The Development of a Propellantless Space Debris Mitigation Drag Sail for LEO Satellites

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ABSTRACT

The KnightSat II is the University of Central Florida's entry in the sixth iteration of the University Nanosatellite Program. The principle objective of the satellite is to deploy a gossamer sail, which will dramatically increase the aerodynamic drag acting on the satellite and reduce the time it will take to deorbit. A prototype sail and deployment system has been successfully built and tested. The other satellite subsystems have undergone extensive design and testing, and have been integrated into a working satellite prototype.

Keywords: Nanosatellite, Space Debris, Drag Sail, Mitigation, Propellantless Deorbit

1. INTRODUCTION

The issue of space debris is a growing concern. The U.S. Space Surveillance Network tracks over 19,000 objects greater than ten centimeters in diameter, and hundreds of thousands of smaller objects. All of these objects pose a serious threat to both commercial and scientific spacecraft [1].

A recent event that highlights this danger was the destruction of the Iridium 33 communications satellite when it collided with the defunct Russian Kosmos-2251. This collision generated over two thousand pieces of new debris [2]. The International Space Station has been forced to execute maneuvers to avoid collisions with debris, which further highlights the danger presented by these objects [1].

These concerns have led to the more strict enforcement of the NASA Procedural Requirements for Limiting Orbital Debris, which requires LEO spacecraft to limit their orbit lifetimes to twenty-five years [3]. NASA Technical Standard 8719.14 states that objects in LEO should be removed or placed in a storage orbit within a twenty-five year period. Objects orbiting at altitudes of less than six hundred kilometers are of little concern, as atmospheric drag typically limits their orbital lifetimes to no greater than twenty-five years [3]. Objects in altitude greater than seven hundred kilometers are of the greatest concern, as they may remain in orbit for centuries.

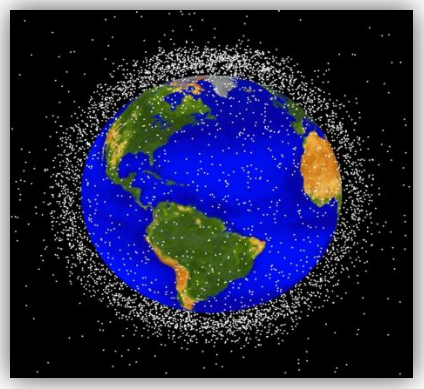

Figure 1 : A Simulation showing the larger debris in LEO. (NASA Orbital Debris Office)

Traditionally, large spacecraft have used onboard propulsion systems to maneuver in orbit and position themselves for removal. Smaller spacecraft generally lack these propulsion systems, and are restricted to an orbit of six hundred kilometers or lower to ensure that they will deorbit within the twenty-five year limit [4]. This has led to the development of propellantless orbital maneuvering systems suitable for smaller spacecraft. One of the simplest of these systems works by increasing the cross-sectional area of the spacecraft. This leads to a dramatic increase in the aerodynamic drag acting on the satellite, effectively increasing the rate of orbital decay. NASA's recent Nanosail D deployed a small experimental solar sail, which has potential to be developed into a breaking system. The future CNES mission MICROSCOPE will utilize a gossamer wing structure in an attempt to reduce its expected orbit time from sixty-seven years to twenty-five years [3]. While these systems work in their specific applications, they either cannot be scaled up to larger spacecraft with their current design, or they do not permit stable flight.

The proposed Attitude Control and Aerodynamic Drag Sail (ACADS) system will allow for a drastic increase in cross-sectional area from a compact, lightweight storage system utilizing the unique folding and deployment of a gossamer sail. This system has been tested using sails as small as 2x2 meters and as large as 20x20 meters, allowing it to be used on spacecraft of various sizes. The uniform deployment of ACADS, along with its perimeter magnetic torque coil will allow for stable flight and provide the potential for future development of propellant-less multi-orbit missions. Simulation results show that the ACADS system to be very effective in reducing the deorbit time of the satellite, which will be described in detail in a later section of this paper.

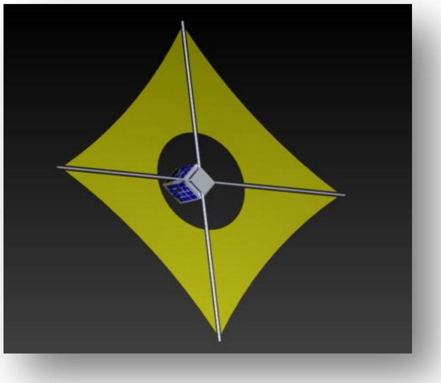

Figure 2: Deployed ACADS attached to KnightSat II

The ACADS sail system was developed as the experimental payload of the KnightSat II project as part of the Air Force Research Lab University Nanosatellite Program (UNP). The UNP provides the opportunity for university student to work with professors and industry professionals on an amateur spacecraft while competing for a launch opportunity. Students were required to design all the spacecraft subsystems from determining system requirement to delivering functioning prototypes.

This paper will detail the design development of the Knightsat II spacecraft, with the primary focus being the ACADS payloads, covering the design requirements and overviews of the support subsystems and the spacecraft structure. This will be followed by a discussion of the simulations used to determine the effectiveness of the sail, as well as the ability of the spacecraft structure to meet UNP requirements.

2. DEVELOPMENT OF ACADS AND KNIGHTSAT II

Missions and Requirements

The missions and primary requirements of the KnightSat II spacecraft were based on the payload, the ACADS sail system. The mission of the KnightSat II team is follows:

“The KnightSat II team seeks to design and build a satellite for research and demonstration of a novel propellantless propulsion and attitude control system utilizing a deployable gossamer sail.”

The specific demonstration for this system would be to facilitate rapid deorbit of the spacecraft with the ACADS sail. The ACADS system achieves this effect by way of aerodynamic drag. This is accomplished by drastically increasing the cross-sectional area of the spacecraft, which will lead to a massive increase in aerodynamic drag. Research was conducted to determine the requirements for drag enhancement devices on LEO spacecraft. Changing the cross sectional area of the spacecraft so drastically, in this case over 30 times, also increases the likelihood of collision. NSS-1740-14 addresses this issue and states the area time product of the system must be reduced [5]. With this information, the requirement for acceptable time for de-orbit can be determined. In the case of KnightSat II, the orbit time must be reduced by greater than 30 times. Simulations had to be conducted to ensure the design met these requirements.

NASA Technical Standard 8719.14 also mentions the use of dag enhancement devices such as ACADS must signifigantly reduce the collision risk of the spacecraft and generating large debris [3]. With ACADS’ increase in cross-sectional area, there is an increased likelihood of impact with orbital debris. With this in mind, it must be taken into consideration that the vast majority of that area consists of extremely thin Kapton, and that any collision with it will likely only create a hole in the sail, and not further debris. Initial findings and interpretations lead the KnightSat team to believe that the increased area due to the sail can be disregarded, and only the boom lengths considered. If the sail component can be disregarded, the area-time product and collision probability would be affected drastically. This requirement is still being researched, and once further explored with input from technical experts from the NASA Orbital Debris Program Office its impact on the final design and deployment of ACADS can be determined.

ACADS Design

The sail system consists of a square stowage box with 4 doors that open outward and permit deployment of the sail. Within the box is an electronics package, pressure vessel, sail, and booms. The electronics control the sequence of deployment, and ensure that the booms deploy in a uniform manner. The pressure vessel provides nitrogen gas with which to inflate the booms. The sail is stored in four segments and each segment is stored on one side of the box. The sail segments are attached to four booms that are conically folded within themselves at each corner of the box. At the perimeter of the sail are ten turns of 30 gauge wire. The wire leads will be laid down the inside of the booms and run through the stowage box and interface with the satellite's C&DH and power systems. These perimeter coils will be used for attitude control experiments, utilizing the large surface area provided by the sail. The sail itself is made of 3µm Kapton, which is 70% emissive and will allow for light to reach the solar panels and minimize the effect of solar pressure on the satellite. 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 disabled when deployment is complete. The booms will be painted in reflective coatings to prevent loss of rigidity once deployed. This material has successfully been utilized in spaceflight.

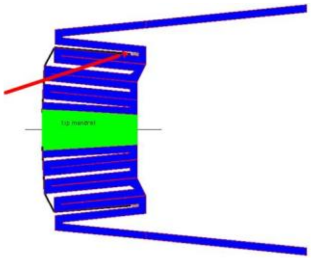

Figure 3: Conical folding of boom segments

The stowed dimensions of the box are 35x35 centimeters. The height is 5cm. The deployed dimensions of the stowage box are 45x45 centimeters and will fit flush with the top surface of the spacecraft. Deployed, the sail will have an area of 10 square meters. The projected mass of the entire sail system is expected to be less than 5 kilograms. The dimensions of the sail are represented below:

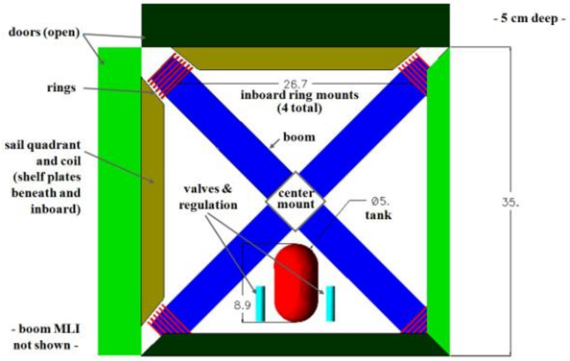

Figure 4a: Stored ACADS sail

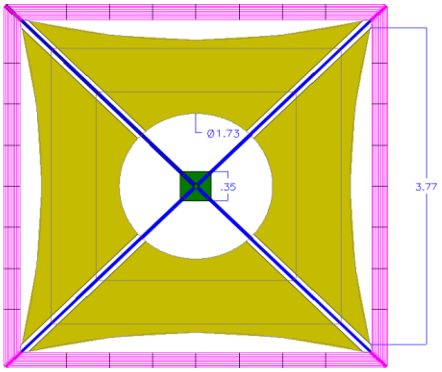

Figure 4b: Deployed ACADS sail

The construction of the sail is being contracted to L'garde Inc., who have fabricated and tested larger 400 square meter sail prototypes that deployed successfully in vacuum chambers and function in the same fashion as KnightSat II's payload. They have also successfully deployed inflatables in space, such as the Spartan-207 Inflatable Antenna Experiment deployed from STS-77 [6].

Safety

Safety is a major concern with ACADS because of the use of pressurized gas in its deployment. The major concern with ACADS is premature deployment, either on the ground or during launch. To address this, the booms and pressure vessel will be vented to the atmosphere/space while on the ground and during the ascent of the launch vehicles. Not until KnightSat II has been released from the spacecraft, charged, and capable of sending power to ACADS would the ascent valves be closed and deployment possible. Electrical inhibits and redundant closed valves between the pressure vessel and the regulator supplying pressure to the booms provide additional mechanisms preventing unwanted deployment.

It has been recommended by NASA personnel that ACADS have at least a two fault tolerant system. Currently research is being conducted as to exactly which components, such as valves and regulators, would be suitable for use in the system. The current concept for the fault tolerance system is presented in the diagram below:

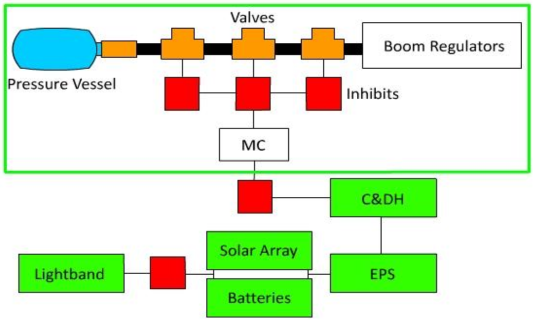

Figure 5. Sail fault tolerance system.

3. SPACECRAFT SUBSYSTEMS

Command and Data Handling

The spacecraft utilizes an Atmel AVR-32 bit MCU on a custom designed board for control of the spacecraft and health monitoring. The Knightsat II software solution will consist of a main loop that prioritizes and calls other programs or functions. The power, communications, and thermal programs have highest priority. In addition to basic spacecraft control, the flight computer will also be responsible for the deployment of the ACADS system.

Attitude Determination and Control System

Initial stabilization of the spacecraft prior to the deployment of ACADS will be achieved by using three magnetic torque rods. Each of the rods is composed of EFI alloy 50, and wrapped with more than two thousand turns of 28 AWG wire. An RCM5700 processor is used to operate the ADCS. The CPU is equipped with three angular rate gyros, three orthogonal DC accelerometers, three orthogonal magnetometers, a multiplexer, a 16-bit analog/digital converter, an embedded microcontroller, and six pulse width modulators. The pulse width modulators are connected to the torque rods, and can be used to manipulate the magnitude of the current that is supplied to the rods.

An H-bridge circuit was constructed using twelve 2n2222A transistors. The H-bridge is able to control the direction of the current to be controlled, enabling complete manipulation of the magnetic torque generated by the rods. A 3DM-GX1 Inertial Motion Unit and a sun sensor provide the necessary data for attitude determination, such as Euler angles, angular velocities, and magnetic field vectors. Data from the IMU and sun sensor will be relayed to the primary flight computer for compression and transmission to the ground.

Communications

The communications system will utilize two CalAmp JSLM2 transceivers connected to a Kantronics 9612+ modem, and will be responsible for sending data to and receiving commands from the ground station.

Electrical Power System

The EPS will perform three primary functions to support the objective of KnightSatII: generate, store, and distribute all electrical power to be used by the spacecraft. Power will be generated through photovoltaics mounted on nonstructural plates on four sides of the spacecraft. Rechargeable batteries will be used for power storage to be utilized during the eclipse portion of the orbit, supplement solar arrays, and maintaining the 9.6V bus for the spacecraft. The primary task for the distribution system will be converting the bus voltage to an appropriate operating voltage, either increase or decrease, for specific components on the spacecraft. The EPS will not be controlling power directly; this role has been passed on to the C&DH subsystem.

Thermal Control

KnightSat II will utilize a mostly passive thermal control scheme. Electric resistance heaters will be used to keep the batteries are a suitable temperature, and preliminary analysis shows the rest of the spacecraft will be at sufficient temperature.

Structure

The structure of KnightSat II was designed to be modular so it would be capable of accepting changes in the subsystems and be easy to work with during assembly. This was accomplished by using an isogrid pattern. The large pattern allowed ease of access to the internals and the ability for the structure to support itself with multiple walls removed during integration. The solar panels are designed to be mounted with standoffs so that the panel itself could be added or the wall and panel can be its own subassembly. The structure was composed of 6061 T6 Aluminum to save cost and chemical film coated to meet standards. Since no launch vehicle has been selected for this mission, specific UNP6 requirements called for the structure to have a fundamental frequency greater than 100 Hertz, and be able to withstand a load of twenty g's in each axis so that as a secondary payload it may be mounted in any way and survive the stresses and vibrations of launch.

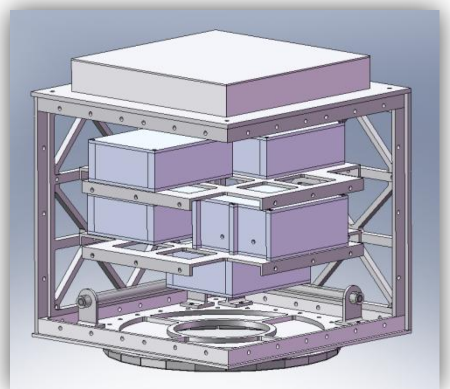

Figure 5: KightSatII structure cutaway

4. ANALYSIS AND SIMULATION

Structure

Analysis was conducted on the KnightSat II structure to ensure that it met UNP requirements in both static loading and fundamental frequency. Masses simulating spacecraft components and ACADS were applied prior to simulation. The static load analysis showed the structure was capable of withstanding the required acceleration of twenty g's in any direction.

Table 1: Static load simulation results

Load Case #	Load	Maximum Vonmises (ksi)	Minimum Margin of Safety, Ultimate
1	20Gs (+x)	3.2	4.0
2	20Gs (-x)	3.2	4.0
3	20Gs (+y)	7.3	1.2
4	20Gs (-y)	7.3	1.2
5	20Gs (+z)	3.1	4.2
6	20Gs (-z)	3.1	4.2

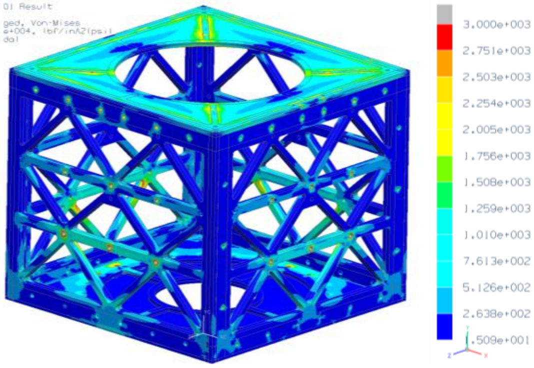

Figure 6: Static load simulation results

The modal analysis conducted showed that the structure and all of its elements met the fundamental frequency requirements set by the UNP.

Table 2: Modal analysis result

Mode #	Frequency (Hz)	Description
1	107	First bending of lower mounting plate.
2	145	First bending of top plate.
3	163	General twisting motion about attachment location.

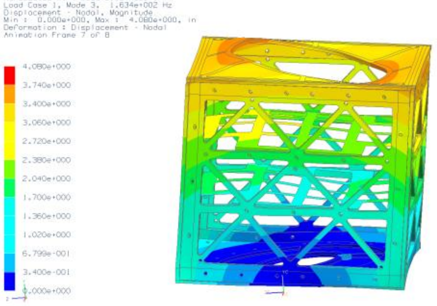

Figure 7: Modal analysis results

ACADS Capability: Drag

A number of simulations have been conducted by students at the University of Central Florida to predict the performance of the spacecraft in orbit with the deployment of the sail. These simulations showed promising results, in that the sail produced a significant enough drag force to reduce the orbit time by a large margin. The effects are significant enough to justify the large increase of cross-sectional area when the sail is deployed.

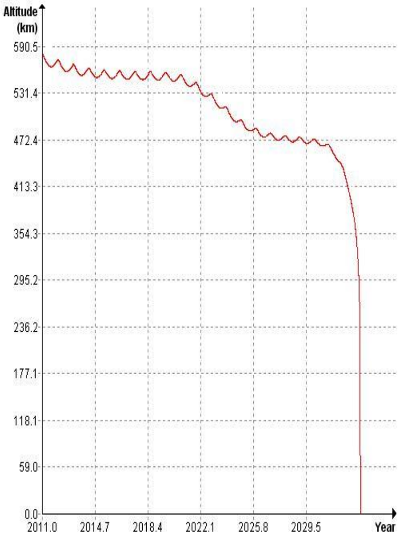

Figure 8: Simulation of KnightSat II without ACADS

The same simulation was conducted with the ACADS system deployed, which resulted in a significant increase in the rate of orbital decay.

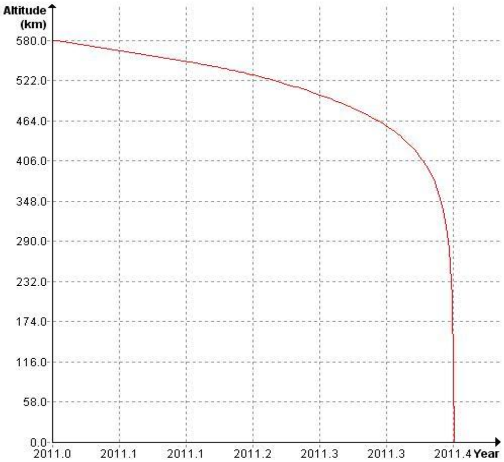

Figure 9: Simulation of KnightSat II without ACADS Deployed

The simulation shows the spacecraft falling from orbit in under six months, and an increase in the possible operating ceiling from the previous six hundred kilometer limit to nine hundred kilometers. This shows that the deployment of the sail brings the spacecraft out of orbit fifty times faster, while creating a surface area thirty-three times greater than the satellite without the sail. This means that the sail successfully decreased the area-time product of the spacecraft as required by NSS-1740-14.

ACADS Capability: Stabilization

In addition to functioning as an effective deorbiting mechanism, the sail is also envisioned as providing an integral aspect of the attitude control system. 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 implemented six-degrees-of-freedom equations of motion with respect to body axis. The results of this simulation show that it would take about two hours for the satellite to stabilize. Clearly this is not a system for a satellite mission in which rapid stabilization is required, but for the mission objectives of the KnightSat II, it is sufficiently effective.

5. CONCLUSION

The KnightSat team has completed the majority of the top level research and design concept work for the sail. Additionally, the analysis conducted by the team shows that the system has the capability of meeting its objectives and providing an effective means of altering the orbit of KnightSat II and eventually removing it from LEO completely at an accelerated rate.

A future goal of the project is to use the ACADS system in conjunction with an electrodynamic tether as a propellantless orbital maneuvering system for LEO spacecraft. This can enable long term, inexpensive multi-orbit missions using the sail to lower the orbit, and current running through the tether to increase it.

ACKNOWLDGEMENT

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REFERENCES

[1] Madler, Ronald A. “Orbital Debris—A Space Hazard,” in *Space Mission Analysis and Design*, Third Edition.

[2] Liou, J.-C. and Shoots, D. “Satellite Collision Leaves Significant Debris Clouds.” *Orbital Debris Quarterly News*. Volume 13, Issue 2. April 2009.

[3] “NASA Technical Standard 8719.14, Process for Limiting Orbital Debris.” Nationl Aeronautics and Space Administration, Washington, DC.

[4] Wertz, James R. “Earth Coverage,” in *Space Mission Analysis and Design, Third Edition*.

[5] NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris. (NSS 1740.14, August 95).

[6] “Spartan 207/Inflatable Antenna Experiment Flown on STS-77.” Preliminary Mission Report.” NASA Goddard Space Flight Center.