Decelerating Hypersonic Flight Experiment Using a CubeSat Platform

Analysis of the Catastrophic Failure of the Columbia Space Shuttle

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By
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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

Hypersonic flight, defined as flight with Mach numbers above five, contains significant challenges with regards to thermal management, maneuverability, and communications (Ambrose & Greene, 2019). Hypersonic flow is most often encountered during atmospheric reentry, where the spacecraft is decelerating from Mach 25 to Mach 10 (Glenn Research Center, 2021). Modeling this flow is important in order to understand both the pressure and heating distributions on aircraft and spacecraft which affect the design of the heat shielding and aerodynamic components.

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 (Sayler, 2021). Some private companies also seek to build hypersonic passenger aircraft, which could connect LA to Tokyo in under two hours (Baggaley, 2019). Collecting flight data is invaluable as it garners interest from both the government and commercial industries, but it presents several technical challenges. Testing of ground-based hypersonic experiments is limited by older testing facilities which are large, expensive, and contain insufficient technology (National Research Council, 1994). Additionally, modeling software poses issues due to lack of technical understanding for concepts such as boundary layer transition at higher Mach numbers (National Research Council, 1994). Limited by the financial costs of hypersonic research, a more cost-effective solution is sought to collect experimental data. Recent developments in CubeSat technology, including commercial off-the-shelf components (COTS) and lowered launch costs, have improved accessibility for spacecraft missions (Nervold et al., 2016). Testing the hypersonic environment with a CubeSat undergoing atmospheric reentry significantly reduces the costs associated with ground testing and provides greater accuracy than model-based testing.

While the technical background for the Cubesat mission is important, so are the social and political factors that will shape its development process and the space program surrounding it. Among these social and political factors are NASA management, the US media's portrayal and analysis of the country's space program, and the US government oversight of NASA's missions. The violent nature of the hypersonic regime of atmospheric reentry with spacecraft makes it one of the most dangerous parts of spaceflight for instrumentation, as well as any humans on board the spacecraft. Past encounters with errors of negligence have caused mission failure, and no matter the technological leaps that are made in aerospace engineering, social and political actors will continue to play a role in the success rate of future missions. Continuing with the design of spacecraft without considering these non-technical factors will not only disrupt the short and long term mission objectives, rendering collected data useless, but also put human lives in immediate danger.

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, and then to outline project team's plan to make it happen. To accomplish this, technical and non-technical factors will be examined concurrently to ensure the best chances for mission success before and after the Cubesat flight itself. At the end of this year, the technical thesis will be in proposal format for potential submission to NASA for funding of the fabrication and testing of the 3U CubeSat design. I will also be developing an STS thesis where I will apply the Actor-Network theory to examine the hypersonic deceleration failure of the Columbia space shuttle in order to determine the physical and social factors that had an effect on the shuttle's compromisation.

Technical Problem

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 objective requires a number of functional (Table 3) and operational requirements (Table 4) and must satisfy the mission constraints (Table 5). The CubeSat must be able to survive extreme conditions (F1, Table 3) so that data collection and transmission do not fail, and so that the CubeSat is able to transmit sufficient data to the University. Extreme condition survival and full power (F4, Table 3) throughout the mission reduce the risk of part, 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. Operational requirement two from Table 4 highlights the importance of the CubeSat's ability to transmit the measured data to an accessible source. Without being able to relay data back to the researchers, the mission loses much of its validity.

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.

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

For this project, 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 for the CubeSat can be obtained through designing, but designing unique parts is 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 which offer ready to install cubesat parts and assemblies at a wide array of prices. 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 are available through the University in the form of a ground station that has satellite communications capabilities. Other college Aerospace Engineering programs and commercial providers such as the Iridium satellite constellation are also available for system support and for use as communications hubs.

STS Problem

In April of 1981, NASA tested the first launch of a new type of reusable spacecraft: the space shuttle. Over the 30 year lifespan of the space shuttle program, 5 reusable vehicles carried out 135 missions with goals ranging from performing basic experiments to assisting in the construction of the International Space Station (Loff, 2017). The shuttles exited the Earth's atmosphere as a rocket, and were able to come back to the planet's surface by using high-tech heat shielding to breach the upper atmosphere, followed by landing as a glider on a runway (Sharp, 2017). On February 1, 2003, NASA's space shuttle Columbia broke apart upon reentry into the Earth's atmosphere during its 28th mission, killing the entire seven-person crew and destroying the spacecraft (Howell, 2021). The Columbia disaster was not the first within the space shuttle program; in 1986 the Challenger space shuttle exploded roughly a minute into its liftoff (The Editors of Encyclopaedia Britannica, 2021). However, the Columbia failure was the first major issue that appeared during atmospheric reentry. During the shuttle's launch, a piece of foam fell off of a bipod ramp and impacted the shuttle's left wing, creating a hole that allowed hot gases to enter the shuttle during its violent hypersonic reentry into the atmosphere. At an altitude of about 200,000 feet and velocity of 18 times the speed of sound during reentry, Mission Control lost communications with the shuttle and received no information until they were informed 12 minutes later that Columbia had been spotted breaking up in the sky over Texas (Howell, 2021).

While the Columbia failure is often solely attributed to the piece of foam damaging the shuttle's left wing, this fails to account for the lack of technological progression over the years in the space shuttle program and understates the roles played by organizational actors such as NASA, the US government, and the American media. For example, upper management at NASA was warned multiple times about the possibility of the Columbia's heat shielding being compromised, but their arrogance was so severe that despite being offered the use of military satellite photography to investigate, they declined to proceed with caution (Sunseri, 2013). If we continue to only think about the exact physical problems that affect our space program failures, we will not be able to understand how these other, non-technical actors influence our successes and failures, permitting even more problems to occur in the future.

Drawing on Actor-Network theory, I argue that while physical damage to the Columbia space shuttle was a factor in the space shuttle's failure, NASA management's overconfidence and negligence, the US government's lack of oversight, and the American media's complacency regarding NASA all assisted in the Columbia's failure. Actor-Network theory aims to characterize a network of technical and non-technical engineering factors within an environment made up of both physical and social actors. In this network, no one actor's power is inherently greater or less than that of another actor, but instead contextual and based on the relationship it was with other actors within the network. Applying this framework, I will outline the process by which the space shuttle program got to where it was at the time of the Columbia disaster, and how the network around it dissolved in the following years. Outlining this network's rise and fall will assist in getting a better grasp on what social and physical actors must be accounted for in future space exploration projects in order to avoid catastrophe. To support my argument, I will be analyzing evidence from NASA press releases, technical reports, and external records.

Conclusion

This project is expected to produce several outcomes. The primary outcome of the technical project will be the assessment of the feasibility and capability of future hypersonic decelerating 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. The STS research section will aim to uncover the network of factors that led to the Columbia space shuttle disaster upon hypersonic atmospheric reentry after dozens of successful missions. This will be achieved by using the Actor-Network theory to demonstrate how various physical and social actors play a role in the development of a space program. The results of the technical and STS sections of this report will help to address both the technical issues regarding the violent conditions faced by spacecraft during hypersonic atmospheric reentry, as well as the social factors that affect how atmospheric reentry is managed. Using this information, even more successful hypersonic deceleration missions will be able to be carried out in the future with increased background knowledge, consistency, and safety.

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Technical Section Word Count: **584**

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