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AL AKHAWAYN UNIVERSITY

School of Science and Engineering

Development and Simulation of a Thrust Vector Control (TVC) Landing System for Rocket Descent: A SpaceX-Inspired Approach

Capstone Design Report

23rd April 2024

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Student Statement

"I, Anas El Fali, affirms that ethics were applied throughout the entire design process, including the selection of the most efficient design. I prioritized safeguarding the public and integrated measures to address it into the design whenever feasible."



Anas El Fali

Approved by the Supervisor



Dr. Moulay El Hassan El Azhari

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List of Acronyms and Abbreviations

AUI: Al Akhawayn University in Ifrane

TVC: Thrust Vector Control

VTVL**:** Vertical Takeoff Vertical Landing

SSTO**:** Single Stage to Orbit

SRB: Solid Rocket Boosters

PID: Proportional – Integral – Derivative

K_d: Derivative gain

K_p: Proportional gain

K_i : Integral gain

ABSTRACT (ENGLISH)

This project analyzes the development, modeling, and implementation of a Thrust Vector Control (TVC) system for a controlled rocket descent, taking inspiration from the innovative approaches used by SpaceX. By creating a digital twin of the rocket, it utilizes complex simulation tools to gather and analyze data, guiding the design of the TVC system towards accurate control and enhanced landing precision. The project uses MATLAB Simulink to simulate the descent dynamics and evaluate the performance of the TVC system [1]. Additionally, the project demonstrates the integration of 3D printing technology for component production, highlighting the combination of theoretical advancements and practical implementation in the field of aeronautical engineering. In addition, the project's approach to integrating theoretical concepts with real-world applications is shown via the design and validation of an electrical circuit using Proteus software. The results emphasize the improvement in landing stability and precision achieved by the TVC system, hence highlighting its importance in the advancement of rocket reusability. This study highlights the potential of digital twins and additive manufacturing in enhancing aerospace design and development, representing a significant advancement in the field of cost-efficient space exploration.

Keywords: *Thrust Vector Control, Precision Rocket Landing, Aerospace Control Systems, Space X, 3D Design.*

RESUME (FRENCH)

Ce projet explore le développement, la simulation et la mise en œuvre d'un système de contrôle de la poussée vectorielle (TVC) pour une descente d'une fusée, s'inspirant de SpaceX. La création d'un jumeau numérique du lanceur constitue un outil de simulation essentiel pour recueillir et analyser les données de performance sous diverses conditions, favorisant une approche informée par les données pour la conception du système TVC. Grâce à l'utilisation de MATLAB Simulink, la dynamique de la descente du lanceur et l'efficacité du système TVC sont modélisées pour garantir la précision des mécanismes de contrôle, améliorant ainsi l'exactitude de l'atterrissage. Le projet intègre également des techniques de fabrication modernes, avec la conception des composants du système TVC pour leur production par impression 3D, démontrant la faisabilité pratique du système de contrôle et soulignant l'engagement du projet en faveur de l'innovation et de la durabilité dans le domaine aérospatial. Un circuit électronique pour opérationnaliser le système TVC est conçu et validé à l'aide du logiciel Proteus, comblant le trou entre la conception théorique et l'application réelle. Les résultats de simulation et de mise en œuvre confirment le rôle crucial du système TVC dans l'amélioration de la stabilité et de la précision de l'atterrissage, contribuant de manière significative à la réutilisabilité des composants du lanceur. Ce projet contribue au domaine de l'exploration spatiale rentable et aux progrès de la technologie des fusées, offrant des perspectives sur l'intégration des jumeaux numériques et de la fabrication additive dans le processus de conception et de développement au sein du secteur aérospatial.

Mots clés : *Contrôle de la poussée vectorielle, Atterrissage précis de fusée, Systèmes de contrôle aérospatial, SpaceX, Conception 3D*

1 Introduction

The landing of rockets is a very demanding and critical part of every space flight. At the onset of the space era, rockets were created to be single use only; they would reach the earth's atmosphere, be destroyed or lost in the ocean when completed with their mission. This being a case, however, this option is expensive and sustainable which means that it is slow to take up space exploration and the frequency of missions. Though the usage of reusable rocket technology has affected the aerospace industry in a dramatic way, the industry has already been influenced by this change. Reusable rockets, which can come back to Earth gently, open the way to the era with ever cheaper and more frequent space flights. The cruise to reusable rocketry is the ability to make accurate and complete landings [2].

Thrust vector control (TVC) is a vital part of the strategy to reach this level of accuracy. TVC allows for the real-time adjustment of rocket's thrust direction which leads to making the rocket undesirable motion-free and to maintain the desired trajectory during the descent. Precise guidance and control of the rocket trajectory is not only for safety of the returning rocket, but also for ensuring the landing accuracy. However, through thruster vectors control, it is possible to decrease the negative effects of atmospheric disturbances, gravity anomalies, and other variables which may lead to the landing process failure.

In short, TVC extends the concept of rocket landing from a risky once -off mission to a safe and repeatable one, paving the way to the New Era of space exploration, where rockets become reusable instead of disposable assets [1]. This technology not only allows up to space and space missions but also makes them more reliable and safer. Thus, knowledge of the principles, issues, and developments in Pitch/Yaw/Roll Control are the backbone of the space technology field and the future of space exploration.

2 Problem Statement

The development of reusable launching systems is critical to achieving long-term space exploration and usage. Rockets have traditionally been built as single-use vehicles, resulting in high launch costs owing to the need to manufacture and assemble a new rocket for each mission. This single-use nature of rockets not only raises the expense of space travel, but it also adds to space debris and environmental issues on Earth because of abandoned rocket stages. A key problem in the shift to reusable rocket systems is performing accurate and safe landings under varying atmospheric conditions, various landing surfaces, and the inherent unpredictability of space missions. Thrust Vector Control (TVC) systems provide a solution to this problem by allowing exact modification of the rocket's fall trajectory and orientation [3]. However, designing, implementing, and optimizing TVC systems presents significant engineering challenges, including the need for advanced control algorithms, rugged hardware capable of withstanding extreme conditions, and integration with the rocket's overall design to ensure reliability and safety. Addressing these issues is crucial for improving reusable rocket technology and enabling cost-effective, long-term space exploration.



FIGURE 1:COMPARISON OF DIFFERENT ROCKET WEIGHT PRICES SENT TO SPACE

3 Project Specifications

The Objective of the project is to develop a TVC system using an Arduino Nano and MPU6050 gyroscope for accurate model rocket landings, with design and testing facilitated by Proteus and 3D modeling.

Key Components:

- **Arduino Nano**: Central control for data processing and servo management.
- **MPU6050 Gyroscope**: Measures orientation for trajectory adjustments.
- **Servomotors**: Adjust rocket's X and Y axes for TVC.
- **3D-Printed TVC Mechanism**: Custom-designed for optimized performance.

System Design:

- Utilize Proteus for simulating Arduino's software before physical testing.
- Design a control algorithm based on MPU6050 data to precisely control servomotors.
- Ensure tight integration between hardware components for real-time flight adjustments.

Performance Goals:

- Achieve precise trajectory control and stability.
- Evaluate responsiveness and efficiency under variable conditions.

Constraints:

- Maintain a lightweight, compact design compatible with small-scale rockets.
- Design within the Arduino Nano's power and operational limits.

4 Steeple Analysis

I conducted a STEEPLE study of the capstone project, which focused on constructing a Thrust Vector Control (TVC) Landing System, to investigate the larger ramifications across social, technical, economic, environmental, political, legal, and ethical aspects. This holistic approach sheds light on the project's possible implications and issues in the greater context.

- **Social:**

The project has the potential to change the way people think about space travel and technology. By developing rocket technology, we may inspire a new generation of engineers, and scientists, developing an innovative and curious culture about space and technology. Furthermore, expanded accessibility to space missions may have far-reaching societal ramifications, such as improved global communication networks and educational possibilities.

- **Technological:**

The adoption of the TVC Landing System marks a major technical advancement in aircraft engineering. It not only improves the accuracy of rocket landings, but it also helps to progress aerospace technology by pushing the limits of what is now possible. This breakthrough is critical for building more advanced and dependable space exploration instruments and processes.

- **Economic:**

Economically, the advancement of a more efficient and secure Thrust Vector Control (TVC) Landing System has the potential to bring about significant changes to the cost structure of space missions, indirectly benefiting countries such as Morocco. With the advancements in TVC technology, rocket landings are becoming more precise, and rockets are becoming more reusable. This has the potential to greatly decrease the costs of space launches. This decrease in expenses, specifically the expenses per kilogram of transporting payloads to space, has the potential to make space more accessible to a wider range of countries and organizations. It could open opportunities for more participation in space exploration and satellite deployment. With the adoption of more cost-effective TVC technology, Morocco can significantly reduce the launch costs of its future satellites, thus further enhancing its space capabilities. This affordability would not just enhance Morocco's space capabilities, but also contribute to the country's strategic objectives in telecommunications, environmental monitoring, and national security by leveraging advanced and cost-effective satellite technology. The success of the project in improving the efficiency and security of the TVC system can have significant economic effects, allowing countries like Morocco to utilize space technology for national development and global positioning.

- **Environmental:**

From the perspective of the environment, the TVC Landing System helps favorably by encouraging sustainability in space missions. It reduces the need for new rockets for each launch, lowering the consumption of materials and energy involved with rocket manufacturing. This drop in manufacturing demand reduces the space industry's carbon footprint and resource consumption, which aligns with larger environmental conservation aims.

- **Political:**

Politically, the initiative has the potential to influence national and international policy on space exploration and technological growth. Governments may be urged to increase their investment in aerospace research and development, recognizing the potential economic and

strategic benefits of improved rocket technologies. Furthermore, it may spark talks about international cooperation and regulation of space operations, considering the global advantages of cost reduction and environmental sustainability.

- **Legal:**

The development and deployment of a TVC Landing System may require navigating complicated legal terrain, including compliance with national and international aerospace rules. Legal issues may include safety requirements, intellectual property rights, and export regulations, needing a thorough understanding of the legal framework regulating space technology development and deployment.

- **Ethical:**

This project has no direct Ethical Impact.

This STEEPLE analysis underscores the multifaceted implications of the TVC Landing System capstone project, highlighting its potential to not only advance aerospace technology but also to contribute positively to economic, environmental, social, and ethical objectives.

5 Scheduling (Gantt Chart)

Efficient scheduling is crucial for effective project management. The Gantt chart below offers a clear timeline of tasks, milestones, and dependencies, allowing for strategic planning and progress tracking throughout the project's life cycle.

TABLE 1 :GANTT CHART OF THE PROJECT

Tasks	January		February				March				April				May	
	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2	W 3	W 4	W 1	W 2
Project Proposal and Scope																
Literature Review and Framework																
Initial System Design and Modeling																
Component Selection and 3D Modeling																
Development of Control Algorithms																
Simulink and Proteus Simulations																
3D Component Printing and Testing																
Electronic Circuit Prototyping																
Assembly of 3D Printed Parts																
Integration of Electronic Components																
Initial Testing and Debugging																
PID Tuning and Control System																
Comprehensive System Testing																
Performance Analysis and Adjustments																
Preparation of Final Documentation																
Project Presentation and Submission																

6 Engineering Standards

- **AS9100 - Quality Management Systems - Aerospace Requirements**

AS9100 is a widely recognized standard that establishes specifications for a quality management system in the aerospace sector. It attempts to improve product quality and dependability by ensuring that aerospace projects meet the highest safety, reliability, and quality requirements. This standard covers essential stages in the aerospace product lifecycle, including design, manufacture, testing, and service, and encourages a systematic approach to quality management. AS9100 raises aerospace organizations' operational standards by embracing risk management, design verification, and continuous improvement procedures, encouraging an excellence culture. Compliance with AS9100 not only displays dedication to maintaining high-quality standards, but it also enhances stakeholder trust by assuring adherence to established aerospace-specific regulations [4].

- **IEC 61131-3:2013 - Programmable Controllers - Part 3: Programming Languages**

IEC 61131-3:2013 standardizes programming languages for programmable controllers, providing a complete foundation for the creation of control software. It describes numerous programming languages and structures customized to the demands of industrial automation and control, allowing for the development of more dependable, efficient, and interoperable software. The standard encourages the use of best practices in control system software development, such as structured programming, documentation, and testing procedures. Adoption of IEC 61131-3:2013 improves software compatibility with a variety of hardware platforms and guarantees that control systems are created in accordance with industry standards. This improves software quality, system stability, and performance, all of which are critical for the complex and demanding applications that industrial control systems often handle [5].

7 Logic Model Framework

7.1 Target Population

The target population is a varied group of stakeholders from throughout the world. These include aerospace engineering corporations that specialize in rocketry and space exploration, university institutions that perform cutting-edge research and instruction in aerospace and mechanical engineering, and government agencies committed to space exploration and defense. Furthermore, the initiative connects with technology aficionados and amateur rocketry groups,

broadening its appeal. This extensive interest emphasizes the relevance of TVC systems in improving the capabilities and safety of rocket landings, which are vital to space vehicle reusability and mission sustainability.

Focusing on Morocco, the target audience for a TVC system project reflects the country's growing interest in aerospace and STEM education. Morocco's strategic expenditures in aeronautical infrastructure and education, intended at developing a qualified workforce and encouraging innovation, provide an ideal environment for such sophisticated projects. Morocco's universities, engineering schools, and research institutes are critical players, with the potential for collaborative research and development. Another crucial demographic is the nation's developing aerospace sector, which includes both local and foreign enterprises. They are interested in the practical uses and possible breakthroughs afforded by television technology. This is consistent with Morocco's overarching aims of technical progress and economic diversification, emphasizing the project's importance to the country's development objectives.

7.2 Understanding Assumptions

For my project, I am focused on developing and implementing a Thrust Vector Control (TVC) system for rocket descent. Our strategy and execution are built upon several crucial assumptions. I assume having access to the required engineering tools and resources, including simulation software like MATLAB Simulink and electronic design tools such as Proteus, as well as 3D printing technology for manufacturing TVC components. The success of the project hinges on the support of a robust academic and institutional framework that provides the essential infrastructure, guidance, and potentially, financial aid. Furthermore, it adheres to rigorous engineering standards and practices, especially in the field of aerospace, to ensure that the project upholds the utmost industry quality and safety standards. These assumptions play a vital role in ensuring the organized planning, design, and successful implementation of the TVC system.

7.3 Resources/Challenges

For the successful development of the Thrust Vector Control (TVC) system for rocket descent, the project is supported by crucial resources while navigating through specific challenges:

Resources:

1. **Technical Tools**: Essential tools include advanced simulation software, electronic design platforms, and 3D printing capabilities for prototyping.

2. **Expertise**: Guided by my capstone university supervisor and drawing on the collective knowledge of the mechatronics team, I gained some skills in aerospace engineering, control systems, and software development.
3. **Funding**: Financial resources are allocated for procuring materials, accessing necessary software, and covering prototyping expenses.
4. **Facilities**: The project benefits from access to the university's mechatronics lab, equipped with the necessary tools and space for assembly, testing, and refinement of the TVC system.

Challenges:

1. **Algorithm Complexity**: Developing accurate and reliable control algorithms presents a significant technical challenge, requiring iterative testing and optimization.
2. **Hardware Integration**: Ensuring the electronic components, servomotors, and the TVC mechanism work in harmony poses integration challenges, crucial for real-time system responsiveness.
3. **Reliability and Safety**: The system must consistently perform safely across all tests, necessitating comprehensive evaluations to meet stringent aerospace standards.
4. **Resource Constraints**: While resources are available, efficiently managing them to avoid overextension is critical for maintaining project momentum and quality.

7.4 Outputs of the Project

For the project on developing a TVC system for rocket descent, the expected outputs include:

1. **Functional TVC Prototype**: A working model of the TVC system, designed, and tested to demonstrate precision control over a rocket's descent trajectory.
2. **Simulation Data**: Comprehensive simulation results from MATLAB Simulink, validating the control algorithms and performance under various conditions.
3. **Technical Documentation**: Detailed design documents, including schematics, code, and testing protocols, alongside a project report outlining the development process, challenges encountered, and solutions implemented.
4. **Presentation and Demonstration**: A final presentation to showcase the project findings, supported by a live demonstration or video of the TVC system in action, aimed at academic and potential industry stakeholders.

7.5 Outcomes

Developing a Thrust Vector Control (TVC) system for rocket descent is focused on creating an engineering solution that improves the accuracy of rocket landings. This project has the potential to make a significant impact in the field of aerospace engineering. It offers a comprehensive case study on the practical implementation of cutting-edge control algorithms and mechanical design for effectively managing rocket descent trajectories. As an educational and research tool, it enhances the academic community's knowledge of thrust vector control challenges and solutions, opening doors for more innovation in aerospace technology. In addition, the successful implementation and demonstration of this TVC system are anticipated to serve as a source of inspiration for future advancements in rocketry. This has the potential to enhance the safety, efficiency, and sustainability of space missions, representing a significant milestone in the development of reusable rocket technologies.

8 Literature Review

8.1 Historical Overview of Rocket Landing Technologies

Rockets, a remarkable testament to human ingenuity, serve as a vital catalyst for the progress of space exploration and the successful launch of satellites. Arising from the modest firecrackers of ancient China, rockets have evolved into sophisticated vehicles capable of defying Earth's gravitational force and exploring the limitless expanse of space. The field of rocketry is at the core of these advancements, encompassing the science of designing, building, and launching rocket vehicles [6]. The function of Rocket is rooted in the fundamental principle of Newton's third law of motion, which states that every action results in an equal and opposite reaction. By expelling exhaust gases with great force in a specific direction, the rocket can generate the necessary propulsion to lift off and venture into the boundless realm of space.

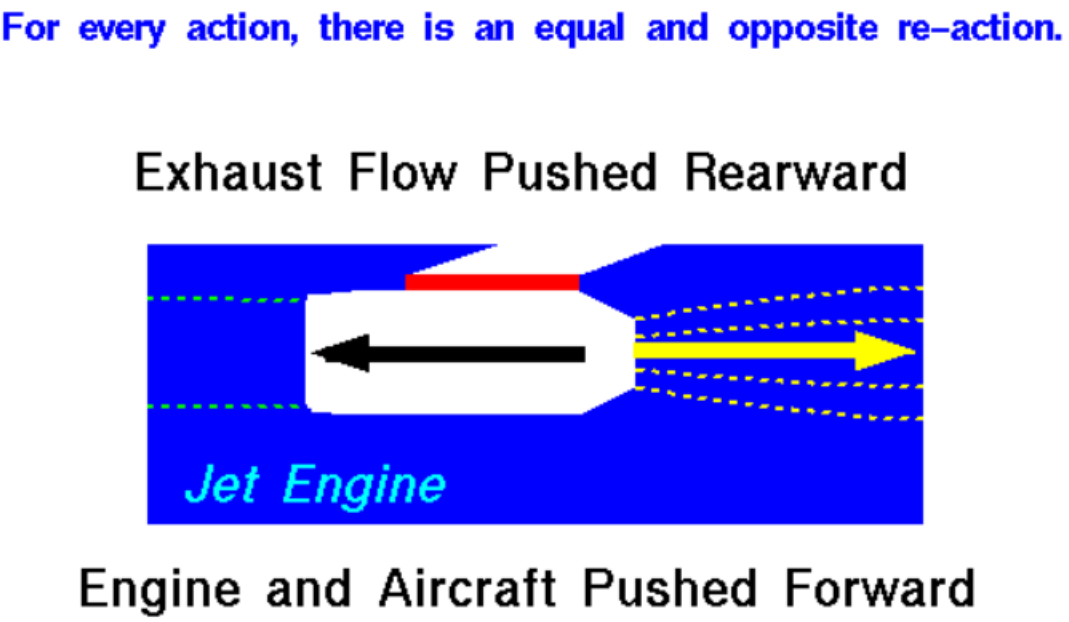


FIGURE 2 :NEWTON'S THIRD LAW APPLIED TO ROCKET JET PROPULSION

The history of rocket landings traces back to the time of uncontrolled descents. Early space missions, such as those launching satellites or exploring beyond Earth's atmosphere, did not prioritize the recovery and reusability of rocket components. These missions usually concluded with rockets and their stages descending into the ocean or onto unpopulated land areas once their fuel was depleted. During that period, the idea of controlled landing was either deemed technologically unfeasible or not given priority, as the main emphasis was on achieving orbit or deep space travel.

TABLE 2 :COST COMPOSITION OF TYPICAL LAUNCH VEHICLES [7]

	First-stage	Second stage
Engine	54.3%	28.6%
Structure	23.5 %	29.5%
Electrical system	8%	27.2%
Valves, cables, pipes, actuators	8.2%	4.9%

The idea of reusability and controlled landings gained significant momentum with the launch of the NASA Space Shuttle program in the 1980s. The Shuttle was designed with a reusable orbiter that safely returned to Earth by gliding and landing on a runway. Additionally, the solid rocket boosters (SRBs) were recovered from the ocean, refurbished, and then reused, showcasing an efficient and sustainable engineering solution. This marked a significant advancement in the

potential for reusing components of launch systems, even though the external tank of the Shuttle was not able to be recovered and reused.

Vertical takeoff, vertical landing (VTVL) vehicles started gaining popularity as technology and control systems improved, allowing for more precise thrust control. Projects and concepts from different space agencies and private companies have delved into the possibilities of VTVL to achieve complete reusability of rocket stages.

- **DC-X**: The Delta Clipper Experimental (DC-X) was a prototype of a reusable single-stage-to-orbit (SSTO) vehicle. The DC-X, developed by McDonnell Douglas for the U.S. Department of Defense, successfully performed short vertical takeoff and landing flights during the mid-1990s. These flights showcased the promising capabilities of VTVL technology [8].



FIGURE 3 :DC-X VTVL ROCKET

- **SpaceX's Grasshopper and Falcon 9**: SpaceX's development of the Grasshopper test vehicle and subsequent successful vertical landings of the Falcon 9 first stages marked a turning point in the operational reusability of rocket components. The first successful vertical landing of a Falcon 9 first stage on solid ground occurred in December 2015, followed by the first successful landing on a drone ship in April 2016. These achievements demonstrated the feasibility and efficiency of reusing rocket stages, significantly impacting the economics of space launches [2],[9].



FIGURE 4 :GRASSHOPPER ROCKET (LEFT) AND FALCON 9 ROCKET (RIGHT)

- **Blue Origin's New Shepard**: Another notable milestone was achieved by Blue Origin with its New Shepard suborbital rocket, which successfully performed a vertical landing after a suborbital flight. This achievement further underscored the viability of reusable rocket technologies for a range of space missions [10].



FIGURE 5 :NEW SHEPARD LANDING ROCKET

Today, the progress in rocket landing technologies, especially with the development of Thrust Vector Control (TVC) systems, flexible nozzle joints, and innovative materials, is still transforming space travel. There has been a shift in focus towards improving the efficiency, reliability, and turnaround time of reusable rockets, with the goal of enabling future missions, such as manned trips to Mars and beyond. This ongoing progress highlights a future where space exploration becomes more sustainable, cost-effective, and frequent, thanks to the continuous drive for improvements in rocket landing technologies.

8.2 Thrust Vector Control (TVC)

Thrust Vector Control (TVC) is a crucial technology in rocketry that allows for precise control of a rocket's flight path and orientation by manipulating its propulsion direction. This advanced control system is crucial for guiding rockets during their journey into space and for achieving accurate landings, which is essential for the reusability of rocket stages.

8.3 TVC Mechanism

Thrust Vector Control (TVC) plays a crucial role in rocketry, allowing engineers to manipulate the direction of the engine's thrust to control the rocket's orientation and trajectory while it's in flight. Basically, TVC allows for the precise control of a rocket's steering by adjusting the direction of the thrust force. Ensuring the rocket stays on its intended path and keeping the engine's thrust aligned along the Z-axis of the vehicle are crucial functions of TVC. Proper alignment plays a vital role in ensuring smooth vertical ascents and accurate landings, enabling the rocket to stay on course and follow its intended path with precision. With the ability to manipulate the thrust vector, TVC systems effectively counteract undesired rotational movements and deviations, maintaining the rocket's stability and proper orientation throughout its mission. This feature not only boosts the safety and dependability of rocket flights but also greatly enhances the efficiency of reaching desired orbits or landing sites [1].

8.4 TVC Mechanism Types

Examining the various Thrust Vector Control (TVC) mechanisms uncovers a wide array of inventive solutions aimed at precisely maneuvering rockets. Each mechanism employs a distinct method to effectively adjust the direction of thrust for optimal control during flight [11].

8.4.1 Gimbal or Hinge

The gimbal or hinge mechanism in TVC systems enables the rocket engine or exhaust nozzle to pivot around one or more axes. This motion controls the direction of the thrust vector, which in turn determines the rocket's orientation and trajectory. Utilizing hydraulic, electric, or pneumatic systems, gimbaling offers precise control over the rocket's flight trajectory, making it a commonly employed TVC method in spacecraft and missiles.

8.4.2 Flexible Laminated Bearing

Flexible Laminated Bearing TVC utilizes layers of flexible material that can be manipulated to change the direction of the engine's thrust in a controlled manner. This approach provides a

more streamlined and potentially lighter option compared to mechanical gimbals, resulting in fewer moving parts, and therefore enhancing reliability. With the laminated structure's flexibility, precise adjustments can be made to the thrust vectoring, enabling meticulous fine-tuning of the rocket's orientation.

8.4.3 Flexible Nozzle Joint

Flexible nozzle joint TVC system incorporates a nozzle with the ability to flex, bend, or deform to alter the direction of the exhaust flow. This flexibility is usually achieved using innovative materials or engineering designs that enable the nozzle to tilt without relying on conventional gimbaling mechanisms. This kind of TVC has its benefits in terms of its simplicity and the decreased complexity in the thrust vectoring system.

8.4.4 Jet Vanes

Jet vanes are strategically placed within the exhaust flow of the rocket engine to precisely redirect the thrust. Constructed with durable materials, these vanes are designed to endure the high temperatures of the exhaust gases. Jet vanes offer a reliable and efficient way to manipulate the rocket's flight path, particularly valuable in solid rocket motors where the engine's orientation cannot be adjusted.

8.4.5 Jetavator

Jetavators function similarly to jet vanes, but they are usually larger control surfaces positioned within or at the exit of the rocket nozzle. They can pivot and redirect the exhaust flow, providing an alternative means of thrust vectoring. Jetavators are commonly employed in scenarios that require significant alterations to the exhaust flow to maintain control over the vehicle.

8.4.6 Jet Tabs

Jet tabs are compact surfaces that can be deployed within the exhaust flow of a rocket engine. Through their extension into the flow, these tabs generate a pressure differential that directs the thrust. This method is straightforward and cost-effective, offering a way to make small changes to the trajectory without the need for major modifications to the engine or nozzle design.

8.4.7 Side Injection

Side Injection TVC operates by introducing fluid, such as fuel or another propellant, into the exhaust flow at the nozzle's periphery. This injection modifies the flow's direction, resulting in an imbalance that directs the thrust. Side injection allows for precise control and real-time

adjustments, providing a flexible method of thrust vectoring without the need for moving mechanical components.

8.4.8 Small Control Thrust Chambers

This TVC method utilizes extra small thrust chambers positioned around the primary engine or along the rocket's structure. These auxiliary engines have the capability to be controlled separately, allowing for the generation of thrust in various directions, which in turn enables the maneuvering of the main vehicle. Compact control thrust chambers provide precise maneuverability, proving especially valuable for space maneuvers where conventional aerodynamic surfaces lack effectiveness.

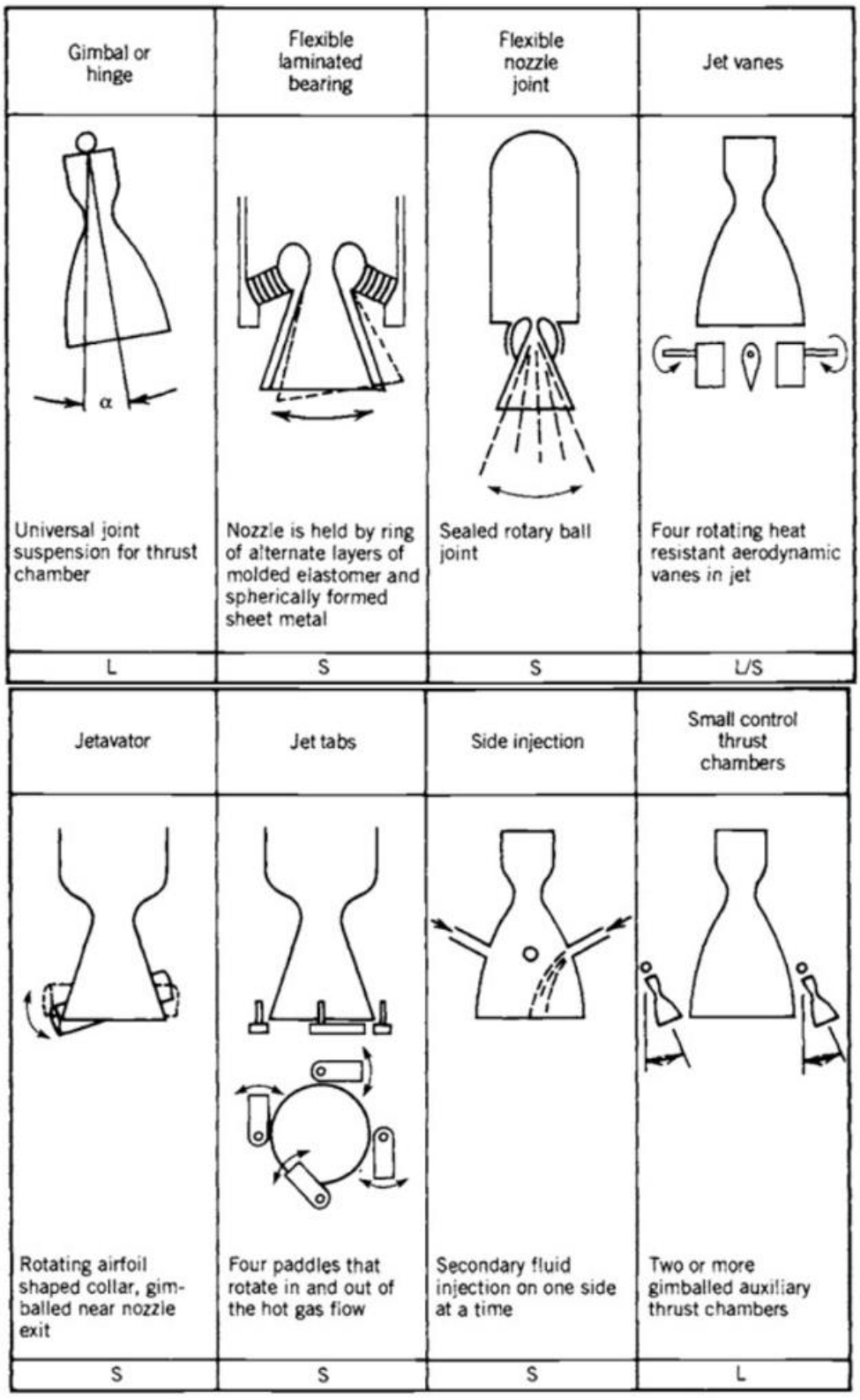


FIGURE 6 :TVC SYSTEM DIFFERENT MECHANISMS [11]

TABLE 3 :COMPARISON BETWEEN DIFFERENT TVC MECHANISMS

TVC Mechanism	Advantages	Disadvantages
Gimbal or Hinge	• Direct and precise control over rocket's orientation • Well-understood technology	• Mechanical complexity • Increased weight and potential for wear and tear
Flexible Laminated Bearing	• Reduced number of moving parts • Potential for lighter system	• Limited range of motion • May not provide the precision control needed for all maneuvers
Flexible Nozzle Joint	• Simplifies nozzle design. • Can reduce Mechanical complexity	• Durability concerns under high temperatures • Precision may vary with material properties
Jet Vanes	• Simple to implement. • Effective for solid rockets	• High thermal stress • Can reduce engine efficiency due to flow obstruction
Jetavator	• Good for large modifications in thrust vector • Robust control in specific scenarios	• Adds complexity and weight. • Similar thermal challenges as jet vanes
Jet Tabs	• Low cost • Minimal modifications to engine required	• Limited control capability • Potential for increased drag and reduced efficiency
Side Injection	• Fine control over thrust vector • No moving parts required	• Requires additional propellant or fluid. • Complexity in fluid dynamics control
Small Control Thrust Chambers	• High degree of maneuverability • Effective in vacuum	• Additional weight from extra thrusters. • Complexity in coordination and fuel usage.

Based on a thorough comparison and analysis of various Thrust Vector Control (TVC) mechanisms outlined in the provided table, I have concluded that the "Gimbal or Hinge" option is the most suitable choice for implementation in my project. Despite its mechanical complexity and potential for increased weight, the precise control it offers over the rocket's orientation makes it a well-understood and reliable technology. Its direct influence on the rocket's orientation aligns perfectly with the project's need for meticulous control, outweighing the disadvantages such as potential wear and tear. The gimbal system's established use in aerospace further assures that the

complexities are manageable and the benefits substantial, thus affirming its selection as the optimal TVC mechanism for my application.

8.5. PID Controller

The PID controller is a commonly employed feedback loop mechanism in control systems, such as in aerospace engineering for rocket flight [13]. There are three distinct constants that make up this.

- **Proportional (P):** This component generates an output that is directly related to the current error value, which is the difference between a desired setpoint and the current state. This could assist in adjusting the rocket's trajectory if it veers off course.
- **Integral (I):** This component integrates the error over time and adjusts for past errors, effectively eliminating any steady-state errors. In rocket control, this would account for systematic biases such as consistent drift caused by imbalanced thrust.
- **Derivative (D):** This segment responds to the rate of change of the error, resulting in a dampening effect that minimizes overshooting and enhances stability. For rockets, it could help optimize adjustments to ensure stability during maneuvers.

In the realm of rocketry, PID controllers play a crucial role in ensuring consistent flight and accurate maneuverability of the rocket. They are utilized to fine-tune the thrust vectoring, which in turn affects the pitch, roll, and yaw of the rocket to guarantee it adheres to the intended ascent profile or descent path for landings. The success of PID control in rocketry stems from its remarkable capability to handle intricate flight dynamics and promptly respond to external disruptions and internal system variations, thereby playing a crucial role in ensuring mission success.

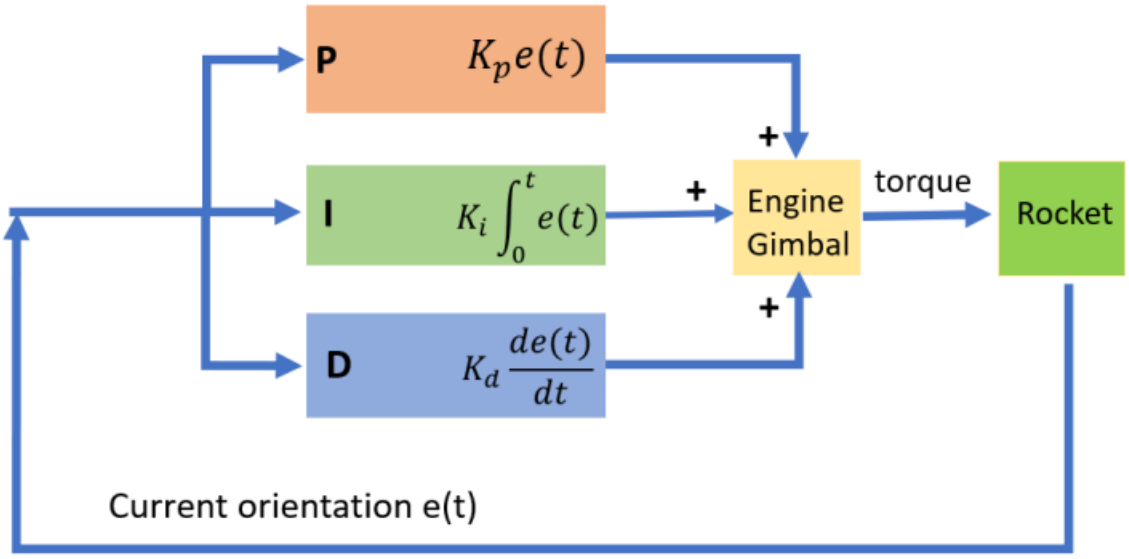


FIGURE 7 :PID CONTROLLER FOR A ROCKET [13]

8.6. Rocket Concepts

Exploring the intricate mechanics of rocketry involves understanding several key concepts that are essential to the design and navigation of these sophisticated vehicles [13]. Here's an overview of some fundamental terms:

- **Gimbal**: A gimbal in rocketry is a pivoting support that allows the rotation of an object about a single axis. In the context of rocket engines, gimballing refers to the method of steering a rocket by altering the direction of its engine thrust. This can be achieved by tilting (gimballing) the engine itself or the exhaust nozzle.
- **Pitch Angle**: This is the angle that measures the orientation of the rocket's nose relative to the horizon. It is one of the attitude angles, which also include roll and yaw. Controlling the pitch angle is essential for directing the rocket's trajectory both during ascent and descent.
- **Angle of Attack**: The angle of attack is the angle between the oncoming air or relative wind and a reference line on the rocket or aircraft, typically the chord line of the wing. For rockets, this concept is most relevant during atmospheric flight and affects aerodynamic forces and stability.
- **Moment of Inertia of the TVC**: The moment of inertia for a Thrust Vector Control (TVC) system refers to the distribution of mass and its distance from the pivot point (gimbal axis),

which affects how much torque is needed for a given angular acceleration. This plays a critical role in how effectively and quickly the TVC can adjust the rocket's thrust vector.

- **Gimbal Deflection Angle**: This is the angle to which the engine or nozzle is tilted from its usual, straight-line position. It determines the direction and magnitude of the thrust vectoring, affecting the rocket's trajectory.
- **The Gimbaled Thrust**: This is the thrust generated by a rocket engine that can be directed via gimballing. The direction of the thrust can be altered, allowing for control over the vehicle's flight path without relying on aerodynamic surfaces.
- **Ungimbaled Sustainer Thrust**: This refers to the continuous thrust produced by a rocket engine that does not have gimballing capabilities. Such thrust is typically aligned with the rocket's central axis, and directional control must be provided by other means, such as aerodynamic fins or secondary thrusters.

9 Methodology

For the development and implementation of a Thrust Vector Control (TVC) system for precision rocket landing, a structured methodology will be followed. This methodology includes initial research, design and simulation, prototype development, testing, and final analysis. This approach guarantees a methodical progression from idea generation to implementation, highlighting creativity, dependability, and practicality.

a) Literature Review and Conceptualization

I will start by conducting an extensive literature review to gain a comprehensive understanding of the current technologies used in thrust vector control (TVC), with a specific focus on their applications in controlling rocket descent. This phase will assist in identifying any deficiencies in current systems and potential areas for creative improvement. After analyzing this review, I will develop a plan for the TVC system, highlighting important goals, factors to consider in the design, and anticipated results.

b) Design and Simulation

Using MATLAB Simulink, I will create the control algorithms that are essential to the TVC system. This will require the modeling of the rocket's dynamics and analyzing the response of the TVC in different descent scenarios. I will utilize 3D design software to create the mechanical components of the TVC system, guaranteeing their compatibility with the control algorithms.

Proteus software will be used to design and test the electronic circuitry required for operating the servomotors and sensors.

c) Prototype Development

After completing the design phase, I will proceed with the development of the prototype. This involves utilizing 3D printing to create the necessary components for the TVC mechanism and then putting together the electronic control system with an Arduino Nano and an MPU6050 gyroscope. I will ensure seamless integration between the hardware and software, allowing for effective communication between the control algorithms and the mechanical system.

d) Testing and Optimization

The prototype will be subjected to extensive testing to assess its ability to control the descent trajectory of a rocket. This will involve a combination of simulated environments and controlled physical tests to evaluate stability, responsiveness, and precision. The feedback obtained from these tests will be utilized to enhance and streamline the system, with a specific emphasis on enhancing efficiency, reliability, and safety.

e) Analysis and Documentation

Finally, I will carefully examine the testing results and compare them to the project's objectives to assess the effectiveness of the TVC system. This analysis will be documented in a detailed project report, which will cover the design process, challenges faced, solutions devised, and suggestions for future research. A presentation of the project findings will be prepared to share the results with academic and industry stakeholders.

10. Capstone Design & Approaches/ Model/ Algorithm/ Application Development

10.1. Software

The integration of MATLAB, Simulink, Proteus, and SolidWorks is essential for the comprehensive development of the Thrust Vector Control (TVC) system.

- **MATLAB Simulink:** Is used to simulate the TVC system and rocket descent dynamics, enabling the precise adjustment of control algorithms for accurate trajectory control. The graphical interface makes it easy to model intricate systems and observe their behavior in different scenarios.
- **Proteus:** Plays a crucial role in the electronic design aspect, facilitating the schematic capture and simulation of the control circuitry that operates the TVC mechanism. It assists in confirming the functionality of electronic components prior to progressing to the

prototyping phase, guaranteeing that the electrical design of the system is reliable and effective.

- **SolidWorks:** Assists in the mechanical design process, utilized for the creation of intricate 3D models of the TVC mechanism and other structural components. It enables material selection, stress analysis, and the creation of models for 3D printing, ensuring the physical design's integrity and manufacturability.
- **Microchip Studio**: playing a crucial role in the development and simulation process of control systems, serving as the pivotal tool for compiling code into a hex file, which is essential for executing simulations in Proteus and validating the system's performance.
- **Fritzing**: virtually prototyping the electrical wiring, allowing for a clear and accurate representation of the connections before the physical assembly of the prototype's control system.

10.2. TVC Design

The concept of gimballed thrust vector control (TVC) was influenced by numerous projects that employed different approaches. After careful evaluation, the chosen design features moveable axes on the side of the engine tube, allowing for precise control over the X and Y axes. The system was selected due to its demonstrated proficiency in rocket control, as evidenced by numerous successful implementations. This reliable mechanism was chosen because of its established history of high performance [14].

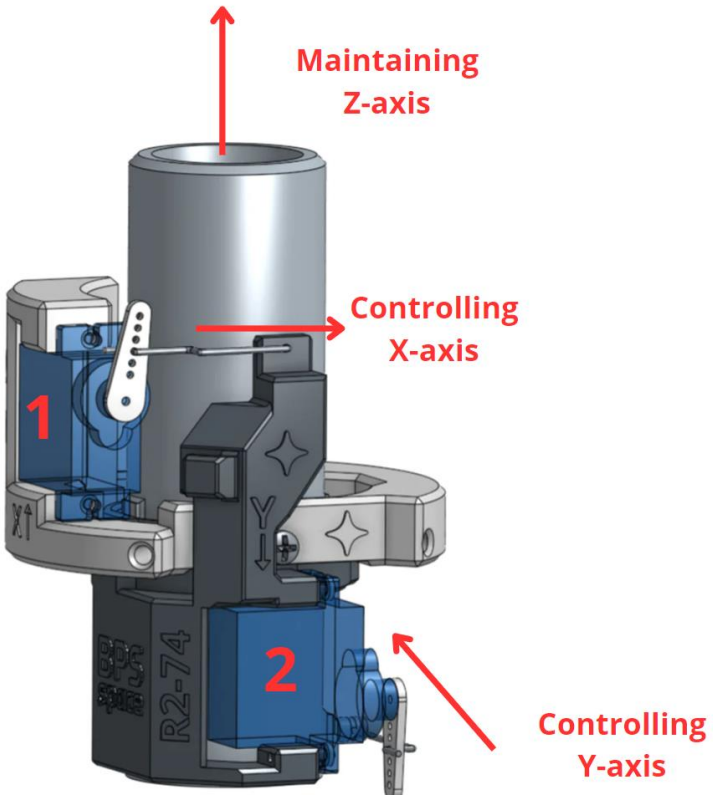


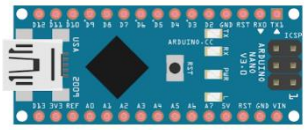
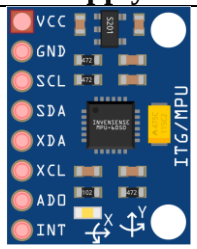
FIGURE 8 :MECHANISM USED FOR THE TVC SYSTEM [14]

The system is designed in a way that Servomotor 1 takes care of controlling the X-axis, guaranteeing accurate movement along this axis. On the other hand, Servomotor 2 is responsible for managing the Y-axis to achieve the same level of precision. The synchronized operation of these two servomotors is crucial for preserving the alignment of the engine tube. This setup is designed to maintain the engine tube's alignment along the Z-axis, ensuring precise balance and optimal positioning throughout all movements. This arrangement is essential for ensuring the smooth and efficient functioning of the mechanism, guaranteeing stability and accuracy in its operations.

10.3. Electronic Components

In this part, I will explain the objective of each material in the project, with a specific emphasis on their contribution to the operational capabilities of the prototype. Each material choice is justified based on its function in assuring the successful performance of the TVC system throughout testing and demonstration stages, from the stiffness needed to preserve structural integrity to the accuracy needed for moving elements. The meticulous evaluation of materials highlights the project's commitment to developing a durable and efficient prototype.

TABLE 4 :MATERIALS AND THEIR FUNCTIONAL ROLES IN THE TVC SYSTEM PROTOTYPE

Electronics Components	Purpose in the Project	
 **Servomotors SG90**	**X-axis control**	This component is tasked with the critical function of maneuvering the TVC mechanism along the X-axis. Its precise movements are fundamental for altering the rocket's flight path and orientation, allowing for adjustments that are essential during both ascent and controlled descent to achieve a targeted landing trajectory.
	Y-axis control	Responsible for the TVC mechanism's movements along the Y-axis, this servomotor is key to maintaining and correcting the rocket's vertical alignment. It ensures the stability and balance of the rocket by making real-time adjustments, contributing significantly to the precise control necessary for a successful landing sequence.
 **Arduino Nano**	The compact yet powerful Arduino Nano serves as the project's microcontroller, orchestrating the entire control system. It processes input data from sensors, computes control commands, and sends signals to actuate the servomotors. Its role is central to the decision-making loop that underpins the TVC system's responsive and accurate performance.	
 **MB102 Breadboard Power Supply**	The MB102 unit provides a reliable power source for the electronic components during the prototyping stage. It ensures that the breadboard setup receives a consistent voltage, which is crucial for preventing malfunctions and ensuring that all parts operate within their specified parameters, ultimately contributing to the overall reliability of the control system.	
 **MPU6050 Gyroscope & Accelerometer**	This sensor module feeds crucial information on the rocket's spatial orientation and accelerative forces to the control system. By accurately tracking pitch, roll, and yaw, along with linear movements, the MPU6050 enables the control algorithms to make informed and precise adjustments to the TVC servomotors, directly impacting the system's ability to maintain the intended flight path.	

10.4. 3D Design Modeling

10.4.1. SolidWorks Design

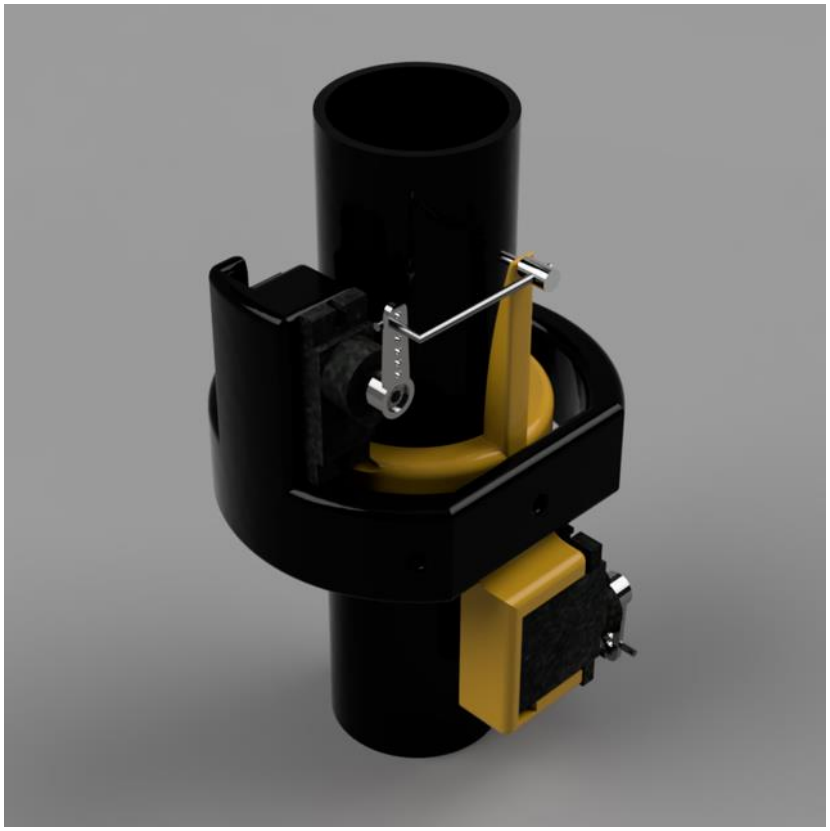


FIGURE 9 :SOLIDWORKS DESIGN

10.4.2. SolidWorks Parts

The 3D-printed components of the Thrust Vector Control (TVC) system had a substantial enhancement from Version 1 to Version 2 throughout the progression of my project. The original design consisted of several distinct components, each adding to the intricacy of assembly and possible vulnerabilities. Acknowledging the need for optimization, a reassessment of the design was conducted, resulting in the creation of Version 2. The updated version is a more efficient assembly consisting of just three primary components, which improves the system's durability and simplifies the building procedure. In addition to expediting the assembly time, the decrease in components also enhances the overall structural integrity of the TVC system. The improved design of Version 2 exemplifies the project's dedication to ongoing improvement and effectiveness, including a refined and pragmatic strategy for attaining the intended functionality of the TVC mechanism.

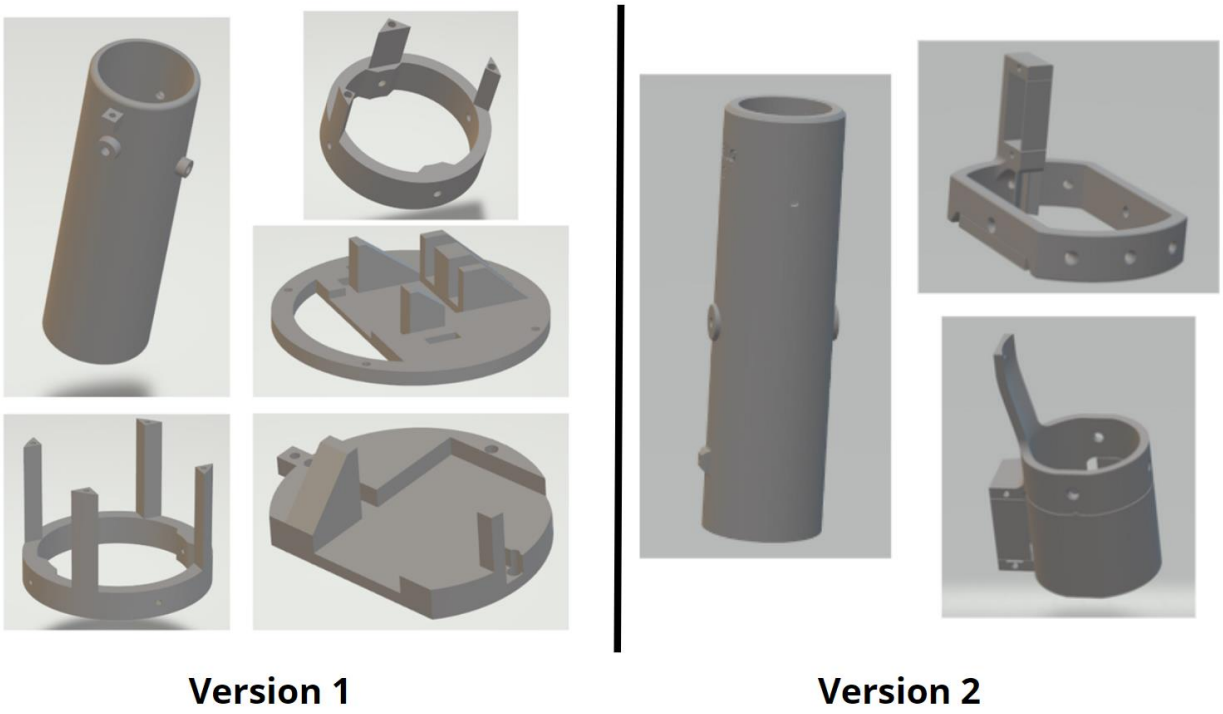


FIGURE 10 :DIFFERENT PARTS OF TVC 3D DESIGN OF DIFFERENT VERSION

10.4.3. Manufactured Parts

The SolidWorks drawings pertaining to the Thrust Vector Control (TVC) system provide a comprehensive and intricate depiction of the design of each individual component. These crucial visual representations serve to connect the divide between abstract ideas and their actual implementation, delineating the exact measurements and assembly prerequisites. By examining these illustrations, we have a deeper understanding of the meticulous engineering that forms the foundation of the system's operation, guaranteeing that every component is optimized for both efficiency and production feasibility.

Figure 11 illustrates a manufacturing component responsible for controlling the X-axis motion inside a Thrust Vector Control system. The design has meticulous cuts and mounting holes, which serve to indicate the interfaces with other components for control purposes. Additionally, the top of the design provides guidance on the proper insertion of the servomotor and ensures accurate articulation along the X-axis. The construction of this section is designed to maximize stability and ensure accurate movement, which is crucial for the proper functioning of the TVC system.

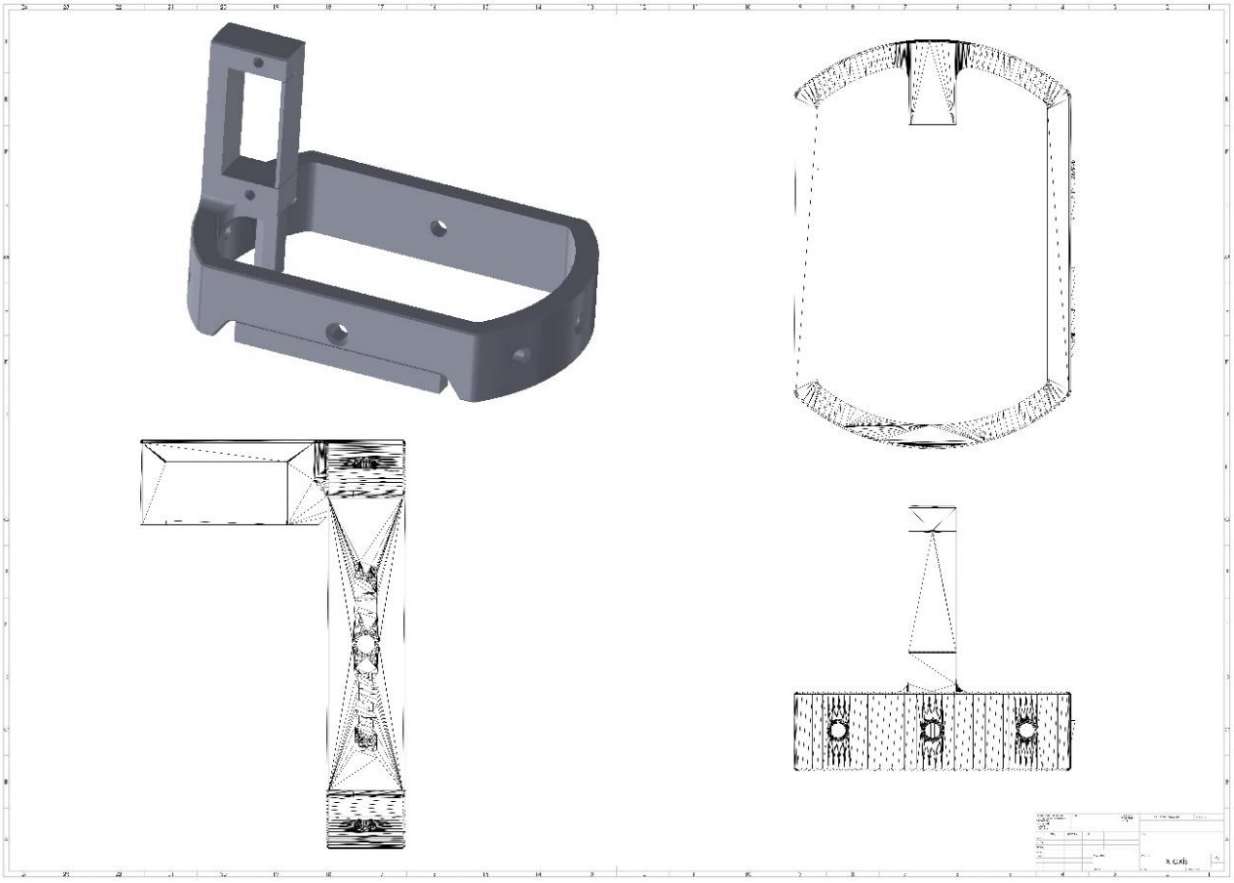


FIGURE 11 :MANUFACTURED DRAWING OF THE PART CONTROLLING X-AXIS

Figure 12 displays a manufacturing design that highlights a crucial component used for controlling the Y-axis in the Thrust Vector Control system. The design has precise cuts for assembly and specific parts for integrating servo motors, which are crucial for achieving precise placement along the Y-axis. The component's sturdy design is specifically designed for reliable operation, guaranteeing accurate and consistent control that is essential for the performance of the TVC system.

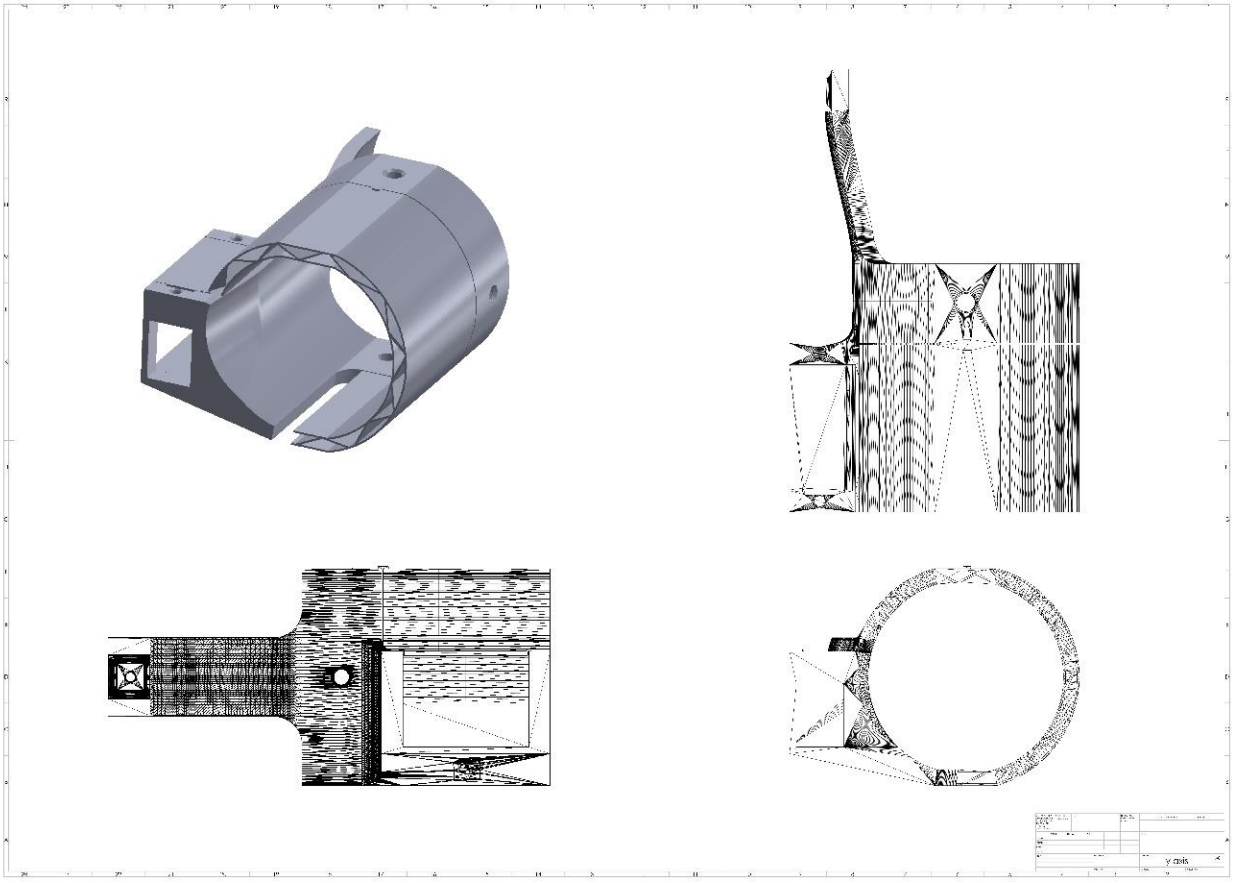


FIGURE 12 :MANUFACTURED DRAWING OF THE PART CONTROLLING Y-AXIS

Figure 13 depicts the engine tube of the Thrust Vector Control system, which serves as a core component for mounting other elements. Its primary function is to guarantee the proper assembly of the TVC mechanism, hence ensuring the alignment of the whole system along the Z-axis. The stability and integration of the TVC system, which allows precise control throughout rocket flight, heavily rely on the tube's design, which includes specialized mount locations and structural reinforcements.

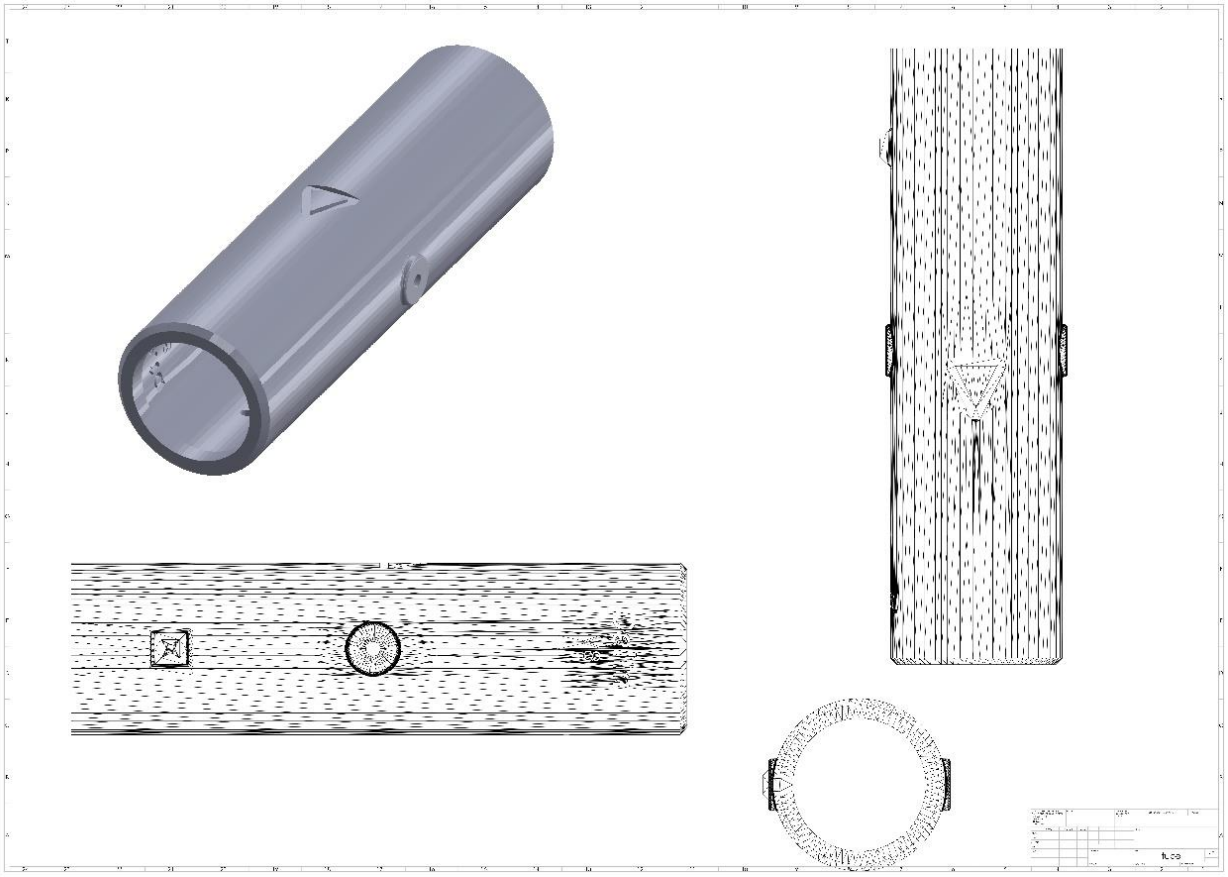


FIGURE 13 :MANUFACTURED DRAWING OF THE ROCKET TUBE ENGINE

11. Feasibility Study

A feasibility study critically assesses the viability of a proposed project, examining technical, economic, and operational factors to ensure its practicality and potential for success.

a. Technical Feasibility:

- Assessing the capabilities of the current technology used in TVC systems.
- Evaluating the design, simulation tools (MATLAB Simulink, Proteus, SolidWorks), and the integration of electronic components for practicality and functionality.
- Determining the capability of 3D print components and ensuring they meet the required specifications for a controlled descent.

b. Economic Viability:

- Estimating the cost of developing the TVC system, including materials, software licenses, and potential manufacturing.

- Analyzing the cost savings that the TVC system could offer in terms of rocket reusability and reduction in new manufacturing needs.
- Exploring potential funding sources or partnerships for development and testing.

c. Market Readiness:

- Identifying the demand for such technology in the aerospace industry.
- Understanding the competitive landscape and potential for commercialization.
- Considering intellectual property issues and the potential for patenting the developed system.

d. Operational Sustainability:

- Checking the compatibility of the system with existing rocket designs.
- Looking at the reliability and safety measures of the TVC system through extensive testing and optimization.
- Considering the environmental impact, such as reducing space debris through the reusability of rockets.

e. Regulatory Compliance:

- Ensuring that the system complies with aerospace regulations and standards such as AS9100 and IEC 61131-3:2013.

f. Risk Assessment:

- Identifying potential risks associated with the project, including technical challenges, budget constraints, and project timeline delays.
- Developing mitigation strategies for each identified risk.

g. Project Management and Scheduling:

- Reviewing the project's Gantt chart for realistic scheduling and milestone tracking.
- Ensuring there are contingency plans for any delays or unforeseen issues.

12. Data Presentation

To effectively design and implement a Thrust Vector Control (TVC) system for rocket descent, a foundational understanding of the project's initial conditions and parameters is crucial. The following initial data points serve as the cornerstone for the development and testing phases, offering a snapshot of the conditions under which the TVC system must operate and be optimized.

- **Initial Rocket Angle**: Starting at a 45-degree angle sets a challenging objective for the TVC system to realign the rocket to a vertical (0-degree) orientation for landing.
- **Final Setpoint (Target Angle)**: Achieving a target angle of 0 degrees is critical for a successful vertical landing.
- **Distance between Center of Mass and TVC Pivot**: At 0.25 meters, this distance impacts the leverage effect of the TVC system on the rocket's orientation.
- **Moment of Inertia**: The moment of inertia, at 0.048 kg*m^2, plays a significant role in how the rocket will respond to adjustments made by the TVC system.
- **TVC Angle Range**: A range of ±5 degrees allow for precise adjustments while maintaining the system's effectiveness and responsiveness.
- **Max TVC Degrees per Second**: The capability to adjust up to 300 degrees per second ensures rapid response to trajectory corrections.
- **Servo Delay**: A minimal servo delay of 0.01 seconds is crucial for real-time control and adjustments.
- **TVC Noise Amplitude**: Simulating TVC linkage flex effects with a noise amplitude of 0.1 degrees adds realism to the control challenges.
- **Angle Sensor Noise Amplitude**: Considering a noise amplitude of 0.5 degrees in angle measurements necessitates robust filtering techniques for accuracy.
- **Angle Sensor Bias**: An assumed bias of 0 degrees in angle sensing underscores the importance of calibration for precise control.
- **Constant Thrust & Thrust Curve Data**: These parameters define the propulsion forces acting on the rocket, with detailed thrust curve data from launch to burnout informing the dynamic conditions the TVC system must navigate.

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This initial data provides a comprehensive overview of the mechanical and operational context within which the TVC system will function. It forms the basis for all subsequent modeling, simulation, and design decisions, ensuring that the system is robust, responsive, and capable of meeting the project's ambitious goals.

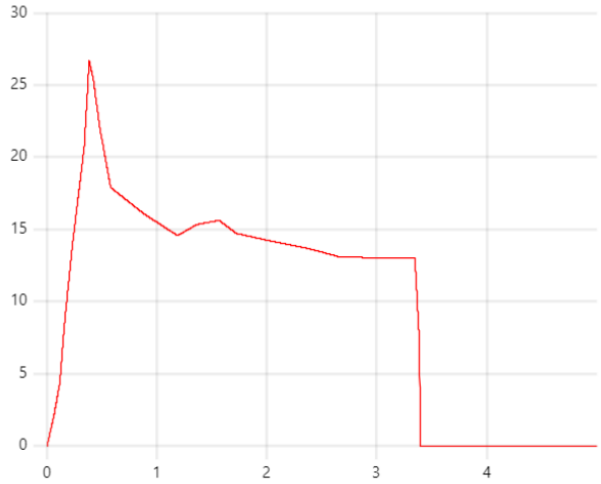


FIGURE 14 :GRAPH OF THRUST VS TIME [MIN] (LANDING PHASE)

The thrust profile shown in Figure 14 illustrates the trajectory of the rocket throughout its landing phase. It starts with a substantial thrust level to facilitate deceleration, thereafter transitions to a rapid decrease in thrust to sustain descent, and culminates in a cut-off moment immediately before touchdown, aiming to achieve a smooth landing. The observed pattern demonstrates the regulated throttle modifications that are essential for achieving a precise and secure vertical rocket landing.

13. Simulation, Results & Interpretation

13.1. Control System Design Simulink Simulation

In this section, I embark on an extensive simulation to model a complete rocket launch and landing sequence. This stage is initiated by defining a set of initial conditions crucial for the accuracy of the simulation, the data is the coming from the SpaceX Falcon 9 data sheet document [15]. These conditions encompass the mass flow rate $\dot{m} = 132,46 \frac{Kg}{s}$, which affects the rocket's thrust; burn time $t_{burn} = 169\,s$, which dictates the duration of powered flight; payload $m_{payload} = 5000\,Kg$ and dry $m_{dry} = 1360,7\,Kg$ mass, which determine the overall mass profile; and landing touchdown speed $v_{touchdown} = 150 \frac{m}{s}$, a critical parameter for a safe landing. Additionally, the simulation considers the initial velocity $v_0 = 0.01\,m/s$, the maximum speed $v_{max} = 940\,m/s$ attained during ascent, and the time allocated for the landing phase. These initial conditions serve as the foundational parameters that will be fine-tuned within

Simulink to realistically simulate the rocket's behavior from takeoff to touchdown, ensuring that the control systems are tested under conditions that mirror an actual launch scenario[15].

The hole Control System Design is in Appendix B.

13.1.1. Control System Functions Roles

The simulation relies on three essential functions: pitch command, thrust, and drag, which play a critical role in determining the flight dynamics of the rocket. The thrust function, which is determined by the rate of mass flow, plays a crucial role in propelling the rocket's upward and downward movement. The drag function computes the aerodynamic resistance by considering the variables of altitude and speed, a crucial factor in the landing phase. The pitch command function is responsible for modifying the rocket's angle by using height and thrust data, ensuring that it adheres to the specified trajectory throughout both takeoff and landing. The combination of these operations collectively guarantees the rocket's operation with a high degree of accuracy throughout its flight.

- **Thrust function:** The thrust function inside the Simulink model, as seen in the accompanying graphic and specified in the MATLAB code, computes the thrust output (T) of the rocket engine during the simulation period, while simultaneously considering the dynamics of fuel consumption.

Persistent Variables: **mfb** and **mfb2** are persistent variables that retain their values across function calls. They are used to track the cumulative mass of fuel burned during the rocket's flight. Fuel Initialization: The total mass of the initial fuel (**mfuel**) is set at the start of the simulation.

Thrust Calculation: When the mass of burned fuel (**mfb**) is less than or equal to 65% of the initial fuel mass, full thrust (**THR**) is generated. The mfb is updated based on time (**t**) and mass flow rate (**m_dot**), which is the rate at which fuel is consumed. If more than 65% of fuel is burned, the thrust is set to zero, indicating the end of the main engine burn phase.

Secondary Thrust Phase: Between specific times (125 to 295 seconds), the function simulates a secondary thrust phase, perhaps a controlled reduction in thrust for descent, indicated by a negative thrust value. During this phase, mfb2 tracks additional fuel consumption at a different rate (**one-third of m_dot**), starting from the moment this phase begins at 125 seconds.

Output Variables: The function outputs the current thrust (**T**), the remaining fuel mass (**m_fuel**), and the fuel burned for the main (**m_fb**) and secondary (**m_fb2**) thrust phases.

The thrust function serves as a mathematical representation of the engine's propelling capabilities, considering the gradual exhaustion of fuel during the duration of the flight. The simulation encompasses the main propulsion phase associated with takeoff and ascension, as well as any subsequent thrust modifications required for landing or maneuvering. The Simulink model utilizes the results obtained by this function to replicate the mechanics of the rocket by manipulating its speed and path, so enabling the assessment of the overall design of the control system.

The code of this function is in Appendix C.

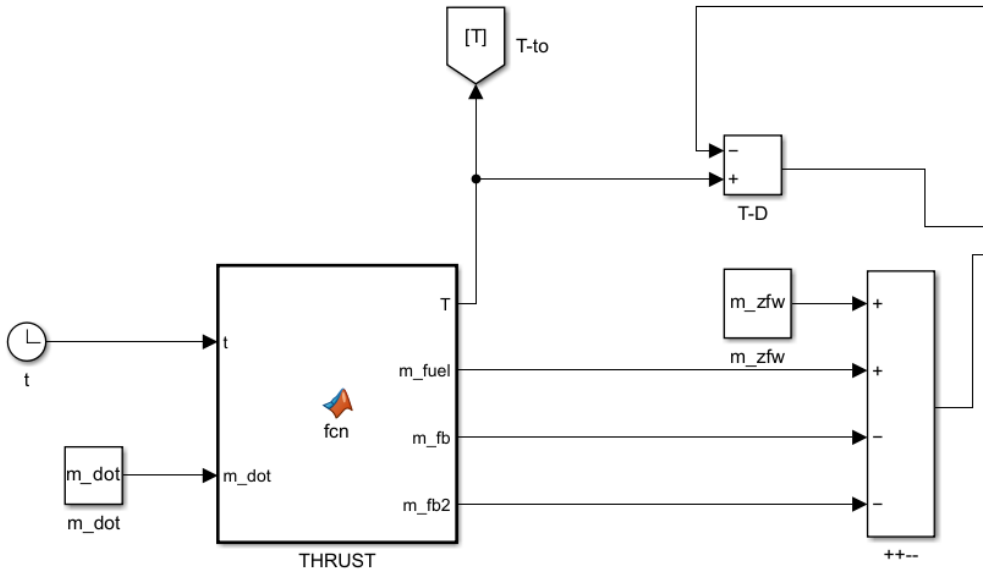


FIGURE 15 :SIMULINK THRUST FUNCTION

- **Pitch Command function:** The pitch command function in my Simulink model calculates the target pitch angle (**tht_c**), for the rocket's control system. It adjusts this angle based on altitude, thrust, and flight path angle inputs, signifying different flight phases: post-engine cut-off orientation, final descent preparation, or trajectory maintenance during powered flight. This function is essential for directing the rocket's pitch through the ascent and ensures a proper orientation for landing, with a flag indicating critical transitions. Paired with a PID controller, it enables precise adjustments to the rocket's trajectory for a successful launch and touchdown.

The code of this function is in Appendix D.

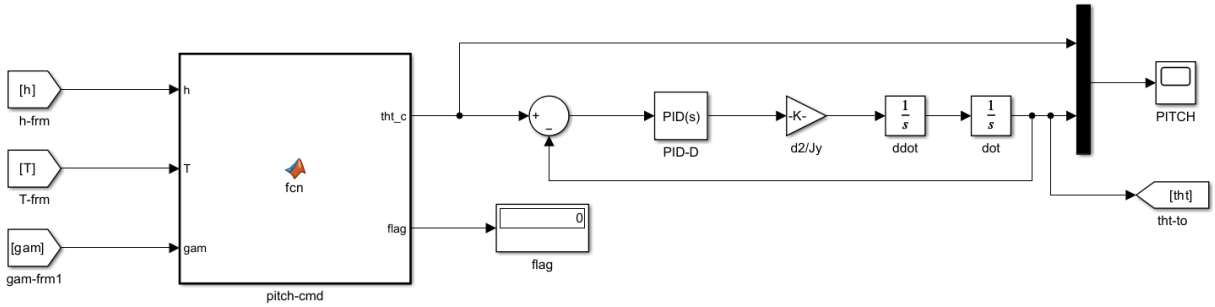


FIGURE 16 :SIMULINK PITCH COMMAND FUNCTION

- **Drag function:** the function is encoded to compute the aerodynamic drag force (**D**) acting on the rocket, which is contingent on both its altitude (**h**) and velocity (**v**). The function is based on the drag coefficient (**CD**), the frontal area (**A**), and atmospheric conditions varying with altitude to calculate the air density (**rho**) following the International Standard Atmosphere (**ISA**) model. This model adjusts temperature and pressure to reflect changes in air density up to the stratosphere. The calculated drag force directly influences the rocket's speed and deceleration, particularly during the descent phase, and is an integral part of the simulation that helps in assessing the rocket's landing dynamics for a secure touchdown.

The code of this function is in Appendix E.

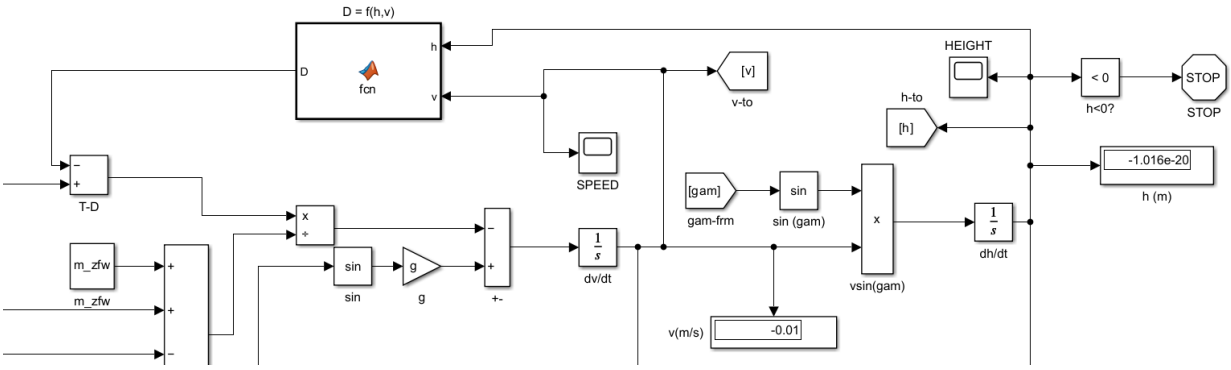


FIGURE 17 :SIMULINK DRAG FUNCTION

13.1.2. Results

The shown graph illustrates, figure 18, the vertical trajectory of the rocket's flight simulation, showcasing a triumphant ascension to its maximum altitude, followed by a carefully regulated drop, culminating in the landing phase at around 150 seconds. The integrated control system effectively manages this phase transition by executing pitch, thrust, and drag instructions.

The post-apogee graph exhibits a smooth curve, suggesting a precise and progressive decrease in altitude. This observation highlights the control system's capacity to regulate thrust and aerodynamic forces, resulting in a gentle landing. Consequently, the system demonstrates its effectiveness in regulating the intricate dynamics of rocket flight.

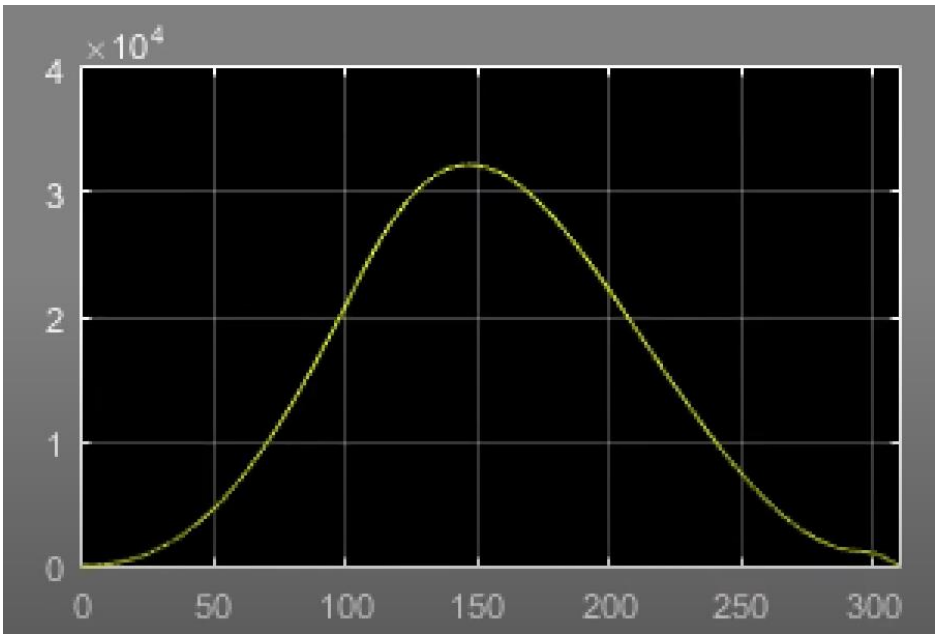


FIGURE 18 :HEIGHT VS TIME (TAKE OFF & LANDING FLIGHT SIMULATION)

The speed profile obtained from the flight simulation, as seen in Figure 19, exhibits a notable surge in velocity after launch, culminating in a peak speed before subsequently decelerating as the rocket reaches the apogee. Following a duration of 110 seconds, a conspicuous shift occurs when there is a substantial drop in velocity, signifying the commencement of the landing phase. The significant decrease in velocity towards the conclusion of the flight indicates the initiation of the rocket's deceleration systems, such as retro thrust, to attain a safe landing velocity. This profile showcases the control system's capacity to accurately adjust speed at various stages of the rocket's flight, which is crucial for achieving mission success.

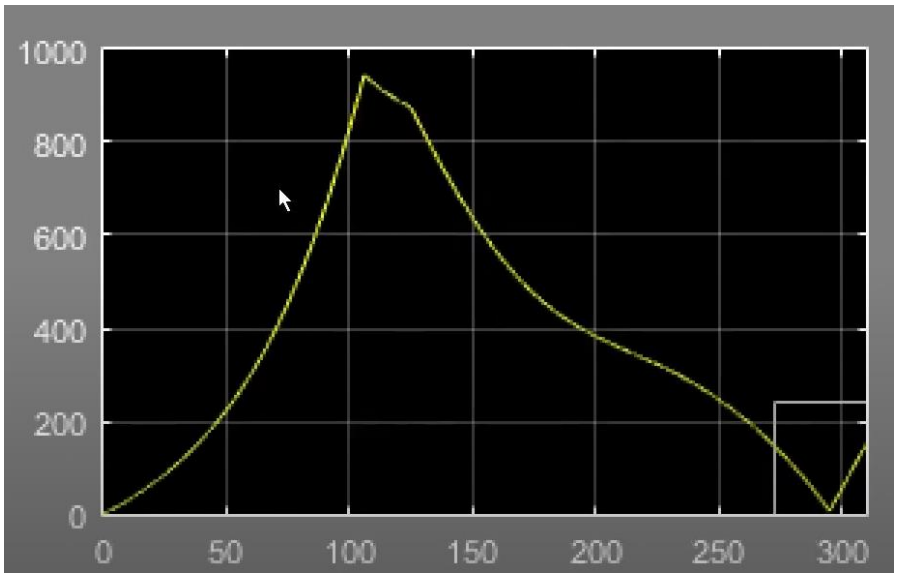


FIGURE 19 :SPEED VS TIME (FULL SIMULATION)

Figure 20 displays a magnified speed profile during the landing phase, illustrating a final approach marked by a sudden decrease in speed, a brief halt, and a subsequent rise in speed. This indicates a bounce or correction during touchdown. The first significant decrease in velocity is a result of braking measures, such as the activation of retro thrusters to decelerate the fall. The transient elevation signifies a temporary recovery or a conformation to the landing surface, followed by a last deceleration to attain a total cessation.

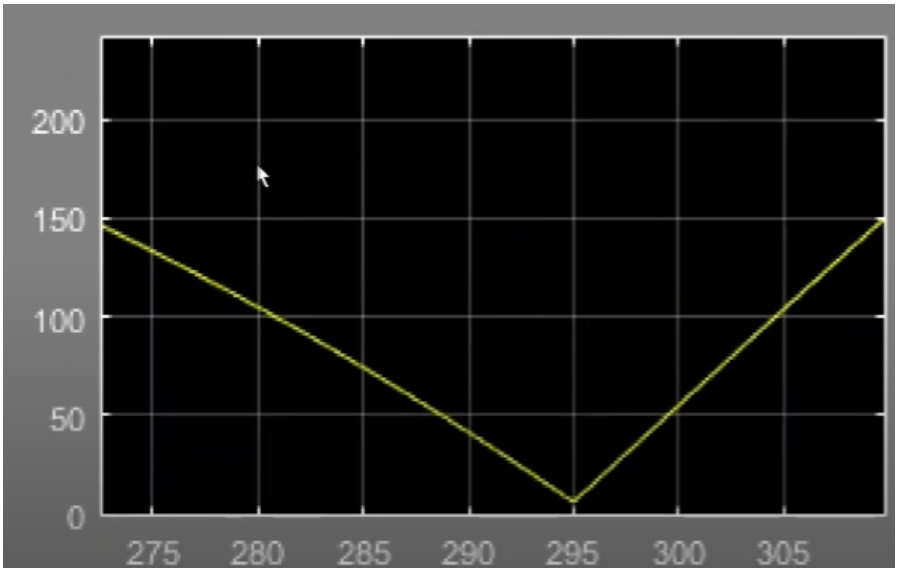


FIGURE 20 :SPEED VS TIME (LANDING PHASE)

The flight path graph shown in Figure 21 illustrates the trajectory of the rocket as it transitions from launch to landing throughout the exercise. At first, the angle of the flight path is positive, suggesting a rapid upward movement. As the rocket ascends and the angle diminishes, this signifies a shift towards a trajectory that is less steep. As the flight nears its midpoint, the trajectory angle decreases to a value below zero, indicating the start of the rocket's fall. The gradual decline towards a negative angle visually represents the deliberate downward trajectory of the rocket as it readies itself for the landing phase. The trajectory exemplifies the meticulousness with which the TVC system, under the guidance of servomotors and onboard sensors, adjusts the rocket's angle to conform to the intended flight trajectory.

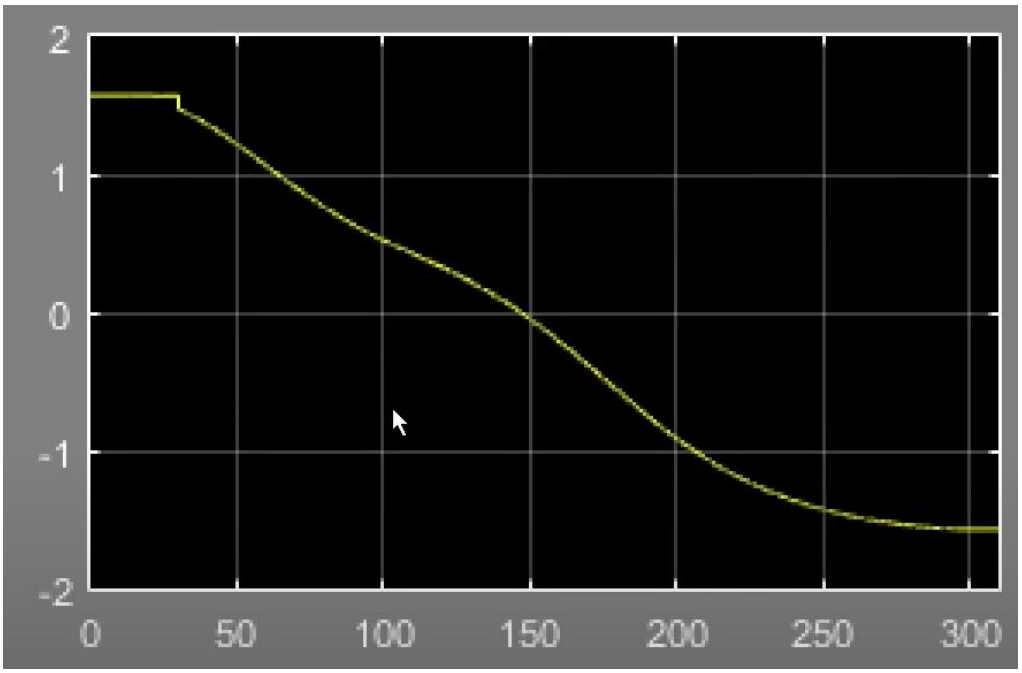


FIGURE 21 :FLIGHT PATH (TEST)

13.2. Electronical Design Simulation

13.2.1. System Block Diagram

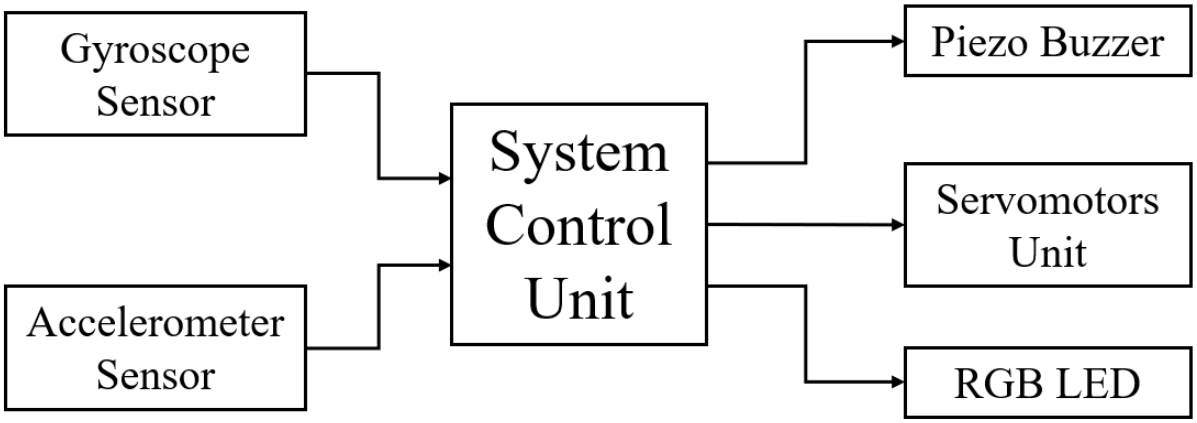


FIGURE 22 :SYSTEM BLOCK DIAGRAM

13.2.2. Proteus Simulation

The Proteus simulation of the Thrust Vector Control (TVC) system has been configured to accurately represent the real-world interaction among the Arduino Nano, the MPU6050 gyroscope and accelerometer, and the two crucial servomotors responsible for controlling the directional corrections of the TVC system. The Arduino Nano serves as the central control unit, responsible for transmitting and receiving signals to and from various components. Its primary function is to coordinate the exact motions necessary to sustain the rocket's desired trajectory throughout flight. The interface between the servomotors responsible for manipulating the X and Y axes and the Arduino Nano is of utmost importance. The X-axis control servomotor is connected to digital pin D6, while the Y-axis control servomotor is attached to digital pin D11. The selection of these pins is based on their Pulse Width Modulation (PWM) capabilities, which are essential for precisely regulating the servomotors and fine-tuning the angular position of the rocket. The servomotors can accomplish precise and responsive motions required for efficient thrust vectoring via these linkages.

In the context of rocket orientation detection and relay, the MPU6050 module plays a crucial role. It establishes communication with the Arduino Nano using the I2C protocol, which is renowned for its effectiveness and dependability in managing sensor data. The MPU6050's SCL

and SDA pins are connected to the Arduino's A5 and A4 analog pins, respectively. The configuration guarantees the constant input of precise data from the gyroscope and accelerometer, pertaining to the rocket's pitch, roll, and yaw, into the control algorithm. The accurate calibration of the communication connection is crucial for the control logic to make well-informed judgments, enabling the dynamic adjustment of the servomotors in response to even the slightest variations in orientation.

The simulation conducted in Proteus encompasses not only the verification of each component functionality, but also the assessment of the whole system's coherence. The preemptive test bed serves as a platform for the simulation of various situations, enabling the monitoring and optimization of the control system's reactions. Conducting simulations of these interactions prior to actual prototyping is a proactive approach to identify and resolve possible problems, improve the dependability of the system, and simplify the development process. The iterative technique used allows for the refinement of the electrical control strategy, so guaranteeing that the system is resilient, responsive, and well-prepared for effective integration into the TVC system throughout the transition from simulation to reality.

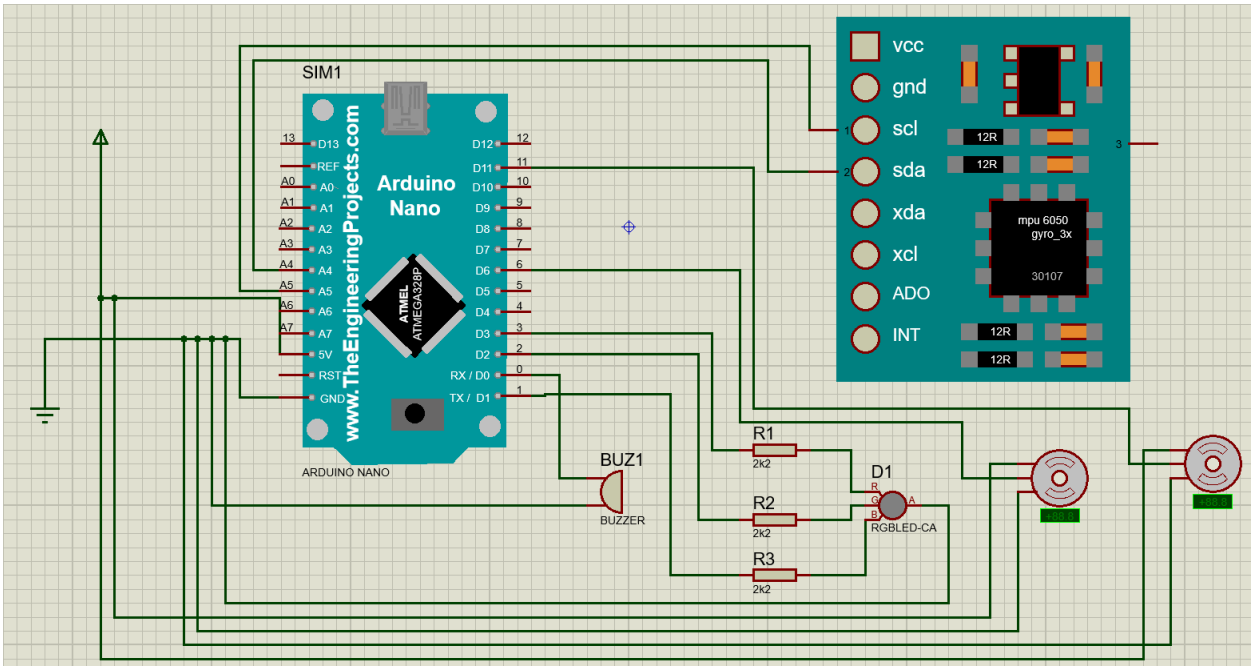


FIGURE 23 :PROTEUS SIMULATION OF THE ELECTRONIC DESIGN OF TVC SYSTEM

14. Prototype

14.1. 3D Impression

When progressing from the design stage to the practical implementation stage, I opted for the use of 3D printing technology to bring the complex elements of the Thrust Vector Control system into existence. To accomplish this crucial duty, I reached out to **LAB360**, a specialist company based in Oujda, renowned for their proficiency in cutting-edge 3D printing methods [16].

The use of cutting-edge technologies facilitated the transformation of precise SolidWorks designs into prototypes of exceptional accuracy and quality. This not only enabled a pivotal stage in the developmental process but also presented a chance to actively participate in and contribute to the growing technology sector in the area.

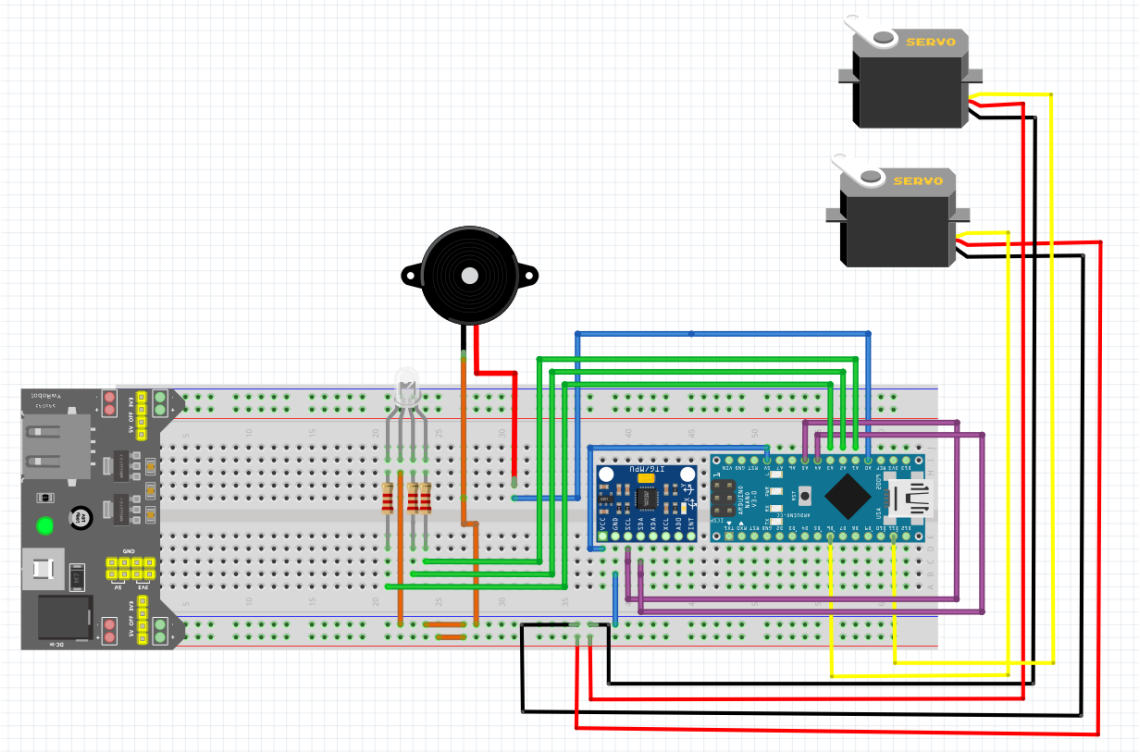


FIGURE 24 :PRINTED PART OF ENGINE TUBE, OUTER GIMBAL, AND INNER GIMBAL

14.2. Electronic Wiring

Before The virtual prototype capabilities of Fritzing software were used prior to commencing the actual assembly of the electrical wire for the Thrust Vector Control (TVC) system. Fritzing provided a user-friendly platform that facilitated the design and visualization of electrical circuits, accurately reproducing the wire arrangement seen in real-world scenarios. This stage played a significant role as it offered an initial synopsis, enabling me to systematically strategize the circuit connections and anticipate probable challenges. Additionally, it enhanced comprehension of the essential elements and their arrangements, guaranteeing a smooth and knowledgeable shift from virtual to actual wiring. Through using Fritzing's user-friendly interface and comprehensive library, I successfully enhanced the electrical design, optimized spatial use on

the breadboard, and verified the whole of the wire layout. This process established a solid groundwork for the subsequent phase of practical execution.



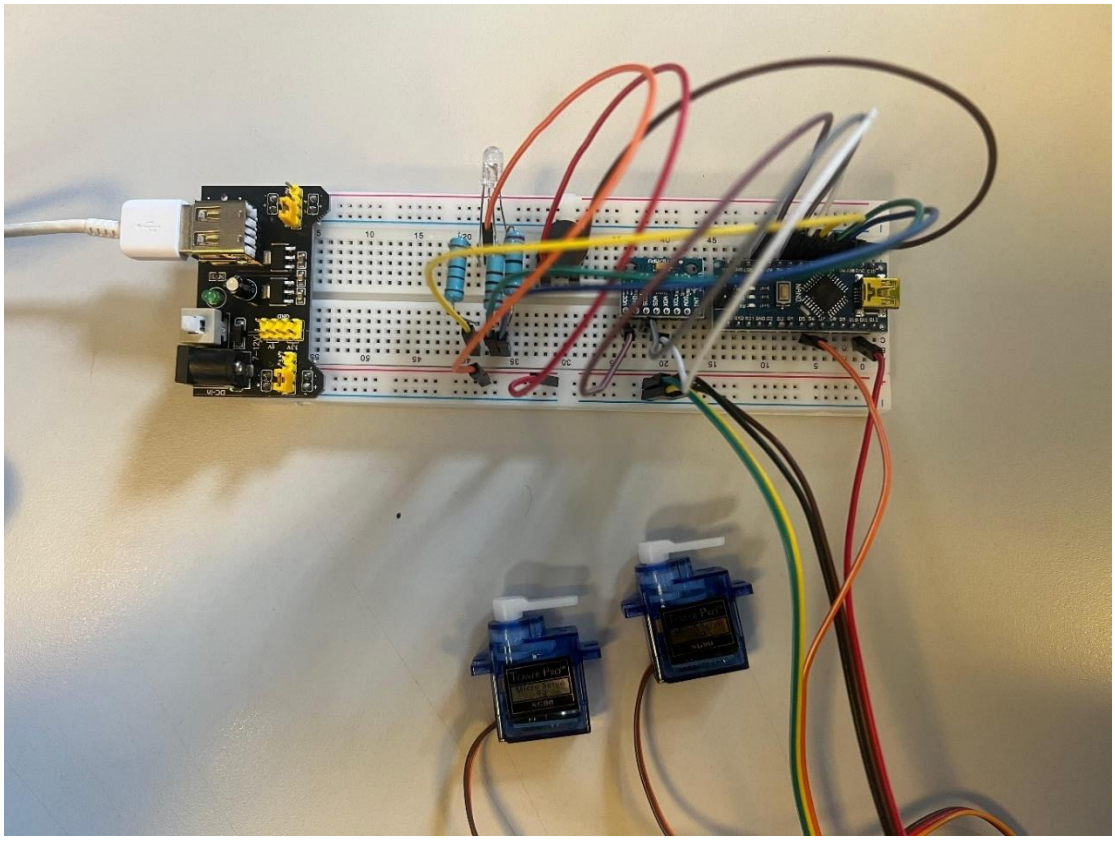


FIGURE 25 :VIRTUAL AND REAL-LIFE ELECTRONIC WIRING OF THE PROTOTYPE

14.3. TVC System Assembly

In this stage, the 3D-printed components, which are particularly tailored for this purpose, are combined with the electrical parts that constitute the control system. The assembly process starts with the attachment of the servomotors to their corresponding mounts on the 3D-printed components, so assuring their precise positioning to govern the X and Y axis of the rocket. In accordance with the established mechanical configuration, the breadboard is integrated to accommodate the Arduino Nano and the MPU6050 sensor. The wiring layout has been meticulously designed to optimize the transmission of control signals from the Arduino to the servomotors, while also ensuring the provision of precise orientation data by the MPU6050. The assembly phase involves the convergence of the project's components, both physically and logically, resulting in the creation of a fully integrated TVC system that is prepared for thorough testing and validation.

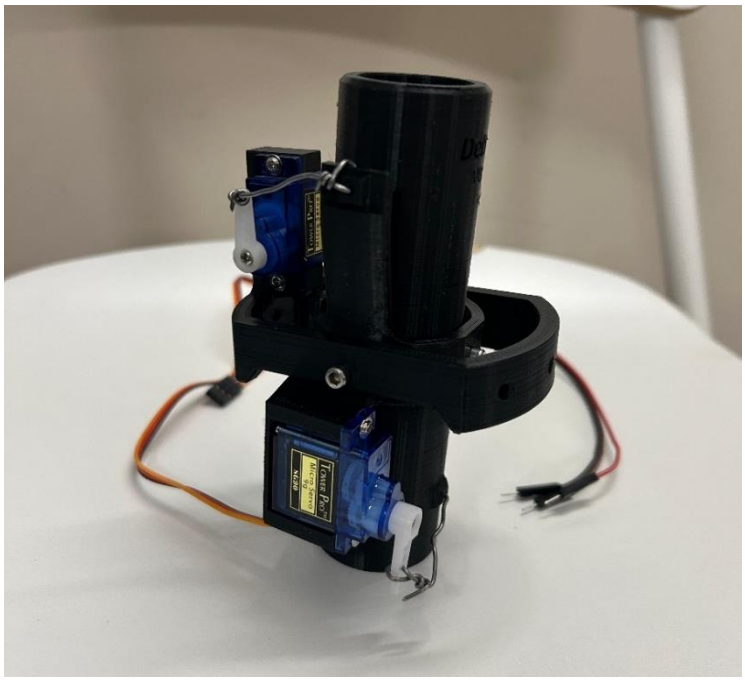


FIGURE 26 :TVC PROTOTYPE (1)

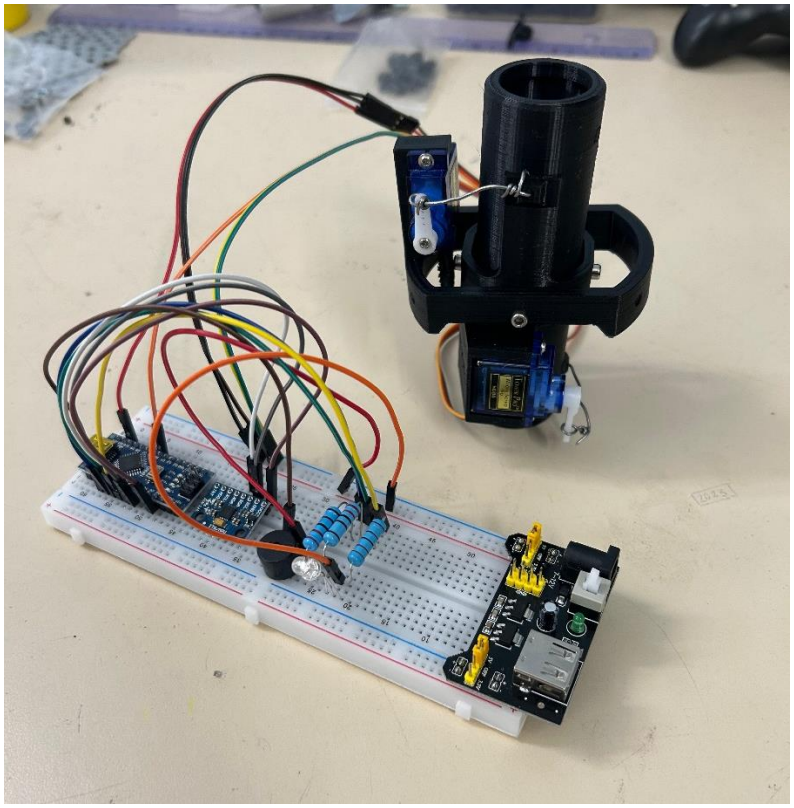


FIGURE 27 :TVC PROTOTYPE (2)



FIGURE 28 : OVERVIEW OF THE PROTOTYPE

14.4. Cost Analysis

TABLE 5 :COST ANALYSIS OF THE PROTOTYPE [16]-[17]

Cost Element	Quantity	Unit Price (MAD)	Total Price (MAD)
Arduino Nano 3.0	1	75	75
MPU6050 Module	1	20	20
Led RGB 5mm	1	2	2
Piezo-Buzzer	1	2	2
SG90 Servo Motor	2	30	60
Breadboard	1	35	35
MB102 Power Supply	1	20	20
Jumper Wires	20	0,6	12
2,2 KΩ Resistances	3	1,5	4,5
3D Parts	-	-	295
Total Price of the Prototype:			525,5

The comprehensive table provided (table 5) in this part enumerates the specific elements used, their respective quantities, unit prices, and the overall price for each component. The use of this methodical technique facilitates a comprehensive comprehension of the specific expenses that contribute to the overall financial demands of the project. The chart presents a concise overview of the overall expenses associated with the prototype, offering a thorough understanding of the financial commitment required to transform the TVC system from an idea into a tangible product. A thorough financial analysis is crucial for budgeting and obtaining the necessary money or permissions to go forward with the project.

Future Work

For Several important innovations are planned for future upgrades of the Thrust Vector Control (TVC) system. Initially, the process of creating and constructing a personalized Printed Circuit Board (PCB) would optimize the electrical components, enhancing the dependability and appropriateness of the system for rocket settings. Furthermore, the enhancement of control algorithms, such as the use of adaptive control or machine learning methodologies, has the potential to greatly enhance the performance of the system in dynamic circumstances.

Increasing the adaptability and marketability of the TVC system might be achieved by expanding it to suit other rocket platforms. To accommodate various rocket sizes and configurations, it would be necessary to make modifications to the mechanical and control systems. Incorporating sophisticated sensors, like high-precision Inertial Measurement Units (IMUs) or Global Positioning System (GPS) systems, might further improve the accuracy of the feedback loop, resulting in more precise control over the rocket's movements.

Ultimately, the implementation of real-world test launches would be crucial. The use of actual flight testing would provide crucial data that models are unable to supply, hence facilitating the further refinement of the system and the identification of any practical concerns. By following these processes, the TVC system will undergo refinement and its applications in the aerospace sector will be expanded, resulting in a technology that is more resilient and versatile.

Lesson Learned

Over the course of this capstone project, several significant insights were acquired that transcended the mere technical components involved in the creation of a Thrust Vector Control system. The use of an iterative design method was crucial, since each iteration of modeling and testing enhanced the system to a greater extent, highlighting the significance of flexibility in the field of engineering. The importance of cohesive cooperation and efficient communication in integrating the mechanical, electrical, and control parts of the project was underscored by the collaboration across many technical domains.

Risk management has become an essential ability, emphasizing the need of proactive planning and the use of contingency solutions to efficiently handle any setbacks. Remaining informed about the most recent technology tools, such as sophisticated simulation software and 3D printing, was crucial, showcasing the influence of technological expertise on the achievement of project objectives.

Additionally, the initiative served to strengthen the significance of resilience. Confronting and surmounting obstacles was an ongoing reality, underscoring the need for perseverance and resolve as essential as technical expertise in attaining project goals. The courses not only enhanced my comprehension of engineering fundamentals but also equipped me with the necessary skills to effectively handle complex projects in the face of uncertainty.

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Conclusion

To sum up In conclusion, the capstone design project for the TVC system for rocket descent is a sophisticated integration of several theoretical concepts and practical applications, exemplifying the innovative nature of contemporary aerospace engineering. The rocket's manufacturers were inspired by industry leaders such as Space X. However, the project achieved significant success by utilizing advanced simulation tools like MATLAB Simulink and Simulink Proteus, as well as 3D printing in innovative engineering. These tools were employed to create a prototype capable of accurately guiding most rocket landings.

The transformative experience in my cognitive and professional approach was evoked throughout the process of developing the prototype, which evolved from an abstract concept to a fully operational system. This exemplified the need for enhanced engineering that is durable and adaptive in forthcoming times. Throughout all stages of the project, including its design, simulation, and testing, it was shown that the integration of diverse technical areas may significantly contribute to the creation of a unique entity.

The estimates of this project not only represent the achievement of academic excellence but also contribute to the advancement of the objective of sustainable and cost-effective space exploration. However, it showcases remarkable potential for academic endeavors to be transformed into advancements for the aerospace industry: reducing expenses, minimizing environmental harm, and paving the way for future space exploration. This sector exemplifies how the combination of theory, technology, and research may lead to the attainment of the best desirable outcome.

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References

[1] Numerical Study of Fluidic Thrust Vector Control Using Dual Throat Nozzle. (2021, January 1). *Journal of Applied Fluid Mechanics*, *14*(01). https://doi.org/10.47176/jafm.14.01.31690

[2] SpaceX. (n.d.). SpaceX. https://www.spacex.com/vehicles/falcon-9/

[3] Wu, H., & Zhang, Z. (2023, September 25). Analysis of the development of reusable launch vehicle technology. Applied and Computational Engineering, 11(1), 65–75. https://doi.org/10.54254/2755-2721/11/20230209

[4] Hammar, M. (n.d.). What is AS9100? Easy-to-understand explanation. 9100Academy. https://advisera.com/9100academy/what-is-as9100/

[5] IEC. (n.d.). IEC - International Electrotechnical Commission. https://webstore.iec.ch/publication/4552

[6] Newton's Third Law of Motion. (n.d.). https://www.grc.nasa.gov/www/k-12/BGP/newton3.html

[7] Wu, H., & Zhang, Z. (2023, September 25). Analysis of the development of reusable launch vehicle technology. Applied and Computational Engineering, 11(1), 65–75. https://doi.org/10.54254/2755-2721/11/20230209

[8] Wang, T. S. (1998, July). Delta Clipper-Experimental In-Ground Effect on Base-Heating Environment. Journal of Thermophysics and Heat Transfer, 12(3), 343–349. https://doi.org/10.2514/2.6367

[9] Howell, E. (2016, February 6). SpaceX's Grasshopper: Reusable Rocket Prototype. Space.com. https://www.space.com/26042-spacex-grasshopper.html

[10] Bieniawski, S. R., Lewis, B., Friia, B., Mahajan, A., Somervill, K., Mamidipudi, P., & Dakin, D. (2022, January 3). New Shepard Flight Test Results from Blue Origin De-Orbit Descent and Landing Tipping Point. AIAA SCITECH 2022 Forum. https://doi.org/10.2514/6.2022-1829

[11] Notes, A. (2021, February 11). *Thrust Vector Control - Propulsion 2 - Aerospace Notes*. Aerospace Notes. https://aerospacenotes.com/propulsion-2/thrust-vector-control/

[12] Kim, D. (2022, April 6). Developing a Control Algorithm and Simulation for Thrust Vector Controlled Rockets. Supercomputer Challenge. Retrieved March 8, 2024, from https://supercomputingchallenge.org/21,22/finalreports/47/Supercomputing%20Final%20Report.pdf

[13] Mishra, D. (2020, June 30). Fundamentals of Rocket Propulsion. CRC Press. http://books.google.ie/books?id=muSSzQEACAAJ&dq=Fundamentals+of+Rocket+Propulsion&hl=&cd=3&source=gbs_api

[14] Thrust Vector Control 3D Files. (n.d.). BPS.Space. https://bps.space/products/thrust-vector-control

[15] Space Launch Report: SpaceX Falcon 9 Data Sheet. (2017, May 1). Nasa. Retrieved March 30, 2024, from https://sma.nasa.gov/

[16] Prototypage Rapide au MAROC - En Ligne - Devis instantanément. (2023, October 16). Prototypage Rapide Au MAROC. https://lab360.ma/

[17] Arduino Maroc, Electronique, Modules, Composants - MicroPlanet. (2024, January 6). MicroPlanet Maroc. https://www.micro-planet.ma/

Appendix A

```
//TVC proteus simulation and prototype code

#include <Arduino.h>        // Standard Arduino library
#include <Wire.h>           // Wire library for I2C communication
#include <MPU6050_tockn.h>  // Library for the MPU6050 sensor
#include <PWMServo.h>       // Library for servo control
#include <PID_v1.h>         // Library for PID control

// Define the PID tuning parameters
double Kp = 1.0, Ki = 0.05, Kd = 0.25; // Proportional, Integral, Derivative
parameters

// Variables for the PID controller for the x-axis
double setPointX = 0; // Desired setpoint for the x-axis
double inputX, outputX; // Input from the sensor and output to the servo for
x-axis

// Variables for the PID controller for the y-axis
double setPointY = 0; // Desired setpoint for the y-axis
double inputY, outputY; // Input from the sensor and output to the servo for
y-axis

// Create servo objects
PWMServo servo1x; // Servo on x-axis, connected to pin D11
PWMServo servo2y; // Servo on y-axis, connected to pin D6

// Define the pin assignments based on the circuit schematic
int red = 3;    // Red pin of RGB LED connected to D3
int green = 2;  // Green pin of RGB LED connected to D2
int blue = 1;   // Blue pin of RGB LED connected to D1
int buzzer = 0; // Buzzer connected to D0

// Create an MPU6050 object
MPU6050 mpu6050(Wire);

// Variable to store the last time we updated the PID
long timer = 0;

// Instantiate PID objects for each axis control
PID pidX(&inputX, &outputX, &setPointX, Kp, Ki, Kd, DIRECT);
PID pidY(&inputY, &outputY, &setPointY, Kp, Ki, Kd, DIRECT);

void setup() {
  Serial.begin(9600);       // Start serial communication at 9600 baud
  Wire.begin();             // Initiate the Wire library
  mpu6050.begin();          // Start the MPU6050 sensor
  mpu6050.calcGyroOffsets(true); // Calibrate the gyroscopes with true to
output calibration status

  servo1x.attach(11); // Attach the x-axis servo to pin D11
  servo2y.attach(6);  // Attach the y-axis servo to pin D6
  // Set the LED pins as outputs
  pinMode(red, OUTPUT);
  pinMode(blue, OUTPUT);
```

```
  pinMode(green, OUTPUT);
  // Set the buzzer pin as output
  pinMode(buzzer, OUTPUT);

  // Turning on the red LED and turning off others at setup
  digitalWrite(red, HIGH);
  digitalWrite(blue, LOW);
  digitalWrite(green, LOW);

  // Turning the buzzer on then off
  digitalWrite(buzzer, HIGH);
  delay(1000);
  digitalWrite(buzzer, LOW);

  // Initialize the PID controllers
  pidX.SetMode(AUTOMATIC); // Set the PID to automatic mode
  pidX.SetOutputLimits(-90, 90); // Set the output limits to match the
servo's range

  pidY.SetMode(AUTOMATIC); // Set the PID to automatic mode
  pidY.SetOutputLimits(-90, 90); // Set the output limits to match the
servo's range
}
void loop() {
  mpu6050.update(); // Read the latest data from MPU6050 sensor

  // Assign the sensor readings as input to the PID controllers
  inputX = mpu6050.getAngleX();
  inputY = mpu6050.getAngleY();

  pidX.Compute(); // Calculate the PID output for the x-axis
  pidY.Compute(); // Calculate the PID output for the y-axis

  // Set the servo positions based on the PID output
  servo1x.write(constrain(90 + outputX, 0, 180)); // Ensure the output is
within the servo's range
  servo2y.write(constrain(90 + outputY, 0, 180)); // Ensure the output is
within the servo's range

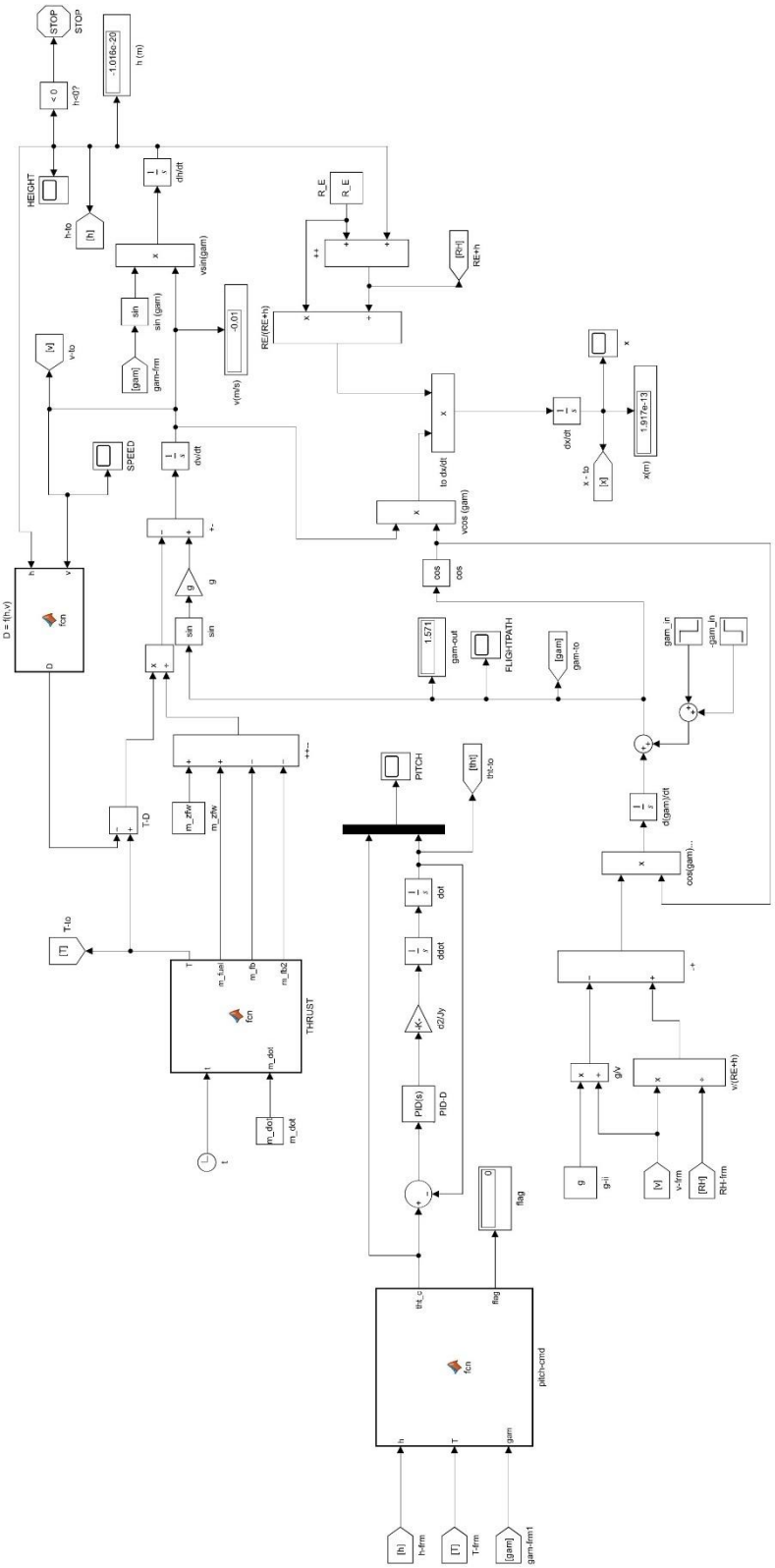
  // LED control based on some conditions or states
  digitalWrite(red, LOW);    // Turn red LED off
  digitalWrite(green, HIGH); // Turn green LED on
  digitalWrite(blue, LOW);   // Turn blue LED off

  // Buzzer control - can be triggered by some conditions
  digitalWrite(buzzer, HIGH); // Turn the buzzer on
  delay(100);                 // Keep it on for 100ms
  digitalWrite(buzzer, LOW);  // Turn the buzzer off

  // Periodically print sensor values to the Serial Monitor
  if(millis() - timer > 1000){
    // Output sensor values to the serial port

    timer = millis(); // Update timer for next interval
  }
}
```

Appendix B


STOP
STOP
h<0?
-1.016e-20
h (m)
HEIGHT
h-to
[h]
dh/dt
vsin(gam)
R_E
R_E
RE+h
[R+]
sin
sin (gam)
gam-frm
[gam]
-0.01
RE/(RE+h)
v(m/s)
v-to
[v]
SPEED
dv/dt
to dv/dt
vcos (gam)
dx/dt
x - to
[x]
x(m)
-1.917e-13
cos
cos
D = f(h,v)
fcn
D
g
sin
1.571
gam-out
FLIGHTPATH
[gam]
gam-to
gam_in
-gam_in
+-
++-
T-D
m_dot
m_dot
T-to
[T]
T
m_fuel
m_fb
m_fb2
THRUST
fcn
m_dot
t
PITCH
[tht]
tht-to
ddot
dddot
-K-
cd/dy
PID(s)
PID-D
0
flag
tht_c
flag
fcn
pitch-cmd
h
T
gam
[h]
h-frm
[T]
T-frm
[gam]
gam-frm1
d(gam)/dt
cos(gam)...
-+
g*v
v(RE+h)
g
g-si
[v]
v-frm
[Rh]
RH-frm

Appendix C

```
% Simulink Thrust function code

function [T, m_fuel, m_fb, m_fb2] = fcn(t, m_dot)
% This function calculates the thrust and fuel parameters over time
% inputs are time and mass flow rate

%codegen

% Initialize persistent variables that hold the accumulated fuel burnt.
persistent mfb   % Fuel burnt during the main phase
persistent mfb2  % Fuel burnt during a secondary phase

% If the persistent variables are empty, initialize them to zero.
if isempty(mfb)
    mfb = 0;
end
if isempty(mfb2)
    mfb2 = 0;
end

% Set initial total fuel mass.
mfuel = 21491.26;  % Total mass of fuel at the start of the simulation.

% Main thrust phase calculation.
if mfb <= 0.65*mfuel
    THR = 346961.2;  % Main engine thrust in Newtons.
    mfb = t*m_dot;   % Calculate fuel burnt until the current time.
else
    THR = 0;         % If more than 65% of fuel has burnt, set thrust to
zero.
end

% Secondary thrust phase for controlled descent.
if (125<t) && (t<295)
    THR = -110000;   % Secondary engine thrust in Newtons (negative for
deceleration).
    mfb2 = (t-125)*(m_dot/3);  % Calculate additional fuel burnt during this
phase.
end

% Set outputs.
T = THR;             % Current thrust output.
m_fb = mfb;          % Fuel burnt during main thrust phase.
m_fb2 = mfb2;        % Fuel burnt during secondary thrust phase.
m_fuel = mfuel - mfb - mfb2;  % Remaining fuel mass.
```

Appendix D

```
% Simulink Pitch Command function code

function [tht_c, flag] = fcn(h, T, gam)
% This function determines the target pitch command (tht_c) and a flag status
% based on altitude (h), thrust (T), and flight path angle (gam)

%codegen

% Use a persistent variable 'f' to store the flag state across function calls
persistent f

% Initialize the flag to 0 if it's empty at for the start of the simulation
if isempty(f)
    f = 0;
end

% Determine the pitch command based on the thrust and altitude
if T <= 0
    % If the thrust is zero or negative, implying engine cut-off
    % set the target pitch to be gam plus pi.
    t_c = gam + pi;

    % Ensure the target pitch doesn't exceed pi, which is the max allowed
value
    if t_c > pi
        t_c = pi;
    end

    % Set the flag to 1 indicating a new phase for preparation for descent
    f = 1;
elseif T <= 0 && h < 1000
    % If the engine is off and the rocket is at an altitude lower than 1000,
    % set the target pitch to pi/2 for a vertical descent.
    t_c = pi/2;
else
    % If none of the above conditions are met, continue with the current
    % flight path angle as the target pitch.
    t_c = gam;
end

% Output the flag and the target pitch command.
flag = f;
tht_c = t_c;
```

Appendix E

```
% Simulink Drag function code

function D = fcn(h, v)
% This function calculates the drag force (D) experienced by the rocket
% on its altitude (h) and velocity (v).

%codegen

% Define constants: Drag coefficient (CD), rocket diameter (Di), and frontal
area (A).
CD = 0.075;         % Coefficient of drag
Di = 1.5;           % Diameter of the rocket
A = pi*Di^2/4;      % Frontal area, assuming a circular cross-section

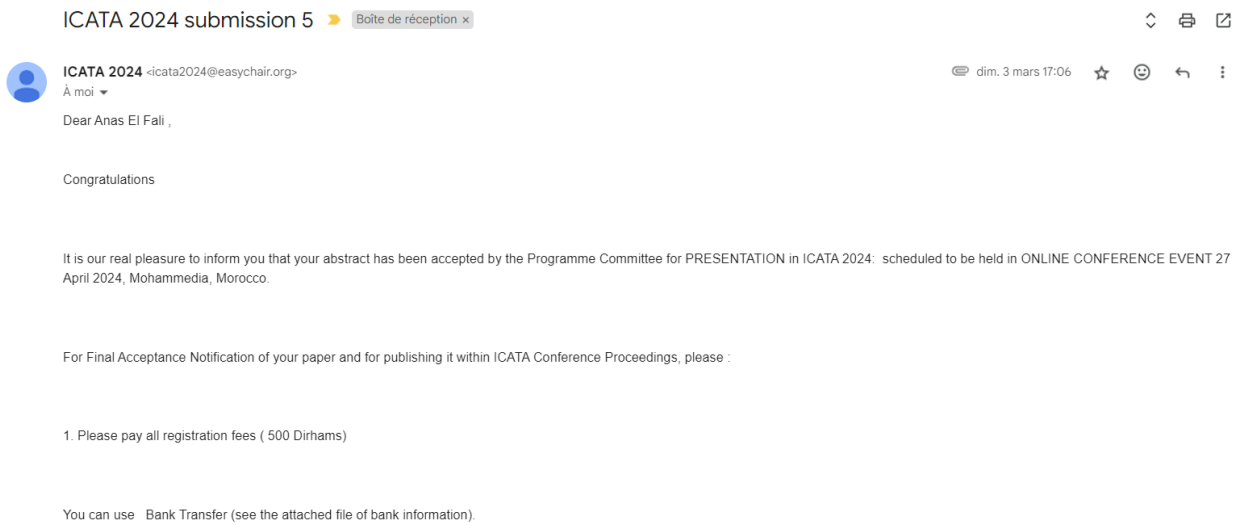
% temperature (T) and pressure (p) based on altitude (h), which are used to
% determine air density (rho).
if h <= 11000
    % Troposphere
    T = 15.04 - 0.00649*h;                  % Temperature lapse rate
    p = 101.29*((T+273.1)/288.08)^5.258;    % Pressure calculation
elseif (11000 < h) && (h <= 25000)
    % Lower Stratosphere
    T = -56.46;                             % Constant temperature
    p = 22.65*exp(1.73-0.000157*h);         % Exponential decrease in pressure
else
    % Upper Stratosphere
    T = -131.21 + 0.00299*h;                % Temperature increase with
altitude
    p = 2.488*((T+273.1)/216.6)^-11.388;    % Pressure calculation
end

% Calculate air density (rho) from the temperature and pressure.
rho = p/(0.2869*(T+273.1));  % Ideal gas law rearranged for density

% Calculate the drag force (D) using the drag equation.
Drag = 0.5*rho*v^2*A*CD;  % Drag force formula

% Output the drag force.
D = Drag;
end
```

Appendix F



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À moi

Dear Anas El Fali ,

Congratulations

It is our real pleasure to inform you that your abstract has been accepted by the Programme Committee for PRESENTATION in ICATA 2024: scheduled to be held in ONLINE CONFERENCE EVENT 27 April 2024, Mohammedia, Morocco.

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