Graphene Foam Deorbit Sail with Failsafe Release Mechanism

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Space debris in Earth orbit poses a major threat to the future of the global space industry, for both manned and unmanned missions. Since advancements in electronics have made small satellites viable and affordable, nanosatellites are now being rapidly launched by both universities and small companies, with 128 launched in 2015 and many more planned for 2016 [1]. The majority of CubeSat's are not designed to deorbit within the 25-year post-mission lifetime guidelines specified by the Inter-Agency Space Debris Coordination Committee [2]. Future satellites must be designed to quickly deorbit at the end of their lifetime to mitigate the creation of additional orbital debris.

A desirable method to deorbit satellites in LEO utilizes external forces, such as atmospheric drag, by deploying a sail to increase the effective area of the satellite. Atmospheric drag creates a force opposite to the satellite's velocity vector, thus reducing the satellite's momentum and decreasing its altitude until it re-enters and burns up in the atmosphere. Importantly, atmospheric drag is an external force requiring no propulsion from the satellite and therefore can be utilized even if the main satellite system has failed. Furthermore, sails create passive attitude stabilization by offsetting the center of pressure from the center of mass ensuring that the sail base remains perpendicular to the satellite velocity.

Current sail designs require actuated booms to separate the sail from the satellite bus and to deploy the sail [3]. These actuation systems introduce significant complexity and risk to the sail design, in addition to requiring significant amounts of the satellite's volume, mass and power budgets. Several satellite sails implemented in space have not deployed properly [3], rendering the device useless and potentially creating additional orbital debris.

Overview of the Deorbit Device

The driving design requirements for this deorbit device are to achieve highly reliable and simple deployment of the sail while minimizing the volume, mass and power impacts on the satellite bus. Graphene foam, which behaves as an isotropic material under compression, is proposed for the sail material to satisfy these requirements because of its unique properties – specifically its low density, high compressibility and high elasticity. Graphene foam can be compressed to 10% of its original volume [4] and will naturally decompress to its original state. This allows construction of a lightweight, low volume deorbit device that can easily be integrated with a satellite. This device contains its own electronic release circuity that can operate independently of the main satellite bus, allowing minimal communication with the main satellite system. The novel graphene foam sail will self-deploy due to graphene's high elasticity, minimizing the mechanical complexity of deployment as compared to current satellite sails. Figure 1 displays the deployed sail attached to a 1U CubeSat structure.

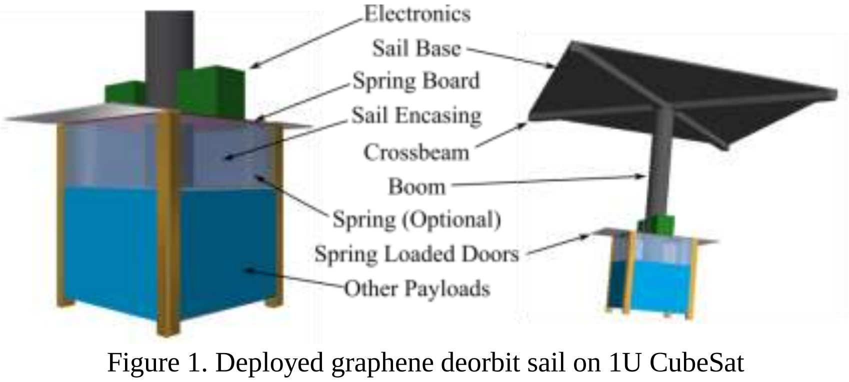


Figure 1. Deployed graphene deorbit sail on 1U CubeSat

A 1U CubeSat (1 kg) released in mean solar conditions at 550 km altitude – for a specified orbit with a semi-major axis of 6930 km – deorbits after approximately six years and a 3U CubeSat (4 kg) deorbits after approximately 15 years, without an active deorbit method. Simulations are performed to determine a suitable sail size to effectively deorbit a CubeSat. Considering the effects of cyclic solar activity [5], two separate cases are analyzed: the sail deployed at 21:00:00 UTC on 21/10/2018, as stated by the mission requirements, and the sail deployed at the start of the solar minimum, which results in the lowest atmospheric density and represents the worst case scenario. Since the sail is designed to be passively attitude stabilized, the simulations consider a conservative case where the sail has not yet stabilized and the sail base is offset from the velocity vector by 45º throughout deorbit, resulting in approximately 70% efficiency of the sail. Figure 2a and Figure 2b shows the deorbit time as a function of sail area for a 1U CubeSat and 3U CubeSat, respectively. A sail cross section of 0.1 m^2 for the 1U CubeSat and 0.2 m^2 for the 3U CubeSat are selected to provide deorbit times of 270 days and 683 days, respectively. Table 1 displays the ballistic coefficients used for these simulations.

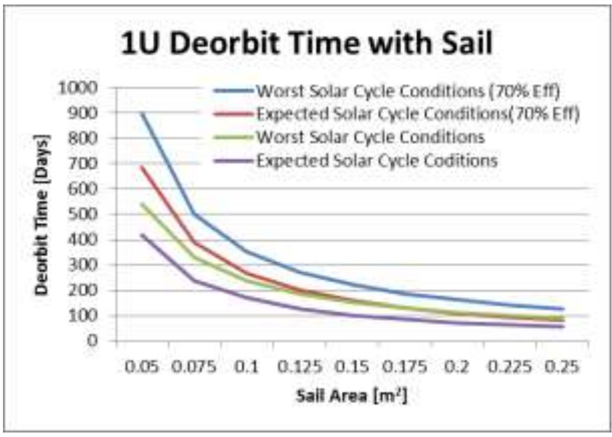


Figure 2a. Deorbit Time for 1U CubeSat (1kg)

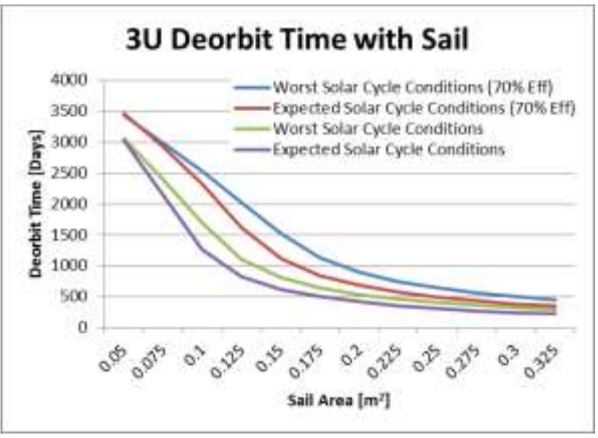


Figure 2b. Deorbit Time for 3U CubeSat (4 kg)

Sail Design

The sail design uses the desirable properties of graphene foam extensively, particularly the high compressibility and high elasticity. The sail must be compressed and rolled to efficiently fit in the encasing. The following criteria are considered when packaging the sail:

- Minimum bend radius of the graphene foam: 2.5 mm [6]
- Simple unfolding of the sail using elasticity
- Efficient use of available space

Figure 3 shows the proposed folding method. The sail base will be slightly compressed along the *x*-axis, and then rolled inwards along the *y*-axis with a conservative minimum bend radius of 4 mm, as shown in A and B of Figure 3. This ensures the crossbeams – made of thicker foam – do not fold onto themselves. Then the sail will be compressed along the *z*-axis, as shown in C of Figure 3. This method ensures no folding of the foam occurs except near the boom, and lightweight dowels are used to ensure the sail does not exceed a 4 mm bend radius. The boom will then be compressed along its length (*x*-axis). The deorbit device electronics, displayed as the grey boxes in C of Figure 3, fit between the boom and the folded rolls. This folding method is designed for the 1U, 2U and 3U CubeSat encasings. Different folding methods will need to be investigated for larger satellites. The elasticity of the graphene foam is used to deploy the sail. The compressed boom will push the sail out of the encasing, and the rolled up section of the sail will simultaneously begin to unfold, further aiding the deployment. Thus the deployment of the device only utilizes the properties of the graphene foam and has no actuated components, significantly reducing the risk of component failure. Further analysis and testing is required to determine if the elasticity of the graphene foam is sufficient to release the sail from the encasing once the graphene foam has been folded as previously described. An actuator-free spring loaded board placed in the encasing below the graphene sail may be utilized to eject the sail from the encasing if required, allowing the graphene foam to decompress and to deploy the sail.

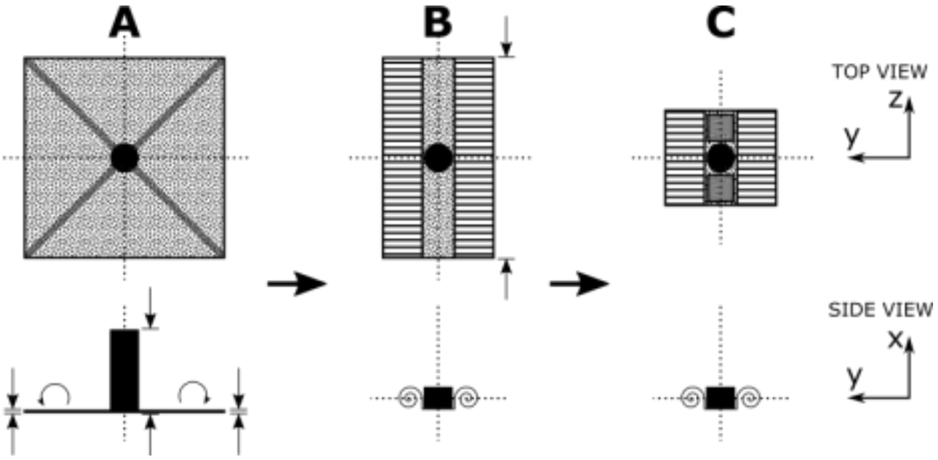


Figure 3. (A) Unfolded deorbit sail. (B) Rolled deorbit sail. (C) Rolled and compressed deorbit sail.

The base sheet consists of a 3 mm layer of graphene foam and is supported by crossbeams with a 10 mm × 10 mm cross section. The boom is attached at the intersection of the crossbeams, which is the strongest part of the sail. The boom is sized to withstand the drag forces with a safety factor of 10. The sail encasing is designed to use minimal space by utilizing the entire cross-sectional area of a CubeSat panel. The length of the boom is greater than half the width of the sail to minimize the chance of the sail snagging on the CubeSat as it unrolls. The encasing is made up of 1 mm thick aluminium to handle pressures up to 10 kPa while the graphene foam is 90% compressed [4], and further analysis will be performed to determine the specific aluminium required. This deorbit sail design is scalable to larger satellites, and Table 1 displays estimated parameters of the deorbit sail design.

Table 1. Deorbit sail parameters for 1U, 2U and 3U CubeSat configurations

Attribute	***1U***	***2U***	**Scale**	***3U***	**Scale**
Area of deployed square sail [m^2]	0.1	0.15	1U x 1.5	0.2	1U x 2
Dimensions of compressed sail [mm]	97 x 96 x 35	97 x 96 x 47	1U x 1.34	97 x 96 x 58	1U x 1.65
Mass of deorbit device payload [kg]	0.232	0.244	1U x 1.05	0.259	1U x 1.12
Typical mass of CubeSat[kg]*	1.0	2.0	1U x 2	4.0	1U x 4
Envelope encasing dimensions [mm]	100 x 100 x 38	100 x 100 x 50	1U x 1.31	100 x 100 x 61	1U x 1.6
Average power through 100 orbits [W]	0.006	0.006	1U x 1.0	0.006	1U x 1.0
Power (release) [W]	2.4	2.4	1U x 1.0	2.4	1U x 1.0
ΔBallistic coefficient [Kg/m^2]**	45.45 – 4.5 = 40.95	90.4 – 6.1 = 84.3	1U x 2.1	181.8 – 9.1 = 172.7	1U x 4.2
Expected Deorbit time with sail [days]	270	390	1U x 1.4	683	1U x 2.5
Estimated Cost [USD]***	$42,787	$56,511	1U x 1.33	$69,428	1U x 1.62

** Typical mass determined from [7]*

*** Calculated from drag coefficient. Sail modelled as a flat plate according to [8], and a conservative drag coefficient of 2.2 is used for a cube.*

**** Cost calculated based on USD $80.73 per cubic centimetre of graphene foam from [9].*

The graphene foam is the most expensive component of this device. Graphene foam has only recently become available for purchase commercially, and it is expected that the price will decrease as demand increases and the scale of manufacturing increases. Chemical Vapor Deposition is used to manufacture graphene foam [10], and this process is commonly used in the semiconductor industry to produce thin silicon wafers. The cost of silicon wafers has decreased dramatically as demand has increased and production scaled up, and a similar trend may be expected for graphene foam.

Release Mechanism Design

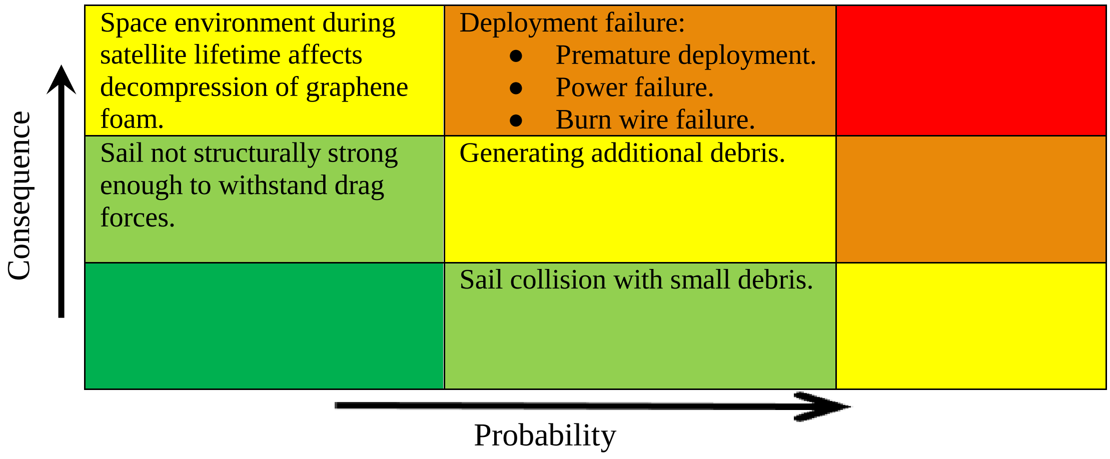
Burn wires, which have a long heritage in the space industry for deployable systems [11], are used to release spring loaded doors that contain the graphene sail. Redundancy is achieved by utilizing multiple burn wires on a single release cord securing the spring loaded doors. To ensure that this deorbit device will deploy even if the release circuit fails, the release cord will be made of a polymer that erodes from atomic oxygen emitted from the sun [12], or potentially a combination of this and commonly used burn release wire such as Dyneema. The polymer will be coated and layered such that the erosion occurs at a predictable rate, which can be estimated to within a two year window. The degradation time of this polymer-based release cord will be determined for the specific satellite that the deorbit device integrates with to ensure the device does not deploy prior to the end of the satellite's operational lifetime. Further analysis and testing must determine the reliability of using a degradable polymer for the release cord.

The circuitry that controls the release mechanism is simple, small and reliable. A small temperature robust NiCd battery [13] is considered to power the release mechanism which fits within the allocated 30 mm × 30 mm × 35 mm space with the additional circuitry. The main satellite power system will periodically charge the NiCd battery. Alternative power sources, such as long life batteries, shall be investigated to remove the need for additional charging circuitry. A timer activates deployment of the sail, and is set prior to launch to ensure the deorbit device is released even if the satellite fails. Once activated, the deorbit device batteries drive current through the burn wires to release the spring loaded doors. This release timer can be reset, or overwritten to deploy the sail immediately via a simple interface with the main satellite bus.

Risk Analysis

Several risks are identified for this deorbit device and displayed in the design risk matrix in Table 2. The greatest risk of this design, as with all satellite sails, is deployment failure. The use of graphene foam greatly mitigates the risks associated with traditional sail designs by using graphene's high elasticity to deploy the sail instead of actuators, resulting in a system with a very low probability of failure. Power failure of the release circuit and potential failure of the burn wire is mitigated by integrating degradable polymers for the release cord. Premature deployment of the sail thus represents the greatest risk to the design, and must be mitigated through extensive ground testing. Although graphene foam is stable over a large temperature range [4], it is currently unknown how the harsh space environment will affect the properties of graphene foam while compressed. Additionally, outgassing of the graphene foam is currently unknown, however other materials with similar lattice structures [14] are considered to be outgassing safe [15]. Thermal-vacuum chamber testing and radiation testing must be performed to verify compressed graphene foam retains its desirable properties throughout the satellite's lifetime.

Table 2. Deorbit sail design risk matrix



Space environment during satellite lifetime affects decompression of graphene foam.	Deployment failure: ● Premature deployment. ● Power failure. ● Burn wire failure.	
Sail not structurally strong enough to withstand drag forces.	Generating additional debris.	
	Sail collision with small debris.	

Conclusion

A proposed graphene based deorbit sail is presented for 1U to 3U CubeSat configurations to mitigate the generation of orbital debris. Graphene foam's many desirable material properties allow for highly reliable, actuator-free deployment. Furthermore, this device is power-failure resistant and independent of the main satellite systems. With this deorbit device deployed, a 1U CubeSat will deorbit in 270 days and a 3U CubeSat will deorbit in 683 days, reductions in deorbit time of 93% and 88%, respectively, when no deorbit method is used. This simple design has a low risk of creating additional debris, and is scalable to CubeSat sizes larger than 3U as well as larger satellites.

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