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Space Debris Mitigation Using Drag Augmentation Device: A Review

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Abstract: The commercialization of space has resulted in a significant increase in the frequency of spacecraft, which is adding to the already large number of objects in orbit. Therefore, future and present missions are at risk from space debris. Most of these spacecraft in orbit have very limited means of mitigation control systems. As a result, certain international regulations are imposed to obtain a license for a spacecraft for launch purposes. The necessity of a feasible debris mitigation technique enables future space missions to be safe and sustainable. This review sheds light on the drag augmentation devices such as dragsail, which can provide an effective means for accelerating the deorbiting process during the EOL phase, making space safe and sustainable without the risk of space debris.
Keywords: Dragsail, Ballistic coefficient, Deorbit duration, Space debris, Low Earth Orbit

I. INTRODUCTION

With expanded access to space, a potentially dangerous population of objects in Earth orbit has emerged. Inactive and uncontrolled objects, ranging from intact but non-operational satellites and upper stages to explosion and collision debris, currently share space with active and operational satellites. This increasing number of objects orbiting the Earth justifies great attention and interest in space observation, spacecraft protection, and collision avoidance. To avoid the growth of space debris caused by collisions that can exponentially increase the number of objects (Kessler's syndrome), debris removal/ mitigation is necessary. According to studies, at least 5-10 defunct objects should be eliminated every year to avoid an exponential increase in the debris population [1]. The objects orbiting the earth are classified on the basis of Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Orbit (GEO). Considering approximately 10,000 objects around the earth, their distribution can be categorized as 7% of operational spacecraft, 22% of old spacecraft, 17% of rocket bodies, about 13% of mission-related objects, and almost 41% of miscellaneous fragments [2]. As a result, it is very necessary to implement appropriate and feasible techniques for the removal of all this debris.

Removal/mitigation techniques are categorized into two approaches; Active Debris Removal (ADR) and Passive Debris Removal (PDR). Large objects are normally mitigated using ADR, whereas small-scale debris is removed using PDR. In the case of Low Earth Orbit missions, the residual atmosphere encountered in the thermosphere offers a potentially simple and relatively low-cost method of bringing objects down into the upper atmosphere, where they can be destroyed by the heat of re-entry. The entire objective of each mitigation technique is to decongest the LEO in order to reduce the probability of collision between different objects. When it comes to GEO, a huge number of satellites present in the orbit and uncontrolled satellites have either exhausted their propellant reserves or have failed along with additional contributions from related objects, such as explosive bolts and lanyards, etc.

A few international regulations and groups have been formed and are still rising for addressing this critical space debris issue, thereby putting up adequate guidelines, suggestions, and options for debris removal/mitigation in space. The key aspects in reference to these groups/regulations include [3], [4]:

1) Control/ Limit of debris released during normal operation
2) Reduce the likelihood of break-ups during operating phases/accidental explosions/collisions
3) Selection of Safe Flight Profile and Operational Configuration.
4) Post-Mission Disposal of Space Structures.

This paper advances further with a detailed review of the final key objective mentioned above. i.e the objective to dispose of the defunct systems at the End Of Life (EOL) or Post Mission can be achieved by integrating a standardized lightweight deorbit package or a drag augmentation device to every spacecraft planned to lift-off. As per the mitigation guidelines, the disposal maneuver of a spacecraft is strictly preferred to be 25 years after the mission has ended. The process is executed by activating a system using signals from the ground station, thereby the system responds back by deploying an aerostable drag sail (see *Fig.1*) that diminishes energy from the host orbit, subsequently accelerating it towards the lower levels of the atmosphere to burn up or get disposed of in graveyard orbit.

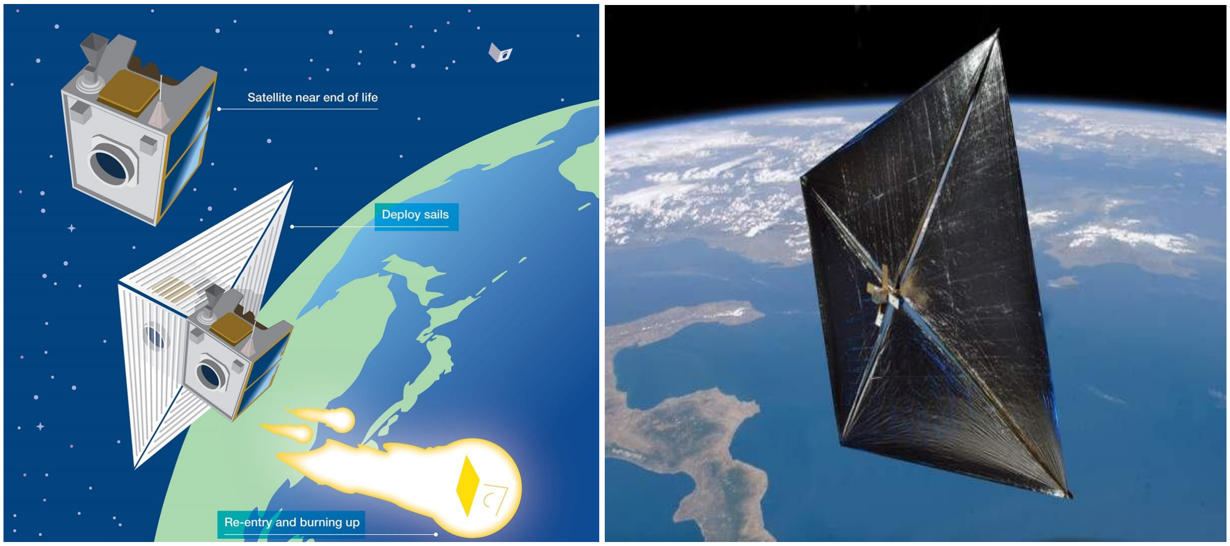

Fig. 1: Drag sail-A drag augmentation device

II. LITERATURE REVIEW

Drag augmentation is a potential, cost-effective PDR technique utilized in LEO to achieve the agenda of de-orbiting after a mission. It is not, however, effective for all objects, particularly heavier objects in orbit. Because heavier objects mean more mass, which negatively affects the ballistic coefficient of the spacecraft [5]. The capacity of a body to overcome air resistance in flight is measured by its ballistic coefficient. The ballistic coefficient C_b is given by:

$$C_b = (C_d \times A_p)/ 2 \times m \qquad (1)$$

where, C_d is the drag coefficient,

A_p is a reference surface area of spacecraft approaching gas molecules present in LEO,

m is the mass of the spacecraft

From *Eq.1*, it's quite evident that the deployment and efficiency of drag devices are hampered by a larger ballistic coefficient, making them unsuitable for the mitigation of heavier objects in orbit. Similarly, a few other factors like the aerodynamic drag, surface area, spacecraft mass [1], [6], and deorbit duration [7] are taken into account while implementing this drag augmentation technique.

Basically, a spacecraft collides with the gas particles present in the LEO and as a result, resistance/force is acted opposite the direction of velocity, called aerodynamic drag. Aerodynamic drag force equation is given by:

$$F_d = C_d \times \rho \times A_p \times v_\infty^2 \qquad (2)$$

where, v_∞ is the spacecraft velocity relative to the atmosphere.

ρ is the atmospheric density,

The atmospheric density generally varies exponentially with altitude; however, the temperature of the air also greatly affects the density and at LEO altitudes, the temperature is determined mostly by the sun. On the other hand, we know that the atmosphere rotates at a comparable rate to the Earth, v_∞ may be determined using the formula [8]

$$v_\infty = v - \omega_e \times r^2 \qquad (3)$$

where, v is the orbital velocity,

r is the position of the spacecraft, and

ω_e is the Earth's rotation rate.

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A. De-Orbit Duration

Deorbit duration of a spacecraft is set to be not more than 25 years, as per the international guidelines. Effect of various factors like ballistic coefficient, density [6], drag coefficient, altitude and area-to-mass ratios (AMR) have direct impact on the determination of this significant value. A drastic decrease in deorbit duration is observed for a space-craft with low mass and reduced ballistic coefficient. In support to this fact, Purdue University has built a 1U Cubesat [9] with an area-optimizing drag mechanism to minimise the spacecraft's ballistic coefficient and perigee altitude during each run. As a result, the predicted deorbit period has been considerably reduced. On the other hand, the duration is expected to be minimum during high solar activity hours. In a study [7] investigating seven spacecraft and dragsail combinations, various high-fidelity analysis tools were used to examine the deorbit durations for several combinations of AMR at varying initial circular orbit altitudes. The associated simulation confirms that C_d and AMR have significant effects on deorbit duration of a spacecraft attached with a drag device (Refer *Fig.1*).

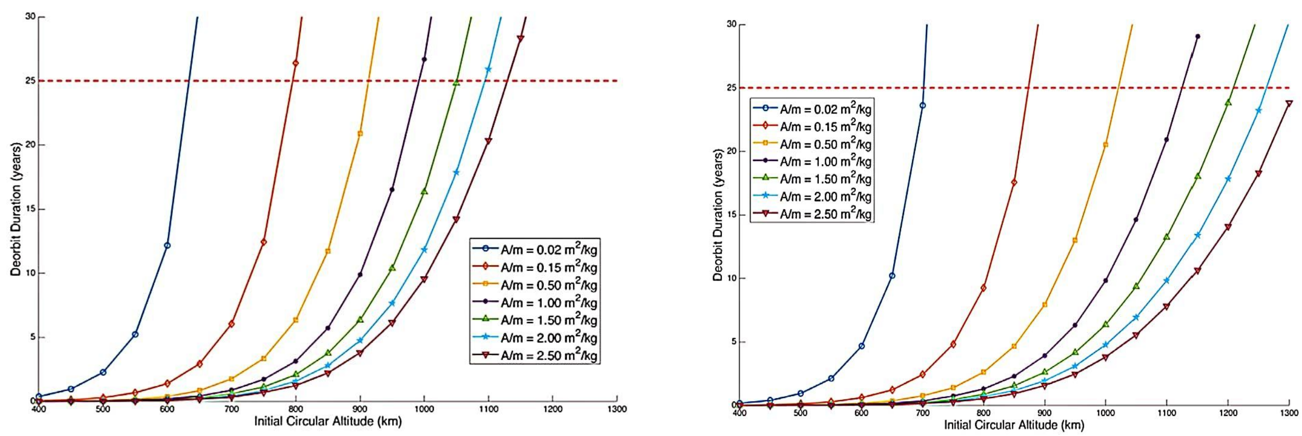

Fig. 2: Deorbit duration as a function of initial altitude and the area-to-mass ratio [7]

The influence of the dragsail in reducing the deorbit duration is quite transparent from the given graph. The deorbiting duration is found to be considerably decreased when the applicability of this analysis was tested in the SSO-A mission [10] containing a mechanical structure, "Free Flyers," that supported the 63 satellites to sun-synchronous orbit. This structure was mounted with a deorbit device, i.e two drag sails whose timing was programmed to deploy 24 hours after the Free-Flyers get separated. Based on the Deorbit Duration Analysis (DDA) techniques mentioned above, the Lower Free-Flyer is expected to deorbit in around 4 years, and the Upper Free-Flyer in fewer than 14 years.

B. Material Selection and Assembling

Environmental considerations like radiation effects, atomic oxygen interaction, and heat extremes based on range from the Sun along with the stoved volume factor affects the determination of the material for the sail membrane, which is usually made out of a thin-film substrate coated with evaporated aluminium, lithium, silver, or another metal by vapour deposition. These are generally termed as reflective substances. Polyimide films such as Mylar, Kapton, Lexan, CP-1, and CORIN can act as appropriate lightweight and flexible substrate materials [11]. These materials are subjected to Atomic Oxygen Erosion of order $3X10^{-24}$ cm^3 /atom [10]. Support structures such as battens may be included into huge sails, and film panels are bonded together at seams. The material of a sail is heavily influenced by its intended working environment. Thermal constraints, photochemical effects from ultraviolet radiation, and ionizing radiation are all concerns with polymeric materials. These impacts can result in material degradation and physical property changes.

The process of assembling involves utilizing a computer-controlled marking and cutting head to mark the fold lines. For more precise and accurate edges, computer-controlled laser cutters are chosen over scissors and sharp blades [12]. The next process is putting the sail together and taping the edge: The adhesive such as Nusil CV1142, DAXX Microcoat [13], 3M Y966 [14] are preferred to tape the sails firmly. The way the sails are packed is a crucial design factor. Many origami-inspired sail folding patterns have been proposed. The most typical approach begins with Z-folding the membrane into a single strip that may then be rolled around a drum or folded inward from either end to make a frog-leg pattern. Similarly, spiral folding patterns that are mechanised around a central hub [3], square twisted patterns are radial-folding (e.g., flasher) schemes are also under consideration for modern missions to enhance the sails's dynamics and packaging efficiency [13].

III. MAJOR MISSIONS

TABLE I
The drag sails used for different missions

Mission Name	Drag Area (m^2)	Status
Deorbitsail	25	Failed to deploy
NanoSail D1 & D2	10	D1(Failed), D2(Flown and deorbited)
Inflatesail	10	Flown and deorbited
CanX-7	4	Flown

A. Deorbit Sail

1) Deorbitsail is a demonstrative collaborative project funded by the European Union. The first flight was scheduled for 10th July 2015 which was placed in LEO successfully [15]. The mission objective was to deploy a 5m X 5m gossamer sail from a 3U CubeSat. Two major challenges encountered during the process were: 1. Manufacturing of sail and folding methods 2. Solar panel configuration [12]. Further issues occurred after the successful flight into space, because of the higher spin of the satellite. To solve this issue, the decision was taken to deploy solar panels which supplied adequate power to all the units of CubeSat. Even though the satellite wasn't stabilized, the first attempt made to deploy the sail was a failure, because motor cables were disconnected and no current was drawn to the motor. Even after many attempts, the demonstration mission was found to be a failure.
2) *Design parameters and the components:*
a) Sail is said to be stacked in the bottom 1U of the 3U system.
b) *Sail payload:* Sail storage area where double Z fold is used to store sail membrane into the small area, which sail is 5x5m in dimension which is made of 12.5 µm thick membrane. Z fold allows the sail to get bundled into 93mm × 50mm × 37mm .
c) *Boom Deployer:* Boom deployer consists of 4 carbon fiber booms, which help sail to deploy and support its structural properties.

B. NanoSail D1 & D2

1) NanoSail D1 primarily focuses on solar sail propulsion system [16] and a secondary objective to use the same solar sail (measuring about 3.3m X 3.3m) as drag sail for deorbiting the whole system from the orbit [17]. The sail membrane is coated with aluminium on the front with 2µm thickness spread all over the sail of 400m^2 in area.
2) NanoSail D2, the successor of NanoSail-D1(Failed mission) is a 3U CubeSat that is launched with objectives to test the packing and deployment efficiency of the sail and to demonstrate its deorbiting capabilities. NanoSail-D2 re-entered the Earth's atmosphere, which took 240 days since the deployment of the sail. NanoSail-D2 is the first-ever solar sail in low earth orbit, has successfully completed its mission without leaving any mark of debris [36].

C. Inflatesail

An ISRO mission, that focuses on removing the satellites from their orbit who have reached the EOL or malfunctioned in the due course of time [18]. The inflate sail is a robust, specific and one of the most useful means which can be deployed in space. Inflatable structures are a very great option to help to deal with the design and structure adjustment during launch. Inflate sail expands and contracts when required according to the situations to save the cubesat from any kind of structural or internal damage. The inflate sail satellite is generally made on 3U Cubesat platform where 1U is specifically dedicated to bus electronics and 2U is for Inflatable mass and deorbiting sail payloads. A deployable panel opens at an end and the inflation boom pushes the mechanism away from the satellite. The Mechanism almost gets expanded to 10m^2 [19]. InflateSail demonstrated how a drag sail in Low Earth Orbit (LEO) may drastically speed up the rate at which satellites lose altitude and re-enter the atmosphere. This keeps the satellite from adding to the 7,000 tonnes of space debris already in orbit, as well as causing any potentially devastating collisions.

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D. CanX-7

CanX-7 is a deorbiting nanosatellite demonstration mission of UTIAS/SFL (University of Toronto Institute for Aerospace Studies/Space Flight Laboratory) [20]. The CanX-7 deorbit technology consists of a thin film sail (See *fig.3*) divided into four distinct modules, each with a drag area of $1m^2$. Spring booms are used to deploy these sail pieces mechanically, which helps to preserve the geometry. Electronics for individual telemetry and command are also included in each module. This feature allows different components of the spacecraft to be operated independently, reducing the danger of a single failure and allowing for unique flexibility to different spacecraft geometries and ballistic coefficient needs for future missions. All four stages of the 2017 deployment were successful. After a month, the deorbit performance was evaluated. The effects of the sail segments accounted for a 20 km/s altitude decay rate at the moment of measurement, according to the deorbit profile [21].

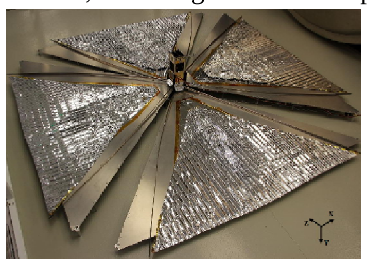

Figure. 3: CanX-7 deployed drag sail during testing

IV. CONCLUSIONS

The importance of drag deorbiting devices for effective removal and mitigation of space debris have been highlighted in the paper. According to the guidelines put forward by several space agencies, the satellites which are decommissioned has to be deorbited in a period of 25 years. However, some of the recent missions have already showcased that increasing the value of C_d (drag coefficient) and Area to mass ratio (AMR) by using drag augmentation devices like drag sail has enabled the satellites to deorbit even before the 25-year timeline. Fundamental equations related to the drag augmentation on LEO has been addressed in brief. Sails are mainly made of Polyimide films such as Mylar, Kapton, Lexan, CP-1, and CORIN which are generally termed as reflective substances. Assembling of the sail into the satellite in order to save the area during the mission is a rigorous task, especially the folding. Several missions, both experimental and passive have already been deployed and many of them have already proven effective of drag sail for the fast deorbiting. Thus, the importance of using Passive Debris Removal (PDR) techniques like Drag Sail for providing a clear and sustainable space environment is thoroughly conveyed.

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