Decelerating Hypersonic Flight Experiment Using a CubeSat Platform
(Technical Paper)

How Commercialization is Changing the Approach to Space Missions and Investments
(STS Paper)

A Thesis Prospectus
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By
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Technical Team Members:

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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Prospectus

Introduction:

Hypersonic flight, defined as flight with Mach numbers above 5 (meaning 5 times the speed of sound), 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 (very small cube-shaped satellites released from orbit as secondary payloads) 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.

Despite increased interest and viability of educational missions such as that of the technical topic, the primary actor driving space exploration and aeronautics is not STEM education and research. Instead, it is the major shift from national organizations such as NASA selecting and funding space mission concepts to private companies such as SpaceX and Blue

Origin. This shift is changing the major players involved, the process of mission design, and the goals of space travel in a transformative way that warrants further investigation by this document for the purpose of understanding and prediction.

Decelerating Hypersonic Flight Experiment Using a Cubesat Platform:

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

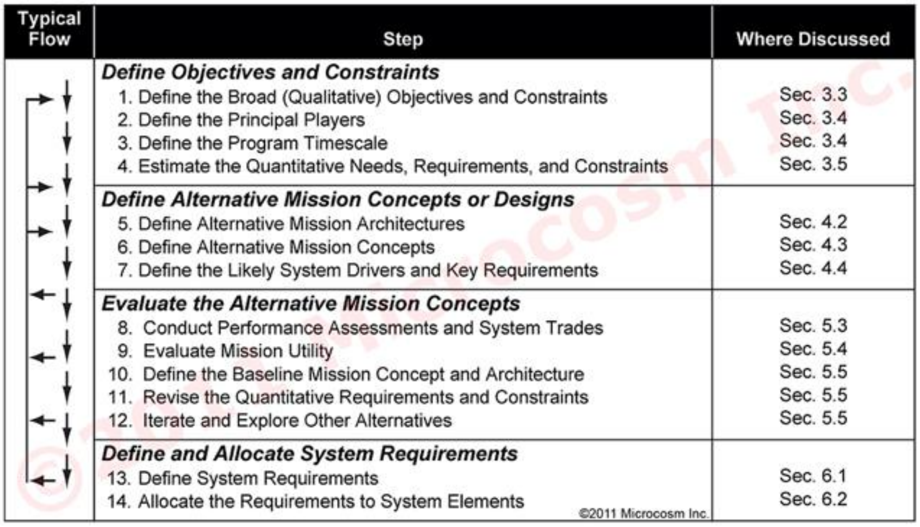
The ability to minimize power consumption will stem from the construction of an efficient CubeSat that properly addresses changing flight conditions. As displayed in Table 5, the CubeSat will need to adhere to dimensional and budget constraints, as well as federal regulations, which will affect manufacturing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

How Commercialization is Changing Perceptions and Activities in Space:

Since the space race captivated the hearts and minds of Americans, the space industry has been a showcase of technical innovation and prowess. In America, the largest spender in the field at over 52% of all space spending and thus the focus of this topic (Koetsier, 2021), the National Aeronautics and Space Admnistration (NASA) is synonymous with space exploration and invention. NASA is a government entity with a relatively large budget and abundant regulations. Until recently, public agencies like NASA were the only entities able to support the cost of space travel. There was simply no viable business model for private, profit driven companies to startup and turn a profit on space travel given the tremendous up-front and operating costs. However, improvements in technology and a growing market for satellites and even tourism have resulted in private companies taking over the space industry. As of 2021, there are now over 10,000 companies involved in the space industry, which is now valued at over 4 trillion (Koetsier, 2021). Many of these companies, such as SpaceX and Blue Origin, are backed by the ultra-wealthy, guaranteeing funding for years to come. However, these companies and backers present their own complications, such as increased lobbying (Forrest, 2021). With no signs of slowing, this shift to private space industry and its repercussions provides a complex topic for study.

The unimpeded shift to private space industry and its network of ultra-wealthy leaders and funding, regulatory bodies, public space agencies, and the intermediaries through which they interact will therefore be analyzed to predict further change in humanity's approach to space exploration. It is inevitable that the increased competition and growing number of actors will have profound impacts on the field, and thus the question posed is as follows: What is the sociotechnical impact of the shift from public to private companies in relation to the space industry and the future of space exploration?

The topic will primarily be contextualized by Paradigm Shift Theory, the concept that new information or methods will become incompatible with old methods conceptualized by American philosopher Thomas Kuhn. The shift from public to private space activity will be referred to as a paradigm shift due to the impact on the approach taken for space mission design and approval. Like the difference in understanding of a molecule between a chemist and a physicist Thomas Kuhn discusses in "The Priority of Paradigms," (p. 51) there is a fundamental difference in the methodology and operation between a private company that is primarily motivated by profit and a traditional government entity. McLeod sums up the most common and relevant criticism of paradigm shift theory in an article on the topic by stating "Kuhn has been accused of being a relativist. Maybe all the theories are equally valid? Why should we believe today's science when it might be overturned in future?" (McLeod, 2020). The use of paradigm shift theory will avoid this criticism by acknowledging that private and public approaches to space activity have already produced tangibly different results.

The paradigm framework will be accompanied by the Actor-Network Theory (ANT), the concept of breaking down everything in the social world into “actors” within a “network,” in order to make sense of the key components spurring change by connecting actors to the forces involved. In “A Brief Overview of Actor-Network Theory” Darryl Cressman states that “ANT attempts to ‘open the black box’ of science and technology by tracing the complex relationships that exist between governments, technologies, knowledge, texts, money and people” (p. 1). Thus, ANT will be used as suggested to connect companies, regulatory bodies, funding, customers, and more to understand the full impact of the public to private shift. The most relevant criticism of ANT for this topic is the difficulty of defining a network of actors that can produce useful understanding. Cressman states that “ANT sets out to ‘follow the actors’; a confusing dictum if only because there are so many actors within any given network, including some who may emerge and disappear long before a recognizable network is finalized” (2009, p. 2). This issue with ANT will be mitigated by limiting the scope of the network from the outset to only companies, agencies, and regulatory bodies most impactful to American space activity.

Research Question and Methods:

The driving question for research is, again, “What is the sociotechnical impact of the shift from public to private companies in relation to the space industry and the future of space exploration?” The analysis of this public to private space activity will be founded on a variety of citations that relate to different actors and types of data. Sources will be gathered by using general scholarly search tools such as google scholar or the University of Virginia’s VIRGO system with relevant keywords such as “Space,” “industry,” and “private.” Despite the lack of specificity, the amount of sources returned is small yet diverse, including economic and scientific journals, books, congressional hearings, and more. This variety in sources is considered beneficial to later establish the complex network of actors with the required perspective, leading to consideration of less typical information. For example, to determine the impact on the types of missions that are funded, it is necessary to source information from regulatory bodies such as congress that ultimately approve space activity, which is often in the form of a script from a congressional hearing. Chosen sources are then investigated independently for their relevance and authenticity. Sources deemed useful were finally assembled to form the backbone for future study.

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 STS topic is anticipated to provide insight into the fundamental changes that the shift from public to private space activity will have on the space industry. By backing the paradigm shift theory with the Actor-Network theory, the shift will be properly contextualized in order to perform the analysis required. Given the applicable frameworks and the selection of relevant sources, the result of analysis should provide detailed and accurate predictions and understanding for the research question.

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