A De-orbit System Design for CubeSat Payloads

Eser Lokcu
3rd Jet Base
Turkish Air Force
Konya, Turkey

Robert L. Ash
Mechanical and Aerospace Engineering
Old Dominion University
Norfolk, VA USA

Abstract--**Compliance with the United Nations recommended 25-year maximum orbital lifetime requirement will restrict future standard CubeSat nanosatellite deployments to altitudes below 600 km. This paper describes a deployable aerodynamic drag device that can be incorporated in basic CubeSat satellite units that can meet the 25-year orbital lifetime constraint for initial orbit perigees of up to 900 km.**

I. INTRODUCTION

Accumulating man-made orbiting objects, with characteristic dimensions of 10 cm or greater, represent a major threat to international space commerce[1]. In 2002, the United Nations Inter-Agency Space Debris Coordination Committee (IADC) proposed a 25-year maximum orbital lifetime limit for orbiting spacecraft and their associated hardware[2], in order to reduce the buildup of orbital debris. Orbital lifetimes are controlled primarily by the initial orbit, the object's line-of-flight cross sectional area and drag coefficient, and is mass, as well as the local atmospheric density. Atmospheric density is influenced strongly by solar activity, while varying simultaneously with altitude and time-of-day, making it difficult to estimate accurately aerodynamic influences on orbital lifetimes[3].

Satellites with orbital masses of 100 kg or less are classified as *Small Satellites*, and are used for a variety of low Earth orbit applications[4]. Small satellites are divided further into subcategories according to mass, *e.g.* microsatellites (10-100 kg), nanosatellites (1-10 kg) and picosatellites (0.1-1 kg), and so on. As integrated circuits and digital processors have continued to shrink, extremely small orbital payloads can be fabricated that are capable of generating valuable scientific results. Since nanosatellites are so small they can be added to other launch manifests, supplemental payloads of high scientific and educational value can be added to other payloads with very modest costs. That was the basis for the CubeSat nanosatellite bus and P-POD launcher,[4] enabling sets of three 10x10x10 cm CubeSat payload modules to be deployed as supplemental payloads. Since the nominal mass of each module is 1 kg, they represent a potentially significant orbital debris hazard; particularly since more than 50 CubeSats are either awaiting launch or already in orbit, and most of the orbiting CubeSats are at altitudes substantially higher than 400 km, with estimated orbital lifetimes greatly exceeding 25 years. The challenge to the international community is making scientific access to space more affordable without overpopulating man-made objects in low Earth orbit. An important area of research is thus the development of small, lightweight nanosatellite subsystems that can assure atmospheric re-entry within 25 years. The design of a deployable aerodynamic drag device to de-orbit CubeSat payloads rapidly is the subject of this paper.

The ballistic coefficient is used to characterize spacecraft orbital decay characteristics, incorporating spacecraft mass, *m*, its line-of-flight cross sectional area, *A*, and associated drag coefficient, C_D, where:

$$BC \equiv \frac{m}{C_D A}. \qquad (1)$$

Unfortunately, variations in atmospheric density, and uncertainties in aerodynamic drag, limit the accuracy of those estimates. The working IADC document[2] indicates that the ballistic coefficient needed to meet the 25-year orbital lifetime requirement for an equatorial orbit with a specified perigee can vary by a factor of five or more depending on solar activity, e.g. for a perigee altitude of 400 km, acceptable ballistic coefficients can be as low as 50 cm^2/kg (small frontal area and relatively large mass) or as high as 500 cm^2/kg.

II. DEORBIT SYSTEM CONCEPTS

Active de-orbit systems such as tethers, digital solid-state thrusters, and inflatable structures proposed.[5,6] Tethers are less complicated, but require specific spacecraft orientations. Solid-state thrusters can be active de-orbit systems, promising high decay rates, but they consume propellant, incurring a significant mass penalty. On the other hand, inflatable structures can be very efficient, utilizing a small stowed volume, and requiring a small overall mass. When inflated, these systems can be towed behind the spacecraft for maximum aerodynamic drag. They also are space proven, and have been studied for use with CubeSats.[6] Inflatable drag devices are the focus here.

Since the lifetimes of objects with ballistic coefficients on the order of 100 cm^2/kg exceed 25 years when deployed at orbital altitudes above 600 km,[7] the development of an inflatable nanosatellite de-orbit device that can increase their effective ballistic coefficients sufficiently to enable initial orbit operations to start at altitudes up to 900 km, while meeting the 25-year lifetime restriction was the goal of this study. Orbital lifetime estimates for a range of ballistic coefficients and launch dates (relative to the solar radiation cycle) were performed using *Analytical Graphics, Inc. STK 9.0.1* simulation software, and it was determined that an inflatable device with a cross sectional area of 0.5625 m^2 (with a drag coefficient, $C_D = 2$) can meet the 25-year operational lifetime restriction.[8]

IIa. Inflatable Geometry Study

Spheres, pyramids, and pillow shaped inflatable geometries were evaluated based on stimated material mass, reliability and ease of construction. Thin-film materials were essential for minimum mass,[8] resulting in the need to minimize the number of joints for reliability and to minimize edge and joint bonding mass penalties.

Since a sphere has a fixed cross-sectional area, it was considered to be a very desirable shape. However, constructing that curvilinear surface from flat thin film layers was surprisingly complicated. A near-spherical shape can be achieved using multiple panels (Figure 1), but it requires many joints/overlaps and precise adhesion or bonding processes, especially at the poles, translating to an increase in overall mass. In addition, folding these curvilinear surfaces produced wrinkles translating to additional stowage volume bulk A pyramidal shape (Figure 2) was simpler that a sphere, but it was difficult to join the gores accurately, particularly at the corners. Furthermore, an inflated pyramid shape could only be achieved by incorporating ribs along the edges, incurring a mass penalty.

A pillow-shape (Figure 3) was found to be the simplest and most reliable design option.

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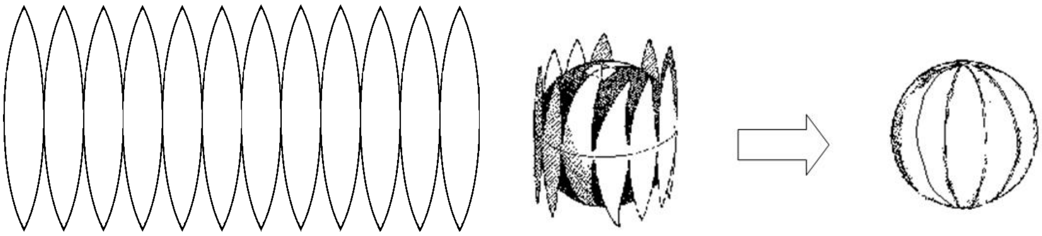

Figure 1. Fold-out and inflated view of spherical de-orbit device.

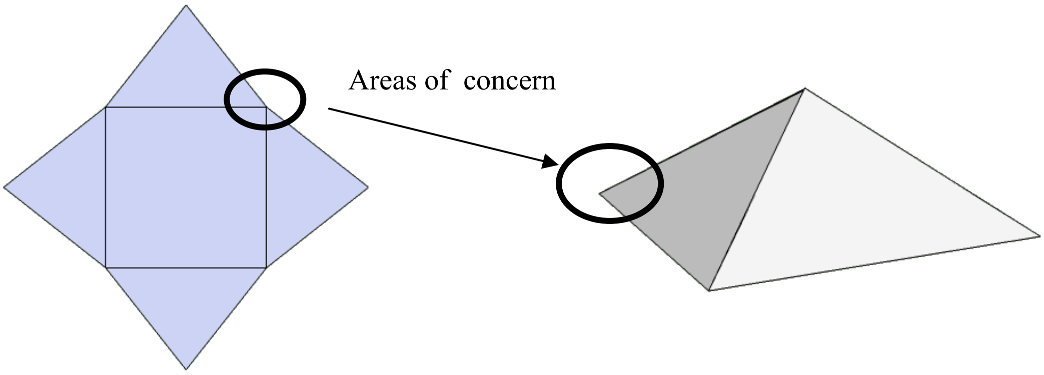

Figure 2. Fold-out and inflated view of pyramid de-orbit device.

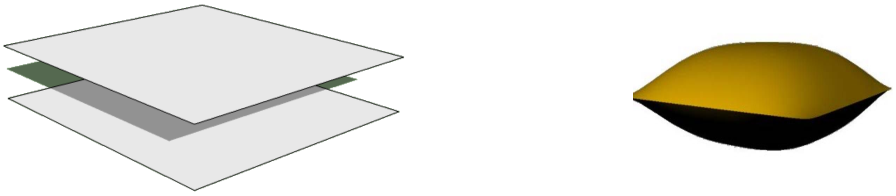

Figure 3. Fold-out and inflated view of pillow de-orbit device.

TABLE I. ESTIMATED MATERIAL REQUIREMENTS FOR DEORBIT SHAPES

	Sphere (4 panels)	***Pyramid***	***Pillow***
Material total surface area (m^2)	2.25	1.1683	1.125
Overlap joint penalty (m^2)	0.0353	0.0108	0.030
Estimated total material (m^2)	2.285	1.1788	1.155

III. MATERIAL SPECIFICATIONS

Material selection was based on: (1) durability and (2) minimization of stowed volume. The inflatable structure must endure such space environmental hazards as atomic oxygen (AO), particulate radiation, UV radiation, thermal cycling, and micrometeoroid impacts, while remaining inflated for nearly 25 years, equating to severe material durability requirements. The stowed volume must be small because the de-orbit system must fit into the volume remaining after accommodating the primary payload. Because of their characteristic low density and ultraviolet (UV) radiation tolerance, polyesters, polymides, and perfluorinated organic thin film polymers are widely used in space. They are easily stowed and can be formed into complex structures.[9] In the Low Earth Orbit (LEO) environment, the most important degradation source is atomic oxygen and, because of their combined environmental resistance characteristics, polymides were identified as the preferred thin film option. Upilex-S® with an integrated SiO_2 coating for protection against atomic oxygen degradation, manufactured by UBE America Inc., is commercially available and has good mechanical characteristics for space. A 50 µm thick sheet with an 0.1 µm SiO_2 coating was determined to be capable of meeting the 25-year-duration requirement.

IV. DEORBIT SYSTEM DESIGN

Since CubeSat nanosatellites are extremely small, the introduction of a secondary component is challenging. The component must minimize the impact on CubeSat mass and volume constraints and it must be easily integrated within the basic geometry. To meet these constraints, the proposed device design required a small container enclosing the de-orbit system components that could be integrated with the CubeSat structure by replacing the existing top panel of the standard CubeSat geometry as depicted in Figures 4 and 5. The specific folded and stowed inflatable aerodynamic drag unit is to be deployed by actuation of an onboard gas pressurization cylinder.

The CubeSat de-orbit system was allowed a maximum and volume mass of 100 g,[8] and a 150 cm^3 (out of a total volume of 1000 cm^3), respectively, and a plug-and-play de-orbit system design was adopted. Containment design constraints based on the *CubeSat Structural Requirements* document[10] were as follows:

- No external components other than the guide rails can be in contact with the P-POD.
- Aluminum 7075 or 6061-T6 are encouraged; other materials must have thermal expansion characteristics similar to Aluminum 7075-T73 (P-POD material) and must be approved by Cal Poly launch personnel.

The first design constraint translated to a requirement that the de-orbit system be integrated with the CubeSat unit by substituting it for the standard Payload Cover Plate Assembly.[11] In that way the de-orbit device storage container could maintain the general CubeSat structural integrity requirement, while meeting the guide rail constraint. The general layout of the basic CubeSat structure, along with the substitute de-orbit system container is shown in Figure 4. The de-orbit system container, depicting optimum positions for the system components is shown in Figure 5. Initially, the de-orbit storage container was to be manufactured from 6061-T6 aluminum and the dimensions of the container are 100x100x15 mm^3. The initial container design resulted in an estimated overall mass that exceeded the 150 gram allocation, but the estimated mass can be reduced further by replacing the aluminum lid with a polyimide membrane cover. The pillow-shaped inflatable structure was to be made of two layers of Upilex-S, joined together using Elastosil® S adhesive. A gas cylinder unit employing SUVA-236fa refrigerant (produced by DuPont™) was selected to inflate the structure. De-orbit system activation can be achieved using common CubeSat batteries, provided that 0.05% of their initial power remains at the time of actual activation.

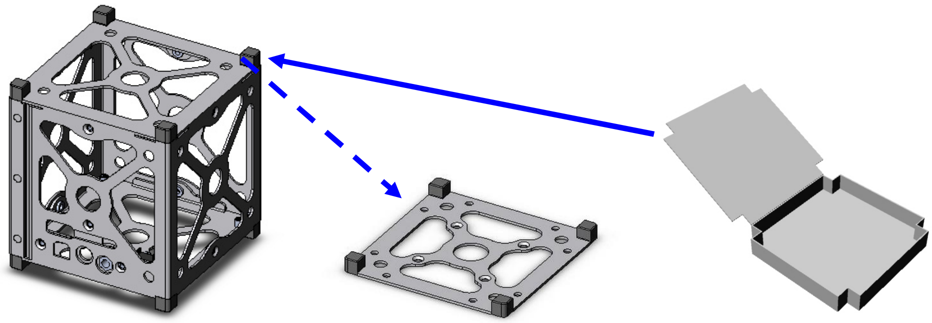

Figure 4. Payload cover assembly and de-orbit device container.

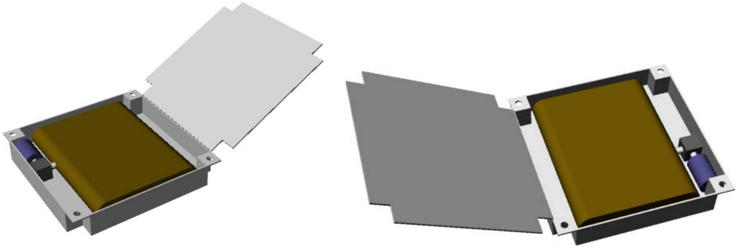

Figure 5: Final configuration of the de-orbit system.

The goal of this study was to enable a CubeSat payload to decay from a 900 km orbit within 25 years. The required cross-sectional area of the aerodynamic drag device was estimated to be 0.5625 m^2. The proposed system was a pillow-shaped inflatable structure constructed from polyimide, utilizing membrane panels joined using an adhesive to form a leak-proof inflatable structure. Folding options were examined, and the best option was identified based on prototype folding tests of a representative 0.5625 m^2 surface area membrane material.[8] Experimentation using the prototype inflatable structure demonstrated that the 0.5625 m^2 size, consisting of two 0.75 m x 0.75 m flat membrane panels was virtually the largest pillow size that could be folded small enough to fit into the 9 cm x 9 cm cross by 2 cm deep de-orbit container. As a result of testing, it was found that after inflation, the actual inflated pillow did not achieve the desired 0.5625 m^2 cross-sectional area. The square membrane panels bulged about their centers when inflated, producing an actual aerodynamic cross-sectional area of 0.37 m^2. The 0.75 m x 0.75 m membrane unit, when folded and integrated with the de-orbit system container, filled the allocated de-orbit system volume and was at the allocated mass limit, but is possible to utilize a larger 92.5 x 92.5 cm inflatable pillow system with slightly thinner material that can fit into the container in order to achieve the 900 km orbit specification. However, it was useful to assess the performance of the smaller aerodynamic device that was actually fabricated and tested.

Using the 0.37 m^2 cross section, orbital lifetime simulations were repeated using the STK 9.0.1 software, showing that the estimated orbital lifetime was slightly more than 30 years, for deployment from an initial 900 km orbit. On the other hand, CubeSat nanosatellites utilizing the smaller de-orbit system could meet the 25 year lifetime restriction if deployed at orbital altitudes of 850 km or less.

SUMMARY

Since most CubeSats are flown as secondary payloads, their orbits are fixed by the primary mission requirements, and to date many of those orbit placements are in the 600 km to 900 km altitude range where the ballistic coefficient for the basic CubeSat geometry results in predicted orbital lifetimes that greatly exceed the desired 25-year lifetime constraint. The design of a small-volume, low-mass, easy-to-integrate generic inflatable drag device for CubeSat nanosatellites has been proposed. That de-orbit system can expand future flight opportunities for CubeSat payloads while meeting international maximum orbital lifetime goals.

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