Analysis of the Performance Characteristics of a Gossamer Sail for Nanosatellite Applications

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The growing population of space debris poses an increasing threat to spacecraft operating in low Earth orbit. By taking advantage of aerodynamic drag, a gossamer sail can be used to dramatically reduce the time it will take for a satellite to deorbit. In addition to rapid deorbit time, a gossamer sail also offers the capability of stabilizing a satellite’s attitude. The deployment system utilizes compressed nitrogen gas to inflate booms that unfurl the sail. A ground prototype has been built and repeatedly tested to demonstrate the feasibility of the sail’s deployment system. The results of the deorbiting and attitude control simulations are presented, demonstrating the effectiveness of the system’s intended usage.

I. Introduction

Space debris consists of artificial objects that remain in orbit while not serving any use. Dead satellites, rocket stages, and fragments from spacecraft explosions or collisions all contribute to the population of space debris. All of these objects have the potential to collide with and critically damage operational spacecraft.

Recent events in orbit have led to a dramatic rise in the population of space debris, and with, the threat that it poses to operational spacecraft.

On January 11, 2007, the Chinese space agency launched a missile to destroy one of its own weather satellites. The satellite’s destruction produced more than two thousand pieces of debris larger than ten centimeters in diameter, making this incident the single largest production of space debris in history. The debris extends from two hundred kilometers up to more than four thousand kilometers in altitude. Much of the debris will remain in orbit for hundreds of years, posing a long-term threat to current and future space missions.

On February 10, 2009, the decommissioned Russian communication satellite Cosmos-2251 collided with and destroyed the Iridium 33 communication satellite. This was the first time in history in which two satellites accidentally collided with each other, and produced hundreds of pieces of space debris that continue to pose a threat to other spacecraft.

There are currently more than 19,000 pieces of debris greater than ten centimeters in diameter and orbit, and an even greater number of smaller objects.

In light of this, NASA has imposed several requirements in the Technical Standard 8719.14, Process for Limiting Orbital Debris, which all future space missions must conform to. One of the requirements is that all debris released during a spacecraft’s mission shall be limited to a maximum orbital lifetime of twenty-five years.

A major contribution to a satellite’s orbital decay is aerodynamic drag, which can be expressed with the equation:

$$D = \frac{1}{2} \rho V^2 C_D A$$  \hspace{1cm} (1)

where $\rho$ is the atmospheric density, $V$ is the velocity of the satellite, $C_D$ is the drag coefficient of the satellite, and $A$ is the cross-sectional area of the satellite. It is clear from this equation that an increase in the cross-sectional area will lead to an increase in the aerodynamic drag, causing the satellite to deorbit faster. A gossamer sail offers satellites this capability, and was the basis for the system that was researched in this study.

The proposed Attitude Control and Aerodynamic Drag Sail (ACADS) system consists of a compact, lightweight storage system and the folding and deployment system of a gossamer sail.

This system offers the capability to dramatically reduce a satellite’s deorbit time, as well as function as an integral component of an attitude control system. In addition to this, the ACADS has the potential to raise the operational ceiling of small satellites. A number of simulations were run to determine the effectiveness of using the ACADS for these capabilities.

The motivation for this study stemmed from the University of Central Florida’s entry in the sixth iteration of the Air Force Research Laboratory’s University Nanosatellite Program, which dictated the largest volume and mass that the satellite could be.

It is for this reason that in each of the simulations, the satellite was assumed to be a cubical prism of 2251

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dimensions 50 cm x 50 cm x 50 cm, with a mass of fifty kilograms.

II. Requirements

The NASA Technical Standard 8719.14 outlines three methods for removing satellites from low Earth orbit at the end of their operational lifetimes. These methods are atmospheric reentry, maneuver to a higher graveyard orbit, and retrieval by another spacecraft.

The delta-v required for a satellite to maneuver from low Earth orbit to a graveyard orbit is prohibitively expensive for virtually all small satellites. It is because of this that the majority of satellites that are placed in graveyard orbits are those that operate in geostationary orbits and geosynchronous orbits.

Retrieving a satellite with another spacecraft is also prohibitively expensive for nearly all small satellite programs, due to the high cost and complexity of building, launching, and operating a spacecraft capable of capturing satellites and returning them to Earth.

For these reasons, atmospheric reentry is the most popular disposal method utilized by small satellites. Most small satellites are placed in orbits in which aerodynamic drag will cause them to deorbit within twenty-five years. If the satellite is higher than this, a propulsion system is utilized to impart sufficient delta-v to cause the satellite to deorbit within twenty-five years. However, many small satellites are unable to support a propulsion system capable of performing the necessary maneuver. It is for this reason that the majority of small satellites are placed in orbits in which aerodynamic drag is sufficient for deorbiting to occur within twenty-five years. The highest altitude for this to be possible is typically no higher than six hundred kilometers.

III. Deployment System

The ACADS system consists of a square stowage box with four doors that can be opened with spring hinges, which are released via solenoid. Once the doors of the box have been opened, the sail can be deployed.

The box will be mounted to the top of the satellite, and will contain an electronics package, pressure vessel, the sail, and booms.

The stowed dimensions of the box are 35 cm x 35 cm x 5 cm. The projected mass of the entire ACADS system is expected to be less than five kilograms. A schematic of the sail stowage box is shown in the following figure:

![Figure 1. ACADS stowage box.](image)

The electronics system controls the sequence of deployment, and ensures that the booms deploy in a uniform manner. The pressure vessel provides nitrogen gas that inflates the booms. The sail is stored in four segments, with each segment stored on one side of the box. The sail segments are attached to four booms that are conically folded at each corner of the box. A schematic of a boom segment is shown in the figure below:

![Figure 2. Conical folding of boom segment.](image)

Once the satellite is in orbit, a signal will be sent to the command and data handling system, which will then supply power to the heaters, heating the booms to a temperature of 25° C. After this is done, the doors of the stowage box will be opened ninety degrees.

The ascent valves will then be closed, and it will now be safe to begin inflating the booms. A pyrotechnic cutter will be used to puncture the pressure vessel. The redundant valves will then be opened, allowing nitrogen to pass from the pressure...
vessel to the boom regulators, and the booms will begin to inflate, taking about ten minutes to completely deploy.

After the booms have been completely inflated, power will be cut to the heaters, causing the booms to cool and become rigid. After an hour has passed, the vents will be reopened, releasing any remaining nitrogen. At this point, the sail is completely and permanently deployed.

Once deployed, the sail will have a cross-sectional area of ten square meters. At the perimeter of the sail are ten turns of 30 AWG wire. The wire leads are laid down the inside of the booms and run through the stowage box, where they interface with the satellite’s power and command and data handling systems. These perimeter coils will provide magnetic attitude control once current is passed through them. By taking advantage of the large surface area provided by the sail, the coils will generate a significant amount of magnetic torque.

![Figure 3. Fully deployed sail.](image)

The sail itself is made of 7.62μm Kapton, which is 70% emissive. This emissivity is advantageous because it will allow for sunlight to reach the satellite’s solar panels after the sail has been deployed, allowing nominal power generation throughout the satellite’s mission, while also minimizing the effect of solar radiation pressure acting on the sail. The booms are made of Sub-Tg resin impregnated Vectran fabric, which is pliable when heated and becomes rigid once cooled. Heaters will be used to prepare the boom segments for deployment and then disabled when deployment is complete. The booms are painted in reflective coatings to prevent loss of rigidity once they have been deployed. Structures and materials similar to this were flown and tested on the Cibola Flight Experiment in the form of deployable antennas.

The construction of the sail is being contracted to L’garde Inc. This company has successfully fabricated and tested gossamer sail prototypes larger than four hundred square meters. These sails have been deployed successfully in vacuum chambers, and function in the same fashion as the ACADS. They have also successfully deployed inflatables in space, such as the Spartan-207 Inflatable Antenna Experiment, which was deployed from STS-77. This experiment provided valuable information about the feasibility of deploying inflatable structures in space.

The safety requirements for the Spartan-207 were extremely high in order for it to have flown on a manned mission. The success of the mission serves as a testament to the safety of using gossamer deployment systems. This is important for ACADS, where safety is also a major concern because of the use of pressurized gas in its deployment.

The major safety concern with ACADS is premature deployment, whether on the ground or during launch. To address this, the booms and pressure vessel will be vented to the atmosphere and the vacuum of space while on the ground and throughout the ascent of the launch vehicle. Not until the satellite has been released from the launch vehicle, charged, and capable of sending power to the ACADS would the ascent valves be closed and deployment be possible.

Electrical inhibits and redundant closed valves between the pressure vessel and the regulator supplying pressure to the booms provide additional mechanisms to prevent premature deployment.

In addition to these precautions, it has been recommended by NASA personnel that ACADS have at least a two fault tolerant system. Ongoing research is being conducted to determine exactly which components, such as valves and regulators, would be suitable for use in this system. The current concept for the fault tolerance system, which consists of several redundant valves and inhibits, is presented in the figure below:
IV. Ground Prototype

A ground prototype of the ACADS was built by L’guard Inc. with the assistance of UCF students for use in educational outreach and technical demonstrations. Given factors such as cost, durability, and available deployment space the system was simplified.

The boom material was changed to one-quarter inch neoprene fabric so that it could be repeatedly deployed and repackaged. The sail material was changed to 0.03 inch aluminized Mylar film for the same reasons. The increased thickness of these materials required a larger stowage box to be used. The size of the sail was reduced to 2 m x 2 m so that it could be deployed indoors. The prototype deployment system utilizes an external pressure system that is attached to a fitting at the center of the four booms. Upon inflation, the booms extend and drag the Mylar sail outward. Attached to the end of the booms are ten turns of 30 AWG wire separated by Kapton tape battens, similar to the ones that will be utilized on the ACADS.

Despite the differences in construction and material, the ground prototype provides a suitable demonstration of the simplicity and reliability of the deployment system, as the booms and membrane are folded and deployed in the same way as the final ACADS components will. This prototype has been deployed dozens of times for testing and demonstrations at various conferences. A photo of the fully deployed prototype is shown below:

V. Comparison with Similar Systems

Other spacecraft have been launched that utilize deployable structures similar to the ACADS, such as the CNES MICROSCOPE spacecraft and the JAXA IKAROS probe.

The MICROSCOPE is equipped with an aero-brake system composed of dihedral membranes attached to deployable boom lengths. The booms are made rigid by way of metallic laminate yielding, where a layered aluminum and Kapton boom is exposed to increased internal pressure to suppress geometrical defects created during folding, permanently resorting the boom to its original extended configuration. Though not requiring additional electrical power to deploy, the membrane-to-boom size ratio is less optimal, and the stowed size of the booms is larger. This requires a surface area larger than that of the ACADS storage box, which leads to a higher probability of collision with space debris.

The JAXA spacecraft IKAROS utilizes a similar square membrane composed of 7.5 μm polyimide film as a means of solar propulsion and power generation. The membrane has solar cells, dust counters, and variable reflectance liquid crystal panels mounted on the surface. Deployment was accomplished by utilizing four masses at the corners of the sail and the spinning of the spacecraft itself to generate sufficient force to unfurl the sail. This design does not require any form of rigidization, but does require that the spacecraft be kept spinning at all times to prevent the sail from collapsing.

Though IKAROS shows great promise for deep space propulsion and maneuvering, such a system is not suitable for the same mission objective as ACADS, as it would not be able to withstand the...
aerodynamic pressure experienced in such an environment.

VI. Deorbit Simulations

The Debris Assessment Software (DAS) was used to perform the debris assessments for the satellite. These assessments included deorbit simulations and the probability of collisions with objects while in orbit.

Developed by the NASA Orbital Debris Program Office at Johnson Space Center, the DAS is intended to assist research projects in performing orbital debris assessments to ensure that the space mission conforms to the requirements specified in the NASA Technical Standard 8719.14. The DAS uses the propagators PROP3D and GEOPROP, which are used by NASA’s debris environment evolutionary models.

The force models include Earth’s atmosphere and gravitational field, solar and lunar gravitation, and solar radiation pressure. Values for the solar flux are used in the atmospheric calculations, and are based on NOAA short-term predictions and NASA long-term predictions.

The DAS was used to find the highest orbital altitude the satellite could be placed in while still deorbiting within twenty-five years. After numerous simulations were run, this altitude was found to be about 580 kilometers. A plot of the satellite’s altitude history is shown in the figure below:

![Figure 4. Satellite orbital lifetime without sail.](image)

This simulation found that in 580 kilometer circular orbit, the satellite would take about twenty-two years to deorbit. If the satellite were any higher than this, it would take longer to deorbit than twenty-five years.

Another DAS simulation was then conducted, this one having the sail fully deployed on the satellite. This simulation showed a significant reduction in the orbital lifetime, as can be seen in the following figure:

![Figure 5. Satellite orbital lifetime with the sail deployed.](image)

This simulation shows the spacecraft completely deorbit in under five months, a dramatic improvement over the deorbit time without the sail.

Because the sail causes the satellite to deorbit in such a short amount of time, the satellite can be placed in a much higher orbit where the drag will cause it to deorbit within twenty-five years.

The new operational ceiling of the satellite is shown in the figure below:
Figure 6. Satellite orbital lifetime starting from 900 km altitude.

With the sail deployed, the satellite would take about twenty-five years to deorbit from an altitude of nine hundred kilometers. For satellites, this could be advantageous for satellites whose missions seek to take advantage of higher altitudes.

VII. Collision Probability

A major concern that every satellite has is the possibility that debris can be generated at any point during its orbital lifetime in the event that it collides with large or small objects. Because of this, the Technical Standard 8719.14 also requires that the probability of a spacecraft colliding with an object larger than ten centimeters in diameter must be less than 0.001. By imposing this requirement, the average probability of an operating spacecraft colliding with objects greater than one millimeter in diameter will be less than $1 \times 10^{-6}$ per average spacecraft.

Using the DAS, it was found that with the sail deployed, the probability of collision with a large object was about $1 \times 10^{-5}$. This is well within the requirements of the Technical Standard 8719.14.

VIII. Attitude Control

In addition to functioning as an effective deorbiting mechanism, the sail is also envisioned as being an integral aspect of the satellite’s attitude control system. Once deployed, the sail will act like a shuttlecock, shifting the satellite’s center of pressure to the center of the sail. This will help to stabilize the satellite after it has been deployed from the launch vehicle.

As mentioned previously, the perimeter of the sail will be laced with ten turns of magnetic coils, which, combined with two magnetic torque rods located within the satellite, will provide magnetic attitude control.

A simulation of this was created in Simulink that utilized several of the functions from the Aerospace Toolbox. The NRLMSISE-00 Atmosphere Model was used to determine the value of the atmospheric density, and the World Magnetic Model was used to determine the magnitude of the Earth’s magnetic field. The simulation implemented a quaternion representation of six-degrees-of-freedom equations of motion with respect to the satellite’s body axis.

A proportional-derivative controller used the Euler angles and their rates to manipulate the magnetic torque that was generated by the torque coils and the torque rods.

The results of this simulation are provided in the following figures:

Figure 7. Orientation.
This simulation shows that it would take about two hours for the satellite to stabilize. For a mission that may require rapid reorientation and stabilization, this may not be the system of choice. But for a mission where rapid attitude control is not required, this system is very effective.

IX. Conclusion

Orbital debris is a serious and growing threat to manned and unmanned space missions alike. If action is not taken to mitigate this threat, then the future may very well be one in which space operations are rendered utterly impossible.

Gossamer sails offer an effective means by which to rapidly deorbit satellites at the end of their operational lifetimes, as well as raise their operational ceilings. This study also showed the effectiveness at using a gossamer sail as an effective part of an attitude control system.

The successful deployments of the ground prototype have proven the feasibility and effectiveness of the ACADS deployment system.

The ACADS could provide a useful demonstration for future systems that could be utilized on satellites. Such systems may even be capable of operating independently from the main spacecraft. The advantage of having such a system is that in the event that the satellite dies, the gossamer sail still deploys successfully and causes the satellite to deorbit within twenty-five years.

References


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