Title: Space Debris Mitigation Using Droplet Stream Technology

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Need

As of January 2009, there are approximately 20,000 orbital debris objects larger than 5 cm in Earth orbit and this number is expected to increase exponentially.[i] These large uncontrolled objects have the potential to create thousands of smaller objects that would join the estimated several hundred thousand pieces of debris that are currently impossible to track but very hazardous to operational spacecraft. Dr. J. C. Liou of the NASA Orbit Debris Program Office prioritized the hazard posed by debris based on its mass and collision probability.[ii] The breakup of the 500 highest priority objects could lead to a situation dubbed the Kessler syndrome in which so much debris is present at certain altitudes that any spacecraft operating at those altitudes will be destroyed and create even more debris. For these reasons, orbital debris represents a significant, and growing, collision hazard to current and future spacecraft. Dr. Liou's research shows that in order to prevent growth of the orbital debris population, there is a need to remove at least five of the highest priority objects each year.[ii] The mission proposed herein would deploy a constellation of nano-satellite pairs capable of generating ionic-fluid droplet streams that can be accurately projected to the surface of objects with high relative velocity to the droplets, changing the momentum of the objects. The transfer of momentum will slow the objects and lower the orbit altitude of the debris to move it out of the path of an operational spacecraft and, in most cases, hasten reentry of the object.

Mission Objectives

The primary objective is to expedite removal of key objects from their current orbit to reduce the risk they pose to functioning spacecraft and reduce their orbit life. Testing at the U.S. Air Force Academy indicates that transferring fluid from one spacecraft to an on-coming object, with impact velocities approaching 15 km/s, will not cause breakup of the object. The transfer of momentum from a satellite to hazardous space objects via droplet streams can alter the orbits of the debris and assist in collision avoidance with important space assets. To achieve mission success, the following tasks must be fulfilled:

1. Measure the variability of droplet impact location following transit through space. Droplet stream pointing accuracy would be validated by transferring streams between two nano-satellites each equipped with sensors to detect impact location.
2. Measure drag, Lorentz, and Coulomb forces acting on droplet streams and use the

results to refine predictive pointing algorithms.

3. Optimize droplet flight path algorithms to maximize momentum transfer.
4. Demonstrate that on-board sensors can accurately refine the location of targeted debris with sufficient precision to reduce the likelihood of any droplets missing their intended target to less than 0.9%.

Concept of Operations

Multiple pairs of nano-satellites at various altitudes are proposed for this mission. The satellites will be traveling in orbits where high priority hazardous debris is located or in orbits that cross paths with these objects. A polar or sun-synchronous orbit is the best candidate orbit for debris removal. Such an orbit allows for high relative velocities with polar and sun-synchronous objects. Highly inclined orbits also allow the debris removal spacecraft to cross paths with objects at lower inclinations. Intercepts with lower inclination objects will reduce the relative velocity of impacting droplets but will allow for more mass transfer during the intercept. Each satellite will have the capability to discharge droplet streams and use optical sensors to detect known debris as it passes within several tens of kilometers. Currently, ground-based radar and optical measurements performed by various organizations allow for the tracking of space debris, but the accuracy of the known position of each object is not sufficient to perform a droplet stream intercept. Prior to an intercept, the most current object orbit information will be transmitted to the debris removal spacecraft via the Air Force Satellite Communication Network (AFSCN). Each spacecraft in the pair will make use of the orbit information to cue an optical sensor that will provide more precise position data to both spacecraft, allowing one or both of them to transfer droplets into the path of the object.

Key Performance Parameters

There are several key performance parameters that indicate mission success. Prior to projecting droplet streams at space debris, a pair of satellites in similar orbits could be used to validate the designs, and pointing algorithms utilized. First, the size and spacing between each droplet generated using a micro-solenoid valve must be consistent, with minimal dispersion from the intended path. Following launch and commissioning, droplet streams can be projected from one satellite to another. Each spacecraft is equipped with fluid-filled capacitors that act as collectors and sensors, to determine droplet impact location. This technology has been demonstrated in vacuum, and provides the sensitivity needed to detect droplets as small a 1mm in diameter.[iii] Knowledge of impact location is used to verify the effectiveness of the model used to predict the effects of drag acting on droplets. Calculations show that droplets will be accelerated 3-4 times more by drag than the spacecraft producing them.[iii] By translating widely spaced droplets between two identical spacecraft, this predictive model can be refined. Since droplets will charge in the plasma environment, they will interact with each other through Coulomb forces. Their path will also be slightly affected by Lorentz forces caused by their own charge and Earth's magnetic field. By simultaneously sending two droplets on parallel paths between companion spacecraft, and measuring their separation at impact, the level of droplet charge can be estimated and predictive charging models refined. By refining path prediction models for droplets, target miss probability is reduced.

Space Segment Description

In the 1980s, NASA and the United States Air Force did significant research on droplet stream generation technologies for use in a Liquid Droplet Radiators (LDR). Researchers in Japan continued LDR development work and, in 2005, conducted weightless testing of droplet streams in drop towers.[iv] Work at the University of Colorado in 2009 demonstrated effective droplet stream generation using micro-solenoid valves.[iii] The fluid is stored in a tank with sufficient pressure to overcome pipe friction losses with enough dynamic pressure to accelerate the fluid to speeds of about 100m/s. To achieve the fluid tank pressure needed, a pressurized gas will be regulated to the requisite pressure and applied to a flexible membrane that will maintain constant tank pressure. It was calculated that 100 grams of fluid is required to lower the altitude of an on-coming 1500 kg object by 10km. Roughly twice this amount of fluid is required to lower a 1500 kg object in a crossing orbit by 10 km.

In order to determine the droplet impact locations, the satellites will be equipped with fluid-filled capacitors that act as sensors. When droplets impact the wire mesh top of the capacitors they are trapped and the capacitance will change. The change in capacitance alters a current signal, indicating the impacted areas of the spacecraft. Initial spacecraft pairs will have one surface covered with these sensors to conduct pointing accuracy tests.

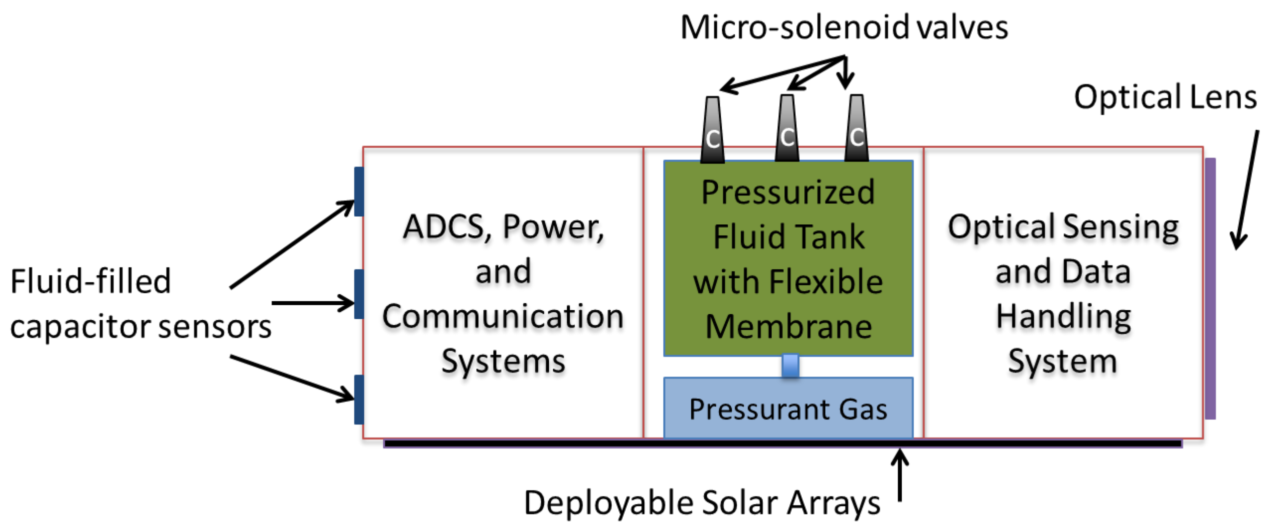

Figure 1. Nano-Sat Component Layout

The attitude determination and control system (ADCS) onboard the satellite will make adjustments to the attitude of the satellite so that the optical sensor is facing the on-coming object. Known object orbit parameters, together with measurements from optical sensors, are fed into the algorithm that outputs desired satellite attitude to allow for droplet stream projection. The control system will make adjustments to the satellite attitude using reaction wheels or electrospray thrusters. The fluid being considered for momentum transfer is an ionic fluid called BMIM-BF4 which is well suited for use as a propellant in electrospray thrusters. Calculations show that either electrospray thrusters or control wheels can produce enough torque to control and slew the spacecraft. Electrospray thrusters require less mass but are believed have a higher level of risk. Figure 2 shows a block diagram that depicts the key elements and flow of information for spacecraft pointing control.

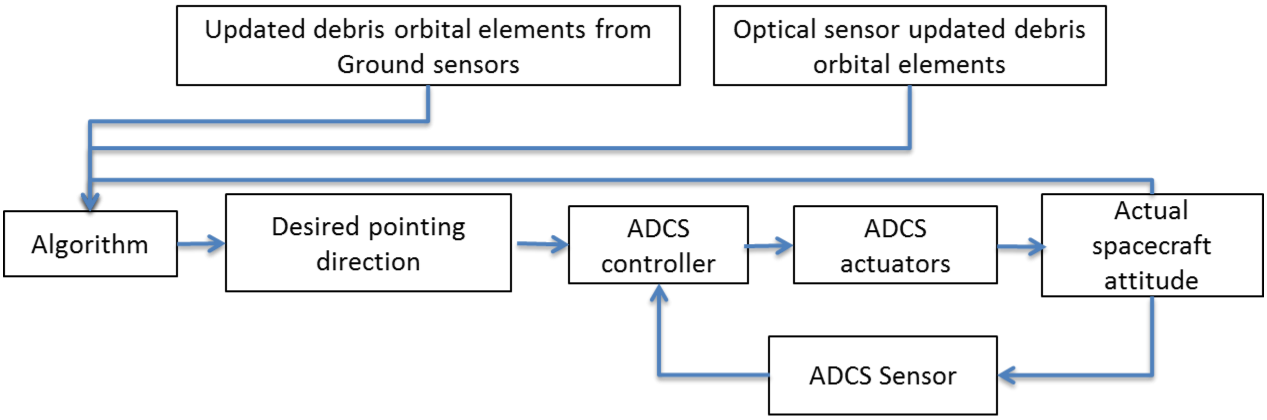

Figure 2. Satellite attitude and nozzle pointing control system

Orbit/Constellation Description

Thousands of smaller objects are typically created when two large objects collide, significantly increasing collision probability with operational satellites. Research shows that the bulk of high-priority objects lie between 600 and 1000 km with inclinations concentrated around 98, 83, 81, 74, 71, and 65 degrees.[ii] Since most of the high priority debris is in highly inclined orbits, the orbits in the constellation should be polar or near polar. This will allow for high relative velocities between the satellites and on-coming debris to minimize the amount of mass needed to slow objects. Highly inclined spacecraft orbits will also maximize the relative velocity between spacecraft and other objects at the high-priority inclinations.

The constellation will consist of satellite pairs at various altitudes to allow various debris altitudes to be reached through stream projection and spacecraft maneuvering. Estimates of maximum droplet transit distance show that high accuracy is possible over several tens of kilometers. The limiting factor in droplet propagation distance is the ability to update known position information in time to project droplets to the path of the object. If a spacecraft conducts both optical sensing and transmission of droplets then transmission distances are limited to less than two kilometers. If, however, a spacecraft is used to provide updated position information to its companion spacecraft, the time afforded the second spacecraft to transmit droplets is increased by tens of kilometers.

Implementation Plan

In the United States NASA is charged with developing orbital debris mitigation techniques. Thus it is hoped that NASA, or a similar organization in another country, will oversee the overall implementation plan for this mission. It is also hoped that such an agency could be helpful in identifying space available launch opportunities to launch dozens of satellite pairs into desired orbits. The U.S. Department of Defense has the best capability for tracking objects in space, and would occasionally be asked to provide timely updates of high-priority object orbit information. Daily tracking and continuous control of the satellites can be performed at the ground station located at the United States Air Force Academy (USAFA). During actual debris intercepts, other space control networks would usually be needed to provide the satellites with updated object orbit information prior to momentum transfer.

Design, development, assembly, integration and most testing can be conducted at USAFA. USAFA is currently developing FalconSAT 7 which is a 3-U CubeSat nano-satellite. FalconSAT 7 has a budget requirement of $1.3M. This budget includes $251k for parts, $1M for labor, and $95k for travel, but excludes the cost of the satellite bus. Based on these estimates, and the cost of past FalconSAT missions, it is estimated that overall development, operations, and launch related costs for this mission would be less than $7M for the first pair of spacecraft and would drop to less than $3M for each subsequent pair. Development is estimated to take 36 months and would follow the same timeline currently used for other spacecraft developed at USAFA. This timeline could be accelerated, but with increased cost. The spacecraft are expected to operate for 2-3 years before running out of ionic fluid. At the end of their operation lifetime each spacecraft would use a reserve of fluid as propellant to expedite their own deorbit with on-board electrospray thrusters.

Project risks are higher than average due to the preferred use of electrospray thrusters and the first-time use of droplet stream generators in space. However, electrospray thruster development is underway by several organizations such as Busek, NASA's Jet Propulsion Laboratory, Air Force Research Laboratory and the Air Force Academy. It is believed that this technology will be considered reliable in the near future. If it is not, reaction wheels are a suitable alternative. Demonstration of droplet stream technology in vacuum and weightlessness has already been accomplished in drop towers in the U.S. and in Japan and similar tests can be done to verify operability of the technology prior to launch. We believe the risks are low enough to warrant production and launch of an initial pair of spacecraft that will pioneer this novel and exciting method of debris mitigation and provide mankind with a method of safeguarding the spacecraft critical to economic, security, and scientific pursuits.

References

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