Software and Avionics Development for a Hypersonic Flight Mission

Analysis of the Failure of Boeing 737 MAX MCAS System and Subsequent Crashes

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Mechanical Engineering

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December 9, 2022

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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

Avionics govern all the electrical systems onboard a spacecraft or aircraft, and as such, they are critical to the operation of both. Consequently, avionics systems are held to rigorous standards as the failure of an avionics component could put lives at immediate risk. Aircraft and spacecraft design dictates multiple redundancies, especially in the most critical systems pertaining to avionics. Notably, modern airliners use state-of-the-art digital avionics suites while still having important standby analog gauges on the side. While the consequences of failure are much higher for manned aircraft and spacecraft, it is still critical to design an effective avionics platform with the necessary redundancies for small unmanned spacecraft missions. A successful mission is still a critical objective due to the significant amounts of time and money that are invested in these missions. To ensure a successful small spacecraft mission, I will take part in designing a reliable and robust avionics system for UVa's Hypersonic ReEntry Deployable Glider Experiment (HEDGE). The success of the mission is highly dependent on the avionics system, as it is responsible for deploying the fins at the appropriate time, collecting hypersonic flight data, and transmitting the data to a ground station.

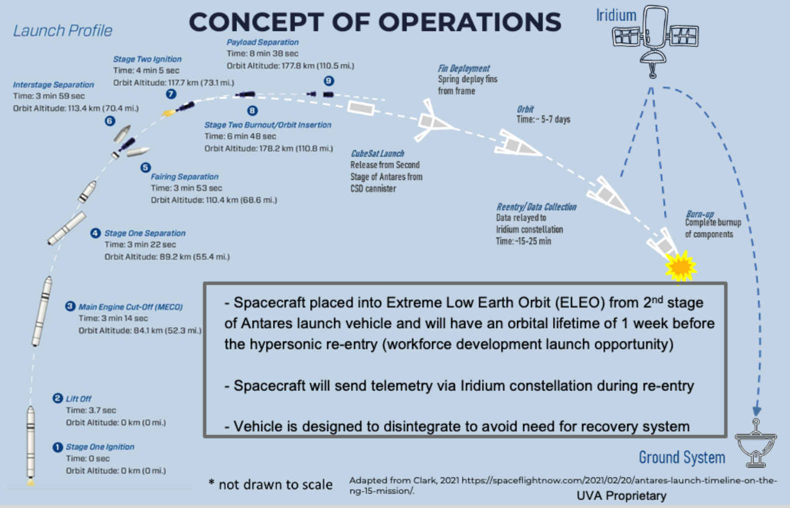
While avionics systems always require thorough design and testing to ensure safety and reliability, there are often significant financial and corporate pressures that can hamper the development of a reliable system. Failing to understand these issues will put lives at risk in the event that maximizing a company's profits becomes prioritized over creating a well-engineered avionics system.

I will apply Actor-Network Theory when studying the failure of Boeing's 737 MAX Maneuvering Characteristics Augmentation System (MCAS) by analyzing the human and non-human actors which contributed to the crashes of Lion Air Flight 610 and Ethiopian Airlines

Flight 302. This analysis will provide insight into how time and cost restrictions may interfere with designing safe and reliable avionics systems.

Technical Project

Hypersonic flight is defined as flight that exceeds 5 times the speed of sound, commonly referred to as Mach 5. Flight research at these speeds is expensive to the point of being cost prohibitive. For example, the Boeing X-51 Waverider (2004) had an estimated cost of 300 million USD and the NASA X-43 (2004) had an estimated cost of 230 million USD (Pike, 2013). The US Department of Defense is interested in collecting real hypersonic flight data, so it is desirable to develop affordable concepts to conduct hypersonic flight experiments. To address this need, students at UVa advised by Professor Goyne have developed HEDGE. HEDGE is an inexpensive Cube Satellite (CubeSat) design that will be deployed as a secondary payload from another rocket (e.g. Northrop Grumman Antares) into Low Earth Orbit (LEO) (Figure 1). HEDGE will not require its own propulsion system once deployed, as hypersonic flight will be achieved upon orbital re-entry.



CONCEPT OF OPERATIONS

Launch Profile

① Stage One Ignition
Time: 0 sec
Orbit Altitude: 0 km (0 mi.)

② Lift Off
Time: 3.7 sec
Orbit Altitude: 0 km (0 mi.)

③ Main Engine Cut-Off (MECO)
Time: 3 min 14 sec
Orbit Altitude: 84.1 km (52.3 mi.)

④ Stage One Separation
Time: 3 min 22 sec
Orbit Altitude: 89.2 km (55.4 mi.)

⑤ Fairing Separation
Time: 3 min 53 sec
Orbit Altitude: 110.4 km (68.6 mi.)

⑥ Interstage Separation
Time: 3 min 59 sec
Orbit Altitude: 113.4 km (70.4 mi.)

⑦ Stage Two Ignition
Time: 4 min 5 sec
Orbit Altitude: 117.7 km (73.1 mi.)

⑧ Stage Two Burnout/Orbit Insertion
Time: 6 min 48 sec
Orbit Altitude: 178.2 km (110.8 mi.)

⑨ Payload Separation
Time: 8 min 38 sec
Orbit Altitude: 177.8 km (110.5 mi.)

CubeSat Launch
Release from Second Stage of Antares from CSD cannister

Fin Deployment
Spring deploy fins from frame

Orbit
Time: ~ 5-7 days

Reentry/ Data Collection
Data relayed to Iridium constellation
Time: ~15-25 min

Burn-up
Complete burnup of components

Iridium

Ground System

- Spacecraft placed into Extreme Low Earth Orbit (ELEO) from 2nd stage of Antares launch vehicle and will have an orbital lifetime of 1 week before the hypersonic re-entry (workforce development launch opportunity)

- Spacecraft will send telemetry via Iridium constellation during re-entry

- Vehicle is designed to disintegrate to avoid need for recovery system

* not drawn to scale

Adapted from Clark, 2021 https://spaceflightnow.com/2021/02/20/antares-launch-timeline-on-the-ng-15-mission/.

UVA Proprietary

Figure 1: UVA Low Cost Hypersonic Flight presentation (UVA 2021)

As the CubeSat naturally de-orbits back into the atmosphere, it will collect hypersonic flight data and either transmit it to a ground station or store it internally if there is a plan to recover the CubeSat. The software and avionics team's purpose is to design and integrate a functional avionics system into the CubeSat, including both hardware and software, to achieve the mission parameters. The avionics system will require: data acquisition, data processing, data storage, data transmission, and control of hypersonic fin deployment. With several other subsystems working onboard HEDGE, the avionics system must interface with each to determine the proper way to handle it with onboard memory.

Environmental factors like loads, vibrations, and heat pose challenges to the vehicle's exterior design. During atmospheric re-entry, HEDGE will travel at velocities exceeding Mach 15 and potentially as fast as Mach 25. As a result, the vehicle will experience extreme temperatures over its surface. The combination of environmental factors and flying at high Mach speeds results in a plasma sheath around the forward-facing side. This formation poses a challenge in exporting data; without the ability to transmit around or through the sheath, the data may be lost, and the experiment would be unsuccessful.

Should a component of the avionics system fail then it would jeopardize the success of the entire experiment. Every subsystem's function is crucial, but a loss of avionics will prevent all data communication or loss of control of the vehicle. Therefore, the importance of comprehensive testing, robust design, and successful integration is a necessity. When talking about the Space Launch System (SLS), a NASA System Manager says, "'The body couldn't function without the nervous system, and similarly, SLS couldn't fly without avionics.'" (Boen, 2017). While SLS operates at a much larger scale than HEDGE, the same sentiments apply here; avionics is crucial to flight operation and recovering meaningful data. An example of the interactions between avionics and the rest of the subsystems is shown in figure 2. All the data from the payload is fed into the flight computer and from there, control decisions are made and sent to their respective systems to maintain the vehicle during flight.

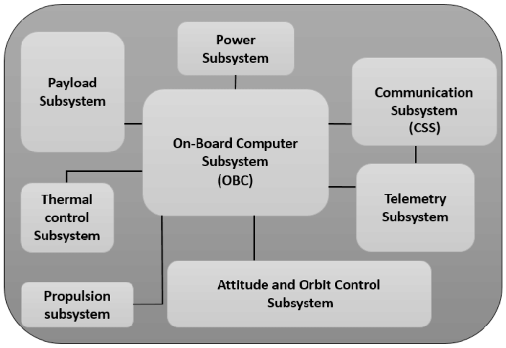


Figure 2: Example of Organization of Subsystems around Avionics (El-Bayoumi, et al, 2015)

The implementation of software is governed primarily by the mission objective to collect hypersonic flight data, however, structural, thermal, and power constraints of the vehicle itself must also be considered. The first step of hardware implementation will be to choose a processor or computer that will be the central part of the software and avionics subsystem. The approach will be to first evaluate the recommendations of last year's team for an onboard computer. Since one of the main constraints for choosing the components of the mission is our budget, other options will have to be considered as well. Highly integrated onboard computing products from suppliers such as EnduroSat are convenient since they combine a processor with memory banks and a variety of standard interfaces, however, they are also expensive (Yost, 2021). A cheaper alternative would be to use commonly available microcontrollers, such as an Arduino or a Raspberry Pi.

In this second year of HEDGE’s project life, we will be finalizing the design and anticipate early prototyping and testing of the software and avionics system by the end of the

Spring Semester. This will lay the foundation for the following year's class so that they can conclude the project and successfully gather hypersonic flight data at an exceptionally low cost.

STS Project

On October 29, 2018, Lion Air Flight 610 crashed into the Java Sea 13 minutes after departure from Jakarta (Indonesian National Transportation Safety Committee, 2018). Approximately 5 months later on March 10th Ethiopian Airlines Flight 302 crashed six minutes after takeoff under similar conditions (Ethiopian Civil Aviation Authority, 2019). These crashes promptly resulted in the long-term grounding of the Boeing 737 MAX 8 fleet. A design flaw in Boeing's MCAS system was attributed to these crashes.

Boeing initially designed the 737 to operate at airports with limited service which resulted in it sitting relatively low to the ground so that passengers could enter and exit with stairs, and since its introduction in 1968 the current airframe still sits low to the ground. In 2011 when Boeing decided to upgrade the engines on their 737 there wasn't enough room under the wing so they moved the engine further up. This changed the handling characteristics of the plane when it was in takeoff and climb power settings as the nose would start pitching too far up (Ethiopian Civil Aviation Authority, 2019). Boeing sought to advertise the 737 MAX as a plane that would require minimal training for 737 pilots and would essentially fly the same. This led to the implementation of the MCAS system which relied on a single angle of attack (AoA) sensor (Hamblen, 2020). The MCAS was designed to push the nose down if a high AoA was detected. The crashes were deemed to be caused by the MCAS receiving faulty data from the AoA sensors, as the pilots were fighting against the MCAS system when it was unnecessarily forcing the nose of the plane downwards.

While the MCAS system may be the primary technical reason for the crash, it is important to understand the external non-technical factors that resulted in flawed engineering and the loss of life which ensued. Analyzing these factors will help guide the design process of many future software and avionics projects as the fundamental actors remain relevant. I will argue that the competition between Airbus and Boeing resulted in rushed engineering which cut dangerous corners to save time and money.

Boeing 737s are designed with two AoA sensors and yet the MCAS system was only utilizing one, thus lacking redundancy in a crucial avionics system. Boeing also failed to require significant additional training for the aircraft (National Transportation Safety Board, 2019). This lack of training was part of Boeing's marketing. Airlines would value not having to retrain 737 pilots as lower in cost and choose to purchase the 737 MAX, which helped it compete with the Airbus A320neo. Additionally, the airlines involved in these accidents should also be held accountable due to their questionable safety record and hiring practices which contributed to the crashes. An investigation by the New York Times found that Lion Air was overworking pilots, falsifying pilot training records, and "forcing pilots to fly planes they worried were unsafe, including the plane that crashed." (Beech, 2019) Ethiopian Airlines also has questionable hiring practices. For example, the first officer on flight 302 had a mere 361 hours of total flight time (Ethiopian Civil Aviation Authority, 2019), whereas major US airlines require 1500 hours of flight time to be hired. A lack of aviation experience may have contributed to the pilot's inability to quickly disable the MCAS system which prevented them from being able to recover the aircraft from its nose dive. Both Ethiopian Airlines and Lion Air have fleets composed of mostly Boeing aircraft, this malpractice of both airlines underscores how Boeing cuts corners to compete with Airbus, as the airlines are effectively representatives of the manufacturer. Boeing has authority over its airline customers due to aircraft maintenance, and Boeing's inability to discourage these hazardous practices indicates that sales are prioritized over safety.

The application of Actor-Network Theory (ANT) attempts to follow the complex relationships between technologies, governments, money, and people in recognizable networks (Cressman, 2009). ANT studies network builders who assemble networks of human and non-human actors to accomplish a goal. In the case of the 737 MAX accidents, Boeing can be cited as the network builder with significant actors including: Airbus, the FAA and NTSB, and Airline customers, namely Lion Air and Ethiopian Airlines. Applying the concept of ANT, I will evaluate the Boeing network to understand the series of faults and omissions which lead to two similar fatal crashes. I will utilize the preliminary accident reports released by the Indonesian National Transportation Safety Committee and Ethiopian Civil Aviation Authority as well as relevant FAA and NTSB reports when conducting this analysis. This analysis will provide a better understanding of how non-technical actors get in the way of competent engineering, as available technology was no obstacle for Boeing when it came to the 737 MAX crashes.

Conclusion

The technical deliverable will provide the foundation for the software and avionics team in next year's class to continue developing our prototype into a finalized design. One that will be capable of successfully controlling the HEDGE spacecraft to complete its mission objectives. The STS portion of the research paper will elucidate the key contributing factors to the shortcomings of Boeing's 737 MAX MCAS system and the crashes it was attributed to by looking at the incident through the lens of Actor-Network Theory. This research paper will underscore the importance of software and avionics in the aerospace industry and how important it is to consider the relevant non-technical factors which may contribute to a project's failure.

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