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A Systems Engineering Perspective in the Development of a Two-Stage Hypersonic Rocket

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Author Note: The purpose of our project is to design and deploy a solid propellant, two-stage, hypersonic rocket aimed to reach the Kármán line defined as 100 kilometers above the earth at the edge of the atmosphere and outer space. The team employs project management and systems thinking techniques to enable the team to successfully test, verify, and validate a hypersonic rocket system as part of an interdisciplinary team consisting of five Mechanical Engineering Cadets, one Systems Engineering Cadet, and one Engineering Management Cadet. The views expressed herein are those of the authors and do not reflect the position of the United States Military Academy, the Department of the Army, or the Department of Defense.

Abstract: High-powered rocketry represents a conflux of interdisciplinary engineering challenges. Developing robust and reliable rocket systems requires engineers to utilize systems thinking – thinking of the launch vehicle as a whole, signifying one with connected and interdependent parts, instead of merely thinking of it as an assembly of isolated subsystems. This requires constant and careful consideration of how each subsystem interacts with others, how changes in one may affect the dynamics of the entire launch vehicle, and, ultimately, how the system itself fulfills the overarching mission. This paper explores the use of the iterative Systems thinking, design and decisions in developing the United States Military Academy's Space Engineering and Applied Research Tactical Hypersonic Orbital Rocket (SPEAR THOR).

Keywords: SPEAR THOR, Systems Decisions Process, Two-Stage Hypersonic Rockets, Decision Analysis

1. Introduction

The SPEAR program at West Point is an interdisciplinary capstone team with the goal of launching a two-stage hypersonic rocket past the Kármán line. This is the team's fourth year in pursuit of this goal. Each year, the team iterates the rocket design, increasing the performance of the rocket. In previous years, the team designed and tested in the fall and launched in the spring. This year, the team decided to launch once in the fall and once in the spring in Black Rock Desert, NV. This decision enabled the team to identify and respond to modes of failure in the fall to address for the spring launch. In the fall, the team focused on stabilizing the rocket and maintaining a successful flight without the rocket spinning out of control. Stabilization required updating the fin design and the nozzle design to gain a consistent thrust for the duration of the flight, reconfiguring the payload to ensure it was stable, and creating a dynamic balancer to balance the entire rocket – payload, motor, and fins. These topics were the focus bins that the Mechanical Engineering Cadets split amongst themselves through the course of the project, while the System Engineering and Engineering Management Cadets focused on requirements and testing analysis, efficiency, budget, logistics, and schedule. We successfully stabilized the rocket for the fall launch. However, the team identified the need for decision analysis on our propellant type to get our rocket to the Kármán line and the inclusion of an active recovery system that would direct the rocket back to a predetermined location for the spring launch. Ultimately, the SPEAR program places West Point on the brink of a historic achievement. Once successful, SPEAR will be one of the first undergraduate teams to propel a rocket past the Kármán line at hypersonic speeds.

2. Problem Definition

In AY22-23, the SPEAR team experienced pitch-roll coupling. Pitch-roll coupling occurs when the rocket wobbles off-axis until it is parallel with the ground. It causes substantial losses in the rocket's speed and altitude. During the AY22-23 spring launch, the rocket reached a maximum altitude of approximately 90 km, not meeting the 100 km target of the Kármán line. To better stabilize the rocket, the team focused on the fins, nozzle, payload, and balance of the vehicle for our fall launch. This can be seen in the hierarchy drawn out in Figure 1.

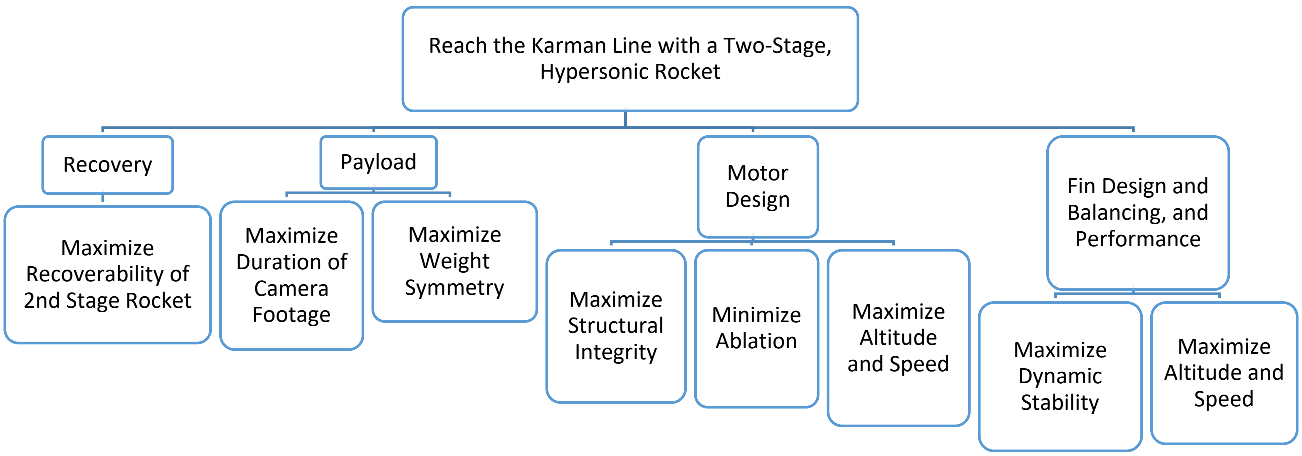

Figure 1: Functional Hierarchy

2.1 Stakeholders

The SPEAR-THOR project garners significant interest and support from various esteemed entities and organizations. Mr. Joseph Maydell, the CEO of Space Launch Technologies, Thonotosassa, FL, and the Aviation and Missile Center (AvMC), Redstone Arsenal, AL, plays a crucial role in the team's endeavors. Mr. Maydell supervises all SPEAR-THOR launches and contributes his extensive expertise and manufacturing resources. He has a level III rocket certification, enabling him to sponsor our launches and ensure the team follows all the regulations corresponding to high-altitude rockets. AvMC serves as both the project owner and client. As world-class innovators and experts in rocketry for the U.S. Army, they provide the necessary funding for developing hypersonic rockets and aid in conducting detailed analyses. The analysis offers critical insights into the management of information and the maintenance of communication channels and allows for the identification and mitigation planning for potential risks in cost, schedule, technicality, and safety.

2.2 Characteristics of the Fall Launch

Previous years teams' introspective analysis pinpointed stability as the rocket's fundamental challenge, thereby underscoring the necessity of employing the systems tools to dissect the launch vehicle into distinct, manageable subsystems. This guided the segmentation and underpinned the coordination and integration of these subsystems, which were distributed amongst the Mechanical Engineering team. These subsystems included the avionics, airframe/stability, optics, motor design, and recovery. In council with Mr. Maydell and AvMC, the team conducted a comprehensive study of historical designs to inform targeted solutions addressing this stability challenge. The team embraced a transformative approach to our testing operations, opting for biannual launches – one in the fall and another in the spring. This strategic change created a crucial informational feedback loop for the team, enabling us to utilize data critical in refining our methods and designs in preparation for the spring. Furthermore, systems thinking led to the strategic decision to manufacture and test rockets with varying fin designs, launching one with canted fins and one with non-canted fins, which will be discussed in detail in section 3.1. This decision would also give the team data for future launches, allowing for further iteration. Based on promising data, the team grew confident in the spin-stabilized rocket based on Rogers Aeroscience (RASAero), an Aerodynamic Analysis and Flight Simulation Software. Optics or video integration also lets the team identify if and how much the rocket spins during flight. Video integration further emphasized the team's decision to launch one of each rocket. The previous SPEAR teams experienced ablation for the nozzle, leading to instability. Ablation is when the throat of the nozzle slowly deteriorates, changing the performance characteristics. The team's analysis and decision to insert and machine a graphite slug into the previous nozzle would likely prevent ablation. When the graphite was inserted, the team had to decide the dimensions for the throat of the nozzle. Decision analysis dictated multiple tests that were conducted on lower-performance propellants, high-powered propellants, and higher-performance propellants. This allowed the team to identify the performance of each nozzle and check for the ablation between tests. The team also gathered pressure and force data, comparing them to each other, allowing for the best-performing nozzle to be used in the fall launch. Finally, the team integrated subsystems and balanced the rocket, ensuring the rocket remained symmetrical and mitigating the threat of pitch roll coupling.

2.2.1 Fin Design, Balancing, and Performance

In previous launches, pitch-roll coupling occurred because as the velocity increased, the drag on the fins caused the rocket to spin at its natural frequency. This caused the rocket to become unstable and go into a flat spin. To counter this, the team calculated the natural frequency at second-stage ignition and burnout and compared this to previous flight data to determine the rocket's actual frequencies during flight. Using this information, the team generated two alternatives for our fall launches: one rocket with canted fins to spin the rocket beyond its natural frequency and one with non-canted fins to keep the roll rate below the natural frequency. The team aimed to keep the rocket at least two hertz above or below the natural frequency for stabilization, and both rockets performed as expected in the small amount of flight time that data was collected (Reddington, 2022). Figure 2 (first launch) below shows the simulated and actual performance of the canted fin design, shown by the gray and orange dots, respectively. The blue points represent the rockets first stage's performance, and the orange points represent the rockets second stage's performance. Figure 3 (second launch) shows the performance of the non-canted fins just on the second stage sustainer. As seen in Figure 3, the max altitude is approximately slightly above 12000 meters. This is due to an unscheduled disassembly of the rocket a couple of seconds into second-stage ignition, which was caused not by a fin design issue but by an over-pressurization in the rocket's upper stage due to the air temperature and propellant type used.

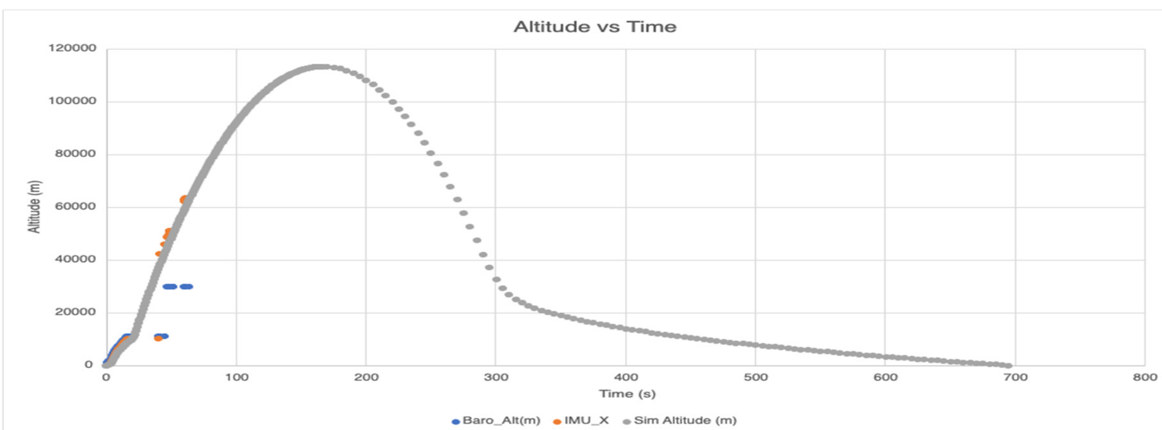

Figure 2: Inertial Measurement Unit (IMU) data from Canted Fins (left)

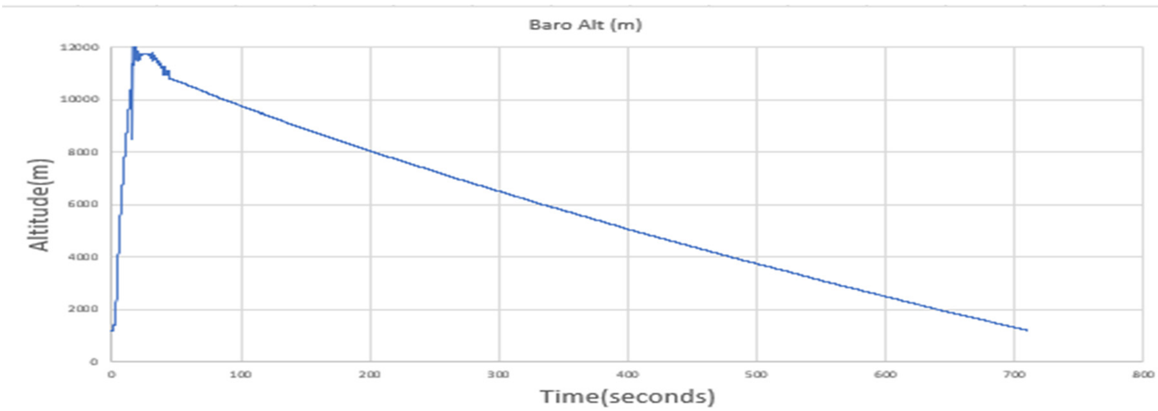

Figure 3: KATE Flight computer data from non-canted fins

Dynamic balancing is also an important focus area considering the problem of pitch-roll coupling. The solution decision being implemented is a testing apparatus that tests the rocket's balance prior to launch. This manufactured apparatus uses accelerometers to measure the force on the cradle caused by natural disturbances. It also incorporates an Infrared (IR) sensor that identifies where instability occurs in rotation (Emerson). Prior to launches, the team places the full vehicle configuration for the sustainer on the dynamic balancer to identify disturbances about the roll axis. The solution is being implemented by placing counterweights to counteract these instabilities. This will minimize the risk of instability upon second-age ignition, especially on the spin-stabilized variant. By meticulously balancing the rocket, there is a reduced probability of pitch-roll coupling, a challenge the team has faced in the past. This approach is particularly beneficial for the spin-stabilized variant of the rocket, where maintaining rotational stability is key to achieving the desired trajectory and altitude.

2.2.2 Motor Design

To achieve the Kármán line with a two-stage hypersonic launch vehicle, two primary concerns are maximizing motor performance to reach Mach 5+ and maintaining stability by preventing off-axis thrust. Performance is linked to the propellant and the nozzle, with the latter being crucial for motor efficiency and stability. Previous models used a commercial glass phenolic nozzle, which presented challenges due to uneven ablation affecting thrust and stability. To address this in our solution design phase, a modified nozzle with a graphite insert was developed. Graphite was selected for its ablation resistance. The modified design aimed to constrict the flow and increase casing pressure to boost impulse which is the efficiency of the propellant or fuel being pushed out the rocket. The initial graphite-insert iteration experienced a flange crack under stress. Subsequently, the design was refined to a straight slug, enhancing impulse by 25%. The final solution design iteration expanded the throat size to mitigate excessive internal pressure risks. Although this version was successful in the AY24-25 fall launch, it introduced two new issues. Key problems faced were the inability to source the Commercial Off The Shelf (COTS) nozzles used to make the custom nozzle and the inability to source the IMAX propellant used in the fall launches. This entails sourcing another propellant with enough performance to reach the Kármán line and designing a custom nozzle that can be manufactured in-house. Numerous alternatives to IMAX were evaluated based on total impulse and availability. The performance parameters for the different propellant alternatives, like White Lightning, Green3, Blue Thunder, Propellant X, and the Black Knight propellant, required that the propellant meet or exceed 10000 Newton seconds (Ns) of total impulse with a custom nozzle. White Lightning, Green3, Blue Thunder, Propellant X, and the Black Knight propellant were analyzed as potential solution design alternatives. With intense stakeholder feedback, ultimately, Black Knight was selected based on overall performance and ruggedness parameters. It produces impulse similar to IMAX with a custom nozzle reaching 11000 Ns of total impulse and utilizes Hydroxyl-Terminated Polybutadiene (HTPB) as the binder, which performs better than the original IMAX propellant in a wider range of temperatures (Cessaroni). As previously mentioned, our fall launched experienced an over-pressurization in the rocket's upper stage due to the air temperature and IMAX propellant. As the next step in building custom nozzles, our next design utilized a fully graphite nozzle that seats into the aluminum boat tail manufactured at West Point. During multiple static fire tests, the nozzle tested well and was ready for flight. This is the most current iteration, and it performed well and is mechanically stable during our fall launches. For our spring launches, the next iteration of the fully custom nozzle design needs to be adjusted for use with the Black Knight propellant, which is cast directly into the casing rather than consisting of grains stacked into a thermal liner. This requires the aluminum boat tail to extend into the casing to support the graphite better and to have the nozzle assembly's face directly against the base of the casted propellant.

2.2.3 Payload

The payload section, including its structure and components, was adapted to give the team a better understanding of the rocket's behavior during flight, greater stability, and a higher probability of recovering the vehicle. A flight camera was a significant addition to the rocket's payload, which was required for additional data-gathering metrics seen in Figure 4. The alternatives for camera integration were the RunCam 5 and the GoPro Hero session. The solution design decision was the RunCam 5 due to its accessibility in the commercial market. To determine the camera settings for quality of footage and temperature increase over time, the RunCam was tested in a vacuum chamber. An aperture was cut into the side of the rocket to allow the camera to record during flight. The payload section includes the RunCam 5, a flight computer, and an Amateur Packet Recording System (APRS) recovery system which provides real time digital communications and tracking data for recovery of the rocket. The design of the payload structure has been iterated between launches, as shown in Figure 4. Each structure is made of 1/8'' Baltic birch material due to its light weight and ability to dampen vibrations.

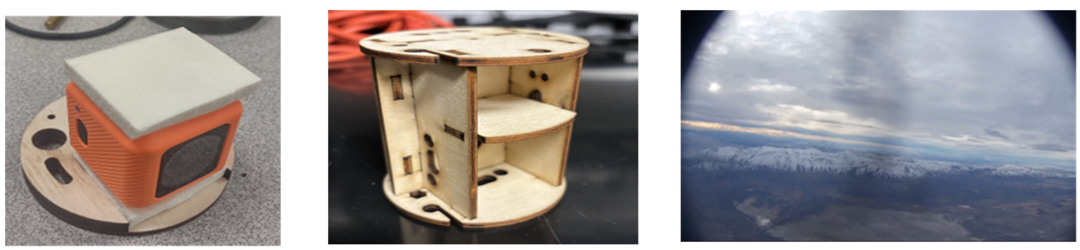

Figure 4: Payload Structures for the Fall Launch featuring the RunCam5 flight camera (right).

2.2.4 Recovery

The team struggled with recovering our hypersonic rockets following a launch in previous years. As a result, the team designed alternatives, weighed solutions, and arrived at a solution—to construct a device that can return a payload to a specified location via a GPS-guided parachute. This solution decision came derived from system design phases, including a literature review, mathematical analysis, and iterative testing. The literature review mirrored at a similar project named "R2Home" on hackaday.io, a "fully autonomous and flight proven GPS guided recovery system" (Hadji, 2021). In addition, the team conducted a proof of concept by acquiring a 32" Gliding Parachute System from Apogee Rocket Components and integrating it into a Zephyr model rocket. This operational test was crucial for evaluating the performance characteristics of paragliders. Successive to the model rocket evaluation, the team embarked on mathematical computations to develop a Proportional-Integral-Derivative (PID) controller that would manipulate the parachute's servos, an electronic device that dictates acceleration and velocity. The servos is governed by an Arduino board-encoded algorithm. The core of this algorithm was a program designed to deduce an optimal trajectory toward a predefined target, considering the current and intended geographic coordinates. By applying the haversine formula, the team could calculate the necessary compass bearing to the target and program the servo actuation to align the GPS-guided parachute on the correct glide path for precise target acquisition (Upadhyay). An iterative design process was used to design the hardware associated with the device as it would be arranged inside the rocket and necessary to tune the coding as needed. Although this GPS-guided parachute was not a considered subcomponent for our fall launches, further testing is ongoing. Once performance measures are met, the team will move toward the solution implementation phase to integrate the device into the rocket for our spring launch.

3. Decision Making

Value Criteria	Objective	Stakeholder Value	Relative Wt	Raw Score			Weighted Score		
				3 Inch	3.1 Inch	4 inch	3 Inch	3.1 Inch	4 inch
Scalability	Max	5	**0.17**	2.00	5.00	7.00	0.33	0.83	1.17
In-Flight Stability	Max	8	**0.27**	9.00	5.00	3.00	2.40	1.33	0.80
Apogee Height	Max	9	**0.30**	7.00	7.00	10.00	2.10	2.10	3.00
Risk	Max	8	**0.27**	9.00	1.00	5.00	2.40	0.27	1.33
SUM		**30**					**7.23**	**4.53**	**6.30**

Figure 5: Weighted Value Scoring Matrix for the 3-inch diameter, 3.1-inch diameter, and 4-inch diameter rocket.

Moving into our Spring launch, the team identified specific values that we deemed crucial to the success of our fundamental objective – to successfully reach the Kármán line with a two-stage, hypersonic rocket. The value criteria determined were scalability, in-flight stability, apogee height (the point in the orbit at which it is furthest from the earth), and general technical risk involved in launching different payload configurations of the launch vehicle. Ultimately, the stakeholders and the team agreed that apogee height, risk, and in-flight stability would be of the highest value to the project. For this particular spring launch, we deemed scalability not as crucial to the success of the current fundamental objective. Raw Scores for each of the three potential configurations were calculated through thorough stakeholder engagement. The 3-inch diameter rocket, with the smallest payload space, scored the lowest on scalability but highest on stability. The relative risk is low, as this configuration has been tested before – hence, the high raw score for risk. The 3.1-inch diameter rocket is obviously slightly larger, hence the higher scalability score. In-flight stability was rated at the mid-point; simulations indicate a stable rocket, but this configuration has never been tested before. The apogee height is weighted the same as the 3-inch, as the propellant and casing would be identical to that of the 3-inch. The 4-inch diameter has been launched by previous teams that were unable to reach the Kármán line, hence the medium score for both risk and stability. The 4-inch diameter rocket has the highest capacity for altitude and scalability, with its larger diameter and capacity for more propellant to get us to the Kármán line. With this weighted scoring model, we see the best alternative to be the 3-inch diameter rocket as the primary vehicle for spring launch.

4. Risk Identification and Mitigation

Launching a high-altitude, two-stage hypersonic rocket has inherent safety concerns. The team established a comprehensive risk identification and mitigation strategy for launching a hypersonic rocket's operational and technical aspects. These risks are divided into phases, with Phase I including the meticulous testing of the launch vehicle and subsystems to confirm performance parameters, like static fire tests, testing with the dynamic balancer, optic vacuum chamber tests, and payload stress testing. Phase II is transporting hazardous materials required for the launch, like the propellant and ignitors for the rocket. These risks are addressed through refined SOPs and close supervision by a safety officer, ensuring secure handling of propellant and appropriate transport measures for all components of the launch. For Phase III, launch risks are addressed through refined SOPs, safety briefs, and close supervision by a safety officer, ensuring secure handling of explosives and stability of the launch rail. General safety concerns, such as the risk of falling debris and the potential for injury during launch rail setup, have been categorized as medium risk and are mitigated by clearance of the area, testing of tracking and recovery systems, and Monte Carlo simulations for accurate trajectory prediction. The recovery parachute system has been thoroughly tested, with a fail-safe SPOT Trace tracking device to track the rocket's location on the descent. External risks, like high winds and unexploded ordnance, are also accounted for. Our launch Go/No-go Criteria include restrictions on wind speed, cloud cover, lightning, and visibility.

5. Conclusion

Upon assessing the challenges in the fall launch, the team redefined the bins for the spring launch. The challenges consisted of losing signal with the rocket and the propellant unable to withstand varying temperatures. This declared one rocket unrecoverable and the other to explode mid-flight. The team pursued alternative GPS tracking devices, including a different APRS antenna configuration, and implemented a SPOT Trace Antenna. As for the propellant, the team, in consultation with our stakeholders, selected the Black Knight Propellant due to its impulse and ruggedness. It is currently undergoing static fire tests. The payload was reconfigured to have stronger material, allowing the camera to stay in place during flight. Due to an unrecoverable rocket in the past, the team is implementing a directional parachute to glide the rocket to a predetermined location as an active recovery system. Ultimately, through a robust, iterative systems design thought process focused on improvements and filling additional needs from past years, the team has made significant improvements. The team is edged closer to the fundamental objective of reaching the Kármán line with a two-stage hypersonic rocket. Pending the team's success in the spring launch campaign, SPEAR-THOR will lay a solid foundation for the continuous evolution of the SPEAR program and its contribution to West Point and the Army's aerospace capabilities.

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