Mitigating Orbital Debris in Low Earth Orbit: A CubeSat Strategy

Analysis of the Challenges Between Space Debris Removal and Equal Space Access

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Currently, over 130 million pieces of space debris orbit Earth as a result of decommissioned satellites, failed rocket launches, and collisions. Less than one percent of this space debris is tracked by space agencies and governments. Even space debris as small as one centimeter can do significant damage to existing space infrastructure, as the debris is traveling thousands of kilometers an hour. Such collisions multiply the debris around Earth, leading to an exponential rise in potential collisions (Cacioni, 2022). These metrics have been the result of only eleven countries' endeavors, highlighting that there is a significant, growing concern pertaining not only to the copious space debris orbiting Earth but to the equality of space access as well (Koop, 2022).

My technical paper will focus on designing and developing a space debris tracking sensor into a modular CubeSat. This is being done to test a viable means for detecting and tracking space debris smaller than ten centimeters so that other spacecraft that are currently in orbit are not at risk of being damaged. The larger comprehensive topic that I am working on is the accumulation of space debris around the Earth because it is constantly growing due to more space endeavors. With the ability to reduce space debris accumulation, it reduces threats against spacecraft that perform critical tasks such as global positioning (GPS) and satellite communication.

The sociotechnical topic that I am researching is improving equal access to space, as some countries still face challenges accessing and developing space technologies. Utilizing this CubeSat technology will make space safer, but it will still maintain the status quo where developed countries have easier access to space. This leads to a sort of "first-come, first-served" monopoly of particular orbits and difficulty in effectively implementing spacecraft (Deplano, 2023). The consequences of not resolving this problem are pivotal, as it will result in nations/agencies with current space capabilities occupying most if not all of the limited orbital paths above Earth. In the future, new space ventures may be forced to choose an inconvenient orbit that will not allow their technology to reach its full potential, or buy the orbital path from a current nation or agency (Ogden, 2023). What may result from this potential conflict is a larger socioeconomic gap between countries that can utilize space and its resources versus those that cannot. The research into this topic is important, as although my topic is improving the safety of outer space, it does not aim to improve equal access to space. This research will improve this situation by outlining how unequal space access is a current and future problem.

Technical Topic

The design of a space debris tracking satellite in the form of a CubeSat highlights a strategy to make outer space safer in the future. Each of these pieces in low Earth orbit is traveling multiple times faster than the speed of a bullet, with the potential for extreme ramifications and the ability to hinder future spacecraft missions (Cacioni, 2022). To start this design process, my design team and I will perform a conceptual design process for the satellite and analyze the underlying principles that govern the functioning of the satellite. These include researching the tracking system used, the system to determine the satellite's location relative to Earth, and the system to control the satellite in orbit. The satellite will accomplish its primary purpose by sending out electromagnetic waves of a specific frequency that best aligns with the power needs of the satellite. As higher-frequency waves can detect smaller objects farther away, they also require more power to be dedicated to this (Parker, 2011). This important power is also necessary for various subsystems onboard, such as data transmission, thermal regulation, and processing done onboard, among other things. An analysis of structural requirements will inform us how much power is available onboard and then shed light on how much power the tracking system can utilize. From the waves that are sent back, their pattern and the time it takes to receive the waves can shed light on how far away from the satellite the debris is as well as its size and shape. Once space debris is detected, the satellite needs to know its location relative to the Earth, so that the location of the space debris can be determined. From trade studies, our team has also determined our satellite needs a communication module that will have an onboard GPS, and from data processing onboard the satellite, the satellite's location, along with information about the debris will be transmitted, to compute the location/orbit of debris. There is also a chance that while in orbit, the satellite may run into space debris that it detects on its current path. This governs the need for a control system on the satellite because if the satellite were to be struck by existing space debris, the total number of space debris would increase significantly. Thus, the satellite needs a robust way to control itself to mitigate this issue. A crucial design choice our team will consider is whether to utilize Light Detection and Ranging (LiDAR) or Radio Detection and Ranging (RADAR) for our tracking system. Both function at different wavelengths and send and receive waves to detect distant objects. Each of these technologies contains its costs and benefits that our team is going to heavily consider in the design process.

With the increase in the number of private space companies as well as governments launching spacecraft to assist with worldwide communications and space exploration, the region of space just above Earth, known as low Earth orbit (LEO), has become increasingly crowded. As a result of this crowdedness, the potential for collisions only increases, and should one collision occur, that can lead to a chain reaction of collisions, exponentially increasing the amount of space debris. When twice as many objects, in this case, spacecraft, occupy a particular region of space, the probability of collision increases fourfold (Isbrucker, 2018). Should this be the case, and more collisions lead to more debris, it could end up becoming that a low Earth orbit is unusable, rendering all of the advanced technologies and research meant to benefit from this, useless.

Alongside this, there is a physical limitation to how well space debris can be tracked from Earth. Most of the tracking is performed from ground stations in the United States that use the debris reflection of sunlight to gather data on the debris and its distance (Cacioni, 2022). However, most of the debris in space is less than ten centimeters in size, which makes it unable to be tracked. In order to do so, there has to be a technology that is physically in space that can perform the tracking without the disturbances of the atmosphere.

Should the issue of space debris accumulating in LEO not be properly addressed, there will be huge costs and consequences. Firstly, tiny particles orbiting the Earth are traveling at multiple times the speed of sound, which if they run into existing spacecraft, can make the original satellite mission more complex than it was originally intended (The Aerospace Corporation, 2023).

The main challenges we will face include being able to successfully integrate a testing device into the CubeSat along with all of the other subsystems, and keeping this whole project under the budget allocated for this project. Our deliverables for this project include a conceptual design review (CoDR), followed by a preliminary design review (PDR), and concluding with a critical design review (CDR). Should all of these be completed on time, our team also anticipates being able to construct a physical prototype for the CubeSat in a 3D-printed outer shell.

STS Topic

With the rapid growth of the outer space industry currently and within the next few decades, there are growing concerns about the transformation of this industry (Marwala, 2024). Mainly, the privatization of this sector and turning space's orbits and resources into commodities will only reflect existing hierarchies of class and economic basis in today's world (Frost, 2017). In fact, as some companies aim to profit off of the finite space above Earth, there is potential that these divides seen on Earth will intensify in space. Already, there are four main players in this space, with nearly trillions of dollars in operations. Not mentioned are private space corporations that are also expanding their footprint. The global space market increased by 8% to $546 billion in 2022, with expectations upward of $737 billion by 2030. The main leaders in this industry include the United States, China, Japan, and India (Marwala, 2024). With certain players establishing themselves on a first-come, first-served basis, the beneficiaries of space are the current players only (Deplano, 2023, p. 1). On top of this, the rise in private space companies has exacerbated the issue. Companies are focusing on profits over equity, including commercial space flight. These are funded by billionaires, with fears that space capitalism will arise–where the same conditions that affect Earth will be mirrored (Sharma, 2021). Private space companies often have narrow, profit-driven goals, whereas governments have a broader public interest in mind. A lack of governmental oversight in outer space may lead to private companies monopolizing and exploiting resources. This may result in governments becoming increasingly dependent on private companies if they cannot develop space programs, which can lead to both conflicts and less developed countries falling further behind developed countries in terms of space "status."

Through my research, I will argue that sufficient frameworks must be developed to prevent the militarization and monopolization of space and to keep it an equally accessible resource for all nations. In this scenario, accessibility refers to the ability to utilize the capabilities that outer space provides–scientific research, strategic/military capabilities, and more. As it is a vital resource that improves lives through numerous technologies, space is beneficial for most as an open frontier. It is the backbone of modern technology. (International Telecommunication Union, 2021). Alongside that, the equal and collaborative use of space technology will allow the United Nations to achieve its Sustainable Development goals (United Nations, 2019). I will address how establishing such a framework is challenging, and analyze past treaty attempts at such to provide evidence for these challenges.

A main challenge to equal space access is the present lack of effectiveness of regulation and space governance. The first instance of space regulation came during the Cold War between the United States and the Soviet Union, which I will eventually delve into after this section. However, when this first regulation was created, there were two main countries with space programs. Today, there are fourteen countries with orbital launch capabilities, meaning the regulations that are created revolve around these fourteen countries, which means the rest of the world is excluded from contributing to these rules (Goguichvili et al., 2021). An additional barrier to effective space regulation is how fast the current industry is evolving. With new missile capabilities, satellite constellations, and reusable rocket launches, space governance has been slow to keep up with the new challenges these technologies pose to the global order. These regulations also find challenges in balancing the militarization of space while encouraging democratization (Goguichvili et al., 2021). The research I pursue is going to scrutinize why these tendencies exist, and how they are detrimental to space prospects. I aim to analyze this through a sociotechnical lens utilizing actor-network theory, where the dynamics of involved actors (spacefaring nations, companies, and non-spacefaring nations) can be analyzed over time. From this, it can be seen how actors and networks (outer space) adapt due to power and influence levels, and why the current space access situation has become what it is today (Actor-Network Analysis, 2023). Spacefaring nations play a large role in this network, and this can be broken into historically spacefaring nations, such as the United States and Russia, and newer, technologically advanced nations such as China and India. These actors are the ones toward whom present legislation is directed, as they control key infrastructure and many of the secret technologies that they are hesitant to share with the rest of the world. Additionally, private companies are big actors, as they are quickly transforming the sector by trying to compete for government contracts and pursuing profits, shaping the sector through partnerships. Another actor consists of non-spacefaring nations striving for space access, but currently rely on dominant nations or companies for services, usually for payment or future debt. International organizations are another part, which are trying to promote the peaceful development of space and regulate resources. Finally, the last actor I will examine is the technology, which enables actors to access space and exert influence over others, such as SpaceX with its satellite constellations.

I look to examine these actors and their relationships over time, particularly by using technological momentum. In this case, the early space nations capitalized on new, expensive technologies, such as rockets and satellite infrastructure. (Dooley & Signé, 2023) From this, a reinforcing cycle was created where wealthier nations could continue innovation as they have ongoing investment and technological resources, while underdeveloped found it difficult to follow suit. Hence, by examining these relationships, actor-network theory can prove useful in providing perceptions on how to change the environment.

My research will also go into the Outer Space Treaty ratified in 1967 which had the goal of being a "constitution" for outer space. From a surface level, its purpose was to serve as a framework for responsible space activities and guide how to use outer space peacefully. Its articles included principles such as outlawing sovereignty over celestial objects. These articles aimed to calm the tensions of the Cold War, with the idea of preventing space from becoming a new frontier for conflict between the United States and the Soviet Union. (Deplano, 2023). However, the main barriers to its usefulness come from the lack of a solidified method of implementation (Deplano, 2023). Additionally, the treaty had weaknesses, which include that its scope focuses on weapons of mass destruction in space and that there is very vague language on how nations should manage their resources. This leads to states themselves defining terms based on their own interests, and since technology and exploration are the cornerstones of many nations' space policies, cleaning up space debris to make more, safer orbits for others, is not a priority for them (Goguichvili et al., 2021).

As a result of failing to properly stabilize the "first-come first-served" nature of outer space today, the socioeconomic divide in space may become too big before any changes can be made. The end product of outer space, therefore, may reflect current advancement trends on Earth: where some nations have extremely advanced science and technologies, while other nations do not, and this propels the advanced nations onto the global stage with an ability to exert power and influence over others.

The past failures of previous treaties to enforce space equality for mutual benefit and the current nature of the industry are what pose threats to the idea of equal space access. The main research question I will address is the following: how do current legislation and the Outer Space Treaty of 1967 fail to address the socioeconomic space gap between predominantly spacefaring nations (i.e. the United States) and non-spacefaring nations? Through analyzing actor-network theory and other challenges, I hope to provide insights on how to mitigate unequal space access via frameworks to allow more parts of the world to benefit from space technology and its resources.

Conclusion

Concluding the research of my technical topic will be a presentation highlighting the accomplishments and successful deliverables of our team, while the STS topic will have a research paper highlighting the topics studied and questions I aim to answer. For my technical topic, the conceptual design review will include our initial design concepts and options that will be assessed through further technical research and trade studies. It will also include our scheduled work, breakdown of labor, and cost estimations. The preliminary design review will build on the conceptual one, as it will contain a more detailed, refined design that has been augmented from the conceptual phase. The critical design review will assess how our design will meet all project requirements and that it is ready for production, where the technology can be built and tested to detect space debris some distance away and track its position. For my STS topic, the research I pursue will serve as a better understanding of how to implement equal space access and why the challenges are so complex. Through an analysis of previous reconciliation attempts, the present nature of space governance, and actor-network theory, my research will aim to provide insights into how to develop frameworks to enable equal access to outer space's resources and capabilities.

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