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# DRAG ENHANCEMENT DEVICE PROTOTYPE FOR MID-SIZE SPACECRAFT

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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**DRAG ENHANCEMENT DEVICE PROTOTYPE FOR MID-SIZE SPACECRAFT**

by

Michelle L. Verbeeck

June 2019



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This study constructed a drag device to demonstrate and evaluate the benefits of including a drag enhancement device for spacecraft self-disposal in Low Earth Orbit (LEO). The study assessed the viability of drag enhancement device deployment and functionality for mid-size spacecraft using a scaled model constructed with polymer materials. While drag devices for CubeSats have been well studied and demonstrated, the mid-size, LEO spacecraft class most commonly deployed by the Department of Defense has not. The motivation for self-disposal is policy driven. This research targeted a simple, cost-effective approach conducted using scaled models for proof-of-concept that will lead to the final development prototype demonstrating effective deployment and functionality. The prototypes were developed using available software tools such as computer-aided design NX and were tested for structural integrity, functionality, and mechanical deployment.

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**DRAG ENHANCEMENT DEVICE PROTOTYPE FOR MID-SIZE SPACECRAFT**

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Submitted in partial fulfillment of the
requirements for the degree of

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# ABSTRACT

This study constructed a drag device to demonstrate and evaluate the benefits of including a drag enhancement device for spacecraft self-disposal in Low Earth Orbit (LEO). The study assessed the viability of drag enhancement device deployment and functionality for mid-size spacecraft using a scaled model constructed with polymer materials. While drag devices for CubeSats have been well studied and demonstrated, the mid-size, LEO spacecraft class most commonly deployed by the Department of Defense has not. The motivation for self-disposal is policy driven. This research targeted a simple, cost-effective approach conducted using scaled models for proof-of-concept that will lead to the final development prototype demonstrating effective deployment and functionality. The prototypes were developed using available software tools such as computer-aided design NX and were tested for structural integrity, functionality, and mechanical deployment.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3D | Three Dimensional |
| ADCS | Attitude Determination and Control System |
| ASAT | Anti-Satellite |
| CAD | Computer-aided design |
| CGG | Cool Gas Generator |
| CFRP | Carbon Fiber Reinforced Polymer |
| DAMAGE | Debris Analysis and Monitoring Architecture for the Geosynchronous Environment |
| DOS | DeOrbitSail |
| EO-1 | Earth Observing-1 |
| Expl Prev | Explosion Prevention |
| GEO | Geostationary/Geosynchronous Orbit |
| HAB | High-Altitude Balloon |
| IADC | Inter-Agency Space Debris Coordination Committee |
| km | kilometer/kilometers |
| kg | kilogram/kilograms |
| LEO | Low Earth Orbit |
| m | meter/meters |
| MEO | Medium Earth Orbit |
| mm | millimeter/millimeters |
| MRO | Mission Related Objects |
| NPS | Naval Postgraduate School |
| OLMA | Orbit Lowering Modular Attachment |
| SRP | solar radiation pressure |
| SSAG | Space Systems Academic Group |
| SSO | Sun Synchronous Orbit |
| UN | United Nations |

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# I. INTRODUCTION

Increasing technological advancements worldwide have directly impacted the space community. More and more nations are utilizing, relying on, and competing in and for space. With this, comes the looming conversation of mitigating congestion in specific, desirable, orbital regimes.[1] Since outer space is not a sovereign territory, regulating the realm poses a significant challenge. Subsequently, policy enforcement becomes more challenging, especially with growing occupancy by space-faring nations. Control of orbital debris is one area of contention. Currently, there is no universally agreed upon orbital debris mitigation plan. Moreover, current space-faring nations do not have an officially recognized orbital debris mitigation plan. Many nation-unique documents provide *guidance* for orbital debris mitigation and encourage "good behavior" in space; however, these guidelines are exactly that: unenforceable, self-regulating, and not unanimously followed.

Two prominent examples of debris-causing events catching international attention include the 2007 Chinese Anti-Satellite (ASAT) test and the 2009 on-orbit satellite collision. The Chinese ASAT test resulted in more than 3,000 trackable pieces of debris.[2] The on-orbit collision of Iridium 33 and Cosmos 2251 resulted in approximately 2,000 trackable pieces of debris.[3] As a result of these two events, many nations have identified orbital debris as an issue. Solutions are needed and expected for future use and success in space. For such solutions to be utilized and implemented, they should not interfere with mission capability, not interfere with the operation or mission of any other spacecraft, not pose a threat to any other space-based asset, and, in the best case, not drive up the cost and mass of the spacecraft. The Orbit Lowering Modular Attachment (OLMA) prototype

[1] James C. Moltz, *Crowded Orbits: Conflict and Cooperation in Space* (New York: Columbia University Press, 2014).

[2] Brian Weeden, "2007 Chinese Anti-Satellite Test Fact Sheet," Secure World Foundation, November 23, 2010, https://swfound.org/media/9550/chinese_asat_fact_sheet_updated_2012.pdf

[3] Brian Weeden, "2009 Iridium-Cosmos Collision Fact Sheet," Secure World Foundation, November 10, 2010, https://swfound.org/media/6575/swf_iridium_cosmos_collision_fact_sheet_updated_2012.pdf

device presented in this thesis is a low-cost, low-mass, adaptable solution to meet orbital debris mitigation guidance.

## A. INTERNATIONAL GUIDANCE

The Inter-Agency Space Debris Coordination (IADC) Committee is a United Nations (UN) sponsored international organization with membership comprised of the primary space-faring nations (Figure 1). The committee's purpose is "to exchange information on space debris research activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities and to identify debris mitigation options."[4] Members participate in four mission-oriented working groups to achieve the respective four aforementioned objectives and ultimately provide a solution to orbital debris issues.[5]

| Agency/Entity | Abbreviation |
|---|---|
| Italian Space Agency | ASI |
| Centre National d'Etudes Sptiales | CNES |
| China National Space Administration | CNSA |
| Canadian Space Agency | CSA |
| Deutsches Zentrum fur Luft- und Raumfahrt e.V. | DLR |
| European Space Agency | ESA |
| Indian Space Research Organization | ISRO |
| Japan Aerospace Exploration Agency | JAXA |
| Korea Aerospace Research Institute | KARI |
| National Aeronautics and Space Administration | NASA |
| State Space Corporation | Roscosmos |
| State Space Agency of the Ukraine | SSAU |
| United Kingdom Space Agency | UKSA |

Figure 1. Agencies and Entities Incorporated in the IADC

Although the IADC Terms of Reference document does not include enforcement, it does provide baseline guidance for space-faring nations to abide by for the safe use of outer space. It is in the best interest of all space-faring nations to follow the guidance in

[4] C. Portelli, et.al., *Terms of Reference for the Inter-Agency Space Debris Coordination Committee*, 93-01 (Revision 11.4), September 28, 2016, https://www.iadc-online.org/Documents/IADC_TOR_rev_11.3_public.pdf.

[5] Portelli, et. al., 7.

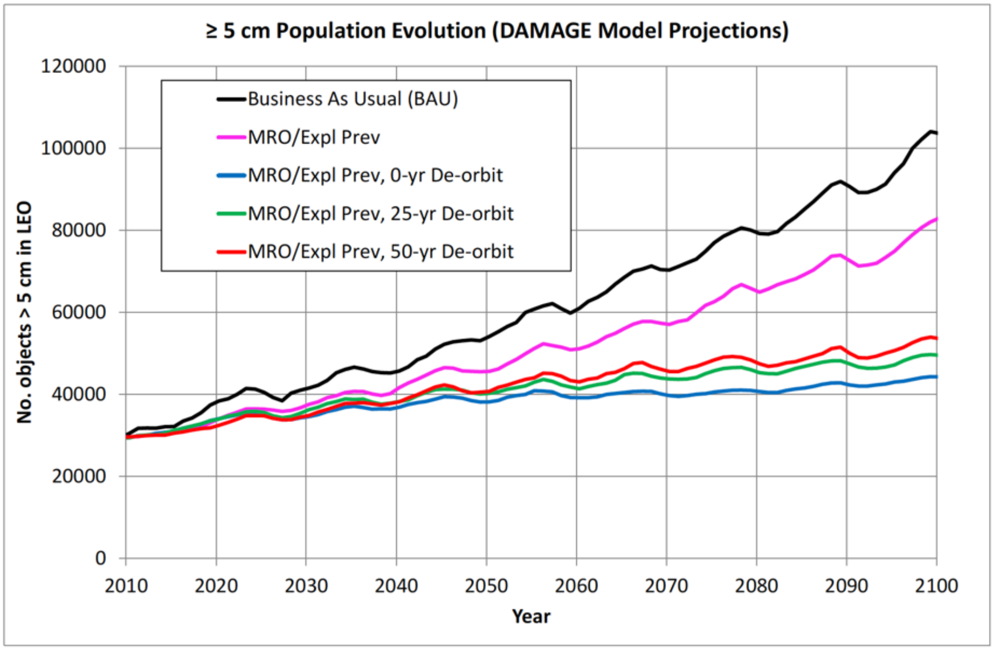
order to safely continue operations while limiting risk to both space-based assets as well as land-based assets and, in some cases, human life.

IADC Working Group 2, responsible for space debris research efforts, ran forecasting software to assess the space environment in Low Earth Orbit (LEO) while implementing different mitigation strategies. The resulting chart, depicted in Figure 2, shows the impactful differential of the orbital debris environment in LEO between the unmitigated scenario and the various mitigation strategies.[6] The Debris Analysis and Monitoring Architecture for the Geosynchronous (GEO) Environment (DAMAGE) software developed by the University of Southampton was intended to analyze the GEO regime but has since been updated to analyze the region from LEO-to-GEO.[7] Per the DAMAGE software model predictions, if left unmitigated, the number of mission-related objects greater than 5 cm in LEO would exceed 100,000 in nearly 100 years. With the implementation of a 25-year deorbit plan, the current post-end-of-mission "standard," the trajectory of debris growth would decrease by approximately 50% over the course of 100 years. Moreover, the model indicated relatively minor differences in projected mission related orbital debris growth in implementing immediate deorbit plans as well as a 50-year deorbit plan relative to the 25-year deorbit plan projection, thus driving the encouragement of a 25-year post-end-of-mission deorbit requirement that would sufficiently impact the space environment in LEO.[8]

[6] Inter-Agency Space Debris Coordination Committee Working Group 4, *Support to the IADC Space Debris Mitigation Guidelines*, 04-06 (Revision 5.5), 32-33, https://www.iadc-online.org/Documents/IADC-04-06%20Support%20to%20IADC%20Guidelines%20rev5.5.pdf.

[7] H. G. Lewis et al., "The Fast Debris Evolution Model," *Advances in Space Research,* 44 (2009): 570, https://doi.org/10.1016/j.asr.2009.05.018.

[8] Inter-Agency Space Debris Coordination Committee Working Group 4, 33.




Acronym and abbreviation information: Mission Related Objects (MRO); Explosion Prevention (Expl Prev)

Figure 2. IADC Debris (≥ 5 cm) Average Population Evolution from DAMAGE.[9]

IADC Working Group 4 is responsible for identifying debris mitigation options. In the 55th Session of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, Working Group 4 formally discussed the insufficient implementation of the 25-year post-end-of-life disposal guidance.[10] Per the guidance set forth by the IADC, spacecraft should be launched with a deorbit plan. Such plans can be executed via controlled reentry, maneuvers to a storage/disposal orbit, or uncontrolled reentry. Each technique offers advantages and disadvantages that are discussed in Sections C and D of this chapter.

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[9] Source: Inter-Agency Space Debris Coordination Committee Working Group 4, *Support to the IADC Space Debris Mitigation Guidelines*, 33.

[10] Mitsuru Ohnishi, "The Inter-Agency Space Debris Coordination Committee (IADC) – An Overview of IADC's Annual Activities," (paper presented at the 55th Session of the Scientific and Technical Subcommittee United Nations Committee on the Peaceful Uses of Outer Space, Vienna, Austria, January–February 2018), 13, https://www.iadc-online.org/Documents/IADC-18-02%20IADC%20Presentation%20to%20the%2055th%20UN%20COPUOS%20STSC%20(2018).pdf.

## B. U.S. POLICY AND GUIDANCE

The United States has taken action to adhere to IADC guidance. The *National Space Policy of the United States of America* pronounces that it is in the best interest of the U.S. to preserve the space environment and operate in space responsibly. Preserving the space environment includes efforts to minimize debris by physical means and policy documentation. Efforts have been made in the policy realm with the establishment of the *United States Government Orbital Debris Mitigation Standard Practices*.[11]

Per the United States government document, "Programs and projects will plan for, consistent with mission requirements, cost effective disposal procedures for launch vehicle components, upper stages, spacecraft, and other payloads at the end of mission life to minimize impact on future space operations."[12] Additionally, the policy specifically calls attention to three methods of disposal for spacecraft and upper stages: atmospheric reentry, maneuver to a storage orbit, and direct retrieval. The direct retrieval option offers an innovative opportunity for a larger discussion on orbital debris remediation. This thesis will focus on the orbital debris mitigation strategies, and specifically, the atmospheric reentry technique.

U.S. policy delineates additional requirements for entities utilizing the atmospheric reentry option. Section 4–1a. states that

> atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit.[13]

Furthermore, the standard practices for orbital debris mitigation requires analysis of the deorbit strategy in relation to risk to human life. It specifically states that "if a space

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[11] Barack Obama, *National Space Policy of the United States of America* (Washington, DC: White House, 2010), https://obamawhitehouse.archives.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[12] *US Government Orbital Debris Mitigation Standard Practices,* 3, https://www.iadc-online.org/References/Docu/USG_OD_Standard_Practices.pdf.

[13] *US Government Orbital Debris Mitigation Standard Practices,* 3.

structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000."[14] The OLMA seeks to meet the aforementioned policy standards set forth by the U.S. government while limiting cost and mass of the overall design and mission.

## C. GRAVEYARD ORBIT AND CONTROLLED REENTRY

The controlled reentry and storage/disposal orbit maneuvers are executed in similar fashions: via change in velocity maneuvers commonly referred to as delta-V maneuvers. Such operations are conducted at end-of-life that utilize fuel reserves to execute the maneuvers. From an orbital debris standpoint, the techniques differ significantly. The storage/disposal orbit is commonly referred to as the graveyard orbit. These graveyard orbits are regions in space where passivated spacecraft can reside in a circular orbit but must maintain orbital parameters that do not interfere with operating spacecraft. There are four graveyard orbit regimes: between LEO and Medium Earth Orbit (MEO), between MEO and GEO, above GEO, and a heliocentric trajectory that allows the structure to escape Earth's orbit.[15] The graveyard orbit is more commonly utilized by spacecraft at higher-altitude LEO regimes at end-of-life.

Controlled reentry maneuvers allow the spacecraft to reenter Earth's atmosphere in a targetable location via a delta-V burn or series of burns. One popular location is Point Nemo, the point on the Earth's surface farthest from land in any direction in the South Pacific Ocean.[16] When executed properly, the controlled reentry will drastically reduce risk to human life.

As previously mentioned, both the controlled reentry and intentional maneuver to a graveyard orbit require the spacecraft to have additional fuel onboard to execute the delta-V maneuver to reenter or to transfer to the desired higher-altitude graveyard orbit. This can be costly and, oftentimes, encourages spacecraft operators to continue operations past end-

[14] *US Government Orbital Debris Mitigation Standard Practices,* 3.

[15] *US Government Orbital Debris Mitigation Standard Practices,* 3.

[16] "Point Nemo, Earth's Watery Graveyard for Spacecraft," Phys.org, March 30, 2018, https://phys.org/news/2018-03-nemo-earth-watery-graveyard-spacecraft.html.

of-mission; disregarding any plan to deorbit. This causes a fuel incentive dilemma where spacecraft operators use the remaining fuel on board to extend operations beyond end-of-mission rather than using the fuel to execute the intended deorbit plan. A prime example of this occurred with NASA's Earth Observing-1 (EO-1) satellite. The spacecraft was launched in November of 2000 to an altitude of 705 km to serve as a technology demonstration for two years after which it would utilize remaining fuel onboard to execute a deorbit plan. However, in January 2003, the EO-1 transitioned to extended mode and continued operations. At this point, NASA estimated the spacecraft would naturally deorbit by 2043. In 2007, the EO-1 spacecraft was granted a waiver to further extend operations, deplete the remaining fuel onboard, and thus exceed the deorbit requirement of 25 years after end-of-mission by approximately 11 years.[17]

**D. UNCONTROLLED REENTRY**

Uncontrolled reentry is acceptable if accomplished within the 25-year limit and the spacecraft is reasonably expected to burn up in the atmosphere, meeting the 1:10,000 human casualty risk. Many spacecraft have to preserve fuel to lower their orbit to achieve the 25-year reentry limit.

Eliminating the fuel requirement associated with delta-V maneuvers allows for a less costly solution. Uncontrolled reentry capitalizes on atmospheric drag in the LEO regime with an appropriate Area-to-Mass Ratio that can enable the spacecraft to reenter through the atmosphere within 25 years after end-of-mission.

The graph in Figure 3 depicts the relationship between altitudes and ballistic coefficients; the slanted line represents the 25-year natural orbital lifetime decay. Region one represents the regime wherein natural decay is sufficient to meet deorbit requirements. Region two, between altitude of approximately 550 – 850 km, is the region where action must be taken to deorbit the spacecraft within guidelines. This is the region of interest for

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[17] National Aeronautics and Space Administration, *End of Mission Plan For The Earth Observing-1 (EO-1) Satellite*, Appendix B, (Greenbelt, MD: Goddard Space Flight Center, 2011), 31-32, https://eo1.gsfc.nasa.gov/new/EO1EndofMissionPlan/Waiver%20OD-07-05%20EO-1%20Orbital%20Lifetime%20Appendix%20B%20V5_Signed.pdf

enhanced drag technologies. Region three, shows that spacecraft at altitudes greater than approximately 850 km would not benefit from drag enhancement devices since solar radiation pressure (SRP) is much greater than drag. Furthermore, the authors indicate that increases in ballistic coefficient necessary in region two are achievable with current drag sail capabilities.[18]

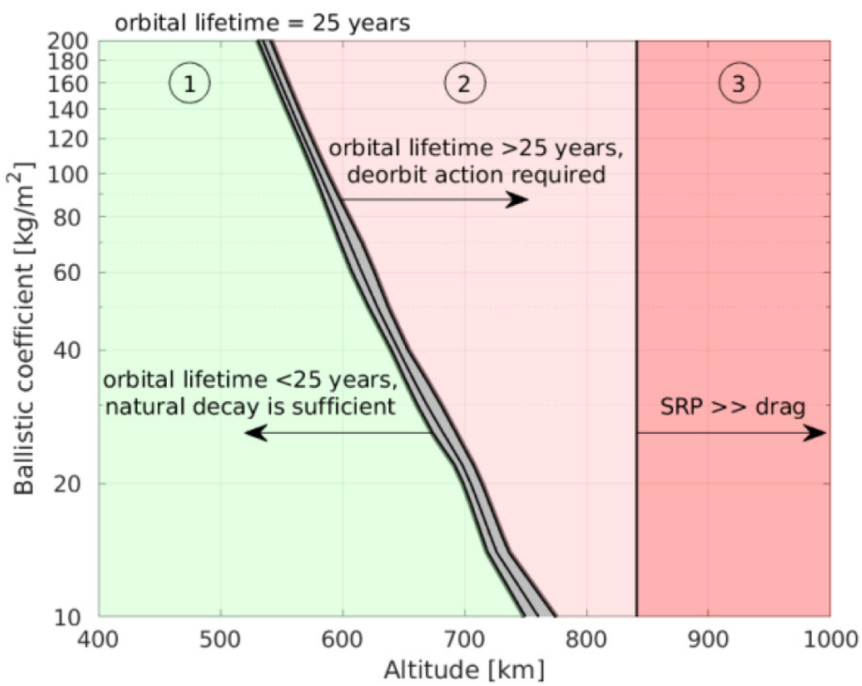


Figure 3. 25-Year Orbital Lifetime as a Function of Altitude and Ballistic Coefficient[19]

Although mid-sized spacecraft and smaller are expected to burn up in the atmosphere during reentry, a consideration of risk to the ground population should be coordinated by the launching organization. Some space agencies, such as those operating in the United States, "require a detailed assessment to show that the spacecraft hardware will burn up sufficiently during atmospheric reentry to pose less than a 1 in 10,000 risk of

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[18] Katrina P. Alsup et al., "Drag-Enhancing Deorbit Devices for Mid-Sized Spacecraft Self-Disposal," 3, (proceedings of the IEEE Conference, Big Sky, MT, March 2019).

[19] Alsup et al., 3.

causing serious injury to even one human."[20] The uncontrolled reentry technique provides a low-mass-solution adherence to IADC guidance for nations to meet the spacecraft deorbit plan.

The OLMA seeks a widely applicable, uncontrolled-reentry technique solution for deorbiting mid-sized spacecraft. This is a relatively low mass and low cost solution. Moreover, it will significantly reduce the fuel incentive dilemma while not interfering with mission capability—forcing compliance of international guidance. This, in turn, results in IADC guidance adherence and directly correlates to an overall decrease of projected total orbital debris in LEO.

## E. PREVIOUS EFFORTS

Previous drag enhancement technology demonstrations have been executed, however, the primary focus has been on small-sized satellites with little attention to larger drag enhancements necessary to deorbit mid-sized spacecraft.

NASA's NanoSail-D mission launched in November of 2010 and deployed its drag enhancing sail the following January. The technology demonstration successfully deorbited the small, 4 kg, satellite after 240 days from an altitude of approximately 650 km.[21] This accelerated the estimated natural deorbit time significantly. The United Kingdom based company Surrey Space Centre attempted a similar demonstration with a 7 kg CubeSat; a standard structure 3U CubeSat. The mission, known as DeOrbitSail (DOS), intended to control drag sail deployment with an electrical powered motor and communications directed by a ground station. However, the mission was unsuccessful due to an electrical connection failure of the deployment device motor cables.[22]

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[20] J.R. Wertz, D. F. Everett, and J. J. Puschell, *Space Mission Engineering: The New SMAD* (Portland, OR: Microcosm Press, 2011), 940.

[21] Brian Dunbar, "NASA's Nanosail-D 'Sails' Home – Mission Complete," NASA, November 29, 2011, https://www.nasa.gov/mission_pages/smallsats/11-148.html.

[22] Herbert J. Kramer, "DeOrbitSail (DOS) Nanosatellite Mission," Earth Observation Portal, https://directory.eoportal.org/web/eoportal/satellite-missions/d/deorbitsail.

A Colorado-based company, MMA Design, in an attempt to bridge the gap in technology available for varying sized spacecraft, developed a scalable deorbit solution known as DragNET. It utilizes a four-triangle sail arrangement to create an apex sail design; offering greater aerodynamic stability as compared to the flatter designs. The sail material can be made of a thin polymer called CP-1, for lower altitudes and shorter missions, or, CP-1 coated with Corin, which provides a silicon dioxide layer of protection from atomic oxygen erosion present at lower altitudes. DragNET utilizes coiled oval-shaped boom arms at the core of the deployment mechanism capable of extending 10 m. Additionally, spring-loaded arm devices are added at the perimeter of the storage box to prevent coil boom bulging when energy is released during deployment.[23] Successful demonstration and utilization of the device was reported by the Air Force Research Laboratory in January 2016 with the accelerated deorbit of the 180 kg Minotaur upper stage 2.1 years post-launch - an estimated rate of 10 times faster than the expected natural orbit decay.[24]

Less extensive work has been done to accommodate mid-sized spacecraft. The limited work conducted has been scalable and proves success in missions such as the CanX-7, InflateSail, and LightSail. Although these missions have demonstrated capability for the CubeSat class, they have been discussed as scalable designs for larger spacecraft.

The LEO-based CanX-7 spacecraft is a 3U (three combined 10 cm cubic busses) CubeSat mission to demonstrate drag sail module deployment spanning nearly 5 $m^2$. The unique feature offered by the success of the CanX-7 mission is the modularity. The 5 $m^2$ sail is comprised of four individual drag sails that can deploy independent of one another. The sail is attached to two coiled steel tape spring booms, which release stored potential energy when the module structure door is opened. An uplink command triggers the heating

[23] Alexandra C. Long and David A. Spencer, "A Scalable Drag Sail for the Deorbit of Small Satellites," *Journal of Small Satellites*, 7 no. 3 (2018), 778-780, https://www.jossonline.com/wp-content/uploads/2019/01/Final-Spencer-A-Scalable-Drag-Sail-for-the-Deorbit-of-Small-Satellites.pdf.

[24] "MMA's DragNET Successfully Deorbits Minotaur Upper Stage," MMA Design LLC, July 19, 2018, https://mmadesignllc.com/product/dragnet-de-orbit-system/.

of a metalized cord to be heated until separation is achieved, thus releasing tension holding the module structure door closed and thereby releasing the booms.[25]

In similar fashion, the InflateSail mission sought a larger sail surface area than previously mentioned examples with the same 3U CubeSat size limitations. Utilizing a Cool Gas Generator (CGG), InflateSail is able to extend a 1 m long, 90 mm thick inflatable mast boom, which, in turn, releases the sail mounted, four carbon fiber reinforced polymer (CFRP) booms creating a 10 $m^2$ surface area drag sail. These components are stored in an intricate origami folding pattern designed to fit in approximately two-thirds of the spacecraft volume while allowing the remaining third of the bus to be utilized for navigation and station keeping components as well as electronic power system components. The CFRP booms are coiled while stowed and extended while deployed; moreover, they are attached to a DC motor granting control of the length during deployment, thus allowing for variability of the sail size to manipulate the surface area. The drag sail was deployed at a 505 km altitude Sun Synchronous Orbit (SSO); however, the sail itself was intentionally un-metallically coated by design as to minimize effects of SRP.[26]

Lastly, the LightSail missions took sail technology to a new level. As with previous examples, LightSail-1 is also a 3U CubeSat, which houses four 16 m long booms that support a 32 $m^2$ solar sail. The booms are rolled, collapsible arms identified as TRAC booms that self-deploy with stored energy. The sail is folded in a varying-length Z-folding pattern that allows for triangular storage and deployment. Mounting the sail to the TRAC booms was executed using reinforced metal grommets with split rings and spring extensions to allow for appropriate tension during events of intense solar radiation

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[25] Grant Bonin et al., "The CanX-7 Drag Sail Demonstration Mission: Enabling Environmental Stewardship for Nano-and Microsatellites," (paper presented at the 27th Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2013), https://utias-sfl.net/wp-content/uploads/Small-Satellite-Conference-2013-SSC13-XI-9.pdf.

[26] Craig Underwood, et. al., "The InflateSail CubeSat Mission – The First European Demonstration of Drag-Sail Deo-Orbiting," (paper presented at the 4th IAA Conference on University Satellite Missions and CubeSat Workshop, Rome, Italy, December 2017), http://epubs.surrey.ac.uk/849323/1/The%20inflatesail%20cubesat%20mission.pdf.

pressure.[27] LightSail-1 successfully launched and deployed its sail technology for deorbiting purposes in 2015; the altitude was too low to demonstrate solar sailing capabilities. LightSail-2 seeks a means of utilizing solar sailing capabilities to raise apogee of the orbit with modified technology from the LightSail-1 demonstration.[28] Appropriate control of the satellite orientation will allow solar sail technology to help lower apogee of the orbit when needed.

There remains a gap in implementation for deorbiting mid-sized spacecraft. Previous demonstrations have been instrumental in portraying the proof of concept for deorbiting spacecraft; however, no further action has been taken for satellites and spacecraft of the typical size and structure. Extending research in the larger drag enhancement realm will prove valuable for the industry standard size satellites in LEO. OLMA seeks to bridge this gap in offering a modular attachment design for wide implementation across mid-sized spacecraft platforms.

[27] Chris Biddy and Thomas Svitek, "LightSail-1 Solar Sail Design and Qualification," *Proceedings of the 41st Aerospace Mechanisms Symposium*, (May 2012), 451-465, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130008824.pdf#page=465.

[28] Bruce Betts et al., "Lightsail 2: Controlled solar sailing using a CubeSat," (paper presented at the 4th International Symposium on Solar Sailing, Kyoto, Japan, January 2017), http://www.jsforum.or.jp/ISSS2017/papers/paper/17053_Paper_Dr.%20Bruce%20Betts.pdf.

# II. CONCEPT OVERVIEW

The OLMA is intended to have two configurations: stored and deployed. The storage mode of OLMA, depicted in Figure 4, serves to keep the sail protected from the space environment within the parameters of the hard casing. The wooden beams shown are solely for stability purposes during testing. They are not part of the OLMA design. Additionally, the red background is an acrylic-coated floor that was used to limit the frictional force experienced from traditional surfaces. The deployment mode of OLMA, depicted in Figure 5, is the operational mode of the attachment intended to be a permanent setting until achieving the desired altitude in which the attachment will burn up in the atmosphere along with the satellite.

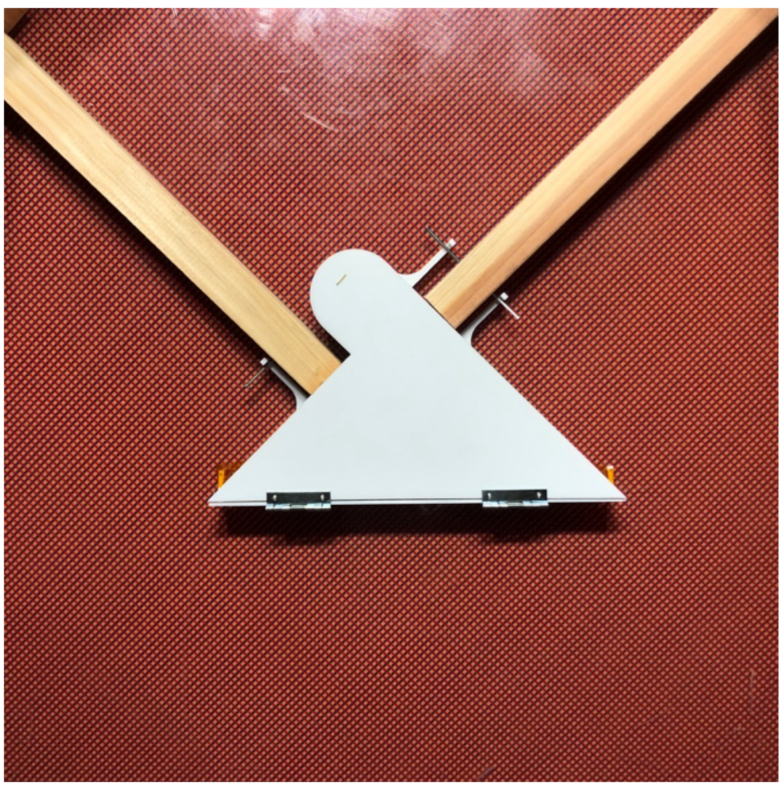

Figure 4. OLMA Storage Mode

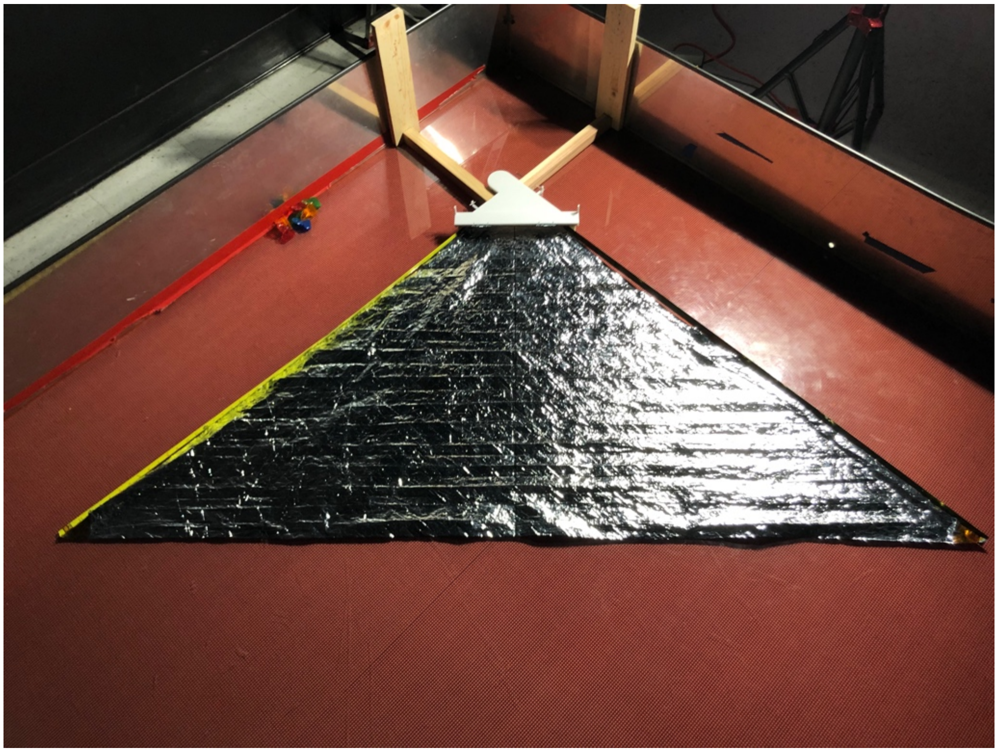

Figure 5. OLMA Deployment Mode

## A. DESIGN REQUIREMENTS

The OLMA is a modular attachment with minimal size and mass specifications to best accommodate the universal intent. The inherent design of the OLMA allows for custom sizing and placement of multiple units as appropriate to achieve the desired drag area. The design requirements are intended for broad use on mid-sized spacecraft. Appropriate Area-to-Mass ratios vary depending on the size of the spacecraft. The objective design requirements are listed in Figure 6. Although this thesis represents the prototype small-scale model of the attachment, it provides a platform to reach the desired requirements for future models. Gaps will be addressed in the future work section.

| Number | Requirement |
|---|---|
| 1 | Total attachment shall be 10 kg or less. (Each unit shall be no more than 3 kg.) |
| 2 | Attachment shall avoid interference with spacecraft's mission performance while in storage mode. |
| 3 | Attachment shall remain in storage mode to prevent inadvertent release. |
| 4 | Attachment shall provide adequate drag surface area to a mid-sized spacecraft when deployed. |
| 5 | Reliability of deployment of the draf sail shall be 90%. |
| 6 | Attachments shall be scalable up to 30 $m^2$. |

Figure 6. OLMA Design Requirements

## B. MATERIAL

All versions of OLMA designed during this research were developed in Siemens NX computer-aided design (CAD) software. Each part identified in the following sections was designed and printed separately utilizing the Naval Postgraduate School (NPS) Space Systems Academic Group (SSAG) 3-dimensional (3D) printer. The material used by the 3D printer is polycarbonate. It is space-grade material for short mission durations. Full implementation of OLMA in its size appropriate form will require longer-lasting space-grade material. Further guidance for space-grade material is found in NASA's *Materials for Spacecraft*.[29] Additional material used to develop OLMA include standard stainless-steel screws and Kapton tape. The sail material is Aluminized Kapton, which is highly durable in space. A composite list of the materials and parts is depicted in Figure 7.

[29] Miria M. Finckenor, *Materials for Spacecraft*, 20160013391, NASA Technical Reports Server, (Hunstville, AL: American Institute of Aeronautics and Astronautics, 2018), https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160013391.pdf.

| Part | Number Used |
|---|---|
| Polycarbonate (3D printing material) | N/A |
| 2 x 1/2 in. Spring Loaded Stainless Steele Hinge | 2 |
| #2-56 x 1/4 in. Screw | 4 |
| #2-56 x 1/2 in. Screw | 4 |
| Paperclip (cut and bent) | 3 |
| Kapton Tape | N/A |
| Stainless Steele Measuring Tape | 2 |
| Aluminized Kapton Sail | N/A |

Figure 7. List of Materials and Parts

## C. STORAGE MODE

The sail is stored in a double-Z folded accordion style bundle in the storage section. The folding technique is discussed in depth in Section B of Chapter III. While stored, the two tape arms will be coiled around the tape spool. Excess portions of the tape arms are intentionally uncoiled and stored in respective guide tracks and attached to the two corner ends of the sail. The aluminized Kapton sail is affixed with Kapton tape at the end of each tape arm and at the separation wall in the base of the storage area. The overall design components without the cover are identified in Figure 8. The design components with the cover and release mechanisms are depicted and described in Section C of Chapter III.

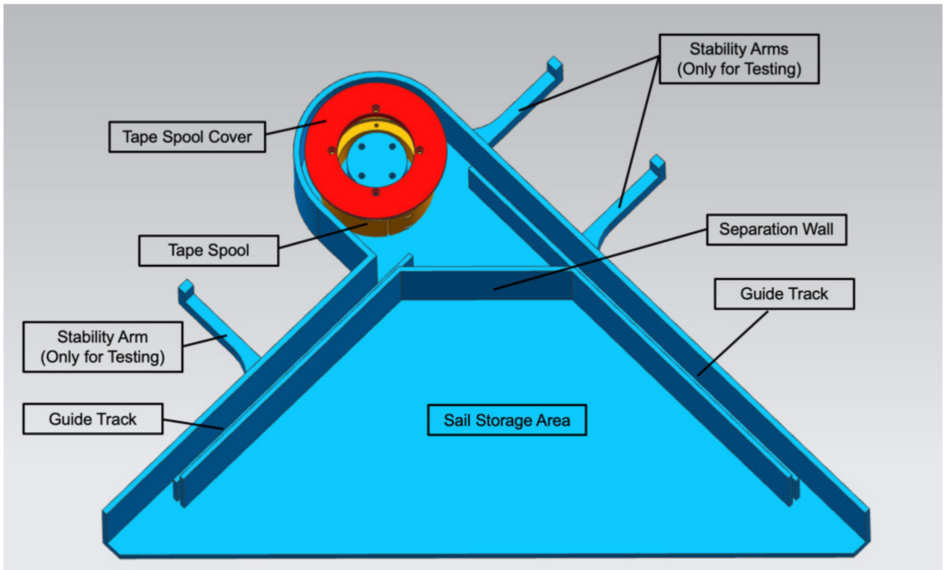


Figure 8. Final Design Components without Cover

For mechanical testing purposes, three stability arms were built into the base; the final, full-scale OLMA model will not incorporate these arms. The Kapton tape was removed and refitted between each round of testing. This allowed for the tape arms to be recoiled, the sail to be re-folded, and the attachment to be reset to storage mode. The stability arms will not be part of the final design.

## D. DEPLOYMENT MODE

When the operator is ready to execute the deorbit plan, OLMA will transition to deployment mode. Three pin puller release mechanisms will be activated; two release the spring-action door in the front while a third pin puller releases the tape spool collectively allowing the sail to deploy. Implementing three separate pin pullers allows for redundancy in the system, which, in turn, prevents premature deployment. This also creates a potential for deployment failure should a pin puller fail to operate as intended. The actuator can experience long exposure to the space environment, which will likely increase risk to inadvertent deployment. The redundancy in the three-pin-puller system was incorporated to ensure the sail does not unintentionally deploy and adversely affect the spacecraft's mission. Further detail pertaining to the redundancy system is discussed in Section C of Chapter III.

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# III. DESIGN AND TESTING

Mechanical testing was conducted during each phase of the design build-up. The sequential order of testing included three phases: kinetic testing with the tape spool and tape arm deployment, sail storage folding pattern testing, and sail deployment on the tape arms to include functionality of the holding and releasing mechanisms.

## A. KINETIC TAPE ARM DEPLOYMENT

Kinetic tape arm deployment testing was the decisive factor of design modifications —unsuccessful tape arm deployment directly correlated to drag sail deployment failure. Figure 9 shows the design evolution of the prototype through the final design. The initial design (Figure 9(a)) incorporated two tape spools in the upper triangular section of the overall model as well as top and bottom guide tracks to help the deployment of the tape arms. After several rounds of mechanical testing, the ultimate design (Figure 9(c)) incorporated a single tape spool with two tape arms attached to the spool separated by 90-degrees.

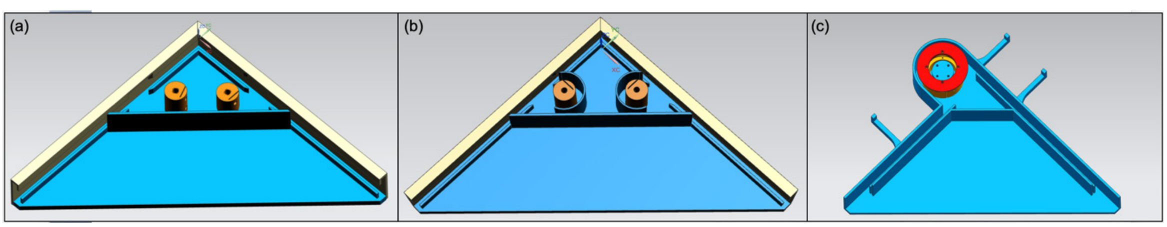


Figure 9. OLMA Design Versions

### 1. Initial Design

The first design, shown in Figure 9(a) and Figure 10, incorporated three main components: a base, two guide tracks, and two tape spools. Conceptually, the tape arms are coiled about the two orange tape spindles such that the curved face of the tape bends outward, away from the center of the spindle. The 1.00 in (25.4 mm) openings in the yellow guide tracks allow for tape arm entry into the guide track. The remainder of the guide track maintains a horizontally aligned gap at the inner-face of the attachment that allows for fastening of the sail to the tape arm. The blue base also incorporated the bottom, 0.02 in (0.508 mm), portion of the guide tracks for the tape arm as well as a 1.00 in (25.4 mm) high separation wall between the upper-triangle tape spool region and the sail storage area.

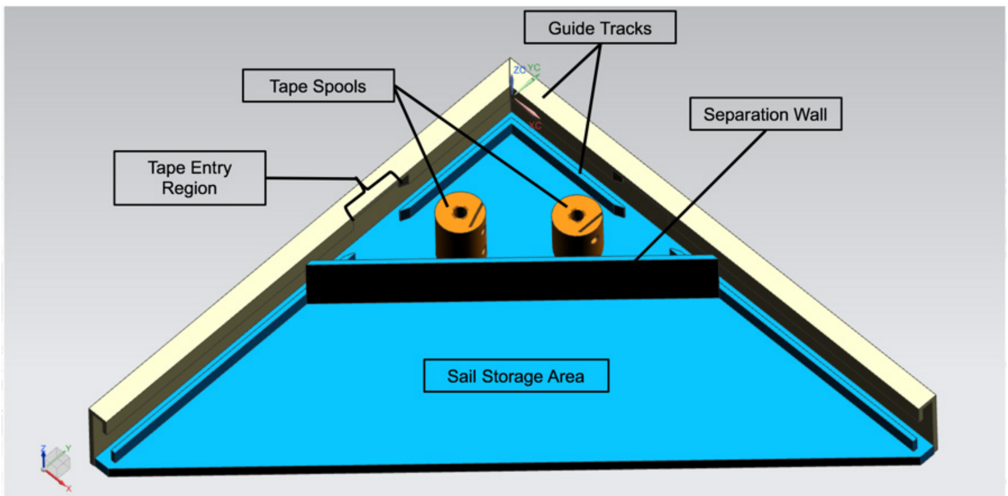


Figure 10. Initial Design Components

Mechanical testing of the initial design resulted in contact between the tape measure arm and guide track "roof." The bending of the tape arm during transition between the flat, coiled position and curved, uncoiled position post-deployment was not accounted for. Figure 11 depicts the width differential between the flat and curved tapes. This effect prevented appropriate tape arm deployment and misdirected the stored energy in the coiled tape. Subsequently, the tape spool unfurled within the upper triangular section of the model rather than the planned linear trajectory along the guide tracks.

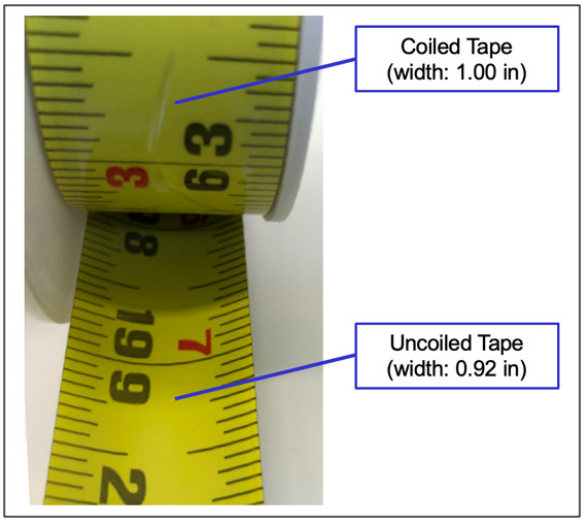


Figure 11. Tape Arm Width Differential

### 2. Second Design

As a result of the initial design mechanical testing results, the second design, depicted in Figure 9(b) and Figure 12, contained several updates. First, the guide track height was extended from 1.18 in (29.9 mm) to 1.38 in (35.1 mm) to account for the tape arm width differential. Second, in an attempt to remedy the misdirected energy within the coiled tape spool, 220 degrees of an outward-facing arc was designed around each tape spool on the base. Ideally, these arcs would help direct the energy and act as anti-unfurling mechanisms during deployment of the tape arms.

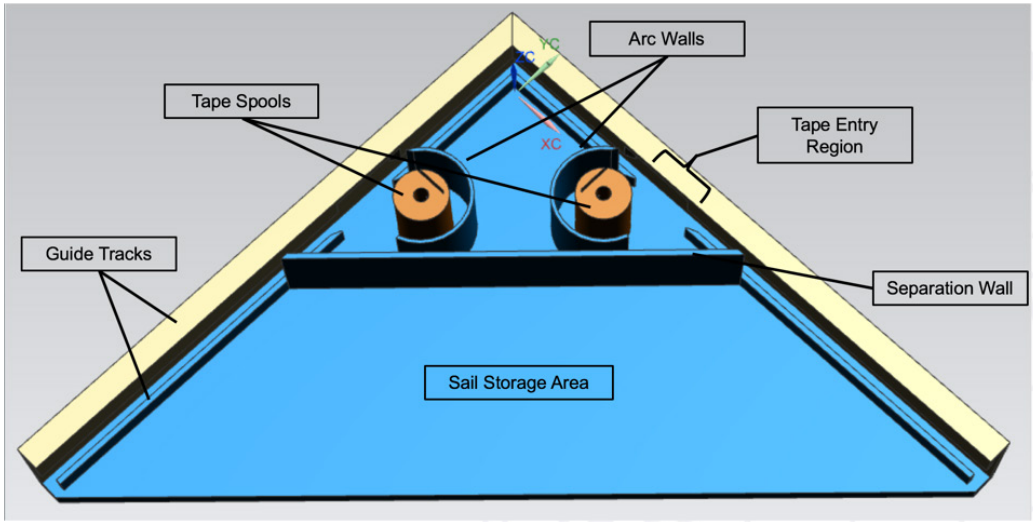


Figure 12. Second Design Components

Additional modification incorporated in the second design included a key release mechanism. The key release mechanism, shown in Figure 13, was solely intended for testing purposes; allowing the tape spool to be rewound for multiple rounds of testing. The key consisted of a pin and box receiver. When the green box receiver does not have the purple pin inserted (Figure 13(a)), it can be used to rewind the tape arms on the spools. When the purple pin is inserted into the green box receiver, the box portion is released from the top of the tape spindle allowing the tape to move freely (Figure 13(b)). Final implementation would not incorporate the removable key component.

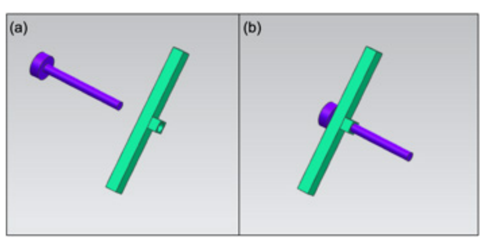


Figure 13. Key Mechanism

Mechanical testing resulted in significant unfurling of the tape spool. As a result, the predicted cause of the misguided energy discovered in the first design was incorrect.

However, the height adjustment of the guide tracks proved successful. Additionally, the key mechanism allowed for a smoother release of the tape spool vice the human hand.

### 3. Final Design

The final design contained several more significant modifications. Firstly, the two tape spools were combined into one spool designed by a previous NPS student.[30] The spool contained designated slit regions in the cylindrical structure with two screw holes that allow for the beginning of the tape arms to be affixed to the tape spool. The four tape arm receivers within the central spindle shown in Figure 14 are spaced by 90-degrees of separation. The intent of this configuration was to test the viability of equal and opposite force while installing the tape arms 180-degrees offset as well as 90-degrees offset. The 90-degree offset allowed for greater end-state stability in deployment mode. The inner diameter of the single spool measures 1.25 in (31.75 mm) (approximately 0.50 in (12.7 mm), larger than the outer diameter of the double tape spool design).

Second, to account for the single tape spool and prevent the need for additional bending of the tape arm during deployment, the base design was modified; relocating the spool to the outside of the original triangular base (Figure 9(c)). A friction-reducing bearing insert was placed between the base post spindle and the single tape spool to ensure smooth movement about the base tape spindle.

[30] Alexander Niederlein, "Design & Development of a De-Orbit Device for the NPSAT1 Small Satellite" (master's thesis, Naval Postgraduate School, 2013), 49-50.

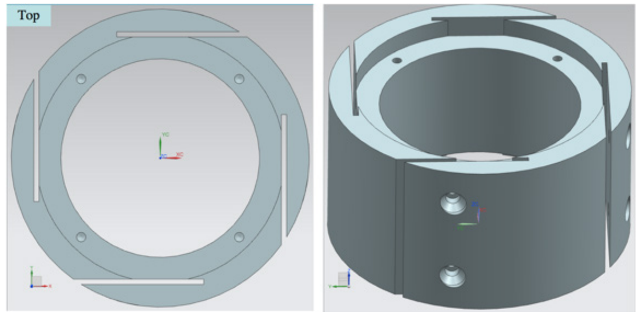


Figure 14. Tape Spool[31]

Mechanical testing resulted in successful deployment of the tape arms for both the 180-degree and 90-degree separation schemes. However, greater end-state stability was present with the 90-degree separation technique and was therefore utilized for follow-on implementation.

Thirdly, the separation wall between the sail storage area and the tape spool was reconfigured to a trapezoid shape with the longer edge outward facing. This design modification provided a flatter surface area for the starting edge of the folded sail. Lastly, the yellow guide track wall segments previously presented in earlier designs were replaced with a base wall around the outermost perimeter of the base (excluding the region where the sail will deploy). The extended perimeter walls served two purposes: an outermost guide track for tape arm deployment and an anti-unfurling mechanism for tape spool containment. A portion of the inner base guide track was extended from 0.20 in to 1.00 in (5.08 mm to 25.4 mm) in height and aligned with the end of the trapezoidal separation wall. This modification allowed for directional guidance of the bent tape arm deployment while not interfering with the sail material or sail attachment region. The overall dimensions are shown in Figure 15.

## B. SAIL STORAGE AND FOLDING PATTERN

The dimensions of the triangle-shaped sail while deployed are 54 in x 54 in (1.37 m x 1.37 m) resulting in 1,458 $in^2$ (0.94 $m^2$) area triangle surface area. Should four OLMAs

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[31] Niederlein, 50.

be attached to a spacecraft in a square configuration, the resulting surface area is just over 5,830 $in^2$ (3.78 $m^2$). The trapezoid-shaped storage area measures 2.76 in x 11.87 in x 4.30 in (0.07 m x 0.30 m x 0.11m), resulting in a surface area of 31.45 $in^2$ (0.055 $m^2$) and with an interior height of 1.53 in (0.039 m), the storage area volume is approximately 48 $in^3$ (0.002 $m^3$) as shown in Figure 15. The sail is stored using the aforementioned double-Z folding pattern. This allows for the right angle of the sail to be affixed along the separation wall while the 45-degree angle corners of the sail are accessible to be affixed to the end of the tape arms at the outward-facing edge of the sail storage area.

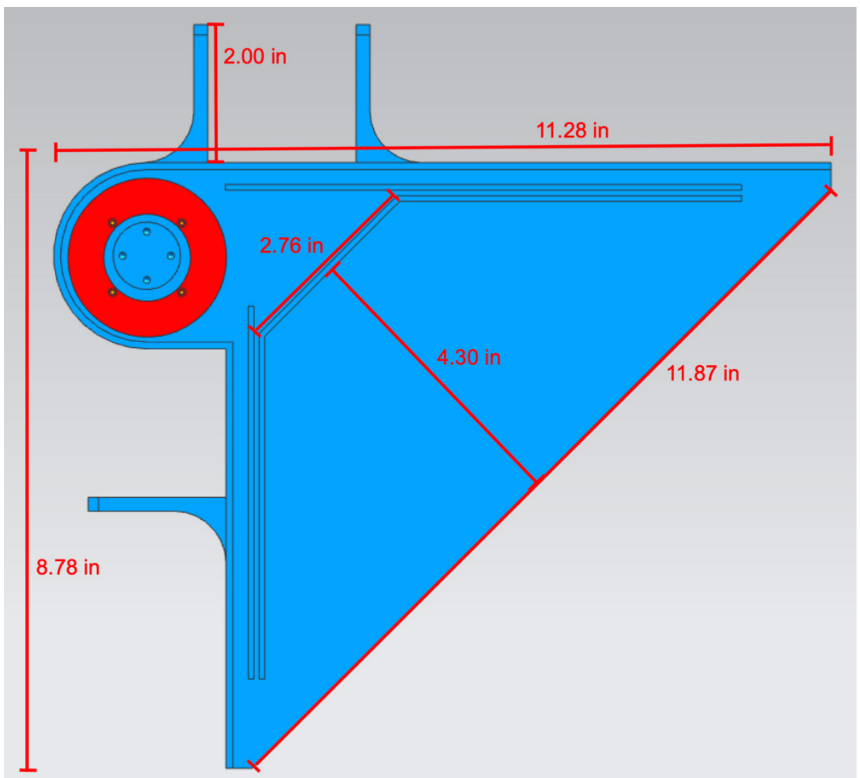


Figure 15. Base Configuration Dimensions

The double-Z folding pattern consisted of two stages. First, the accordion-style fold starting from the short edge of the trapezoid base and continuing until the hypotenuse of the triangle sail (Figure 16). Second, the accordion-style fold starting at the center and pulling the strip of folded sail inward until both sides are compact within the sail storage area (Figure 17). Coupling both accordion-style folds together creates the double-Z pattern allowing the outermost folds of each stage to unfold first. Springfloaded clips were used to hold the sail folds in place between stages. The clips were removed once the completely folded sail was set in place.

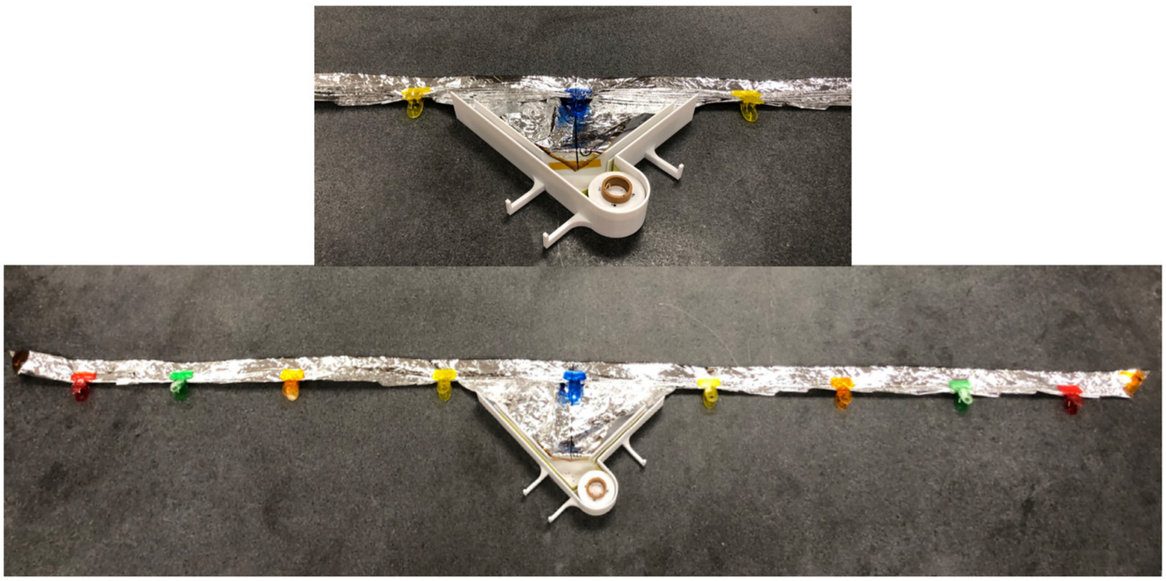

Figure 16. Stage One of Double-Z Sail Folding Pattern

Figure 17. Stage Two of Double-Z Folding Pattern

Kapton tape was used to affix the sail to the base of the storage area as well as at the ends of the tape arms. Figure 18 shows the end of the tape arms taped to the sail such that the adhesive-free side is outward-facing. The values presented on the tape measure arms do not reflect actual length.

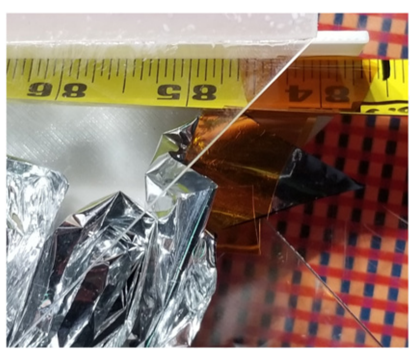

Figure 18. Sail Affixed to the Tape Arm (Kapton Tape)

## C. SAIL DEPLOYMENT

The final stage of testing included implementation of the previous stages. The folded sail was adhered to the tape arms and the deployable components were placed in storage mode until the operator initiates deployment mode. To reduce the cost of testing, paper clips were utilized in place of the pin pullers.

The cover depicted in purple in Figure 19 serves three purposes: protection to the sail in storage mode, fail-safe mechanism for deployment of the tape arms and sail, and stable mounting material for the pin pullers, doors, and hinges. Pin pullers 1 and 2 are located near the front of the attachment on opposite ends of the front door. They hold the front door in storage mode; preventing tape arm deployment and preventing the sail from unfurling. Pin puller 3 is located on the top of the cover above the tape spool. It holds the tape spool locked in place via a hole drilled through the cover and the tape spool. When the pin pullers are activated, the stored energy in the tape spool is released and the front door is opened thus allowing OLMA to transition from storage mode to deployment mode. The stages of sail deployment are shown in Figure 19.

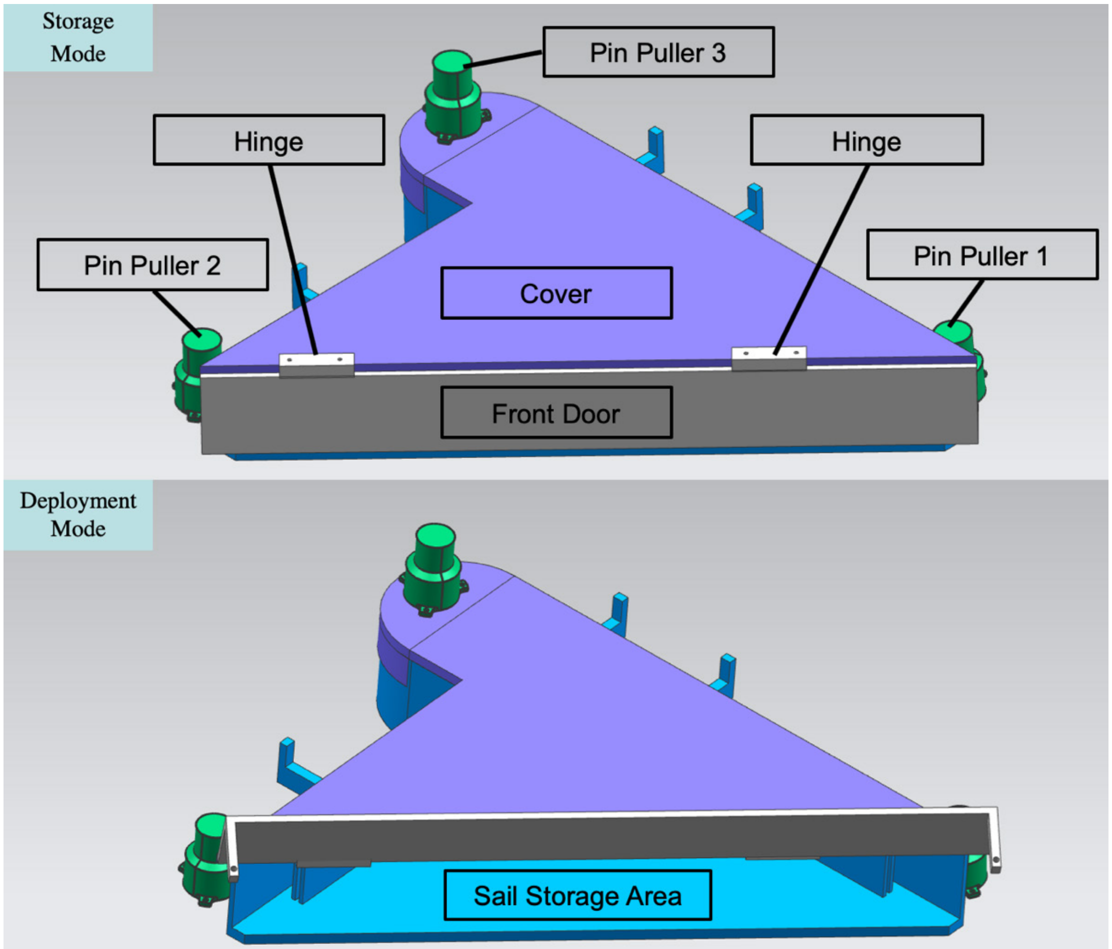


Figure 19. Stages of OLMA Deployment with Pin Puller Initiation

Testing at this stage proved successful. Of the 40 rounds of mechanical testing during this stage, four rounds resulted in failure; successful sequential deployments occurred for 32 rounds resulting in 90% reliability. Failure occurred during rounds 33–35 and 39 as a result of human error. Such human error included untidy folding of the sail, transition lapse issues when installing the cover, and imprecise use of Kapton tape when affixing the sail to the tape arms. Eliminating these errors allowed for successful deployment of OLMA.

## D. REQUIREMENTS CHECK

Per the scope of this thesis, the OLMA prototype was able to meet four of six requirements. The overall mass of the attachment is 0.80 kg. Implementing three units would result in an overall mass of 2.40 kg; this meets the first requirement. The third requirement is met with the implementation of the three-pin-puller system. The redundancy in the release mechanisms allows the attachment to remain in storage mode therefore preventing inadvertent release. Although this thesis presents the prototype that creates a surface area of approximately 1,458 $in^2$ (0.94 $m^2$), the modularity of the concept allows for many attachments to a single spacecraft as long as they do not interfere with each other or other components. For example, four OLMAs would result in approximately 5,830 $in^2$ (3.78 $m^2$) surface area. This allows requirement four to be met. Given the 40 rounds of mechanical testing of sail deployment, 36 of which were successful, the reliability remains at 90% - meeting requirement five. Future work related to the OLMA implementation on a spacecraft will address requirement two and six (i.e., spacecraft compatibility for volumetric constraints and scalability).

# IV. CONCLUSION AND FUTURE WORK

## A. SUMMARY

As this thesis demonstrates, a low cost, less than 10 kg mass design can be produced to comply with the orbital debris mitigation guidance set forth by the international space community for mid-size spacecraft. This thesis proves a cost and mass-efficient solution is viable to adhere to international guidance on deorbiting larger payloads from LEO. For a more cost-effective solution during research, the author sought durable design materials that are cost-effective given the various models produced.

This thesis research included Siemens NX CAD software design, 3-D printed building, and testing of the OLMA device. Additionally, this thesis utilized commercial products such as tape measures, screws, hinges, and polycarbonate printing material. Various models were designed, built, and tested for functionality. Mechanical testing demonstrated successful implementation of OLMA capabilities. This prototype can serve as a platform for future drag sail deployment development given its inherently scalable, adaptable, and modular characteristics.

## B. FUTURE WORK

This thesis provided a prototype of OLMA, a spacecraft deorbiting modular attachment. Future work can range from more efficient design in mass, material, and cost to mission integration.

### 1. Efficient Design and Material

Future NPS students can continue research on the OLMA design scalability. Students can modify the NX CAD model such that it can accommodate a larger sail. Additionally, students can work with the NPS machine shop to produce the OLMA in material that has greater durability and longevity in the space environment. Utilizing such material will allow for OLMA implementation during missions of long duration such that when present in the space environment, atomic oxygen erosion does not impede functionality. More suitable mechanisms may be researched for affixing the sail to the tape arms. Grommets were initially considered during this thesis, but concern arose when considering imperfections in the sail material that could cause significant harm to sail functionality. More research can be done to find a better solution than Kapton tape while not harming the sail material. Moreover, additional research can be conducted to analyze best means of attaching OLMA to a spacecraft.

### 2. Further Testing

The OLMA has endured mechanical testing. Additional testing can be conducted to prove readiness for mission integration. Strength analysis of the material and fasteners under various loads can be conducted to ensure structural integrity is sound for mission integration. Thermal vacuum chamber testing at NPS can be conducted. Due to size limitations, this testing can be executed while OLMA is in storage mode. After thermal vacuum chamber testing is complete, the student can return to mechanical testing in deployment mode to note any affects to functionality.

An additional testing resource available at NPS is the vibration table. Similar to thermal vacuum chamber testing, OLMA can undergo vibration testing while in storage mode to ensure survivability during launch. Should OLMA experience premature deployment during vibration testing, design modifications would be required.

Moreover, testing can be conducted to measure the energy released during drag sail deployment. This data would benefit operators during implementation. Understanding the impact of the energy released would help determine the impact on the orbit of the spacecraft as well as the impact to the spacecraft attitude determination and control system (ADCS).

### 3. Electronics and Control Systems

The current design and research included the use of pin-pullers from a conceptual standpoint; simulation of pin-puller functionality was conducted with paperclips and human interference. Further research can be conducted to develop and design the electronic system that can control the pin-pullers to release the sail. A series of actuators will likely be required to initiate deployment. Additional consideration of industry standard for compatibility of electronic systems onboard spacecraft should be considered for broad use of OLMA full-scale model, with a surface area of approximately 4 $m^2$. To ensure redundancy, each pin-puller should be initiated sequentially and separately; respective electron systems need to maintain the same reliability as the pin-pullers.

### 4. Mission Integration

Future NPS students can coordinate with faculty, staff, and potentially other students to coordinate mission integration testing. In proving the OLMA can function as conceptually described, an in-flight demonstration will serve well. Launch opportunities, schedules and missions will need to be coordinated. Possible launch vehicles include the High-Altitude Balloon (HAB) and the targeted LEO rocket projects previously researched by NPS students. The deployment mechanism can be tested on the HAB at a desired higher altitude.

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