see Figure 5). Once released, angular contact bearings will allow the spools to spin, resulting in extension of the booms and deployment of the drag sail.

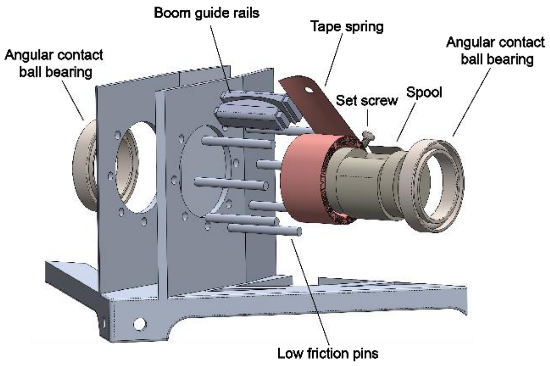


Figure 5: Exploded view of spool and boom CAD assembly.

4.2. Hold-Down and Release Mechanism

HDRMs are electromechanical devices used to deploy payloads on the satellite. These devices fall into two main types: pyrotechnic (explosive) and non-pyrotechnic. A first list of requirements was developed prior to the selection process of the best HDRM as reported in Table 1. In general, it was agreed that the HDRM task of stowing the drag sail was more important than its release because an accidental deployment would undermine the whole mission. For this reason, the HDRM of the drag sail shall meet some rigorous requirements in order to be employed on the CubeSat [10].

Table 1. List of HDRM high-level requirements

Requirement Number	Requirement	Description
1	*Redundant*	Back-up mechanism necessary
2	*Reliable*	>90% chance of successful deployment
3	*Synchronous*	Mechanism must activate at same time at different locations
4	*Controlled*	Actuation must be controlled by host spacecraft
5	*Safe for Space Environment*	No hazard shall be posed to space environment (debris, cords hanging, etc.)

Universities, private companies, and space agencies have developed different architectures of HDRMs, each one particularly suited for a specific application. In the case of ASTRAEUS-01, it was decided to maintain the drag sail in its stowed configuration using a set of cords, hence pyrotechnic HDRMs such as separation nuts were immediately discarded. The team therefore evaluated two of the most common devices used on CubeSats, namely the CYPRES™ Cutters and the Nichrome Burn-Wire Mechanism. Additional requirements were developed in order to proceed with a rigorous selection of the best HDRM for application on ASTRAEUS-01:

- Low Volume – the HDRM must occupy the least amount of space. The gap between the drag sail structure wall is very limited.
- Low Weight – the device must be as light as possible to limit the total mass of the CubeSat. This could have a significant impact on launch costs.
- Reliability – this requirement comprises redundancy, years of mission, percentage of successful deployment and humidity acceptance. The HDRM must prevent accidental deployments and account for a possible failure.
- Power Efficient - the power consumed by the mechanism must be compatible with the power supplied by the Electric Power System (EPS).
- Cost-effective – to demonstrate the accessibility of the technology.
- Complexity – manufacturing and integration within the drag sail structure.

CYPRES™ cutters have been proven to be extremely versatile devices by Cranfield University, who employed them on their TechDemoSat-1 [12]. These devices are extremely reliable since they are used as parachute tether-cutters in reserve chute deployment and therefore are commercially available and inexpensive. Despite the several advantages stated above, the cutter has a length of 48mm [8], which makes them unsuitable for installation within the drag sail structure of ASTRAEUS-01. The focus shifted to the Nichrome Burn-Wire Release Mechanism, developed at the Naval Research Laboratory (NRL). This mechanism uses a nichrome burn wire, which heats up when activated and cuts through a Vectran cord effectively used as a hold-down mechanism [2]. This HDRM has been tested in both air and vacuum, also with Vectran cords of different thickness. The significant advantages identified in this mechanism are its simplicity, high customisability and low cost that make it more accessible to university CubeSat projects. Tension in the cord and cutting time (dependent on operating conditions) are however key aspects that need further investigation.

The final design of the burn-wire mechanism took inspiration from a device developed by the Naval Research Laboratory [9]. The size of the component was critical since the space in the drag sail structure is very limited. In order to successfully deploy the drag sail, a clean cut must be executed to sever the hold-down cord and release the booms. This can only be achieved by supplying a constant current of 1.60±0.05 A to ensure that a reliable cut will take place while preventing the nichrome burn-wire from overheating [9]. The design shown in Figure 6 uses two M1.6 bolts to fit the mechanism to the wall of the drag sail structure and two M2.5 screws hold the nichrome burn-wire in position and ensure that the electrical connections are in contact with the wire. The electrical connections will be fed directly from the PCB.

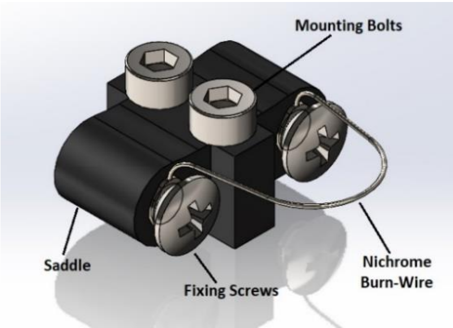


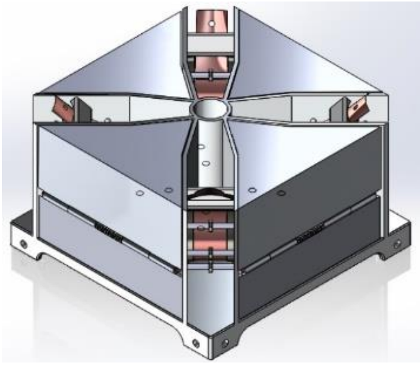
Figure 6: CAD model of initial nichrome burn-wire HDRM.

4.3. Housing Door Mechanism

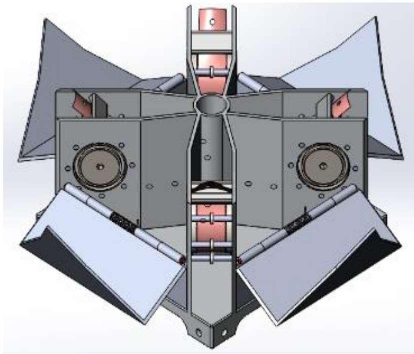
The drag sail membrane needs to be covered and protected throughout the mission to prevent any possible damage caused by environmental effects of LEO. In particular, the membrane cannot be exposed to AO and UV radiation as these would deteriorate its surface (erosion), eventually leading to holes and damage of the sail that would undermine its successful deployment and functioning [1]. A deployable cover compatible with the existing drag sail structure was therefore designed after having defined the main design criteria stated above. In addition to the environmental requirements, minimisation of weight and cost were also key elements to obtain the best design. Using the material selector Granta EduPack in combination with material data from NASA [1,13], it was decided to design the drag sail covers using anodized aluminium. According to NASA reports, the reaction efficiency of most metals is relatively low, with values approaching zero for aluminium and magnesium:

$$R_e = \frac{\Delta m/\rho}{\varphi t A} \qquad (1)$$

This implies that these materials do not show any macroscopic changes when exposed to LEO effects and are therefore suitable for application on ASTRAEUS-01 [1]. The design chosen for the cover doors consists of two sections, one fixed and the other able to open when the HDRM is activated. The two sections of the cover are connected by a hinge and the deployment is actuated by a torsion spring as shown in Figures 7. The doors will be held closed by a cord similar to the one used to hold down the booms. The same type of burn-wire HDRM will be used to trigger the deployment of the cover doors prior to the opening of the drag sail itself.



(a) Undeployed state



(b) Deployed state

Figure 7: CAD of drag sail assembly.

4.4. Final Configuration

ASTRAEUS-01 will be equipped with four burn-wire mechanisms that will be installed on the internal walls of the drag sail structure as shown in Figure 9. A Vectran cord will pass through the four doors, keeping them closed throughout the mission. HDRMs 1 and 3 in Figure 8 will be used to cut the cord and release the doors. Similarly, another cord will prevent the spools from deploying and it will be cut by HDRMs 2 and 4. With this configuration, the deployment of the doors is independent from the deployment of the drag sail and, by using two HDRMs for each deployment, the necessary redundancy is ensured to increase the reliability of the release system. This critical deployment will be extensively tested, also considering the addition of an extra two cords to prevent any premature deployment that would undermine the mission.

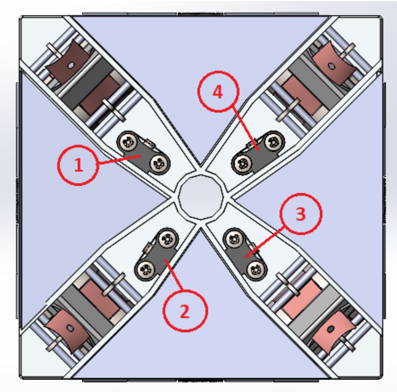


Figure 8: Disposition of HDRMs within ASTRAEUS-01.

5. Discussion

The next step on improving this technology is to make it a system useful not only for the end-of-mission phase, but also for tasks such as attitude control [11] or even orbital transfer without the need of a propulsion system. Moreover, with the development of materials engineering, optimised alloys will appear and set a new and improved standard in terms of performance and area-to-mass ratio.

Throughout the design process of the drag sail subsystem presented in this report, modularity and compatibility with standard CubeSat form factors has been a top priority. It is hoped that the development of this low-cost and versatile de-orbit technology can make space sustainability more widely accessible, particularly for start-ups and SMEs in the burgeoning nanosat sector.

6. Conclusions

This paper has presented the design selected for the drag sail of ASTRAEUS-01 and its deployment mechanism. This payload is extremely significant to GU Orbit for preventing the accretion of space debris that could undermine present and future human activities in space.

The quasi-rhombic design of the drag sail shall facilitate the de-orbit of the 3U CubeSat within 12 to 24 months by exploiting the interaction with the AO present at the CubeSat's operational altitude**.** Kapton has been selected as the constituent material of the drag sail membrane. Despite its known mechanical, thermal, and optical properties, the membrane will be extensively tested to ensure that the mounting points to the booms and structure do not pose any risk to its structural integrity (i.e. internal stresses). The deployment of the four membranes that constitute the drag sail will be completed using tape spring booms, each coiled around a spool when stowed.

Finally, the deployment of the drag sail will be actuated by a HDRM, which for ASTRAEUS-01 has been selected to be a nichrome-burn wire. This inexpensive and versatile mechanism will be used to sever the cords that prevent the tape springs and protective drag sail cover doors from deploying. The design will be further optimised for the available volume of the drag sail structure and rigorous testing will be used to validate this HDRM for ASTRAEUS-01's mission.

Acknowledgements

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