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Presenter Information

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A Novel Approach for Controlled Deorbiting and Reentry of Small Spacecraft

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NASA's Launch Services Program (LSP) is collaborating with the University of Florida to create a novel maneuverable drag device capable of modulating the drag force in order to control the orbital decay of CubeSats, small spacecraft, or space debris in Low Earth Orbit (LEO). This unique, non-propulsive solution enables spacecraft to comply with NASA's 25-year Orbital Debris Policy whose orbits would otherwise violate. This methodology can also be used for space traffic management by reducing debris in desirable orbits or active constellations in a controlled and coordinated manner. The Deorbit Drag Device (D3) is contained within a 1U CubeSat platform; it uses retractable booms and an on-board targeting algorithm to control the ballistic coefficient of a space vehicle. After completion of the primary spacecraft's (or spent upper stage) mission, D3 uses a targeting algorithm to vary boom deployment and actively steer the spacecraft to an atmospheric interface point at a pre-determined latitude and longitude. Decreased orbital life reduces the amount of time for which fault-based liability under Article III of the Liability Convention applies. This maneuvering methodology may reduce risk of human casualty by targeting a reentry over non-populated areas. The D3 offers a solution for passive spacecraft in LEO, enabling them to be active participants in mitigating orbital debris.

Nomenclature

ADAMUS	=	Advanced Autonomous Multiple Spacecraft (laboratory)
C_b	=	ballistic coefficient $[m^2/kg]$
D3	=	Deorbit Drag Device
KSC	=	Kennedy Space Center
JSpOC	=	Joint Space Operations Center
LEO	=	Low Earth Orbit
LSP	=	Launch Services Program
NASA	=	National Aeronautics and Space Administration
NPR	=	NASA Procedural Requirements
NTS	=	NASA Technical Standard
SC	=	Spacecraft
U	=	Generic CubeSat form factor in which 1U has a mass of 1 kg and volume of 10cm x 10cm x 10cm

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I. Introduction

MITIGATING the potential collision or impact damage due to CubeSats, small spacecraft, or space debris in LEO is a growing concern. NASA has developed policy, procedural requirements, and a standard for limiting orbital debris, which are implemented via the following publicly released documents:

- NPR 8715.6A, NASA Procedural Requirements for Limiting Orbital Debris [1]
- NASA-Handbook, Handbook For Limiting Orbital Debris [2]
- NTS 8719.14A, Process for Limiting Orbital Debris [3]

Current technologies for LEO spacecraft deorbiting are based on thrusters, or on interactions with the environment (electromagnetic, drag). These approaches may be prohibitive or inadmissible for small spacecraft due to cost or design considerations. Prototype development for drag sail deorbiting systems that have one-time deployment mechanisms, which passively decay the orbit, have been developed. The limitation of this approach is that it can only provide uncontrolled deorbiting, but cannot control the spacecraft's orientation or reentry interface location.

In 2015, LSP, in conjunction with the University of Florida, began funding a study to develop a phased approach to create a variable drag system, able to modulate the drag force during orbital decay for LEO spacecraft, as well as to control the vehicle's orientation.

There are multiple benefits to actively controlling the rate of orbital decay. This methodology could enable delivery of a spacecraft to LEO that would otherwise not meet the NASA Orbital Debris lifetime requirement of an orbital period of less than 25 years. Also, it would provide the ability to drive the satellite to desired re-entry points in orbit, which is particularly desirable when parts of the satellite may be made of materials that survive re-entry or may be otherwise hazardous (e.g. titanium used in optical benches). In addition, such a system could reduce the amount of time for which fault-based liability under Article II of the Liability Convention applies. The footprint of this system could enable improved ground-based tracking, thereby leading to easier determination of fault-based damage in a spacecraft collision or, better yet, avoiding potential collisions. This maneuvering methodology may alleviate or mitigate risk of human casualty by targeting non-populated areas.

This system offers a solution for passive spacecraft in LEO, enabling them to be active participants in mitigating orbital debris.

II. Application and Benefit to Industry

THE study, to date, has determined five significant benefits to the implementation of the D3 system .

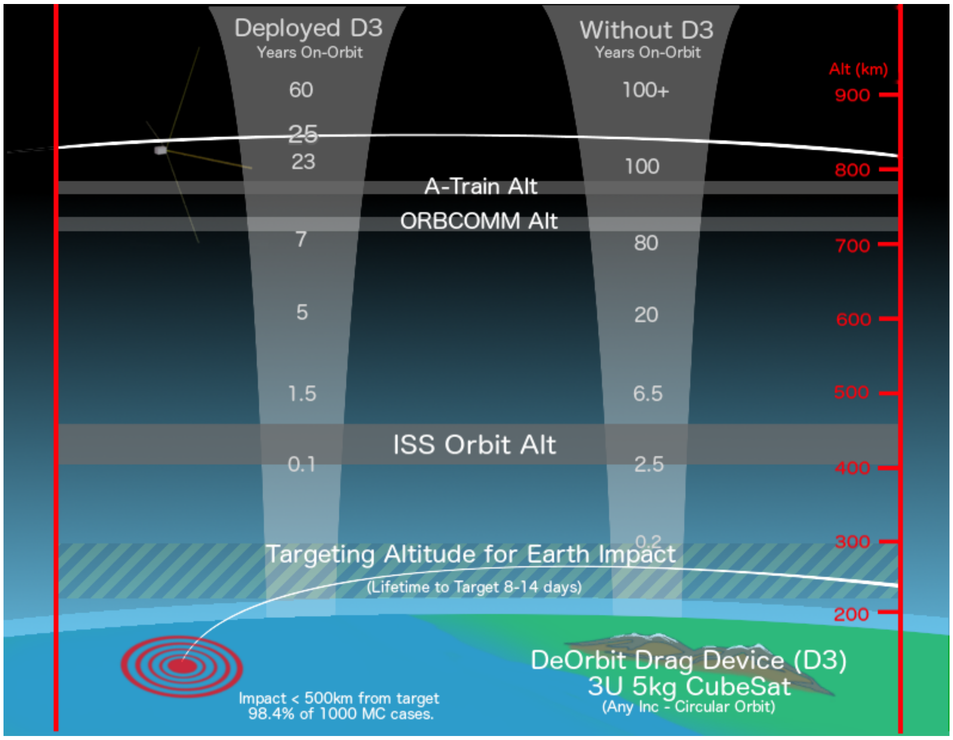

Figure 1: 3U CubeSat Operational Orbits

1. Differentiation from CubeSat Deployed Compliments

One of the challenges that CubeSats / Small Spacecraft face upon deployment is identification from other recently released SC by the JSpOC cataloguers. It can often take days or weeks of drift to occur before proper orbital elements can be conveyed to the SC operators in order for them to establish ground-based contact. D3 with its variable geometry booms can provided differentiating cross sections with which to provide identification immediately upon injection.

> *Concept of Operations: In a Secondary Payload complement of more than 10 CubeSats, a D3 equipped a CubeSat could extend their booms to a predetermined length or pattern (1/4, 2/4, ¾ booms deployed) providing a distinct target for the space fence system to identify. JSpOC will be able to correctly catalogue the CubeSat on the first pass, providing accurate antenna pointing data to operators early in the mission life.*

2. Orbital Lifetime Compliance (<25 year lifetime)

The D3 opens up new orbital regimes for CubeSats and small spacecraft. For 3U CubeSats the orbit regime altitudes 700-800km now becomes accessible for operations where as 600km circular is the current limit to 3U CubeSat orbital lifetime. Figure 1 provides a graphical summary of this concept.

> *Concept of Operations: A CubeSat / Small Spacecraft is dropped off at an altitude in which they will survive longer than 25 years and is not compliant with the NASA Orbital Debris policy. Shortly after deployment, D3*

will extend its booms to the largest designed area configuration increasing the spacecraft's ballistic coefficient. Deployment early in the mission life decreases the probability of component failure prevents the boom deployment entirely. The additional atmospheric drag of the D3 will ensure the spacecraft deorbits in the 25-year limit.

3. Orbital Decay Controllability

A pending future concern will be the number of CubeSats and SmallSats decaying through active satellite constellations (both NASA and commercial). In fact, Orbcomm has sought to halt the Falcon9 launch of Formosat-5/Sherpa containing 87 CubeSats citing that they pose an unnecessary risk to their operating constellation of communication satellites**Error! Reference source not found.**. As D3 is able to modulate the drag force effectively changing the orbital decay rate of a CubeSat, SmallSat or other orbiting object. The system provides a new level of non-propulsive control to space operators.

> Concept of Operations: *For CubeSats/SmallSats that are planning on being released above active constellations, communications can be established between SC operators to help avoid on orbit conjunctions and conjunction alerts. As CubeSats/SmallSats decay relatively rapidly they would be able to coordinate a plan for transiting the active constellation or assets. In this way CubeSats/SmallSats can become active members in preventing orbital debris and excessive strain on traditional SC operators.*

4. Controlled Reentry / Targeted Impact Point

Two of the key components in the D3 system are the ability to modulate the cross sectional area as well as implementing an algorithm to target a controlled reentry. The D3 physical system and algorithm could be scalable to any system that can modulate its cross sectional area reliably; current analyses/predictions show scalability from objects ranging from 1U CubeSats to Pegasus 3rd stages or ESPA class spacecraft. The analytical work done to date has been able to show a target reentry error of less than 500km in 98.4% of a 1000 run Monte Carlo sample set. This analysis result enables the use of components that survive reentry while still complying with NASA Orbital Debris Policy regarding on human casualty probability.

> Concept of Operations: *For a CubeSat, SmallSat, or spent stage equipped with a D3 system the targeting algorithm begins measuring position and velocity about a week before atmospheric entry interface (reentry). Using onboard computation, the reentry-targeting algorithm analytically solves for orbit and designated impact area solutions by managing 3 control variables (current ballistic coefficient, time of changing ballistic coefficient, and the next ballistic coefficient). The targeting algorithm and the boom deployment mechanism work in a closed-loop fashion to control the orbit The algorithm executes at least once per orbit until the entry interface point is achieved at the targeted latitude and longitude away from populated landmasses.*

5. Scalability

The D3 algorithm can be scalable to larger objects (launch vehicle hardware or spacecraft) as long as D3's control surfaces can affect at least two of the three ballistic coefficients for the combined bodies; either through D3's active attitude control or variable-position deployable booms. On an orbit-by-orbit basis, the larger the differences are between the ballistic coefficients, then the greater the effect on orbital decay. Current analysis shows that the minimum difference needed for the desired effect is 7%. That theoretical minimum is predicated on absolute knowledge of atmospheric models, which is unlikely resulting in a larger needed minimum difference in ballistic coefficients.

> Concept of Operations: *The physical boom design of the D3 system can scale up to dimensions where the mass penalty is still acceptable such as non-propulsive spacecraft, spent solid rocket bodies, etc. Estimates suggest that a D3 system with four booms 8cm x 10 m could be installed on a body as large as a spent Pegasus XL 3rd Stage (Orion 38) in LEO and control that stage's orbital decay and within a 1250 km target over the ocean.*

III. Deorbit Drag Device: Algorithm and Drag Device Design

THE LSP project's goal is to develop and demonstrate a simple, reliable, low-cost, non-propulsive system for deliberate deorbit of small spacecraft, including CubeSats. In order to achieve this goal, the project's focus is on developing a proof-of-concept design that will control the orbital decay, up to the atmospheric ballistic entry point, of CubeSat form factors up to 12U. CubeSat control while deorbiting will be achieved by deploying/retracting four independent "measuring tape-like" booms. Attitude control will be obtained by allowing the booms to be maneuvered independently, thus offsetting the center of pressure with respect to the spacecraft's center of mass, generating control torques about two body axes. This will enable fine decay control and attitude control.

Controllability is defined as the ability to achieve any desired final state in a finite amount of time from a given initial state and range of control parameters. If not configured correctly, there may be some cases where there is not sufficient controllability to target any desired impact location with a latitude below the orbit inclination.

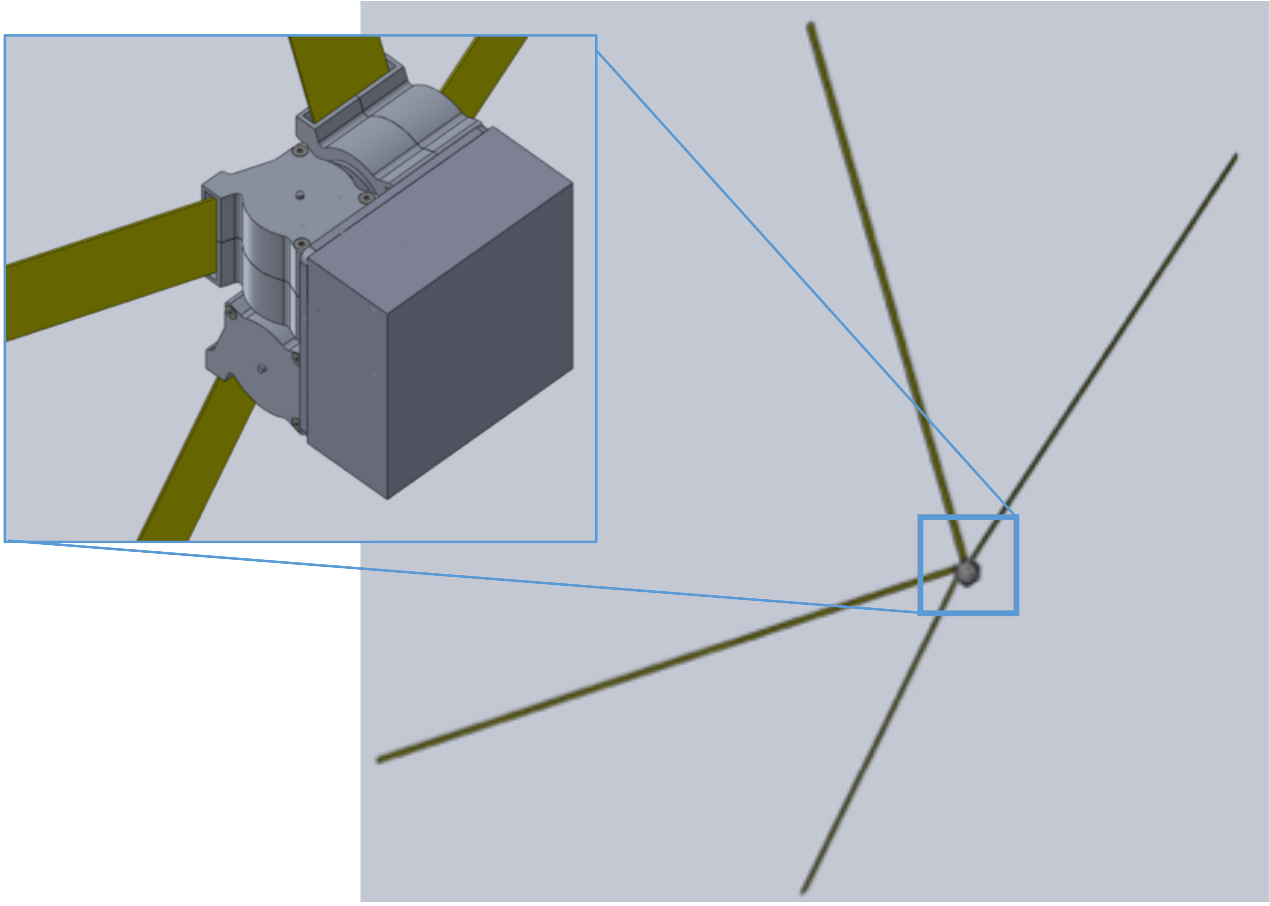

Figure 2: D3 booms fully deployed System (with detailed view)

V. Project Implementation Phases and Objectives

THIS study, which began in 2015, has been comprised of a series of phases and objectives:

- Conduct analytical studies and identify planning for experimental studies, which include, but are not limited to: identifying interfaces, orbital parameter controllability, and environmental considerations (2015).
- Perform Monte-Carlo high fidelity simulations to validate the deorbiting capabilities of the surface chosen as minimum to deorbit in 25 years from a maximum altitude of 700km. Test the targeting algorithm in a variety of cases, using a high fidelity orbital propagator. Design a deorbiting system and identify a general interface to mount on typical CubeSats between 1U and 12U. Fabricate engineering models and prototypes to perform laboratory dynamic and environmental testing (2016).
- Design a flight ready D3 system to fit into a 1U CubeSat form factor and integrated onto a 3U CubeSat (2017). The design process will:
  - Establish CubeSat and mission requirements and mission success criteria (System Requirements Review). Develop a Concept of Operations (ConOps) that will be developed which will include D3 autonomous functions along with interaction with earth-based ground stations. The ConOps will also include establishing requirements for ground station support of the mission. This phase will establish mission success criteria and metrics for a future CubeSat deployment.
  - Complete the design of the 1U CubeSat through a series of Preliminary and Critical Design Reviews. The D3 will include, among other features, a GPS, a radio, a high-capability computing board (for the targeting algorithm), the boom subsystem, and magneto-torquers. The D3 will have mechanical and electrical interfaces to connect to the host CubeSat. As a configurable option, the design of D3 will be flexible to allow removal of the internal GPS and radio in order to reduce cost and/or complexity when connected to another CubeSat that is providing navigation and communication for the integrated assembly. Analyses such as thermal, loads/stress and dynamic environments will be performed and will be based off of representative environments produced by Venture Class launch vehicles and ISS resupply launch vehicles. Flight design analyses will include Monte-Carlo testing of the targeting algorithm, including adaptive control to track the trajectories created by the targeting algorithm. The design will include a set of mission success criteria, which will include metrics for system performance and reentry accuracy.
- At this point the project will transition from the design phase to manufacturing and test of two flight-ready D3 CubeSats (2018). This phase will consist of test, verification, and validation of the hardware and software utilizing laboratories at both University of Florida and KSC. Test environment levels will be bounded by Venture Class launch vehicles and ISS resupply launch vehicles. This phase will also develop protocols for verification and validation of D3 CubeSat systems on-orbit data against the modeling-targeting algorithm to determine if the mission success criteria are met; these mission success criteria and associated protocols will be presented as part of the SAR.
- A System Acceptance Review will be performed (2018), which will provide the verification that the CubeSat is in compliance with all functional, performance, and design requirements.
- Evaluate maturation of the targeting algorithms to accommodate the D3 autonomous functions on larger mass objects, such as >100kg spacecraft or spent launch vehicle stages (2018).
- Identify launch and/or flight opportunities (2018-2019). Perform in-flight evaluation of the information produced by the D3 CubeSats to determine the effectiveness of the current design and evaluate future design changes (2019). This information will then be utilized to research and/or develop targeting algorithms and modular design to accommodate the D3 autonomous functions on larger spacecraft or spent launch vehicle stages.

VII. Scalability

At a 300 km circular orbit, the D3 system begins its targeting algorithm calculations to determine what ballistic coefficient should currently be set, what the ballistic coefficient will be set to next, and when to make the switch. Critical to this calculation is the atmospheric model used (NRLMSIS-00).

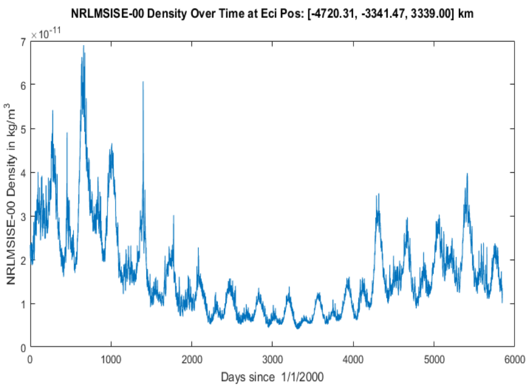

Figure 3: MSISE Atmosphere Model

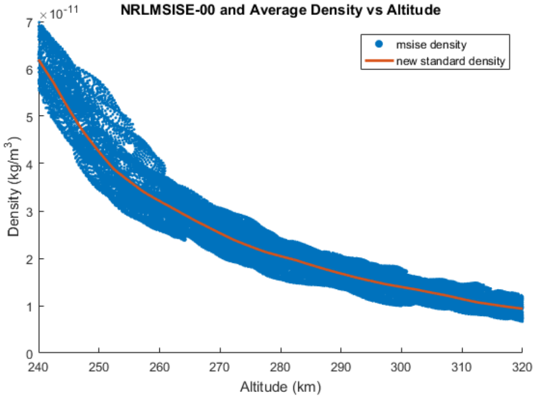

Figure 4: New Derived Atmosphere Model

The reentry latitude-targeting portion of the algorithm finds a solution using the NRLMSISE-00 atmosphere (pictured left). Then a new atmosphere model (pictured right) based on the MSISE is created. The new model sub divides the atmosphere into bands, where density exponentially decays with altitude. This new model is used in further iterations to target longitude and speed up processing.

An inner loop control system will be able to modulate the ballistic coefficient throughout real world variations beyond of the MSISE model. We need to ensure the control surfaces are appropriately sized to allow the control loop enough ballistic coefficient latitude.

The more boom that is available to be extended the more controllability the system can display. Following the variation in MSISE density, the theoretical minimum change in ballistic coefficient would need to be 7.14% of surface area change from the initial configuration (low drag) to the final (high drag) configuration, specifics can be found in the technical paper, "Spacecraft Re-Entry Impact Point Targeting using Aerodynamic Drag".[7]

Most D3 systems will be sized to ensure the vehicle/spacecraft/stage deorbits in a certain time and in a specific attitude to ensure control can be expressed while deorbiting (sub 300km region). This generally ensures the minimum surface area for control is exceeded.

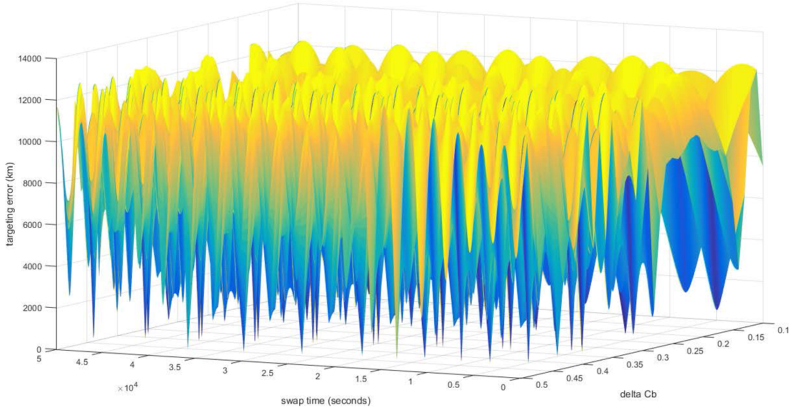

Figure 5: Control Parameters Trade Space

Figure 5: Control Parameters Trade Space shows how the error in achieved target point (km) varies with the time of the ballistic coefficient switch and the total change in ballistic coefficient. This graph shows the sensitivity of the system intuitively, and that low targeting error (lower blue spikes) can be achieved using multiple swap times and different ballistic coefficient combinations.

Different spacecraft classes were investigated to get an idea of the dimensions of the needed D3 device to achieve a target within 1250 km error (8% C_b diff with 1 week targeter ops). Details on the targeting algorithm can be found in the detailed paper[7].

Table 1: D3 Scalability

	D3 Boom Dimensions for Controllability (4 booms/system)		
SC Mass (lbm)	**Spacecraft Type**	**Width (in)**	**Length (ft)**
863	**Pegasus XL 2nd Stage (Orion 50 XL)**	**8**	**131**
400	**ESPA Class (400lbm SC)**	**8**	**59**
226	**Pegasus XL 3rd stage (Orion 38)**	**8**	**33**
61	**CYGNSS Body**	**2**	**0.5**
53	**12U**	**2**	**0.3**

VIII. Legal Aspects

SINCE the Sputnik launch in 1957, space has continuously grown in its value to mankind. The benefits of spaceflight are ubiquitous and essential to current progress. Laws, domestic and international, have developed around spaceflight to ensure that space remains a resource for all who pursue it. The D3 supports many of the principles found in law.

Firstly, Article I of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space**Error! Reference source not found.**, including the Moon and Other Celestial Bodies (Outer Space Treaty) guarantees access to and use of space by all countries, irrespective of economic or scientific development. Small Satellite technology has furthered this principal by making space technology less financially restrictive and more standardized. More participants now have the means to create a satellite. However, the useful and functional life of many small satellites is ephemeral. As the use of small satellites has increased, so has the amount of debris resulting from them. In many cases when the functional lifespan of a small satellite terminates, it then becomes free falling, non-maneuverable debris. In order to comply with the 25 Year Orbital Debris Policy of NASA[1] and the Space Debris Mitigation Guidelines of the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS)[4], these spacecraft have been limited to certain orbits. The D3 would potentially make it possible for more participants to explore and utilize more of space. This allows decluttering of some of the lower orbits as well as more rapid reentry for those in lower orbits, helping to preserve the space environment. The D3 also enhances the ability to decrease the potential of harmful interference with other space activities as required by Article IX by allowing for more accurate orbital decay planning and controllability. Through its targeting and decay control, the D3 also strengthens the ability to maintain more control of the spacecraft while in outer space mandated by Article VIII of the Outer Space Treaty**Error! Reference source not found.**. 51 U.S.C. § 31501 mandates that NASA "shall take steps to develop or acquire technologies that will … decrease the risks associated with orbital debris," and the D3 is a step forward in this goal.

As the drive to promote commercial use of space grows in accordance with 51 U.S.C. § 20112(a)(4), the mechanisms by which NASA accomplishes this function must take into account commercial interests. With every new space activity, space becomes a little more crowded with active spacecraft, non-functional spacecraft past their functional life, and spent launch vehicle components. Each new object creates a new collision risks and inherently increases the risk associated with space activities. Articles VI and VII of the Outer Space Treaty**Error! Reference source not found.** introduce the idea of liability for damages arising from space activities, and the Convention on International Liability for Damage Caused by Space Objects (Liability Convention) elaborates on the idea of liability for space activities. Article II of the Liability Convention states that a launching State shall be absolutely liable to pay compensation for damage caused by its space objects on the surface of the Earth or to aircraft, and Article III makes a launching state liable for damage due to its fault in space. Through various sections of Title 51 of the U.S.C., this liability is flowed down to commercial entities through requirements for insurance and cross-waivers. Another benefit of the D3 is its impact on liability. The larger cross section created by the deployable booms makes it easier to track and distinguish while in close proximity to other spacecraft. The targeting and decay controllability would allow for space objects, satellites or spent launch vehicle components, to pass through another spacecraft's orbit more safely to avoid collision. The D3 could greatly reduce the risk of fault-based liability by decreasing the likelihood of an in-situ space collision. It also can greatly reduce the amount of time this liability attaches to the spacecraft. For instance, in Figure 1 above, rather than a government or non-governmental entity having 20 years of liability exposure for a spacecraft at 600 km, the exposure with D3 deployed would only be for five years. This drastically reduces the risk posture for the launching entity. Rather than planning for a twenty-year freefall, the planning would be for a controlled decay of five years, thereby freeing up contingency reserves or decreasing insurance costs. Further, by targeting a non-populated area for the reentry, the D3 also reduces the risk of absolute liability with damage caused by the returning spacecraft on earth.

While targeting and controlled decay reduces liability concerns, it may also increase the types of resources that small satellites can fly. For instance, the Federal Communication Commission may refuse to grant spectrum usage to a small satellite that flies with materials that are particularly resistant to the forces encountered on reentry since orbital debris mitigation issues are a valid public interest consideration in the Commission's licensing process. The D3 could target non-populated areas for reentry, dramatically reducing the probability of casualty, and possibly allowing for more usage of the resistant materials, like tungsten or tantalum, to obtain the desired science.

Since the D3 does not rely on propulsion systems, the need to plan for that weight and technology is reduced. This also makes it more likely that, with regard to export controls, the export of D3 technical data will not be governed by the International Traffic in Arms Regulations (ITAR), but rather the Export Administration Regulations (EAR). Reviews of technical data to date are in line with this prediction. As this study matures, decisions regarding technology transfer, licensing, patenting, and other intellectual property issues will be made.

The D3 aligns with NASA's missions and supports domestic and international laws and guidelines. The potential benefits include maximizing access to space, decreasing orbital debris, decreasing the probability of collisions and casualties, and supporting greater use of space by more participants.

IX. Conclusions

THE D3 system addresses a number of the issues concerning CubeSats with respect to space traffic management, including orbital debris mitigation and satellite controllability. The system is able to achieve this using a robust yet elegant design, which is scalable to larger bodies, such as spent stages. The deorbit targeting algorithm contained in the D3 system provides an additional benefit which reduces casualty/property risk due to re-entry debris. The use of this system will provide for a significant increase in potential CubeSat users, as that use of the D3 system will significantly expand the operational regime of these satellites.

X. Future Work

THE project envisions carrying on the D3 into a flight ready system and then launching it into LEO in order to verify the system in a space environment. The following describes future phases of work:

- Design a flight ready D3 system to fit into a 1U Cubesat form factor and integrated onto a 3U CubeSat (2017). The design process will:
    - Establish CubeSat and mission requirements and mission success criteria (System Requirements Review). Develop a Concept of Operations (ConOps) that will be developed which will include D3 autonomous functions along with interaction with earth-based ground stations. The ConOps will also include establishing requirements for ground station support of the mission. This phase will establish mission success criteria and metrics for a future CubeSat deployment.

  - Complete the design of the 1U CubeSat through a series of Preliminary and Critical Design Reviews. The D3 will include, among other features, a GPS, a radio, a high-capability computing board (for the targeting algorithm), the boom subsystem, and magneto-torquers. The D3 will have mechanical and electrical interfaces to connect to the host CubeSat. As a configurable option, the design of D3 will be flexible to allow removal of the internal GPS and radio in order to reduce cost and/or complexity when connected to another CubeSat that is providing navigation and communication for the integrated assembly. Analyses such as thermal, loads/stress and dynamic environments will be performed and will be based off of representative environments produced by Venture Class launch vehicles and ISS resupply launch vehicles. Flight design analyses will include Monte-Carlo testing of the targeting algorithm, including adaptive control to track the trajectories created by the targeting algorithm. The design will include a set of mission success criteria, which will include metrics for system performance and reentry accuracy.
- At this point the project will transition from the design phase to manufacturing and test of two flight-ready D3 Cubesats (2018). This phase will consist of test, verification, and validation of the hardware and software utilizing laboratories at both University of Florida and KSC. Test environment levels will be bounded by Venture Class launch vehicles and ISS resupply launch vehicles. This phase will also develop protocols for verification and validation of D3 CubeSat systems on-orbit data against the modeling-targeting algorithm to determine if the mission success criteria are met; these mission success criteria and associated protocols will be presented as part of the SAR.
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