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Orbital Debris Mitigation: Exploring CubeSat Drag Sail Technology

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Introduction

In an era marked by remarkable advancements in space exploration and research, the advent of satellite technology has contributed accordingly to the lives of people here on Earth. Through applications that tie into broadband connectivity, weather forecasting, disaster management, etc., the occupancy in orbital domains like Low-Earth Orbit (LEO) only continues to grow. However, the presence of orbital debris emerges as a significant concern, posing threats to both operational satellites and future space missions. Resulting as a consequence due to decades of activities since the launch of Sputnik 1 in 1957, as more countries ventured into space so did the number of spacecraft, each leaving behind remnants of their missions (The Aerospace Corporation, 2022). Coupled with major events such as China's Anti-Satellite Test in 2007 and Iridium-Cosmos' Collision in 2009 producing thousands of fragments from destroyed space assets, this furthered the overall accumulation of space debris (Hadley, 2023; National Aeronautics and Space Administration, 2009). As it stands now, more than 27,000 pieces of orbital debris traveling approximately 15,700 mph have been recorded in LEO (National Aeronautics and Space Administration, 2021). Varying in size and carrying the potential to deal substantial damage, orbital debris mitigation measures are of paramount importance to ensure the sustainability for continued space operations long-term.

Orbital Debris Mitigation Technical Approach

Henceforth, a selection focusing on CubeSats employing drag-inducing sails to deorbit LEO space debris is proposed as a solution. Given that atmospheric drag stems as the largest force affecting the motion of objects in LEO, increasing the effective area of a satellite via sails to accentuate such a force can reduce the timeframe required for defunct space objects to burn up in Earth's atmosphere (Nwankwo et al., 2021; Serfontein et al., 2021). Through serving as a passive mitigation method, the avenue of drag-inducing sails also yields the potential to reduce the likelihood of collision risks which could result in Kessler's Syndrome (Serfontein et al., 2021; Visagie et al., 2015). What's more, from drag sails facilitating key strengths such as minimal propulsion requirements, low mass, and scalability, this opens the door in CubeSat deployments to target smaller debris that may be harder to track from Earth. That said, with countries like the United States, Europe, Japan, etc., already having engaged with drag sail technology (Martin, 2023) and CubeSat specifications, this concrete foundation can serve to enhance this mission's overall capabilities.

Orbital Debris Mitigation Mission Specifications

Diving into the specifics, a total of 35 6U CubeSats units operating between 300 km – 800 km in LEO will help to deorbit space debris ranging from tens of centimeters (10 – 70). Equipped each with five 4m^2 drag-inducing sails designed + manufactured by Vestigo Aerospace, a fluorinated polyimide material called CP-1 is used to allow solar photons to pass through and resist degradation from the monatomic oxygen in LEO (Hill, 2020; Purdue University, 2020). This is quite imperative given that major issues surrounding drag sails is their dependency on solar radiation to generate opposing thrust and likelihood to wear down from the harsh conditions in the space environment (Visagie et al., 2015). Hence, CP-1's dual property of facilitating efficient photon transmission and resilience can address these limitations, enabling the effective use of drag-inducing sails.

Building upon this, implementation of the KRAKEN robotic arm created by Tethers Unlimited is issued to assist the necessary CubeSat docking procedure to properly apply a drag sail to each targeted defunct object. Upholding a modular design + a TRL (Technology Readiness Level) of 6, the KRAKEN is a 1m, 7 degree-of-freedom apparatus that enables a

CubeSat to conduct various duties like assembly, servicing, and debris capture in LEO that could otherwise be challenging + constraining for such a small spacecraft (National Aeronautics and Space Administration, 2023; Tethers Unlimited, n.d.). That said, in order to properly situate the functionalities associated with each CubeSat, the implementation of various subsystems such as power, propulsion, communications, etc., are additionally accounted for. Adapting from a proposed mission concept of a debris-removing nanosatellite called DeOrbiter CubeSat, Hakima and Emami (2020) underline these components to having a long space heritage and being commercially available. All in all, facilitating a necessary means in optimizing this mission's integration, design, and development to mitigate orbital debris in LEO.

Literature Review

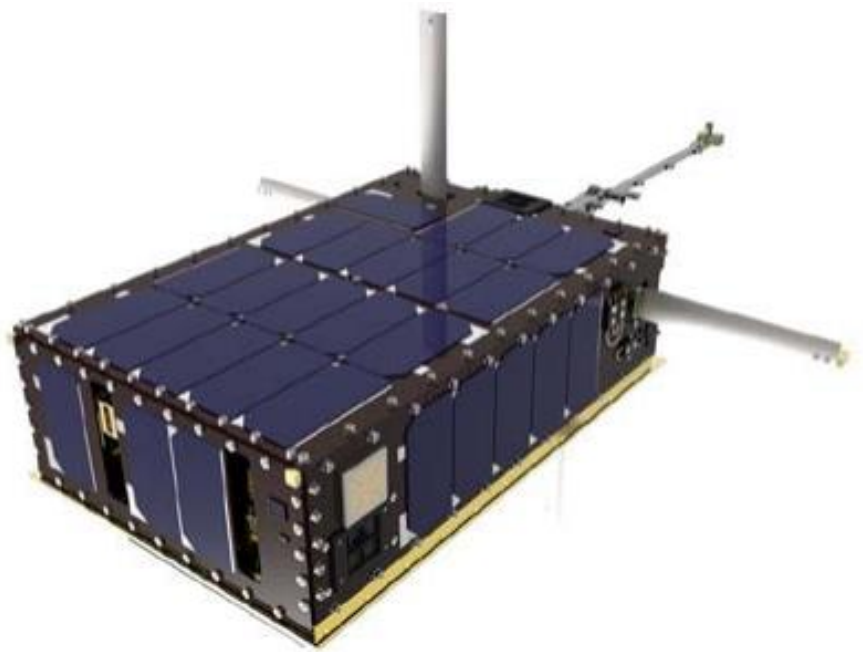
Laying the foundation for a comprehensive exploration of this orbital debris removal system employing a synergistic integration of CubeSat technology, drag sail innovation, and robotic arm capabilities, it is essential each element be properly weighed to gauge their individual contributions. Overall, paving insight into the feasibility and effectiveness of such a multifaceted approach toward orbital debris management.

CubeSat 6U Design

Starting with the CubeSat themselves, each are to follow a 6U form factor design. From a presented model in **Figure 1**, Ostrom and Opiela (2021) underline that the associated max mass and area-to-mass ratios for such a unit are 12.0 kg and $4.58 * 10^{-3}$ m^2/kg respectively. Through enhancing nanosatellite applicability, the 6U CubeSat structure is able to provide more power + volume for instruments, avionics, actuators, and propulsion (Bright Ascension, 2020). Overall, situating potential for future missions in attaching drag sails to spent rocket bodies of varying sizes to mitigate their effect on the on-orbit debris environment (Abercromby & Ostrom, 2021). That said, with previous missions like RemoveDEBRIS already showcasing the deployment of a drag-sail to increase the drag of a CubeSat 2U satellite (Aglietti, 2019), this paves a solid foundation in emphasizing the possibilities that a larger and more capable CubeSat can achieve.

Figure 1

CubeSat Model Design



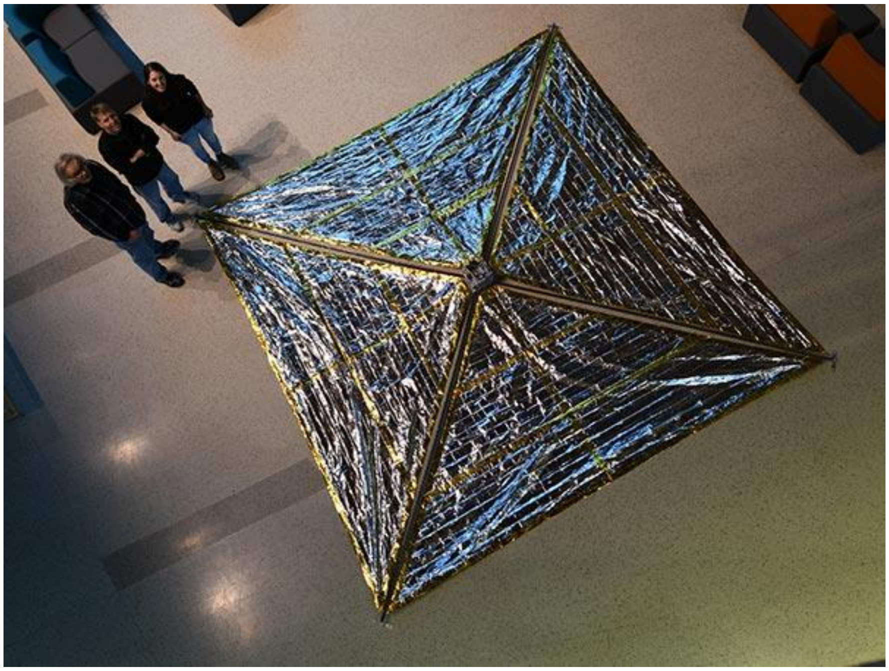
Note. Example of a 6U CubeSat. From *CubeSat 101: Basic Concepts and Processes for First-Time CubeSat Developers*, by National Aeronautics and Space Administration, 2017, (https://www.nasa.gov/sites/default/files/atoms/files/nasa_csli_cubesat_101_508.pdf)

Vestigo Aerospace Drag Sails

Switching over, the usage of drag sails will be developed by Vestigo Aerospace. Highlighted in **Figure 2**, each product utilizes standard mechanical and electrical interfaces to the host satellite, allowing straightforward integration. Coupled with a power source, adjustable timer, and targeted reentry, drag sail deployment can occur autonomously or upon command from ground controllers (Vestigo Aerospace, n.d.-a). What's more, from the low requirement needed in a SWaP-C approach, this further adds value to targeting orbital debris in order to reliably meet the FCC's 5-year deorbit rule (Vestigo Aerospace, n.d.-b). All in all, initiating a more controlled deorbit maneuver in conjunction with CP-1 material to effectively reduce a defunct space object's orbital velocity to bring it closer to Earth's atmosphere gradually.

Figure 2

Drag Sail by Vestigo Aerospace



Note. Image of Vestigo Aerospace designed drag sail. From *Dragsails*, by Vestigo Aerospace, n.d.-a, (https://vestigoaerospace.com/dragsails/)

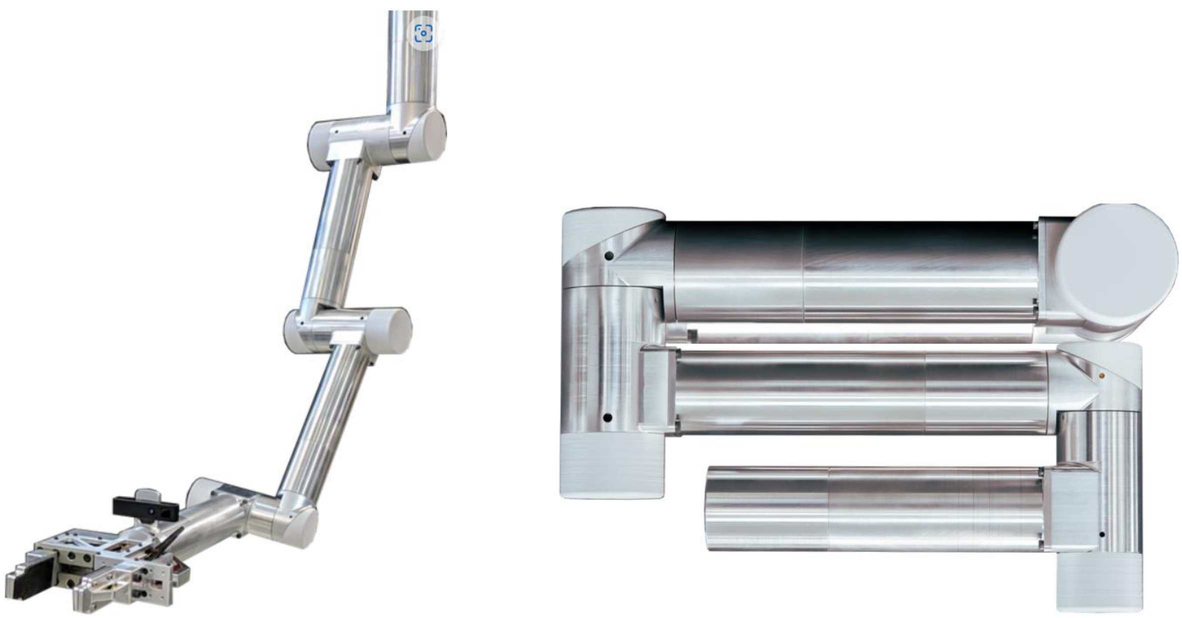
KRAKEN Robotic Arm

Moving onwards, the necessity of the KRAKEN Robotic Arm to assist in precision and control operations in space is to be produced by Tethers Unlimited. Denoted in **Figure 3**, the KRAKEN facilitates a stowage volume of 190 x 270 x 360 mm and a mass of 5 kg (National Aeronautics and Space Administration, 2023). Fostering an advanced control architecture as well, the KRAKEN low-SWaP arm aids in enabling the safe manipulation of objects in space, while its EtherCAT backbone gives the speed to support rapid sensing + control to close the loop

(Tethers Unlimited, n.d.-b). Playing to a modular configuration, it is also important to mention that the KRAKEN harbors four different joint sizes to vary up to its stated length accordingly and has autonomous adaptive tooling to account for various mission needs (Tethers Unlimited, n.d.-b). Whether this be assembly, manufacturing, or servicing, the KRAKEN Robotic Arm stands as a versatile solution poised to revolutionize the capabilities of orbital debris removal.

Figure 3

KRAKEN by Tethers Unlimited



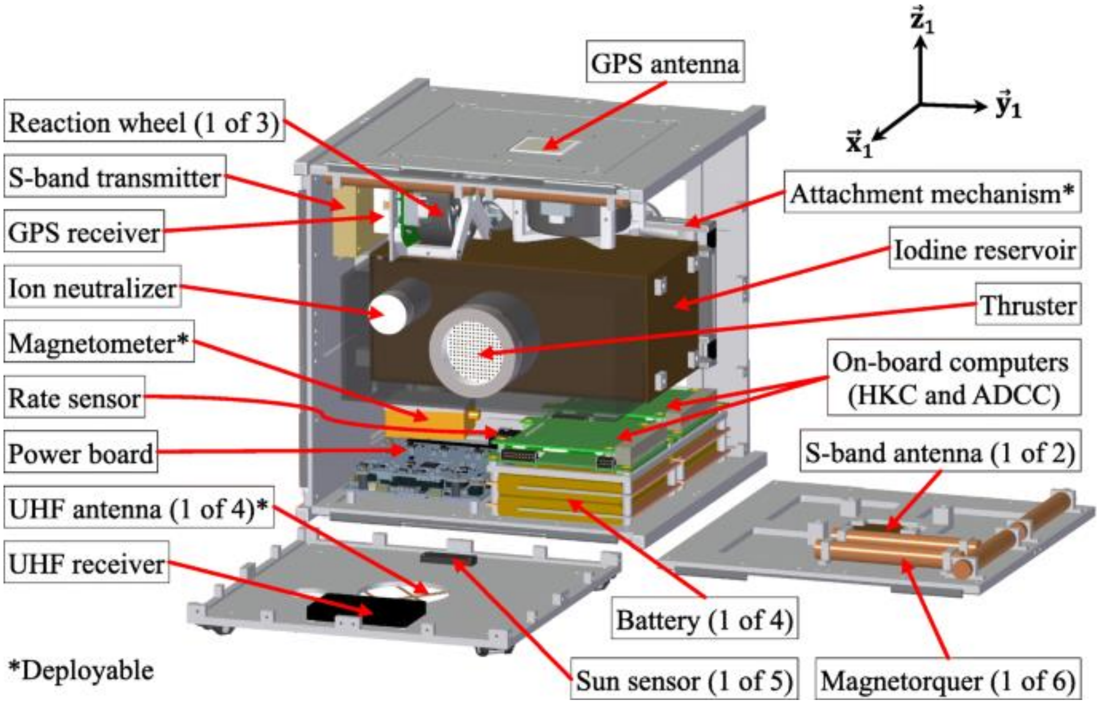
Note. Deployed (left) and stowed (right) positions of the KRAKEN Robotic Arm. From *KRAKEN*, by Tethers Unlimited, n.d.-a, (https://www.tethers.com/robotic-arm/)

CubeSat Subsystems

Lastly, the implementation of various CubeSat subsystems are to adapt a similar approach to that of another CubeSat orbital debris removal mission. Titled as DeOrbiter, the selected components aboard each 8U unit illustrated via a cutaway view in **Figure 4** are listed to be commercially available and have a long space heritage (Hakima & Emami, 2020). All in all, paving the way for a cost-effective and reliable solution to support our mission's objectives.

Figure 4

DeOrbiter CubeSat Engineering Model



Note. Internal components shown aboard each DeOrbiter CubeSat model. From *Deorbiter CubeSat System Engineering*, by Hakima and Emami, 2020, (https://doi.org/10.1007/s40295-020-00220-5)

Commencing with the Attitude Determination and Control System (ADCS), it plays a pivotal role in managing the spacecraft's orientation. Here, hardware certified at a TRL 9 comprises five sun sensors, one three-axis magnetometer, one three-axis rate sensor, three reaction wheels, and six magnetorquers (Hakima & Emami, 2020). Simultaneously, the Command and Data Handling subsystem, responsible for storing and processing operational data, employs two onboard computers certified at TRL 9 (HKC – Housekeeping & ADCC –

Attitude Determination and Control) with an option to enhance configurability via a daughter board for additional power interfaces + connections (Hakima & Emami, 2020). Moving on to communications, this facet of the spacecraft employs 2 radio module types (S-band & UHF – Ultra High Frequency) commonly used in CubeSat missions and serve the essential purpose of transmitting telemetry data from the spacecraft while also receiving signals from the ground station (Hakima & Emami, 2021). As a result, helping to ensure duties in space are carried out with utmost safety and optimality.

In tandem with these core systems, maintaining a stable and efficient power supply is nevertheless paramount for the spacecraft's operations. Through a power subsystem encompassing a comprehensive array of components, these include batteries, 62 high-efficiency exterior solar cells provided by Azur Space, meticulously designed wiring harnesses, and a sophisticated power board equipped with converters + battery charge/discharge regulators (BC/DR) (Hakima & Emami, 2021). On that note, when it comes to propulsion, the adoption of an electric system proves imperative due to its substantially reduced propellant consumption compared to its chemical counterpart for achieving specific delta-v requirements (Hakima et al., 2018). Within this framework, the proposed solution involves the utilization of a BIT-3 ion thruster manufactured by Busek Space Propulsion and Systems, coupled with a 7 kg solid iodine reservoir and supplementary avionics + sensors (Hakima et al., 2018). Tying it all together, the meticulous integration of these subsystems and their seamless coordination exemplify adaptable planning to be used in our own mission.

Findings and Analysis

Building upon the foundational knowledge established above, the assessments arising from an in-depth exploration will serve as an additional platform for subsequent insights. This, in turn, facilitates a more gradual + comprehensive understanding of the supplementary factors such as constraints, assumptions, and cost considerations that encompass the technical components of this orbital debris removal mission.

CubeSat 6U Design Factors

Examining the CubeSat 6U in detail, its design significantly influences the architecture of this mission. Priced at approximately $540,000 USD per unit, it confronts substantial challenges tied to space-based radiation and radiofrequency spectrum management (SatCatalog, n.d.; Novak et al., 2022). CubeSats, while compact, typically employ a modest 0.20 cm aluminum shielding, rendering them susceptible to unpredictable trapped radiation and solar particle events in Low Earth Orbit, posing risks of onboard component failures or degradation. Furthermore, escalating congestion within the lower frequencies of CubeSat operations has led to interference issues among different systems (Novak et al., 2022). Addressing these impending obstacles, emerging techniques such as Z-shielding provide a promising alternative to traditional aluminum shielding. Here, Z-shielding involves layering metal materials, offering a low-cost and easily implementable solution for safeguarding CubeSats against LEO space radiation (Damadeo, 2019). These innovations, coupled with CubeSats' inherent modularity and rapid development capabilities, collectively contribute to a culture of continuous improvement.

Moreover, in the context of this orbital debris removal mission with prominent entities like NASA, DARPA, and the U.S. Space Force, the prioritization of ground systems targeting specific frequencies emerges as a potential solution to optimize CubeSat operations. As a result, this alignment with established organizations and their specialized ground systems underscores the mission's commitment to achieving its objectives efficiently while benefiting from collaborative synergies.

Vestigo Aerospace Drag Sail Factors

Moving onwards, there are similar points to note when talking about drag sails in space. As previously mentioned, significant concerns regarding drag sails include their reliance on solar radiation for generating counteractive propulsion and their susceptibility to degradation due to the harsh conditions of the space environment (Visagie et al., 2015). Without the expenditure of additional propellant, the consistency and effectiveness for the 5 drag sails each CubeSat is to carry is likely to fluctuate. What's more, from continuous operations in LEO the exposure of solar radiation can damage the structural integrity for drag sails causing them to become brittle over time (Serfontein et al., 2022). Nevertheless, with each Vestigo Aerospace Drag sail approximated to be $80,000 USD, its emphasis on a fluorinated CP-1 polyimide materials aims in mitigating these barriers (Martin, 2023). Supporting a requested 4 square meter drag sail design similar to the CanX-7 drag mission, the usage of CP-1 in addition to its stated benefits offers a high transparency and a low dielectric constant (Sears, 2014; Aalto University, 2017; Urone et al., 2022; NeXolve, n.d.), which could help to deorbit defunct space objects more effectively. Not only this, but with additional characteristics tying into UV resistance, conductive/non-conductive offerings, and a 10 year rated life in GEO (NeXolve, n.d.), the durability of Vestigo Aerospace Drag Sails is promising in supporting an orbital debris removal mission sufficiently. That said, communication with this vendor will be essential to guarantee the availability and future optimization of these sails beforehand.

KRAKEN Robotic Arm Factors

Transitioning over, the KRAKEN Robotic Arm introduces specific elements that must be considered when it comes to space operations. While it plays a crucial role in performing physical tasks, utilizing a robotic manipulator in general within a microgravity environment presents challenges related to force application and stability. Additionally, its range of motion may be constrained to accommodate the limited payload capacity of spacecraft, which must also house various other electronic components. That said, with an estimated price of $16,000 USD per 2 units aboard each CubeSat, it should be noted alongside this device's benefits, a situated ± 330° joint rotation, 484 Nm peak torque, and 1.5, radius workspace (Bernier, 2021; Tethers Unlimited, n.d.-b) further aids in manipulating/capturing debris objects more freely.

CubeSat Subsystem Factors

Finally, addressing subsystems for CubeSats there are a couple of constraints that come to attention. Upholding stricter power budgets and shorter development timelines, there exists a limited capacity which could affect the quality of operations conducted. In any case, the implementation of a deployable six 6U 20W Solar Panels costing $17,500 in conjunction with solar cells and batteries stated for each CubeSat, aids in the increased total power generated to ensure all electronics remain functional (Andrews Space, 2014). On that note, with these subsystems totaling around $500,000 (Hakima & Emami, 2020), there underlined long space heritage + commercial availability also adds a consistency in accelerating the integration process that every CubeSat is to follow prior to launch.

Synthesis and Interpretation

Looking at an overview for this orbital debris removal system, **Table 1** highlights a comprehensive breakdown of the costs associated with each essential component. Alongside the considerations outlined for Design and Structure, other elements namely Operations + Contingency are also accounted for. Starting with Operations for small satellites, an estimated total of $50 million USD is presented as a result from assuming 10% of the provided budget (Spremo et al., 2017). Here, Operations encompass satellite tracking, mission planning, communication, etc., with respective agencies/organizations and their associated ground stations. Switching over, 5% of the provided budget is allocated for this mission's contingency. Yielding $25 million USD, this serves as a vital safeguard against any unforeseen changes, delays, or disruptions that may arise. Whether these challenges stem from technical issues, external factors, or evolving mission requirements, the contingency funds are strategically set aside to ensure that the missions remain adaptable and flexible. On that note, with this orbital debris removal system bolstering a combined total of $130 million out of the provided $500 million budget, there remains still a significant portion of the budget, approximately $370 million, available for potential adjustments as the mission progresses. Nevertheless, to ensure profitability is generated, 15% of the project's total estimated cost is assumed as a $19.5 million fee (Serbu, 2019). In the end, harboring a profitable outcome from consumers to maintain steady operations.

Table 1

Orbital Debris Mitigation System Final Costs

ODM Component	Estimated Cost Per Unit	Total Estimated Cost
35 6U CubeSats	$540,000 USD	$18,900,000 USD
Vestigo Aerospace Drag Sails	$80,000 USD	$14,000,000 USD
KRAKEN Robotic Arms	$8,000 USD	$560,000 USD
CubeSat Subsystems	$500,000 USD	$17,500,000 USD
6U 20 W Solar Panels	$17,500 USD	$612,500 USD
Operations	N/A	$50,000,000 USD
Contingency	N/A	$25,000,000 USD
Project Budget: $500,000,000 USD		**$130,000,000 USD**

Note. Elements and associated costs for orbital debris mitigation system

Summary

As both commercial and government missions become increasingly common, the risk of orbital space debris also continues to rise. To ensure the safety of these missions and protect valuable space assets, it is imperative to develop methods that address these changes progressively. From a proposed orbital debris removal system costing around $130 million USD total, it represents a significant leap forward in this endeavor. Comprised of varying sub-technologies that yield great applicability and prospective in their own regard, further emphasis is placed on the value in conducting missions with utmost optimality to target various defunct space objects.

Conclusions

Ultimately, while tackling the multifaceted issue of orbital debris will require a comprehensive approach, the deployment of CubeSat units equipped with drag sail technology + robotic arms represents a promising step. Paving insight for larger-scale efforts as well, these small but impactful solutions yielding steady improvements over time can help to foster greater international collaboration in the realm of space debris management. Moving onwards, as humanity navigates the challenges of orbital debris, it is clear that innovative methodologies at various scales will be key to ensuring long-term sustainability and safety for activities in space.

Recommendations

Approaching the technicalities for this orbital debris removal project, two recommendations in particular can contribute towards improving cleanups. The first ties into adopting a larger CubeSat model per unit to support operations. Whether this be an 8U, 10U, or 12U design, the additional room onboard serves as a foundation to not only accommodate more advanced propulsion systems and capture mechanisms but also to carry larger payloads, such as advanced sensors + communication equipment. As a result, extending the capacity of each CubeSat to track and interact with debris more effectively. Next to this, a second approach involves launching an additional 35 CubeSats to target more debris objects. By learning from the performance of the first group, improvements can be made as necessary to enhance additional success. Being quite significant, these changes all together could take advantage of the remaining budgetary resources. In the end, situating a larger impact for initial consumer parties namely NASA, DARPA, and the U.S. Space Force.

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