Hypersonic Atmospheric Reetry Deceleration Experiment (HARD-E)
(Technical Paper)

The Sociotechnical Implications of Space Debris: The Dilemma of Space Debris Production and Mitigation Legislation
(STS Paper)

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On my honor as 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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Prospectus

Introduction

From popular depictions in media, images of technology on par with the Millenium Falcon or of exploration missions far beyond Earth's familiar backyard typically come to mind when thinking of future human endeavors into outer space. In practice, the logistics of space missions can be less fantastical with similar considerations to that of activities conducted on Earth. Since the first space missions of the 1950s, nonfunctional artifacts, known as space debris, have been discarded from spacecraft where they remain in orbit for considerable time (Gregersen, 2021). These artifacts range in size from depleted rocket stages to chips of paint (Gregersen, 2021). Unlike garbage floating in the ocean, space debris fragments behave more like high-energy projectiles than simple waste due to the incredibly high speeds associated with orbit (Garcia, 2021). A collision event with orbital debris can devastate a spacecraft, and in its wake, produce a cloud of thousands of new orbiting fragments (Gregersen, 2021). If left unchecked, fragment clouds can effectively condemn entire orbits, preventing their use until the fragments are removed or fall into the atmosphere (Gregersen, 2021). Abandoning the use of entire orbits is especially problematic in the context of low Earth orbit, where most functional spacecraft are currently located and where orbital pollution is predictably the highest ("About Space Debris," n.d.). In response to the impending issue of space debris, the STS topic proposal seeks to address the sociotechnical aspects of space debris production, mitigation, and removal, with the ultimate goal of helping facilitate a sustainable future in space. The technical topic proposal, as outlined in the following section, seeks to assess the viability of utilizing CubeSats, or miniature research satellites, in extreme low Earth orbit for the purposes of conducting cost-effective decelerating hypersonic flight research. As the future of space exploration looks towards applications such as reusable rockets, research concerning hypersonic atmospheric reentry will prove to be critical. The advent of reusable rockets is predicted to cause a great decrease in the cost of spacecraft launches, contributing to the decades-long downward trend, and can usher in a new golden age of spacecraft (Fearon, n.d.). Decreasing launch costs and increasing launch frequency, however, will likely accelerate the issue of space debris, as more spacecraft in orbit will bring about more waste and increase the probability of collisions. In essence, the topics of decelerating hypersonic flight research and space debris are linked; improvements in atmospheric reentry can facilitate the advancement of spacecraft, increasing the amount launches and crafts in orbit, though also increasing the quantity of debris, exasperating the risk to objects in orbit and hindering their use. In order to aid in the facilitation of spacecraft advancement, it is paramount that the production of future space debris is properly managed and mitigated while current, high-risk structures are removed from orbit.

Decelerating Hypersonic Flight Experiment Using a CubeSat Platform

Introduction

Hypersonic flight, defined as flight with Mach numbers above 5, contains significant challenges with regards to thermal management, maneuverability, and communications (Ambrose & Greene, 2019). Hypersonic flows are most often encountered during atmospheric reentry, where the spacecraft is constantly decelerating from speeds as high as Mach 25(Glenn Research Center, 2021). Modeling these flows is important in order to understand pressure and heat distributions for spacecraft during reentry, both of which will affect the design of its heat shielding and aerodynamic components. In addition, motivated by threats from China and Russia, the United States military and Department of Defense have recently begun expanding funding and research into hypersonic flight for use in weapons systems (Sayler, 2021). Some private companies also seek to build hypersonic passenger aircraft, which could connect LA to Tokyo in under two hours (Baggaley, 2019). With hypersonic flight presenting several technical challenges, collecting flight data is invaluable and it garners interest from both government and commercial industries.

In order to design these hypersonic flight systems, engineers need to obtain accurate flow data from the hypersonic regime, which poses several challenges. Testing of ground-based hypersonic experiments is limited by the size and expense of new systems and the insufficient technology of many existing test facilities (National Research Council, 1994). Obtaining flight data from a prototype hypersonic aircraft is generally an even more costly solution. Additionally, modeling software poses issues due to a lack of technical understanding for concepts such as boundary layer transition at higher Mach numbers (National Research Council, 1994). From 2021 to 2022 alone, the FY Pentagon requested a budget increase for hypersonic research from 3.2 to 3.8 billion dollars to attempt to overcome these difficulties (Stone, 2021). Limited by the financial cost of ground testing and motivated by the desire to lower hypersonic research costs, a more cost-effective solution is sought to collect hypersonic data.

Recent developments in CubeSat technology in the form of commercial off-the-shelf components (COTS) and lowered launch costs have improved accessibility for spacecraft missions (Nervold et al., 2016). As a result, the use of CubeSats in university funded projects has risen dramatically. Testing the hypersonic environment with a CubeSat undergoing atmospheric reentry could significantly reduce the costs associated with ground testing and provide greater accuracy than model-based testing. CubeSat reentry also presents an opportunity to study hypersonic deceleration at the undergraduate level.

This project team seeks to assess the feasibility of using a CubeSat to study the deceleration of the spacecraft at hypersonic speeds and collect data that will be transmitted to engineers and scientists studying hypersonic flight. At the end of this year, the technical thesis will be completed in proposal format for potential submission to NASA for funding of the fabrication and testing of the 3U CubeSat design. The purpose of this document is to outline the plan that this project team will follow to solve the technical problem presented. The document will discuss the technical problem and its objectives, the technical approach, program management, the resources available to the team, and desired outcomes.

Technical Problem

Research Objectives

The primary objective for this project is to design and implement a 3U CubeSat that will be launched into low Earth orbit (P1, Table1) and collect data as it reenters the atmosphere at hypersonic speeds (P2, Table 1). Additional primary objectives include delaying atmospheric burnup (P3, Table 1) and collecting and transmitting sufficient and reliable data to the UVA ground station (P2, Table 1). The use of CubeSats offers undergraduate students the opportunity to be involved in the space mission engineering process in a cost-effective manner over a short term (S2, Table 2). Proving the feasibility of CubeSats for hypersonic flight experiments has the potential to promote Aerospace Engineering to the general public (S1, Table 2), which may improve funding, resources, and general interest for future projects.

Table 1: Primary Objectives

ID	Primary Objectives
P1	Successfully launch a 3U CubeSat bus into extreme low Earth orbit
P2	Collect and relay decelerating hypersonic flight data upon atmospheric entry
P3	Delay atmospheric burnup to maximize the quantity of collected data

Table 2: Secondary Objectives

ID	Secondary Objectives
S1	Promote Mechanical and Aerospace Engineering to the public
S2	Provide the opportunity for students to engage in cost-effective educational space mission engineering and design

The primary objectives have a number of functional (Table 3) and operational (Table 4) requirements necessary for success, and must satisfy the mission constraints (Table 5).

The CubeSat must be able to survive extreme conditions (F1, Table 3) so that the electronics and sensors necessary for control, data collection, and transmission do not fail when exposed to extreme temperatures and high forces, and so that the CubeSat can gather and transmit sufficient data to the University. Extreme condition survival and full power (F4, Table

3) throughout the mission reduce the risk of component failure, data collection, and data transmission failure.

Table 3: Primary Functional Requirements

ID	Requirement
F1	Survive extreme conditions of deorbit and reentry for as long as is necessary to obtain data (extreme high and low temperatures, forces up to 7.8g)
F2	CubeSat sensors collect effective and purposeful data that proves mission success or failure
F3	Have capability to return mission data to the University for study
F4	Remain powered through entire mission (5-7 Days)

An unstable CubeSat upon atmospheric reentry will not be able to provide credible data and would likely cause an early burnup of the system. Prior to this burnup, O2 from Table 4 highlights the importance of the CubeSat's ability to transmit the measured data to an accessible source.

Table 4: Primary Operational Requirements

ID	Requirement
O1	Maintain stability of CubeSat at hypersonic velocity during atmospheric reentry
O2	Directly or indirectly transmit data throughout mission
O3	Minimize power consumption of avionics and sensors during operation while fulfilling requirements

The ability to minimize power consumption will stem from the construction of an efficient CubeSat that properly addresses changing flight conditions. As displayed in Table 5, the CubeSat will need to adhere to dimensional and budget constraints, as well as federal regulations, which will affect manufacturing techniques and potential commercial products.

Table 5: Primary Mission Constraints

ID	Constraint
C1	3U CubeSat weight and dimension specifications as specified by CalPoly: 100x100x340.5 mm, maximum mass of 4000 grams.
C2	The CubeSat must mate with the CubeSat dispenser by following constraints for exterior size/shape and connector rails (laid out in CDS)
C3	CubeSat must be compliant with federal regulations (FAA, NOAA, NASA)
C4	Material cost must stay under budget of $100,000
C5	Availability of manufacturing techniques and commercial products for mission components

Technical Approach

To achieve the objectives discussed in the previous section, the Space Mission Engineering (SME) process will be applied. As shown in Figure 1, the SME process can be loosely divided into four main sections: Define Objectives and Constraints, Define Alternative Mission Concepts or Designs, Evaluate the Alternative Mission Concepts, Define and Allocate System Requirements.

Typical Flow	Step	Where Discussed
	Define Objectives and Constraints	
	1. Define the Broad (Qualitative) Objectives and Constraints	Sec. 3.3
	2. Define the Principal Players	Sec. 3.4
	3. Define the Program Timescale	Sec. 3.4
	4. Estimate the Quantitative Needs, Requirements, and Constraints	Sec. 3.5
	Define Alternative Mission Concepts or Designs	
	5. Define Alternative Mission Architectures	Sec. 4.2
	6. Define Alternative Mission Concepts	Sec. 4.3
	7. Define the Likely System Drivers and Key Requirements	Sec. 4.4
	Evaluate the Alternative Mission Concepts	
	8. Conduct Performance Assessments and System Trades	Sec. 5.3
	9. Evaluate Mission Utility	Sec. 5.4
	10. Define the Baseline Mission Concept and Architecture	Sec. 5.5
	11. Revise the Quantitative Requirements and Constraints	Sec. 5.5
	12. Iterate and Explore Other Alternatives	Sec. 5.5
	Define and Allocate System Requirements	
	13. Define System Requirements	Sec. 6.1
	14. Allocate the Requirements to System Elements	Sec. 6.2

Figure 1: The Space Mission Engineering Process

The broad qualitative objectives and constraints were defined in the previous section. Principal players, including the Primary and Secondary Customers, Sponsors, Operators, and End Users, need to be identified in order to assess particular agendas and understand each player's needs. Deadlines set by principal players additionally allow for the creation of a more rigid project timeline. For the purpose of this project, and with the goal of approval and funding from NASA, there will be a Conceptual Design Review, Preliminary Design Review, and Critical Design Review before product manufacturing can occur, culminating in the actual launch of the satellite after a nearly three-year process.

Program Management

With respect to task delegation, the team was divided into six subgroups: the Project Management team, Communications team, Software and Avionics team, Power, Thermal, and Environment team, Attitude Determination and Control System and Orbits team, and Structures and Integration team. At the subsystem level, SME steps 5-14 will be explored by each subteam to develop more concentrated mission elements such as particular drivers, constraints, and requirements. The development of SME steps 5-14 will be facilitated by each subteam's preliminary research of literature in their relevant fields of expertise.

Available Resources

Available resources for the 3U CubeSat include personnel and information resources, monetary funding, parts sourcing, and systems/communications support. Personnel and information resources are available through university professors and databases, which have ample information from previous space missions. Previous spacecraft design projects provide an excellent structure for the basis of the hypersonic deceleration design project. The project is supervised by Christopher Goyne and UVA has access to a volunteer communications advisor, Michael McPherson. Subject matter experts are also available through NASA, the DoD, UVA faculty, and industry experts.

The NASA CubeSat Launch Initiative (National Aeronautics and Space Administration, 2020) is an available resource that allows for a free ride into space for promising satellite projects. Funding for development is available through the NASA Space Grant Project, which provides funding to college programs intending to strengthen the bond between the public and engineering communities (National Aeronautics and Space Administration, 2021), as well as the DoD, military contractors, non-profit organizations, and other aerospace-centric companies.

Parts and assemblies can be independently designed and fabricated, though this process can be costly both in time and money. A better alternative is to use commercial off-the-shelf parts (COTS) which are available online through various websites. Some examples include *Cubesatkit.com* and *Cubesatshop.com*. These websites offer ready-to-install CubeSat parts and assemblies at a wide range of prices, many of which are conducive to an educational environment. Additionally, UVA has extensive 3-D Printing capabilities, which can compensate for parts that cannot be purchased or sourced online.

Systems and communications support for the CubeSat is available through the University in the form of a ground station that has satellite communications capabilities. Other college Aerospace Engineering programs and commercial providers of satellite constellations, such as Iridium or Starlink, are also available for system support and to use as communications ground stations.

Conclusion

The project is expected to produce several outcomes. The primary outcome of the project will be the assessment of the feasibility and capability of future hypersonic decelerating CubeSat experiments. The data collected and returned to the University of Virginia, including position, velocity, acceleration, temperature, pressure, and orientation, will provide the means to perform this analysis. Assuming successful collection of intelligible data, possible results of study include complete validation of mission goals and predictions, evidence of premature spacecraft incineration, or evidence of premature slowdown to sub-hypersonic speeds. The results of student and professional assessment of the mission may lead to further exploration and study by UVA or other entities. Students involved in this or future missions will gain experience in engineering design and project management while exposing the public to mechanical and aerospace engineering.

Achieving the expected mission outcomes could prove vital for developing future spacecraft concepts. If the data collected confirms expected results, development of decelerating hypersonic spacecraft, such as modules meant to return astronauts to Earth, would have a cost-effective method to confirm results of simulations and test aircraft components. The UVA

Decelerating Spacecraft Design Team will therefore use its collective knowledge and available resources, such as guidance from experts in space mission design, to progress the project in the direction necessary to achieve its goals.

The Sociotechnical Implications of Space Debris: Production, Mitigation, and Removal

Not unlike the shortsighted human behaviors that accompanied large-scale industrialization, such as unsustainable natural resource consumption, rash and irresponsible conduct in space can potentially pollute nearby orbits to such a degree that opportunities to leave Earth will be diminished. Due to the importance of investigating the space debris dilemma, the primary purpose of this paper is to explore the sociotechnical aspects of space debris production, mitigation, and removal. In his 1978 paper, NASA scientist Donald Kessler warned of the self-propagating nature of space debris (Kessler et al., 2010). Due to the high velocity of objects in orbit, which can be as high as eight kilometers per second in low Earth orbit, even relatively small pieces of orbital debris can damage a much larger craft (Gregersen, 2021). A catastrophic collision can reduce spacecraft to clouds of individual fragments, as was seen in the 2009 collision between an Iridium satellite and a defunct Russian military satellite (Gregersen, 2021). These fragments then encircle the Earth, increasing the probability of future collisions, which would then produce debris clouds of their own (Gregersen, 2021). Even if all space operations were halted and additional spacecraft were not placed into orbit, the number of random collisions would still increase until all objects at that particular orbit were reduced to fragments (Kessler et al., 2010). In the case of heavily polluted orbits, because of the high probability of a spacecraft's destruction, these orbits, and particularly low Earth orbits, could effectively be rendered useless until the debris' orbit decayed (Gregersen, 2021). The cascading phenomenon of space debris was coined Kessler's Syndrome, after the author of the 1978 paper (Kessler et al., 2010). The grim scenario in which space operations face such an overwhelming obstacle could become a reality without proper management. The decreasing cost of launches over the previous forty years has, predictably, caused in upward trend in the number of launches and spacecraft in orbit (Chakrabarti, 2021). Large systems of satellites, known as satellite constellations, will likely become more common, as seen with the likes of SpaceX's Starlink (Lewis et al., 2017). Additionally, inexpensive, small-scale satellites, such as CubeSats, have become more commonplace in low Earth orbit for cost-effective research (Lewis et al., 2017). Both of these new conditions further exasperate the risk of space debris collisions (Lewis et al., 2017). In order to maintain normal space operations, the normative business-as-usual approach to space debris will likely need to be discarded. Particularly, spacefaring nations need to be held accountable for debris production, being impelled economically and legally to produce, launch, maintain, and discard spacecraft responsibly (Kessler et al., 2010). Additionally, problematic artifacts, such as defunct satellites, will need to be removed from orbit (Kessler et al., 2010).

In analyzing the issue of space debris, the most prominent of the STS theories to be applied will be that of wicked problems. A wicked problem is that which is difficult or impossible to solve indefinitely, is characterized by non-constant constraints and resource demands, has an incomplete definition, and depending on the particular stakeholder, the problem can be understood differently. In the wicked problem framework, space debris can be characterized as a wicked problem. Due to the incredible volume of space and range in the dimensional scales of debris, the issue of space debris will never be "resolved"; the financial burden of removing every single fragment of debris would render the task near impossible (Kaplan, 2009). Additionally, waiting for orbital decay to remove all debris could take many,

many centuries (Gregersen, 2021). Because of the large resource and time investments needed to completely reduce the risks associated with space debris, space debris is a problem to be continuously monitored and managed rather than that of one to be definitively solved. Proper management, however, is characterized by a relatively large amount of resource investment and is limited by technological capabilities (Kaplan, 2009). Additionally, it requires strong cooperation from the entire spacefaring international community, with meaningful punishments levied towards bad actors. The use of wicked problems as the primary framing method is not entirely without issue, as there are some criticisms to the theory. Particularly, the framework recognizes problems almost entirely in a dichotomy of wicked or tame problems (Termeer et al, 2019). Through wicked problem framing, it is difficult to assess the level of wickedness and to differentiate very difficult issues from impossible issues. The different aspects of space debris management, for example, are characterized by different degrees of wickedness. Due to the unsurmountable demand of resources required to remove all space debris fragments, space debris removal is sufficiently more wicked than space debris production and mitigation, which, though difficult, can be more adequately achieved through innovation and policy.

Research Question and Methods

As mentioned previously, the particular research goal of this paper is to investigate the sociotechnical elements of space debris, including the production, mitigation, and removal of space debris. The primary means of investigation will be accomplished through documentary research methods, discourse analysis, policy analysis, and wicked problem framing. Documentary research methods and discourse analysis will be used in order to organize and evaluate technical literature as well as dialogues amongst leading experts pertaining to the topic of space debris. In gathering sources, key words would, predictably, include items such as “space debris," "space debris consequences," "space debris remedies," and "space debris mitigation." The process of policy analysis will be used to evaluate past, current, and proposed future legislation pertaining to space debris management on both a national and international level. Policy analysis will likely contribute to a significant portion of the STS research paper, given that successful space debris management is largely dependent upon effective and enforceable rules followed by the entirety of the international spacefaring community. As explained in the previous section, wicked problem framing will additionally be necessary for the analysis of space debris.

Conclusion

The topic covered in the technical portion of this paper, cost-effective decelerating hypersonic flight research, and space debris, are inherently interrelated; space debris in low Earth orbits increases the risk of collision to adjacent spacecraft. By increasing the number of spacecraft in orbit, either to conduct research or as the result of innovations brought about by research, the risk of collision is enhanced and, if not properly managed, can reduce the usability of the same orbits. The primary goals of the technical topic are to assess the feasibility of using CubeSats, or miniature research satellites, for decelerating hypersonic flight research and to collect coherent flight data upon atmospheric reentry. In successfully doing so, a method of conducting real-world, cost-effective research on decelerating hypersonic flight would be validated. Further research on decelerating hypersonic flight would, in turn, help facilitate the advancement of spacecraft such as hypersonic reentry vehicles. To ensure the long-term viability of spacecraft in low Earth orbit, such as the proposed research spacecraft outlined in the technical topic, the STS topic seeks to address the critical risk of space debris. The primary goal of the STS topic is to investigate and provide insight on the sociotechnical elements of space debris, including space debris production, mitigation, and removal. Unchecked space debris production has the potential to obstruct crucial orbits, which could hinder or halt the advancement of spacecraft and their applications. It is hoped that investigations of space debris can help facilitate a more sustainable future in which space missions can continue unobstructed.

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