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Design and development of a gossamer sail system for deorbiting in low earth orbit

Juan M. Fernandez [a,*], Lourens Visagie [a], Mark Schenk [a], Olive R. Stohlman [a], Guglielmo S. Aglietti [a], Vaios J. Lappas [a], Sven Erb [b]

[a] Surrey Space Centre, Faculty of Engineering & Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, UK
[b] ESA/ESTEC TEC-MEC, Keplerlaan 1, 2201 AZ, Noordwijk, The Netherlands

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ABSTRACT

The accumulation of space debris in low Earth orbits poses an increasing threat of collisions and damage to spacecraft. As a low-cost solution to the space debris problem the Gossamer Deorbiter proposed herein is designed as a scalable stand-alone system that can be attached to a low-to-medium mass host satellite for end-of-life disposal from low Earth orbit. It consists of a 5 m by 5 m square solar/drag sail that uses four bistable carbon fiber booms for deployment and support. Prior to deployment of the gossamer structure, a telescopic enclosure system is used to displace the sail from the host craft in order to extend the sail without hindrance from the host peripherals, and also provide passive stabilization. The principal advantage of an entirely passive operational mode allows the drag augmentation system to act as a “fail-safe” device that would activate if the spacecraft suffers a catastrophic failure. Several scenarios are analyzed to study the potential application and performance of the system to current and future missions. A detailed breakdown of the mechanical subsystems of the Gossamer Deorbiter is presented, as well as the characterization process of the deployable booms and sail membrane and the full qualification testing campaign at component and system levels. Finally, the performance scalability of the concept is analyzed.

1. Introduction

Due to the historical practice of abandoning in orbit decommissioned spacecraft, payload fairings, and launch vehicle upper stages there is currently a shell of synthetic debris around the Earth. As of October 2013 the U.S. Space Surveillance Network is tracking over 13,000 Earth-orbiting space debris objects larger than 10 cm [1]. The threat this poses to active and future spacecraft is an ever growing problem, in particular for LEO altitude regions where the accumulation of debris is more severe. There are currently no international laws that sanction the generation of new space debris. However, a number of orbit debris mitigation strategies and guidelines have been proposed over the years by NASA [2,3] and ESA [4,5]. In 2007 all space-faring nations that form the Inter-Agency Space Debris Coordination Committee (IADC) drew up a voluntary code of best practice that established mitigation guidelines to be followed in the use of outer space [6]. These include mission planning, satellite hardware design strategies, explosion prevention guidelines, collision avoidance techniques, as well as the non-regulated 25 year maximum post-mission lifetime requirement. Targeted active debris removal of high risk objects is also seen as an action needed for a sustainable Earth orbit environment.

* Corresponding author. Tel.: +44 1483686025.
E-mail address: lofaso@hotmail.com (J.M. Fernandez).

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Several studies have been funded in the last two decades to evaluate techniques for end-of-life disposal of space assets of a range of masses and initial orbit altitudes [7,8]. In the case of deorbiting spacecraft, the more widely accepted techniques can be categorized in four groups: chemical propulsion maneuvers, low-thrust propulsion transfer, drag augmentation, and electrodynamic tethers. Nevertheless, most recent case studies have only focused on evaluating propulsion technologies as means of deorbiting in LEO. For example, in [9] traditional mono or bi-propellant systems, cold gas, solid propulsion and electrical propulsion were compared and traded-off.

In the last decade advances in the field of gossamer structures have led to proposals for drag-augmentation concepts as near-term solutions for end-of-life disposal from LEO. These ultralight deployable structures may take the form of spheres [10], pyramids or shuttlecocks [11–13], dihedrals [14], and planar surfaces [15–18]. Some of these are low-cost prototypes that are envisioned for nano-satellite applications that require small deployed areas. NASA's NanoSail-D program [15] was aimed at demonstrating in-orbit gossamer technology for solar sailing and also proved the drag deorbiting capabilities of ultralight sails. The NanoSail-D2 3U cubesat launched in 2010 had a mass of about 4 kg and was inserted into a 640 km circular orbit. From this initial altitude it took 240 days to re-enter the atmosphere with the aid of its 9 m^2 thin film square sail. This was two to three times the initial expected deorbiting time [19]. The discrepancy was attributed to the sail tumbling (flat spin mode) that reduced the effective drag area. This illustrated the need for passive stabilization capability on these gossamer deorbiting concepts.

Other of the aforementioned concepts are matured systems that have gone through the qualification process needed to fulfill the set of requirements imposed for a deorbiting mission onboard a large commercial platform. The Astrium IDEAS system [14] with two V-shaped 6 m^2 wings supported by inflatable/rigidizable booms will target CNES' 100–150 kg class MYRIADE microsatellites. MMA Design LLC supplied two of its 14 m^2 square sail DragNET systems with pantograph extendable booms to deorbit the recently launched 180 kg STPSat-3 microsatellite and the 900 kg Minotaur I rocket upper stage used to insert it into its initial 500 km circular orbit [20].

In 2011 ESA funded through its ARTES 5.1 program the project "*Deployable Gossamer Sail for Deorbiting*". It entails the development to a Technology Readiness Level of 5–6 of a low-cost scalable system based on gossamer technology for the deorbiting of future European space assets. The proposed lightweight system derived from the early concept for CubeSail [21], and has been developed to target a wide range of low-to-medium mass host craft in LEO.

This paper presents a detailed overview of this ESA funded project with the purpose of assisting development efforts of similar programs aimed at tackling the problem of space debris in LEO. The main focus is to show the potential of such systems, the different analyses carried out to assess their needs, the challenges in their design, and the qualification process to satisfy the set of requirements imposed. A detailed mission and orbit analysis, and attitude control analysis of the Gossamer Deorbiter will be the focus of an upcoming publication.

2. Requirements and mission analysis

The activity carried out in the ESA "*Deployable Gossamer Sail for Deorbiting*" project focused on the mitigation of the creation of new debris within the LEO environment. The activity consisted of the development of an end-of-life deorbit system. This system, coined the *Gossamer Deorbiter*, will enable new spacecraft to comply with the European Code of Conduct for Space Debris Mitigation [5]. The objective of the Gossamer Deorbiter is, after a period of up to 15 years of storage, to deorbit space assets in LEO within 25 years using drag and solar radiation pressure. The aim is to provide an overall mass reduction of 70% compared to an equivalent all-chemical propulsion deorbiting system. For this, the total mass of the Gossamer Deorbiter needs to be below 3–4 kg for a large range of satellites and orbits. The maximum envelope of the system when stored is set at $15 \times 15 \times 27$ cm^3. It must be fully enclosed by an external system that also offsets the sail plane a significant distance from the host prior deployment of the sail in order to extend the sail without hindrance from the host peripherals, as well as to benefit from passive stabilization. The gossamer sail size to be designed manufactured and qualified was 25 m^2 but the design had to be scalable while meeting the mass performance target. It also had to make use of deployable booms for deployment and structural support. Fig. 1 shows a sequence of the different deployment stages for the concept proposed.

2.1. Mission analysis

There are three approaches for accelerating the natural altitude decay of low altitude Earth-bound spacecraft: progressively take energy from the orbit by for example letting the thin atmosphere deorbit the object with a drag-augmentation device (un-controlled deorbiting), direct retrieval and deorbiting from an initial altitude (controlled deorbiting), or maneuver to an orbit from which atmospheric drag will remove the satellite within a given time frame (hybrid-controlled deorbiting). Depending on the on-board propulsion system, the initial altitude and mass of the object, and the likelihood to survive reentry that would risk life on ground, one of these options will be selected by mission designers.

A recent publication part of this project [22] produced a wide-ranging survey of end-of-life disposal techniques and strategies for comparison against a gossamer structure. Atmospheric drag augmentation was found to be of most benefit for end-of-life disposal when an entirely passive means is required (uncontrolled deorbiting), allowing the device to act as a "fail-safe", which would activate if the spacecraft suffers a catastrophic failure. The use of an atmospheric drag augmentation system is generally applicable to sub-tonne spacecraft, or spacecraft that are unlikely to survive atmospheric re-entry, hence minimizing risk to human life. However, the sail system is also attractive for hybrid-controlled deorbiting planning if the