Final Report:
Development of a Rocket Landing Simulation Using a Gimbal and Landing Gear

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Ignite Design Challenge

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Introduction

This paper explores the development of a rocket landing simulation that aims to enhance the landing efficiency and stability of the rocket landing vertically. Designing efficient and reliable landing systems for rockets remains a crucial challenge to safely and consistently land a rocket. The rocket explored in this paper has been modified to reduce mission costs and play a significant role in advancing reusable space technology. The design implemented gimbals for thrust vector control and robust landing gear systems, along with a redesign of the nose cone to realistically model the rocket that would go through both launching and landing. The design leverages gimbal systems to dynamically adjust thrust direction, ensuring precise control of the rocket's orientation during descent. Additionally, including landing gear improves stability upon touchdown, mitigating the risk of tip-over or damage. This solution addresses two fundamental challenges in rocket landings: maintaining attitude control during descent and ensuring structural integrity upon contact with the ground. By tackling these issues, the design enhances the reliability and efficiency of rocket recovery systems, paving the way for advancements in reusable rocket technology.

Problem

Background

The challenge of landing a rocket upright is both a technical and operational problem central to modern aerospace engineering. Traditional expendable launch systems discard hardware after a single use, driving up costs and limiting the efficiency of space exploration and transportation. In contrast, successful vertical landings of reusable rockets can drastically reduce costs and environmental impact. In industry, notable companies like SpaceX and Blue Origin have pioneered reusable rocket technology by implementing advanced systems such as thrust vector control (TVC) and deployable landing gear **[1]**. These technologies enable rockets to correct their attitude during descent and safely absorb impact upon touchdown. Thrust vector control, often achieved through gimbaled engines, allows for fine-tuned adjustments to the rocket's trajectory. Additionally, landing gear equipped with damping mechanisms ensures stability during landing, even on uneven surfaces.

Research highlights the complexities of balancing stability, accuracy, and robustness. For example, Reuben Ferrante illustrates how gimbal systems contribute to minimizing drift during descent while investigating computational methods for simulating controlled landings **[1]**. A second project that influenced the use of gimbals and a redesign of the nose cone is a launch report from the AIAA Regional Student Conferences which tested the launch of a rocket by replacing the fins with a gimbal **[2]**. These advancements inspire our approach to integrating gimbals and landing gear into a simulation that accurately models the dynamics of a rocket landing while implementing a better thrust-to-weight ratio **[3]**.

Purpose

Landing a rocket upright is a valuable problem to solve due to its implications for cost efficiency, safety, and the feasibility of sustainable space exploration. The difficulty lies in maintaining stability during descent and ensuring a secure touchdown on varying terrains. Without reliable control mechanisms, rockets risk instability, which can lead to mission failure, loss of valuable hardware, and environmental hazards.

This problem affects industries and organizations striving to make space travel more accessible. Reusable rockets can significantly reduce the cost of payload delivery, increasing accessibility to orbital applications for research institutions, private companies, and governments.

Design Criteria

To address the problem quantitatively, our team established the following design criteria:

1. **Stability During Descent:** The rocket must maintain an upright orientation with minimal angular drift, measured as the deviation from vertical (in degrees).

2. **Landing Controls:** The code for the rocket simulation must result in a zero velocity when altitude approaches zero, while maintaining stability to disturbances that can occur during landing.
3. **Impact Absorption:** The landing gear should effectively dampen forces upon touchdown to prevent structural damage, quantified by measuring landing impact forces (in Newtons).
4. **Minimized Mass:** No amount of material should be carried needlessly. All parts should be designed to perform their purpose with the minimum amount of additional material, and of the lightest possible material.

Solution

Overview

Our solution to the problem of landing a rocket upright integrates three key mechanical components: gimbal implementation, landing gear addition, and a nose cone redesign. The material these parts are manufactured from also plays an important role and has been considered carefully. Finally, vertical landing requires robust controllers in both the vertical axis and in the gimbal that can accommodate disturbances introduced from a variety of sources.

Together, these elements address the critical challenges of stability, precision, and impact absorption, as defined in our design criteria. Each component has been developed with an emphasis on efficiency, reliability, and adaptability to ensure successful landings under various conditions.

Topic 1: Material Selection

AISI 321 Annealed Stainless Steel SS

Property	Value	Units
Elastic Modulus	1968040.273	kgf/cm^2
Poisson's Ratio	0.27	N/A
Tensile Strength	6322.201972	kgf/cm^2
Yield Strength	2390.422007	kgf/cm^2
Tangent Modulus		kgf/cm^2
Thermal Expansion Coefficient	1.7e-05	/ºC
Mass Density	0.0080000001	kg/cm^3
Hardening Factor	0.85	N/A

Figure 1: Material Properties of AISI 321

Stainless steel was selected for numerous reasons. The most significant factor is the ability to maintain a high yield strength at increasing temperatures. Compared to 6061 Aluminum, AISI 321 stainless steel is significantly heavier and more expensive. The thrust from the engines was adequate to compensate for the additional mass, while the ability to withstand higher temperatures accounted for the additional price. The need to withstand high temperatures is very important as the rocket will travel above the speed of sound. The choice of stainless steel for large rockets has been proven with the most notable example being SpaceX Starship.

Topic 2: Gimbal Implementation

Gimbal systems are crucial for thrust vector control, enabling the rocket to adjust its trajectory during descent. By tilting the engine's thrust direction relative to the rocket's center of mass, gimbals allow for fine-tuned corrections to stabilize orientation and counteract disturbances such as wind or uneven terrain below.

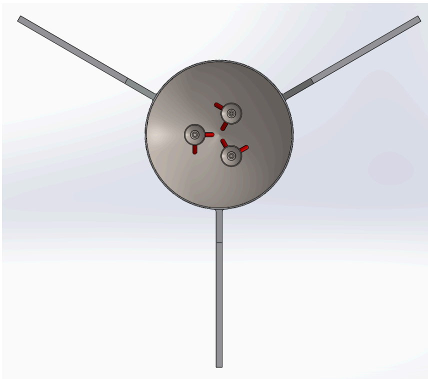

Figure 2: Bottom and side view of the gimbal engines at the base of the rocket

Design Approach

The design incorporates three thrusters mounted on gimbals, which adjust the orientation of each thruster to dynamically control the thrust vector based on real-time feedback from onboard sensors. A proportional-integral-derivative (PID) controller processes data from gyroscopes and accelerometers to maintain vertical alignment, minimizing angular drift even under external disturbances. Stability is further enhanced by strategically positioning the fins, as seen in **Figure 3**, and ensuring the center of pressure is located behind the center of gravity, promoting aerodynamic balance throughout descent. The three engines are designed around the specifications of Raptor V3 with a slightly heavier gimbal. The red linkages are hydraulic actuators for thrust vector control. The first of the orthogonal actuators is for the x position, while the other is for the y position. Three engines are used as this would allow for finer control in series with the gimbal to increase the precision of control.

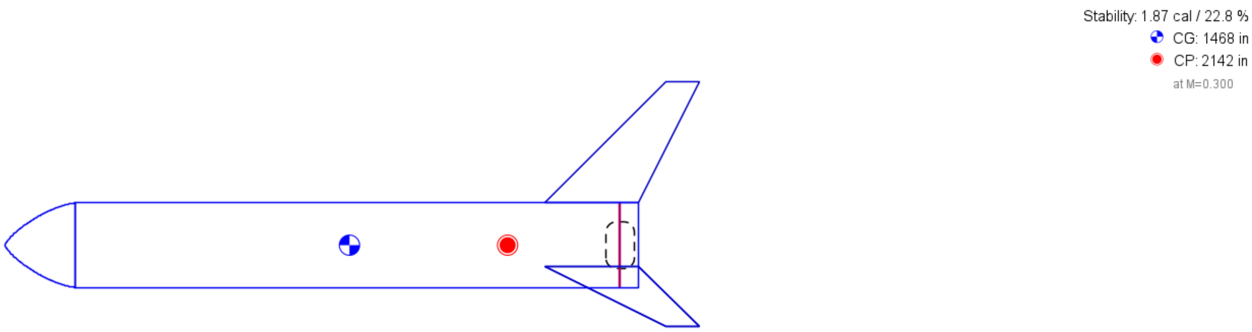

Figure 3: OpenRocket Simulator modeled rocket.

Topic 3: Landing Gear Addition and Topology Optimization

Landing gear provides critical support to absorb impact forces and stabilize the rocket upon touchdown. The design incorporates collapsible legs with shock-absorbing mechanisms to prevent tipping or structural damage.

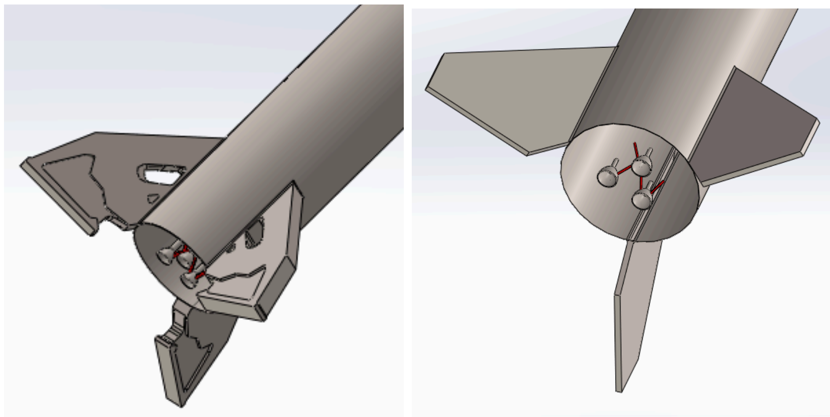

Figure 4: Isometric view of the original landing gear/fins vs final design

Design Approach

The landing gear consists of stainless steel fins equipped with pneumatic dampers that compress upon impact to dissipate energy. The legs are arranged around the rocket's base to maximize stability and are foldable to minimize drag during ascent. In the future, the system should also include footpads designed to distribute forces evenly, even on uneven terrain.

Implementation and Results

Using SolidWorks Topology Optimization, the design space was iteratively refined to remove unnecessary material while retaining the structural integrity required to support the calculated loading weight. The final design achieves a 28% weight reduction with respect to the base mold while meeting all performance criteria for impact absorption validated through FEA with a Factor of Safety of 8.3, as seen in **Figure 5**.

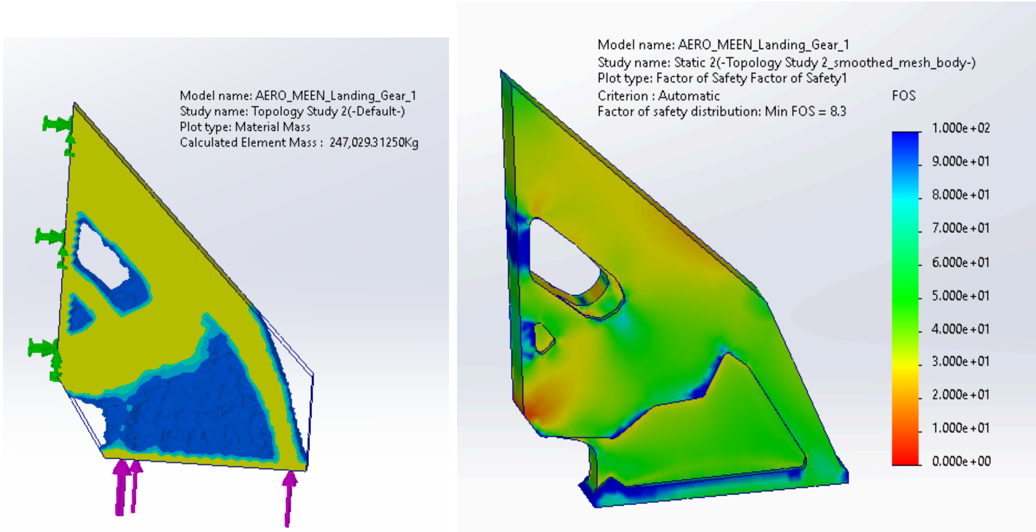

Figure 5: Landing gear topology and FEA analysis

Topic 4: Nose Cone Re-design and Computational Fluid Dynamics (CFD)

The nose cone plays an essential role in aerodynamics during ascent and stability during descent. By optimizing its shape and material properties, we improved its performance in both phases of flight.

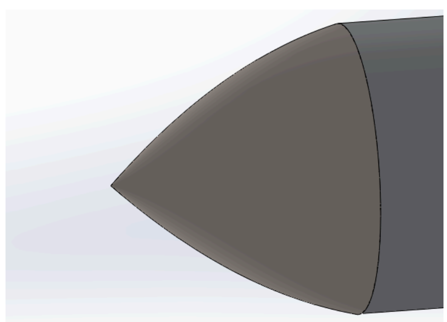

Figure 6: 3/4 Parabolic nose cone design, side view

Design Approach

The redesigned nose cone (**Figure 6**) features a 3/4 parabolic shape that minimizes drag during ascent and promotes aerodynamic stability during descent. The 3/4 parabolic shape is one of the most efficient shapes at supersonic speeds [7]. The nose cone also houses sensors that work in conjunction with the gimbal system to monitor wind patterns and atmospheric conditions.

Implementation and Results

Using SolidWorks' Flow Simulation, the nose cone design was tested at standard flight conditions during the ascent stage (500 m/s). Compared to the cone design, the new nose cone resulted in a 12.5% reduction in drag forces and a lower distribution of pressures at the nose cone caused by the supersonic flows, as seen in **Figure 7**.

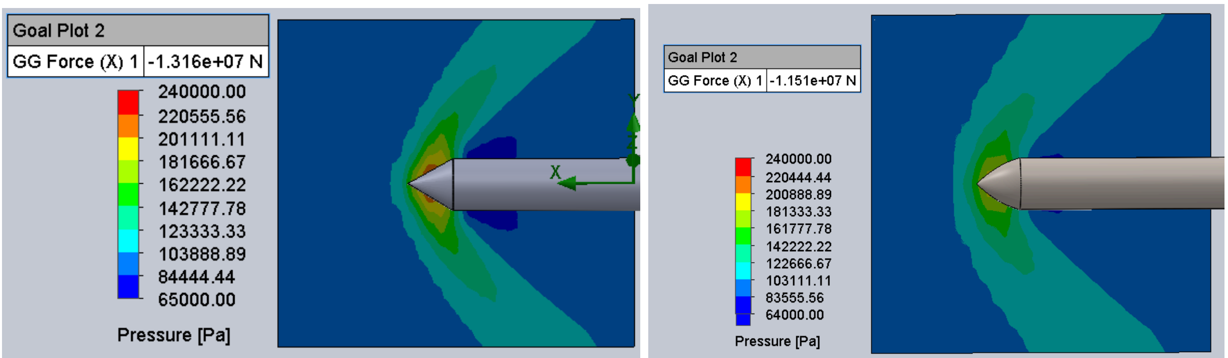

Figure 7: Nose cone CFD analysis of old vs final design at supersonic speeds

Additionally using CFD, the coefficient of drag was calculated from the model by using the coefficient of drag equation and the drag forces. The flow was directed upward from the bottom of the rocket to simulate the downward movement upon descent at 50 m/s. This resulted in a coefficient of drag of 1.427 (**Figure 8**), which was used for the trajectory simulations.

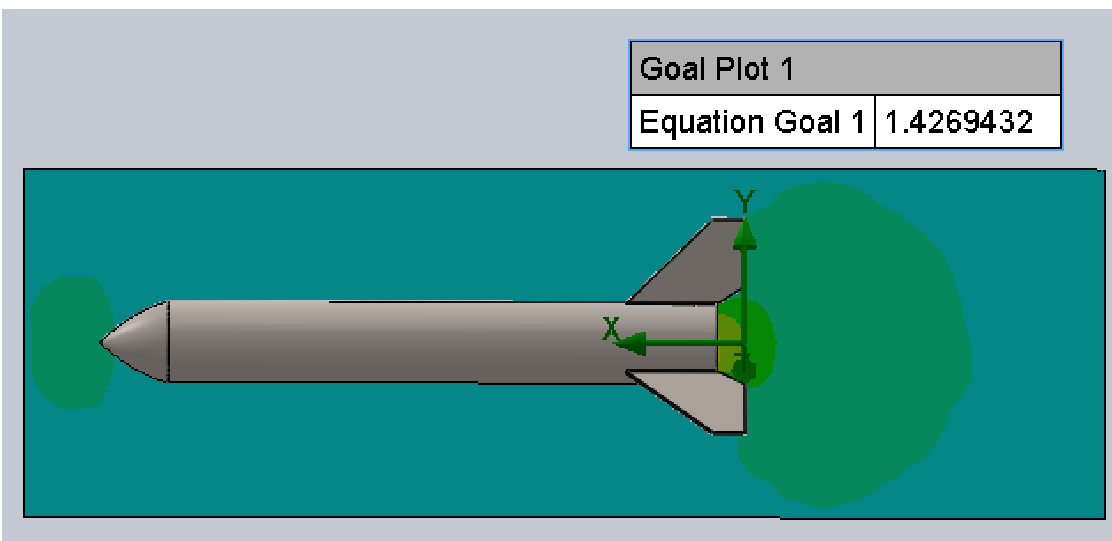

Figure 8: CFD of the rocket in descent & drag coefficient

Topic 5: Landing Controls

The control algorithm for the descent and landing process is a crucial element of the success of a rocket's performance. The descent must be controlled, feasible, and minimize the normal force of landing applied to the rocket as it touches down. There are many factors that could be considered, including but not limited to fuel efficiency, landing time, peak force minimization, thruster performance accommodations or acceleration constraints. Regardless, a solution focusing on optimization would require an in-depth cost function analysis of these parameters. Solving for an optimal solution to this very complex problem **[6]**; however, for the scope of this report, only feasibility and force minimization will be considered.

```
# --- Constants Section ---
g = 9.81  # Acceleration due to gravity in m/s^2
mass = 685000 # mass in kg
Cd = 1.427  # Drag coefficient from CFD simulation
rho = 1.225  # Air density at sea level in kg/m^3
A = 0.5 # Cross-sectional area of the rocket in square meters
engine_thrust = 3.2*1000000 # thurst per engine
num_engines = 3 # number of engines
```

Figure 9: Rocket landing forces script inputs

```
Rocket Landing Forces:
Time to touchdown: 36.60 [s]
Touchdown Velocity: 0.190 [m/s]
Deceleration during landing: 0.018 [m/s^2]
Impact Force: 6.732 [MN]
Normal Force at landing: 13.452 [MN]
Net Power Applied 75.744 [GW]
```

Figure 10: Rocket landing forces script output

Design Approach

The landing controls system ensures the rocket maintains stability and lands upright by processing real-time sensor data to dynamically adjust thrust and orientation. This system combines a model representing a stable hover with an error-driven controller that integrates feedback from onboard sensors with control algorithms, enabling precise adjustments to gimbals and thrusters during descent. This system demonstrates effective landing in reasonable conditions with a minimal touchdown velocity **[Figure 10]**.

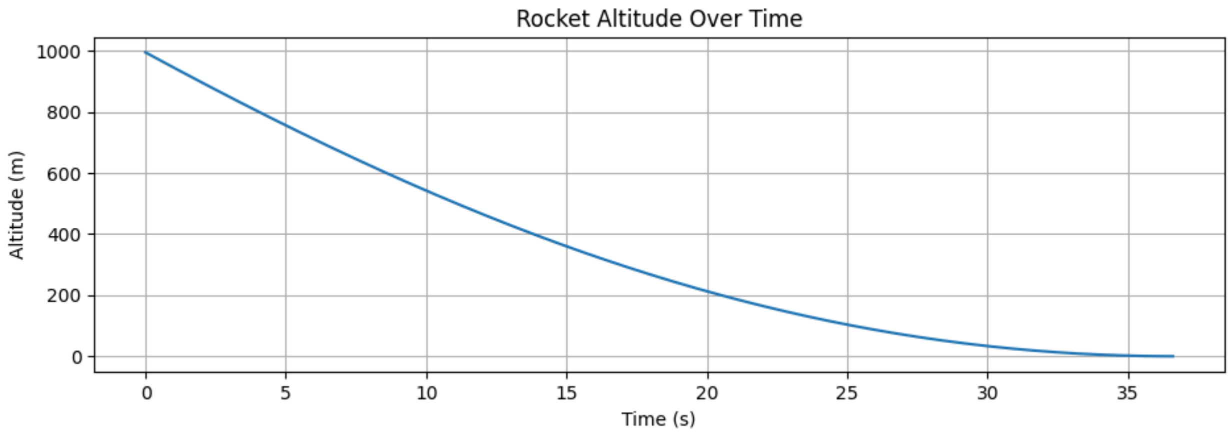

Figure 11: Simulated rocket altitude while landing

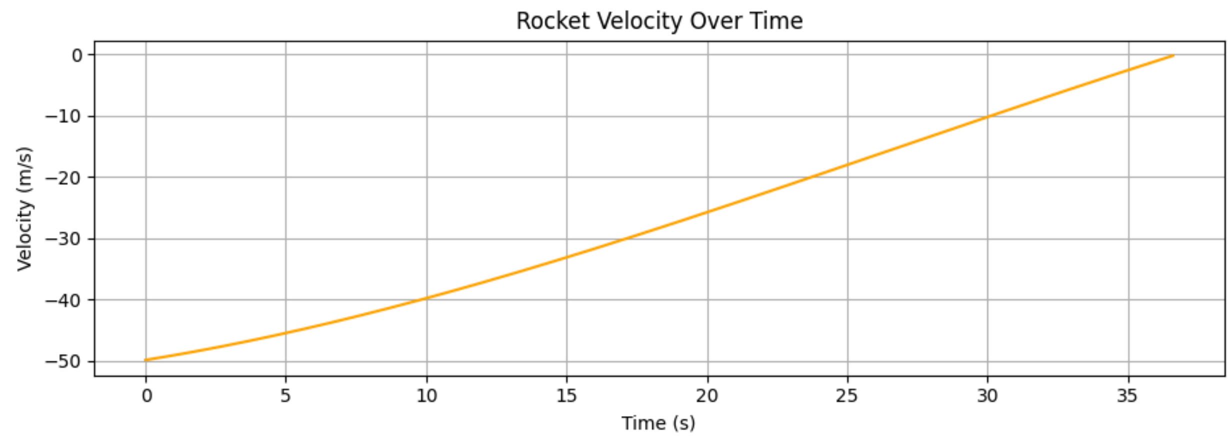

Figure 12: Simulated rocket velocity while landing

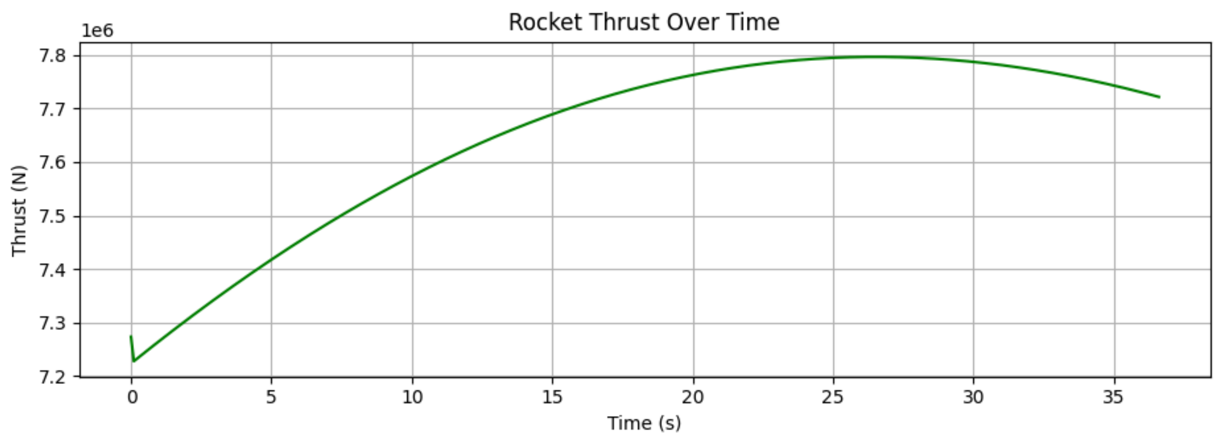

Figure 13: Simulated rocket thrust while landing

Altitude Control Algorithm Design

The control system is based on a Hybrid Controller or Model Predictive Controller (MPC) containing both a model term and an error-driven term. The model term is based on precalculated values known about the object being controlled and its current position, whereas the error-driven Proportional-Integral-Derivative (PID) controller element processes data from accelerometers, tachometers, and altimeters to correct the actual differences between setpoints and real-time measured outputs **[Figure 9]**, **[Figure 10]**. The model calculates the thrust required to maintain the current velocity by accounting for the weight and drag forces known, and the PID algorithm calculates the necessary adjustments to the thrust output to account for all variance from equilibrium. This system has advantages over purely Model Driven approaches as it can account for disturbances during flight to ensure that disturbances cannot accumulate into large errors. This system has advantages over purely error-driven approaches as the model accounts for a majority of the thrust required, and the PID controller can be more narrowly refined to account exclusively for the adjustments to the model **[Figure 11], [Figure 12], [Figure 13]**. This system will likely have a marginally slower refresh rate as compared to either of the previously discussed approaches, however, the increased reliability and performance would consistently outperform the alternatives **[4]**.

The starter code provided the foundations for solving the dynamics problem while leaving the controller open-ended, with a bias towards an open-loop controller with no feedback **[9]**. The solution implemented has the advantage of resilience towards disturbances.

Gimbal Control Algorithm Design

The gimbal control system would be based purely on an error-driven PID controller, which processes data from gyroscopes, accelerometers, magnetometers and an Internal Measurement Unit (IMU) to minimize the error between the current state of the rocket and the neutral vertical position. The PID algorithm calculates the necessary adjustments to the gimbals to maintain vertical alignment and counteract external forces such as wind or drift. This system does not require a model driven element in the current application as it is meant to purely maintain the stability of the flight. If a model were to be implemented in this system, it would be based on a two-dimensional inverted pendulum, for which each axis could be solved independently **[5]**. This kind of extended functionality would allow for horizontal displacement correction, allowing for precise control over the location of landing.

Conclusion

The challenge of safely and efficiently landing a rocket upright is pivotal in advancing reusable spaceflight technology. Our solution integrates three key innovations: gimbal implementation for thrust vector control, landing gear to absorb impact forces and maintain stability, and a redesigned nose cone for improved aerodynamics and sensor integration. Together, these components address the critical design criteria of stability during descent, precision of landing, and effective impact absorption, demonstrating a holistic approach to solving this complex engineering problem.

Challenges and Lessons Learned

Throughout the project, the team faced several challenges, including balancing lightweight designs to durability, ease of simulation and accuracy, and accurately simulating real-world conditions. The team also had to work on parallel development and understanding how one layer of analysis affected the others. For example, as we were performing the Computation Fluid Dynamics, we realized that an error meant that there was a slightly different drag coefficient, and we needed to retune the PID controller for this new value. Many times in industry, this kind of thing will happen, and this experience demonstrates the need for organized planning and coordination for dependent processes.

Overall, these challenges highlighted the fundamentally interdisciplinary nature of many classically-disciplined engineering challenges that occur in industry and research, while underscoring the importance of iterative testing, collaborative development and project planning.

From this experience, we learned to approach engineering problems systematically, breaking them into manageable components and validating each step through simulations. Additionally, we gained insights into how theoretical knowledge translates into practical design considerations.

Contributions

- **Ian Wilhite**: Designed the control algorithms for the landing, ensuring stable descent.
- **Eduardo Burciaga-Ichikawa**: Led the development of the landing gear, including material selection and impact testing, along with running topology and CFD analysis.
- **Kalen Jaroszewski**: Designed and tested the aerodynamic properties of the nose cone, integrating sensors for enhanced feedback.
- **Julia Sopala**: Consolidated data, and ensured alignment of all components with the design criteria and reporting it.

Room for Growth

Looking forward, next steps for the project could include a more in depth comparison of materials and consideration of design for manufacturing of parts, testing the design under more variable environmental conditions, and prototyping scaled physical models for validation. The controllers could be expanded to utilize the varied power between the three thrusters, or to include drag manipulators like flaps. Testing could include further validity testing with the current altitude controller, and implementation of the gimbal controller and full system simulations. In implementing the ideas discussed, this system could become a reliable method for assisting rocket landing accuracy and improving affordability of space missions.

References

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