Analyzing CubeSat Risk to Orbital Debris and Their Impact on Future International Regulation in Space Waste Mitigation

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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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Abstract

CubeSats are nanosatellites that lower the barriers to entry for spaced-based scientific study by providing a cost effective platform that is capable of being rapidly deployed. This has resulted in the popularity of the technology exploding in recent years, particularly within government, commercial organizations, and academia. However, despite their small form factor, the increasing number of CubeSats in orbit poses the risk of adding to the challenging problem of space debris. In this paper, I use the Social Construction of Technology framework to explore CubeSat waste mitigation and its effects on international regulations for space waste. I find that while the threat of CubeSat debris is minimal when compared to the orbital debris of traditional satellites, international regulation must be improved to help mitigate the generation of new debris and facilitate debris removal efforts.

Introduction

CubeSats have gained increased popularity and attention within the last 20 years (Davis, 2023), and have risen as a tool for universities, commercial companies, and the government as a low-cost alternative. This rise in popularity has brought about an exponential number of CubeSats being launched (Novak, 2022). This bears the question, how does using CubeSats as a low-cost alternative to hypersonic flight research affect space waste mitigation and regulation? In this paper, I will discuss the level to which using CubeSats as a low-cost alternative to hypersonic flight research reintroduces the risks of orbital debris, in addition to how this concern of risk affects future international regulation in space waste mitigation, through mitigation of future debris, collisions, and collection.

Background

A CubeSat is a “square-shaped miniature satellite” that is “roughly the size of a Rubik’s cube” (Canadian Space Agency, 2022). The advantage of CubeSats over traditional satellites is that they “provide a cost effective platform for science investigations, new technology demonstrations, and advanced mission concepts using constellations” (NASA, 2024). Additionally, They are traditionally 3-D printed, which not only reduces their weight and cost to launch, but facilitates a more rapid deployment. The Iridium Satellite Network “consists of 75 satellites that are cross-linked in space just 780 kilometers above Earth” (Iridium Communications, 2024). Through this cross linked constellation architecture, Iridium is “the only network that covers 100% of the planet” with satellites that provide “reliable, low-latency, weather-resilient connections that enable communication anywhere in the world” (Iridium Satellites, 2024). The advantage of the Iridium Satellite Network for CubeSats is that its low-earth orbiting network "enables the use of smaller omni-directional antennas, resulting in devices with a compact, lightweight and streamlined form factor and shorter network registration times" (Iridium Communications, 2024).

Social Construction of Technology

As technology advances, expenses at times can increase expeditiously. This cost increase expands the barriers to entry which can limit stakeholders who can benefit from such projects. Therefore, the objective of the technical team is to send a CubeSat into space to orbit for a week to mimic space flight for research. When it falls back into the atmosphere, thermocouple sensors and pressure transducers will measure the temperature and pressure of the CubeSat and send this data through the Iridium satellite network back to earth. This will determine if a CubeSat can be used as a cheaper alternative to fostering advanced hypersonic glider flight research by obtaining vital flight measurements and sensor readings without needing to build a hypersonic glider. In providing a new, more affordable research mechanism, this project can limit these barriers and enable increased access to technology garnered information. However, striving for a low-cost alternative to this research can prove complicated. Desiring lower cost alternatives to technology inspires the creation of new technology that can generate additional risk. As human action to lower cost shapes the development of new technology, this economic incentive was brought about through the Social Construction of Technology (SCOT) framework.

SCOT argues that "technology does not determine human action, but rather human action shapes technology" (Klett, 2018). It is the needs of stakeholders within the social community that lead to developments in technological fields. This theory assists researchers in giving detailed and insightful accounts of the development of technology in society through discussion of relevant social groups. While these could be engineers, companies, contractors, politicians, or mundane citizens, these social groups all have some form of “equal expertise” (Wikipedia, 2024), with no one group having special priority. Each stakeholder has their own concerns and experiences that are no more important than the other, despite the scale of importance being typically favored towards engineers. Additionally, SCOT offers a conceptual framework for politicizing a technological culture, opening technological issues for political debate. SCOT argues that “the ways a technology is used cannot be understood without understanding how that technology is embedded in its social context” (Klett, 2018). This brings new technology being developed into the social spotlight, with the impacts and purpose being weighed in a public sphere. Through SCOT, engineers and companies do not have full power and custody over what specifically gets developed as this is driven through the needs of society and their stakeholders. SCOT claims that the adoption and acceptance of a new technology rests not only on the effectiveness of the product, but more so on its effect on the social world. Technological developers “must look at how the criteria of being the best is defined and what groups and stakeholders participate in defining it” (Klett, 2018). Relevant social users, those indirectly affected by the technology, and bystanders all determine the feasibility of a product in the current social realm.

Literature review & Case Study

The case study performed by Swartwout and Jayne at Saint Louis University analyzed data of University-class spacecraft (Swartwout, 2016). This class of miniature satellites were then grouped and measured for their overall success, failure, and the level of debris generated as a result of these campaigns. It is important first to discuss the success of CubeSats for research, as the failures to perform are ultimately what lead to higher levels of debris collection. In the study, it was found that approximately “one-eighth of all university missions are lost to launch failure”, and with “40% of all [total] university-class missions failing to achieve any of their primary mission objectives”. This number is out of proportion, however, because the university CubeSats are frequently placed on rocket platforms that are “making their first-ever launch attempt”, with “first flights having a significantly higher failure rate than later flights”. By putting the CubeSats on less secure mission payloads, it skews the data regarding the feasibility and success of CubeSats as a low-cost alternative to research. Additionally, university-class CubeSats are being placed on payloads in conjunction with a multitude of other CubeSats. The case gathered that “university-class missions tend to be launched in groups of 6-20”. With this information, it can be determined that a single rocket failure can lead to a high number of CubeSat failures.

In reference to the level of debris generated from CubeSat missions as a whole, the case calculated “461 CubeSat spacecraft [that] have been launched [with 137 being university-class] since 2000”. This is, in relative to the number of orbit missions, a small number and of those, only “233 are currently still in orbit”. In contrast, the case analyzed that over “40,000 manmade objects have entered into earth orbit” with approximately 17,000 still remaining. Worse, “only 4,000 of those left are classified as payloads, with over 13,000 objects classified as debris”. The 13,000 debris from non-CubeSat missions is more significant than the 233 CubeSats, with most being still working and not of debris class. Furthermore, “NASA’s office of space debris estimates there are 500,000 objects in earth orbit [both natural and manmade] between 1cm and 10 cm in size”. This size is only slightly smaller than the size of a CubeSat which is 10cm x 10cm x 10cm. With small natural debris already plentiful within earth orbit, the debris potentially caused from a malfunctioned CubeSat would cause only a fraction of added harm to spacecraft in orbit. To put this in perspective, if in the next year 1000 CubeSat missions malfunctioned and became debris, this would be only a 0.2% increase in debris of that size.

To support this case, a study addressing and analyzing the risk posed from CubeSats to debris will be discussed. In a 2016 IEEE Aerospace conference, the concern over CubeSats leading to enhanced debris was discussed in comparison to the current level of debris in orbit (Swartwout, 2016). It was found that in 2009 when Iridium-33 and Kosmos-2251 collided, these 2 objects became 2,200 CubeSat sized fragments. Additionally, in 2007 China performed an "anti satellite demonstration on its own Fengyun-1C spacecraft" which resulted in 3,400 CubeSat sized fragments. With this combined fragment amount of 5,600 CubeSat sized debris, this supports the case's claim of 233 CubeSats in orbit being a small number. This amount of debris is not enough to warrant a risk assessment of debris for CubeSat launches within the correct altitude. It does not warrant regulation towards the launching, however it warrants regulation regarding the altitude of orbit.

Currently, the best strategy for mitigating the collision threat posed by CubeSats is to "continue to place them in compliant orbits". For example, NASA mandates that all its CubeSats be placed in "naturally-decaying orbits", with pedigrees well below 500 km. By maintaining a low orbit, CubeSats launched remain in orbit for only a couple weeks before reentering the atmosphere and burning up. This leaves little room for collision as opposed to high pedigrees where collision is more likely to occur with either the ISS or other satellites. Another strategy is an implementation of path planning for self-collision avoidance. At a Space Engineering University in Beijing, China, students developed a new form of CubeSat that employs crash detection and avoidance models. It does so by "converting the binary map into a map with dangerous potential fields and searching for the safest path using the MDPF algorithm" (An, 2022). This was proven to avoid self-collisions successfully. This working alternative to mitigating collision debris by reducing the number of collisions is a new method developed in 2022. Because of this, more research and testing within space-induced environments needs to be conducted to ensure the validity and repeatability of this method.

The modern method for debris mitigation is outlined by the National Orbital Debris Implementation Plan derived from the Presidential Orbital Debris Interagency Working Group. The first mitigation method is "improving the component design of spacecraft" (The White House, 2022). By making launches more durable, this lowers the impact of small debris in causing a larger object to make more debris. The second is to prioritize "safe on-orbit operations". This is in reference to safe use, adhering to right-of-way flight policy, and government review of licenses for new satellite development. The third method is the use of devices that provide improved "tracking, maneuvering, and remediation". This involves advancements in drag devices and automated disposal systems that are designed and used for active debris removal. These methods are currently working in that they are lowering the risk of collisions and debris generation. While collision detection is improved, more work needs to be done on removing space debris that is already in orbit.

Current regulations on CubeSat usage "require licensing through the Federal Communications Commission (FCC)". There are a set amount of frequencies able to be used for communication protocols. Through the FCC and NASA, it is outlined that CubeSats must be in "naturally-decaying orbits", to ensure their quick reentry. While the regulations regarding CubeSat usage is all-encompassing, the FCC's mandated jurisdiction only covers "the 50 states, the District of Columbia, and United States territories". This isn't enough regulation as

University-class missions were launched by countries all over the world. It was gathered that of the University-class missions launched, 33.33% were from Russia, 31.3% from the United States, 10% from Japan, 8.8% from India, 8.3% from the ISS, and less than 5% between China and Europe. With this global reach, this regulation can be changed to merge with other countries' regulations in a conglomerate of space regulation. By combining the regulations on CubeSats, a more clearer understanding on the mitigation tactics of space debris can be achieved.

Analysis of Stakeholders

Currently, the testing of space research is expensive, with CubeSats potentially offering a cheaper alternative. This new landscape, however, poses risks to various stakeholders within the social world. This is seen, particularly, in testing of hypersonic gliders, with the government and commercial companies who send out the contracts and are ultimately launching and/or flying these aircraft have the most amount of power as they provide the funding and the contracts. Their main goal is to advance their hypersonic gliders to promote their own military/political agenda. For the government specifically, this is due to the glider's "responsive, long-range, strike options against distant, defended, and/or time-critical threats when other forces are unavailable, denied access, or not preferred" (Congressional Research Service, 2021). If the government or private company doesn't like the results that were given through CubeSat research, they have the power to withhold future contracts. Their stake in the research development is that potentially suboptimal data gathering techniques could lead to reduced performance in gliders. They desire to mitigate space waste because space debris has the chance to damage their commercial/government satellites that are already in space which has the chance to cost millions in repairs. They, therefore, have a responsibility of transparency in launches, by reporting the number of spacecraft launched as well as their dimensions for waste data collection. A similar group to commercial companies, universities that are utilizing CubeSats to provide the public with data and research on space have a moderate amount of power in the process as they are assisting in the development and launching of CubeSats. The universities have a responsibility to the public both to report their launches, and to make publicly available the details and results of their results and data collection. Bystanders have the least amount of power over this decision as they are indirectly affected by potential negative impacts. Stakeholder groups who are affected the most negatively typically have the least amount of decision power. Environmentalists may have negative viewpoints towards CubeSat flight research with fear of irreparable harm to the Earth, however they unfortunately have no internal stake in the companies running this CubeSat platform and cannot intervene. Additionally, with CubeSats launching into space within the payload of a rocket, launch companies will be wary of the risk this cheaply made product poses to their rocket and other payloads in the event of a malfunction. Thus, companies such as NASA and SpaceX launch rockets with hundreds of payloads on board, with schools and private companies buying space on the payload (Groh, 2024). CubeSats are not as robust as other satellite counterparts, and if they were to catch fire or explode on the payload this would endanger the other equipment on board as well as the rocket itself. NASA, SpaceX, or another launching company has a lot of power over this as they can choose which equipment to allow on their spacecraft. This power of the launching company was seen after the Russia Ukraine invasion, where SpaceX refused to house any Russian CubeSats on their payload (Yale, 2024). Furthermore, the power of commercial companies and universities were put on display as, after this attack, they refused to contract with any Russian launching companies. Bystanders encouraged termination of Russia contracts although did not have any power to enforce this recommendation.

Analysis of Current CubeSat Waste Mitigation Strategies

Stakeholders such as commercial and government are receiving a positive impact from the rise of CubeSat usage as a low-cost alternative both in risk and in monetary benefit. It should be analyzed then, the extent of negative impact this rapidly growing technology has on the level of orbital debris. First, the reliability of the data in the case study to suggest that the impact of CubeSats on orbital debris levels is insignificant will be examined. The methods to calculate debris generated from satellite collisions are threefold. The first is with large orbital debris, meaning debris that are bigger than 10 cm. These debris are tracked “routinely by the U.S. Space Surveillance Network” (NASA Orbital Office, 2024) to ensure safety and protect collision trajectories that interfere with important satellite paths such as the ISS. Secondly, objects between 10 cm and 3 mm can be detected by “ground-based radars” which can provide a basis for a statistical estimate of their numbers. Lastly, population assessments for orbital debris smaller than 3 mm can be conducted by “examining impact features on the surfaces of returned spacecraft”. Analysts are able to study the shape of the rips, breaks, and cracks to determine an estimate for the number of debris created from impact. This, however, is the least reliable estimate. For CubeSats, they fall under the first category, being 10 x 10 x 10 cm. Due to this, the number of debris in earth orbit that are “CubeSat size” can be calculated very accurately using satellite imaging or ground-based radars. With this in mind, it can be observed through the case study that the number of CubeSat sized debris was accurately calculated in comparison to the existing number present within low earth orbit.

Additionally, the case study reports that this debris not only is insignificant, but will soon safely burn up in the atmosphere. In study, the altitude that satellites are launched bears importance on the livelihood of debris in the atmosphere. Debris that are left in orbits "below 600 km" often fall back to Earth "within several years" (NASA Orbital Office, 2024). This is because the low altitudes that these satellites are launched in "experience rapid orbital decay" (National Academic Press, 1995a). Objects in Earth orbit are subject to force influence which alters their orbit. In low Earth orbit (below 2000 km), objects are "subject to atmospheric drag" (Space Academy, 2024). This drag reduces the altitude of the objects' orbit and causes it to eventually fall back onto Earth, at differing rates depending on how low of an altitude it is launched in. CubeSats are (on average) launched at altitudes between "350-700 feet" (Donmez, B., Azam, I., & Karabulut Kurt, G, 2023). As this is more often than not below 600 km, an average CubeSat only has a lifetime of several years.

Analysis of Current Regulation Efforts

With the threat levels of risk imposed regarding CubeSat usage being discussed, the next step is to evaluate the extent of successfulness of the current regulation to reliably ensure the continued proper use of CubeSats to reduce orbital debris. This is particularly important given that the U.S. CubeSats have a higher success and effectiveness rate than international deployments with the U.S. having an "in-orbit non operational" rate of 11% and international CubeSats having a rate of 31.5% (Swartwout, 2016). Regarding current international regulation efforts, there currently exists an international space debris agency. It is known as the Inter-Agency Space Debris Coordination Committee (IADC). The IADC is an "international governmental forum for the worldwide coordination of activities related to the issues of man-made and natural debris in space" (IADC, 2019). This committee addresses orbital debris issues and encourages operations in Earth orbit, which can limit the growth of orbital debris. The IADC includes the "ASI (Agenzia Spaziale Italiana), CNES (Centre National d'Etudes Spatiales), CNSA (China National Space Administration), CSA (Canadian Space Agency), DLR (German Aerospace Center), ESA (European Space Agency), ISRO (Indian Space Research Organisation), JAXA (Japan Aerospace Exploration Agency), KARI (Korea Aerospace Research Institute), NASA (National Aeronautics and Space Administration), ROSCOSMOS (State Space Corporation), SSAU (State Space Agency of Ukraine), and the UK Space Agency" (Tuozzi, 2018). This conglomeration of international space agencies represents an accurate depiction of the majority of nations where debris originates from. The primary purpose of the agency is to "exchange information on space debris research activities", "facilitate cooperation in space debris research", and "identify debris mitigation options". In this way, the IADC is not a regulatory agency, but rather provides "technical recommendations to the world space communities".

Despite this conglomerate of international agencies, there are currently no international laws, however, that govern the collection or correction of space debris in Earth orbit. There are three treaties with vague relevance to orbital debris that have been established. This is the "Outer Space treaty", the "Liability Convention", and the "Registration Convention" (National Academic Press, 1995b). The Outer Space Treaty declares that "states party to this treaty shall bear international responsibility for national activities in outer space" (United Nations Office for Outer Space Affairs, 2024a). This is a fairly vague line that brings about general, avoidable repercussions for outer space violations. Another section states that damage caused by objects that have launched into space can lend those in the treaty party liable. Again, this is also non-encompassing as it can be difficult to discern responsibility in a debris damage scenario. The Liability Convention works to solve this by making parties liable for damage "caused elsewhere than on the surface of the Earth to a space object of one launching state or to persons or property on board such a space object of another launching state" (United Nations Office for Outer Space Affairs, 2024b). This article of the Liability Convention provides undeniable fault to satellite collisions in an attempt to encourage mitigation of them all together. In comparison, the Registration Convention requires all parties to "notify the UN of any objects they launch and provide the UN with the objects' orbital parameters" (United Nations Office for Outer Space Affairs, 2024c). This provides a greater level of accountability in both the number of spacecraft launched as well as the size for tracking purposes. While these codes address previous debris generated and repercussions for those, they don't mention in great detail the need for measures to reduce the creation of new debris, nor the removal of old ones. This is an important piece of international legislation for CubeSats, as these are a rapidly growing field type of satellite launch.

Analysis of Current Trends in CubeSats

There have been 461 Cubesats that have been launched between 1999, when they were first created, and 2016 (Hatch, 2024). Following the 2016 case study, CubeSats launches have increased exponentially. As of April 2024, over 2300 CubeSats have been launched (SV Microwave, 2024). That is about a 1900 increase in CubeSat launches within the last 8 years, which is roughly a 500% total increase. Notably, the majority of launches from 1999 to 2016 were for Academia, with this shifted in the last 8 years to be of majority commercial launches. As commercial companies are starting to latch onto the aforementioned affordability and rapid deployment of CubeSats, the developers of CubeSats are expanding to groups and companies that have the resources to design, manufacture, and launch at a quicker rate. This could potentially manifest into an explosion of launch growth, accelerating the need for improved regulation on waste mitigation.

Conclusion

With an exponential growth in CubeSat launches over the past 20 years, it is important to understand the extent to which they contribute to the rising concern of orbital debris. Using CubeSats as a low-cost alternative to hypersonic flight research reintroduces the risks of orbital debris, however, it is in a magnitude that is miniscule compared to current debris levels. However with the recent growth within the last 8 years, Cubesats could pose a future threat to space waste if regulations regarding altitude placement, self-collision avoidance, component design, and licensing are not adhered to. While there is lower risk involved with these launches, future international regulation must be improved upon in the topic of mitigating the creation of new debris and the removal of old ones.

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