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GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES



**COMPARISON OF LANDING CONTROL ALGORITHMS FOR
VERTICAL LANDING ROCKETS IN SIMULATION
ENVIRONMENT**

M.Sc. Thesis by

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ANKARA

**COMPARISON OF LANDING CONTROL
ALGORITHMS FOR VERTICAL LANDING ROCKETS
IN SIMULATION ENVIRONMENT**

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the Graduate School of Natural and Applied Sciences of Yıldırım Beyazıt
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by

Ümit KARADAYI

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ANKARA

M.Sc. THESIS EXAMINATION RESULT FORM

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COMPARISON OF LANDING CONTROL ALGORITHMS FOR VERTICAL LANDING ROCKETS IN SIMULATION ENVIRONMENT

ABSTRACT

This study aims to comprehensively compare the performance of different landing algorithms developed for vertical landing rockets in a simulation environment. Vertical landing rockets are of great importance in space missions and other aerospace applications. The successful landing of these rockets depends on the efficiency and accuracy of the control algorithms used. The performance of the landing algorithms plays a critical role, especially in the transition from high speeds to low speeds and in the final stages of the landing. The study addresses four main control methods that affect this performance: PID control, DDPG control, and MPC control approaches. Each algorithm was subjected to various test conditions in different landing scenarios and evaluated in terms of key parameters such as accuracy, fuel efficiency, landing speed, and stability.

The simulation results have identified the strengths and limitations of each algorithm, providing in-depth analyses of which algorithm performs better under specific conditions. These analyses provide significant insights for the future development of rocket landing algorithms. In particular, it has been determined which algorithm is more efficient under certain environmental conditions and which types of missions it offers ideal performance for. The findings of the study aim to contribute to making rocket technology safer, more efficient, and more cost-effective, serving as a resource for the development of landing systems for future vertical landing rockets.

Keywords: Simulation, Rocket, Vertical Landing, Control

DİKEY İNİŞLİ ROKETLERİN İNİŞ ALGORİTMALARININ SİMÜLASYON ORTAMINDA KARŞILAŞTIRILMASI

ÖZ

Bu çalışma, dikey inişli roketler için geliştirilen farklı iniş algoritmalarının performansını kapsamlı bir şekilde simülasyon ortamında karşılaştırmayı amaçlamaktadır. Dikey inişli roketler, uzay görevlerinde ve diğer havacılık uygulamalarında büyük bir öneme sahiptir. Bu roketlerin başarılı bir şekilde yere iniş yapabilmesi, kullanılan kontrol algoritmalarının verimliliğine ve doğruluğuna bağlıdır. İniş algoritmalarının performansı, özellikle yüksek hızlardan düşük hızlara geçiş ve inişin son aşamalarında kritik bir rol oynar. Çalışmada, bu performansı etkileyen temel dört kontrol yöntemi olan PID kontrol, DDPG kontrol, MPC kontrol tabanlı yaklaşımlar ele alınmıştır. Her bir algoritma, farklı iniş senaryolarında çeşitli test koşullarına tabi tutulmuş, doğruluk, yakıt verimliliği, iniş hızı ve stabilite gibi önemli parametreler açısından değerlendirilmiştir.

Simülasyon sonuçları, her bir algoritmanın güçlü yönlerini ve sınırlamalarını belirlemiş, belirli koşullarda hangi algoritmanın daha iyi performans gösterdiğine dair derinlemesine analizler sunmuştur. Bu analizler, roket iniş algoritmalarının gelecekteki gelişimi için önemli çıkarımlar sağlamaktadır. Özellikle, hangi algoritmanın hangi çevresel koşullarda daha verimli olduğu ve ne tür görevler için ideal performans sunduğu belirlenmiştir. Çalışmanın bulguları, roket teknolojisinin daha güvenli, verimli ve düşük maliyetli hale getirilmesine katkıda bulunmayı amaçlamakta olup, gelecekteki dikey inişli roketlerin iniş sistemlerinin geliştirilmesine yön verecek bir kaynak oluşturmaktadır.

Anahtar Kelimeler: Simülasyon, Roket, Dikey İniş, Kontrol

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NOMENCLATURE

CG	Center of Gravity
CP	Center of Pressure
D	Derivative
DDPG	Deep Deterministic Policy Gradient
I	Integral
Mb	Milibar
MPC	Model Predictive Control
P	Proportional
PID	Proportional-Integral-Derivative Controller
TD	Temporal Difference
VTVL	Vertical Takeoff Vertical Landing

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CHAPTER 1

INTRODUCTION

1.1 Definition of Research Topic

Rockets are vehicles that generate their own thrust. The fundamental operating principle of rockets is based on Newton's third law of motion (for every action, there is an equal and opposite reaction). According to this law, when a rocket expels propellant gases in one direction, it causes the rocket to move in the opposite direction.

Rockets can be used for various purposes, including space exploration, military applications, scientific research, and commercial uses. Rocket technology is continually evolving to become more efficient, safer, and more economical. Reusable rockets (such as SpaceX's Falcon 9 and Falcon Heavy) are helping reduce the cost of space flights and contributing to the commercial growth of the space industry[1].

Landing control algorithms for vertical landing rockets are among the most crucial components that ensure the rocket safely and successfully returns to the Earth's surface. These algorithms are designed to address the challenges that the rocket may encounter during the descent process, continuously monitoring and regulating the rocket's position, speed, orientation, fuel levels, and environmental factors. As the rocket grapples with variables such as atmospheric turbulence, gravity, wind speeds, and terrain features, these control algorithms implement various maneuvers to facilitate a safe descent.

Vertical landing rockets have transformed space travel by enabling the reusability of rockets, significantly lowering costs. However, this achievement is contingent upon the precise management of a highly complex landing process. The fundamental goal of landing control algorithms is to ensure a controlled and smooth landing without excessive acceleration or deceleration. To accomplish this, the algorithms constantly track the rocket's speed, position, and orientation, making necessary adjustments based on this data. Additionally, effective fuel management is one of the greatest

challenges during landing, as it is critical to maintain sufficient fuel while avoiding unnecessary maneuvers.

Another important function of landing control algorithms is to accurately direct the rocket to the designated landing area. This is particularly significant for commercial missions and safety reasons, as it is essential for the rocket to land within the specified zone. The algorithms strive to optimize both the accuracy of the landing and to minimize the impact of external factors that may arise during descent. For instance, environmental conditions such as wind and atmospheric pressure are continuously taken into account and dynamically adjusted to ensure a successful landing.

1.2 Problem Definition

The general problems with reusable rockets, or vertical landing rockets, stem from the complexity of the landing process and various technical challenges. For vertical landing rockets to achieve a safe and successful landing, many factors must be carefully managed[2]. The common challenges faced by vertical landing rockets include control, fuel management, soft and precise landing, and environmental factors.

The comparison of landing algorithms for vertical landing rockets in simulation environments is of paramount importance for both the advancement of rocket technology and the achievement of successful and safe landings. This process plays a critical role in testing and optimizing the performance of algorithms, enabling the selection of the most suitable one for real-world conditions.

1.2.1 Safety and Risk Management

Rockets face numerous risks during real-world landings. These risks can stem from external factors such as atmospheric conditions, changes in gravity, wind speeds, fuel depletion, and terrain variations. Simulations allow for the modeling of such scenarios in a safe environment, enabling the testing of different algorithms without jeopardizing the rocket's landing. Actual flight tests can be extremely costly and dangerous, making the testing of landing algorithms in a simulated environment a way to mitigate these risks and ensure safety.

1.2.2 Cost Efficiency

Real rocket testing is highly expensive. The costs associated with fuel for each attempt, testing equipment, and potential damages from failures are significant. Simulations allow rocket engineers to test various algorithms and landing strategies at a lower cost. This enables the selection of the most efficient and effective algorithms before conducting real-world tests, optimizing costs. While hundreds or even thousands of tests can be conducted in a simulation, real-world tests are limited in number.

1.2.3 Flexibility of Environmental Factors

Landing control algorithms must manage various environmental factors. Variables such as atmospheric pressure, wind speeds, temperature fluctuations, gravitational forces, and surface structure directly impact landing algorithms. Simulation environments facilitate the modeling of these environmental factors across a wide range. Testing how algorithms perform under different scenarios enhances preparedness for challenges that may arise during actual landings, allowing for the identification of weaknesses and necessary improvements.

1.2.4 Comparison of Algorithm Performance

Different vertical landing control algorithms have their strengths and weaknesses. For instance, PID (Proportional-Integral-Derivative) control is a simple and effective method but may struggle with complex environmental factors. MPC (Model Predictive Control) provides advanced control but may incur high computational costs. AI-based algorithms like DDPG (Deep Deterministic Policy Gradient) can adapt better to dynamic conditions, although their training processes can be lengthy. In simulation environments, the performance metrics of these algorithms—such as fuel efficiency, landing accuracy, speed control, and maneuverability—can be compared under varying conditions, allowing for the identification of the optimal algorithm based on mission requirements.

1.2.5 Optimization and Improvement Opportunities

Simulations provide opportunities for the continuous improvement of algorithms. After testing algorithms under various scenarios in a simulation environment, shortcomings or weaknesses can be identified. Adjustments can be made based on this feedback, enhancing efficiency. Conducting such optimizations during real flight tests is challenging and costly; however, the iterative process can progress continuously in a simulation environment, leading to more reliable and robust algorithms.

1.2.6 Time Efficiency

Testing vertical landing algorithms in a simulation environment offers significant time advantages. In the real world, a rocket test requires extensive preparation processes and logistical requirements, while simulations eliminate such needs. Rocket engineers can quickly model different scenarios and conduct hundreds of tests in a short timeframe, facilitating faster project progress and accelerating development.

1.2.7 Preparation for Future Missions

Tests conducted in simulation environments yield valuable data for upcoming rocket missions. Especially when developing next-generation rockets and landing systems, safer and more efficient landing strategies can be formulated based on simulation results. This not only contributes to the advancement of current technology but also lays the groundwork for future complex and risky missions.

1.2.8 Multi-Scenario Testing

Simulations allow for the testing of vertical landing algorithms under a variety of scenarios. Variables such as differing gravity conditions (Mars, Moon, or Earth), atmospheric conditions (dense atmosphere, thin atmosphere), and landing surfaces (flat, sloped, rocky) can be simulated. This offers the opportunity to assess how algorithms perform not only on Earth but also on different planets, leading to the development of more reliable landing systems for space exploration and colonization goals.

1.2.9 Conclusion

The comparison of landing algorithms in simulation environments is a critical step in advancing rocket technology. Simulations provide advantages such as safety, cost efficiency, time savings, and environmental flexibility, allowing for faster optimization of algorithms and assessment of their performance under different conditions. This process enables rockets to achieve safe, precise, and fuel-efficient landings, thereby contributing to the furtherance of space exploration and commercial space transportation.

1.3 Purpose of the Research

The aim of this study is to conduct an in-depth analysis of the challenges encountered in vertical landing rockets and to evaluate the effectiveness of the control algorithms used to overcome these challenges. Vertical landing is a significant area in rocket technology, encompassing various technical difficulties essential for achieving safe and precise landings. This research examines the impact of environmental factors in order to understand these challenges and propose potential solutions.

The investigation will address key factors that affect rocket performance under different environmental conditions. These factors include variables such as atmospheric pressure, wind speed, temperature fluctuations, and terrain features. Identifying the effects of such environmental elements on fuel consumption, landing speed, and precision is crucial for the optimization of control algorithms.

The study aims to compare the performance of three distinct control approaches—Model Predictive Control (MPC), Proportional-Integral-Derivative (PID) control, and Deep Deterministic Policy Gradient (DDPG)—under various conditions. Each control algorithm will be analyzed regarding its performance in terms of fuel efficiency, landing speed, and accuracy in reaching the target under specific environmental conditions. This will help determine which control algorithm provides the most suitable solution for particular situations and offer valuable insights for the advancement of vertical landing rockets.

In conclusion, this research seeks to contribute to the assessment of control algorithms necessary for the successful landing of vertical landing rockets and aims to shed light on the future development of rocket technology.

1.4 Importance of the Research

This study holds significant scientific and technological importance for several key reasons. Vertical landing rocket technology plays a crucial role in areas such as space exploration and commercial space transportation. Therefore, advancements and innovations in this field are critical for contributing to both the body of scientific knowledge and industrial applications.

1.4.1 Space Exploration and Reusable Rocket Technologies

Space exploration is one of humanity's future objectives, and vertical landing rockets are central to this endeavor. Reusable rocket technologies have the potential to significantly reduce the costs of space travel. This research aims to optimize vertical landing processes, establishing a foundation for safer and more cost-effective space missions. In this context, improved control algorithms can enhance the success of space operations.

1.4.2 Control Systems and Robotics

The control of vertical landing rockets is directly linked to advancements in robotics and automation. By facilitating the comparison of different control approaches, this study may provide new methods and strategies for enhancing control systems. Scientifically, it will contribute valuable insights to control theory and applications, thereby enriching the existing literature in this domain.

1.4.3 Impact of Environmental Conditions and Adaptive Systems

The research offers a significant framework for understanding the effects of environmental factors on rocket performance. The various environmental conditions encountered during landings necessitate adaptive systems. By examining how control algorithms adjust to environmental variables, this study allows for the development of

more flexible and resilient systems in future designs. From a scientific perspective, this highlights the importance of environmental factors in engineering design processes.

1.4.4 Efficiency and Performance Improvement

Performance indicators such as fuel consumption and landing accuracy are vital for the efficiency of rocket technology. This study analyzes the impact of different control algorithms on fuel efficiency and landing precision, facilitating the development of new strategies for more efficient rocket designs. This not only signifies a scientific advancement but also represents a critical development for industrial applications.

1.4.5 Guiding Insights for the Future

Finally, this research has the potential to provide guiding insights for future space missions. As rocket technology rapidly evolves, every new piece of information can be integrated into engineering and design processes to create safer and more effective systems. This study aims to serve as a valuable reference for researchers and engineers alike.

1.4.6 Conclusion

Finally, this research has the potential to provide guiding insights for future space missions. As rocket technology rapidly evolves, every new piece of information can be integrated into engineering and design processes to create safer and more effective systems. This study aims to serve as a valuable reference for researchers and engineers alike.

CHAPTER 2

LITERATURE REVIEW

2.1 Development of Vertical Landing Rockets

Vertical landing rockets represent a transformative technology in the fields of space exploration and commercial space transportation. These rockets have garnered attention for their potential to reduce costs and enable reusability. Vertical landing is a complex area within rocket technology, and advancements in this field are critical for both scientific and industrial progress[3]. This literature review will examine the historical development of vertical landing rockets, current technologies, and potential future applications.

2.1.1 Historical Development

The foundations of vertical landing rocket technology can be traced back to the mid-20th century. Initial examples emerged as military and scientific endeavors. However, the first practical applications of this technology became evident in the late 1960s and early 1970s. The Apollo program's Lunar Module is a significant example of vertical landing technology, demonstrating the ability to navigate the challenges of landing on the Moon's surface[4].

In the late 1970s and early 1980s, NASA's Space Shuttle program made significant contributions to the advancement of vertical landing rockets. The Shuttle was notable for its capability to land in both atmospheric and space environments. This phase highlighted the potential for reusability in rocket technology, although it faced challenges related to cost and safety.



Figure 2.1 Apollo Lunar Module [5]

2.1.2 Modern Advancements

The early 2000s marked a pivotal shift with the entry of the private sector into the space industry, leading to rapid advancements in vertical landing technologies. SpaceX, in particular, emerged as a prominent player. The development of the Falcon 9 rocket marked a critical milestone in vertical landing capabilities. The Falcon 9 can safely land on ocean-based platforms and designated ground sites, paving the way for reduced costs and increased reusability of rockets[6].

2.1.3 Current Technologies

The applications of vertical landing rockets today are supported by several advanced technologies:

Autonomous Control Systems: Advanced control algorithms, such as Model Predictive Control (MPC), Proportional-Integral-Derivative (PID) control, and Deep Deterministic Policy Gradient (DDPG), are utilized to manage the rocket's position, velocity, and orientation during landing.

Enhanced Sensors: Various sensors, including LIDAR, radar, and GPS, are employed to enable rockets to accurately perceive their environmental conditions. These sensors ensure precise positioning and the safe execution of landing maneuvers.

Reusability: Emerging technologies have significantly enhanced the reusability of rockets. SpaceX's Falcon 9 is designed for reuse after landing, leading to substantial cost reductions. Other companies are also pursuing similar reusable rocket systems.

2.1.4 Impact of Environmental Conditions

The performance of vertical landing rockets is influenced by numerous environmental factors. Variables such as atmospheric pressure, wind speed, temperature fluctuations, and surface characteristics directly affect landing algorithms. Various studies focus on understanding these environmental impacts and propose optimizations for control algorithms to enhance landing performance.

2.1.5 Future Perspectives

Vertical landing rocket technologies are poised to gain further significance in future space missions. Particularly, human missions to Mars and other planets are on the horizon, necessitating the advancement of landing capabilities. Additionally, increased competition in the commercial space transportation sector is expected to drive rapid technological innovations.

2.1.6 Conclusion

The history of vertical landing rockets is intertwined with humanity's aspiration to explore space. Today's technology reflects this historical evolution, with expectations for continued advancements in the future. These developments will contribute to a greater understanding of our place in the universe and enhance the efficiency and safety of space travel. The ongoing evolution of vertical landing rocket technology is a critical step for both space exploration and commercial space endeavors.

2.2 Landing Algorithms Used Today

Vertical landing rockets play a crucial role in space exploration and commercial space transportation. The ability of these rockets to land safely and accurately relies on the effective use of advanced control algorithms. Vertical landing presents various technical challenges in space travel; therefore, a thorough examination of the methods

developed to overcome these challenges is essential. This paper aims to delve into the control algorithms commonly employed in vertical landing rockets.

2.2.1 Proportional-Integral-Derivative (PID) Control

PID control is one of the most widely used methods in automatic control systems. PID control algorithms play a significant role in ensuring stability during the landing process of vertical rockets. However, their performance may be limited under complex environmental conditions and requires specific tuning parameters. Particularly, during unexpected situations like atmospheric turbulence, the effectiveness of PID control can diminish. Consequently, the limitations of PID control have paved the way for the development of more advanced algorithms[7].

2.2.2 Model Predictive Control (MPC)

Model Predictive Control (MPC) is a frequently employed strategy for controlling dynamic systems. This method utilizes a model to predict the future behavior of the system and determines the optimal control action over a defined time horizon. MPC is capable of optimizing solutions in multivariable systems while considering constraints, aiding in determining the best landing trajectory based on various factors (speed, position, environmental conditions). A key advantage of MPC is its ability to optimize predefined constraints, ensuring the rocket's safe landing. However, its high computational cost may pose challenges for real-time applications[8].

2.2.3 Fuzzy Logic Control

Fuzzy logic control emerges as an effective method for systems characterized by uncertainty and complexity. This algorithm simulates a decision-making process akin to human intelligence. In vertical landing rockets, fuzzy logic control provides a viable solution to manage uncertainties, such as variations in atmospheric conditions. This approach enhances the flexibility of control algorithms and allows for adaptation to environmental factors. Instead of providing a definite solution for a given condition, fuzzy logic offers probabilistic solutions. Thus, fuzzy logic control plays an essential role in mitigating uncertainties that rockets may encounter during landing.

2.2.4 Machine Learning and Deep Learning-Based Algorithms

In recent years, machine learning and deep learning-based algorithms have gained significant traction in control methods for vertical landing rockets. These algorithms optimize control strategies by learning from large datasets. Specifically, deep learning techniques have led to the development of intelligent control systems capable of adapting to landing conditions. Such algorithms possess the potential to improve their performance over time by learning from past experiences. Machine learning allows for continuous updates to a particular control strategy, enabling rapid responses to environmental changes.

2.2.5 Deep Deterministic Policy Gradient (DDPG)

DDPG is an algorithm utilized in reinforcement learning, effective in continuous action spaces. In the context of vertical landing rockets, DDPG enables the rocket to simulate various scenarios and learn the optimal landing strategies. This algorithm comprises two primary components: the actor and the critic. The actor determines which action to take in a given state, while the critic evaluates the expected value of that action. DDPG stands out for its ability to adapt quickly to environmental changes, contributing to improved performance in different landing conditions. Its suitability for dynamic situations makes it an ideal control algorithm for vertical landing rockets[9].

2.2.6 Adaptive Control

Adaptive control refers to a method that can respond to changes in system dynamics. In vertical landing rockets, adaptive control algorithms are critical, considering factors such as changes in atmospheric conditions or deviations in rocket position. These algorithms continuously update system parameters to determine the most suitable control actions. Adaptive control serves as a vital tool for managing uncertainties encountered during the rocket's landing process.

2.2.7 Sliding Mode Control

Sliding mode control is a technique used to manage dynamic systems, ensuring that the system remains within a specified state range. In vertical landing rockets, sliding mode control is employed to maintain the rocket on a defined landing path. This approach increases the system's resistance to external disturbances while guaranteeing that it reaches the desired target. One of the key advantages of sliding mode control is its enhanced robustness to sudden changes in system dynamics, which is essential for dealing with unexpected situations during landing.

2.2.8 Genetic Algorithms

Genetic algorithms are optimization techniques inspired by evolutionary processes in nature. These algorithms develop the best solutions through an evolutionary process toward a specific objective. In vertical landing rockets, genetic algorithms can be used to optimize control strategies and determine the most effective landing trajectories. This method allows for the exploration of a wide range of solutions through trial and error, facilitating the rockets' adaptation to various environmental conditions.

2.2.9 Linear Quadratic Regulator (LQR)

LQR is part of optimal control methods aimed at minimizing system dynamics. In vertical landing rockets, LQR helps determine optimal control actions for the rocket's maneuvers. This algorithm minimizes a predefined cost function, ensuring that the rocket reaches its desired goal. LQR is typically effective for simpler and deterministic systems. However, as system complexity increases, the performance of LQR may decline, necessitating integration with more sophisticated control methods.

2.2.10 Reinforcement Learning

Reinforcement learning is based on an interaction process between an agent and its environment. The agent learns which actions yield better outcomes by receiving rewards or penalties from its surroundings. In vertical landing rockets, reinforcement learning algorithms can aid the rocket in determining the most suitable control strategies during the landing process. This method allows the rocket to leverage real-

time data to identify optimal control actions. Particularly, reinforcement learning proves effective in dynamic and uncertain environments.

2.2.11 Conclusion

The control algorithms used in vertical landing rockets are vital for achieving safe and effective landings in space exploration. While each algorithm possesses unique advantages and limitations, all contribute to the rockets' capability to manage complex landing scenarios. The development of these algorithms will aid future space missions and lay the groundwork for innovative approaches in the field of space exploration.

This literature review presents a general framework of control algorithms, illuminating the advancements in vertical landing rocket technology. Future studies will require further research and development to enhance the performance of these algorithms and create safer, more efficient rocket systems. In this context, the integration of multiple control strategies may lead to improved outcomes in complex landing scenarios, ultimately opening new horizons in the realm of space exploration and transportation.

2.3 Simulation Environment Used Today

Simulation technologies play a vital role in the field of aerospace engineering, providing engineers and researchers the ability to model, analyze, and optimize rocket landings. These technologies are critical tools that allow for the assessment of various scenarios while minimizing risks and costs, effectively evaluating rocket performance before real-world testing. This literature review examines the software and tools used to simulate rocket landings, emphasizing their importance in enhancing the reliability and safety of rocket technology.

2.3.1 Importance of Simulation in Rocket Landings

Simulations are essential for understanding the complex dynamics involved in rocket landings. Through simulations, engineers can:

Conduct Performance Analysis: By modeling different landing scenarios, they can evaluate the impact of various factors such as atmospheric conditions, terrain types, and rocket configurations on landing performance.

Optimize Control Algorithms: Simulations allow for the testing of control algorithms to develop safe and efficient landing strategies.

Reduce Costs and Risks: Physical testing can be extremely costly and risky; simulations eliminate the need for such tests, offering a cost-effective alternative.

2.3.2 Software Used for Simulations

Several software tools are available for simulating rocket landings. Among the most widely used are:

MATLAB/Simulink: A powerful tool for mathematical modeling and simulation, MATLAB is commonly used in aerospace applications. It enables the creation of dynamic models for rockets, simulating their behavior during landing, and analyzing control algorithms. When used in conjunction with Simulink, it simplifies the simulation of dynamic systems.

ANSYS Fluent: This software is a computational fluid dynamics (CFD) tool used to analyze airflow around rockets during landing. By simulating aerodynamic forces, engineers can optimize rocket designs. ANSYS can also be utilized for structural analysis across various physical parameters.

OpenRocket: An open-source software designed for model rocket simulations. It allows users to model rocket flights and analyze performance parameters. Its user-friendly interface makes it popular among both amateur and professional rocket designers.

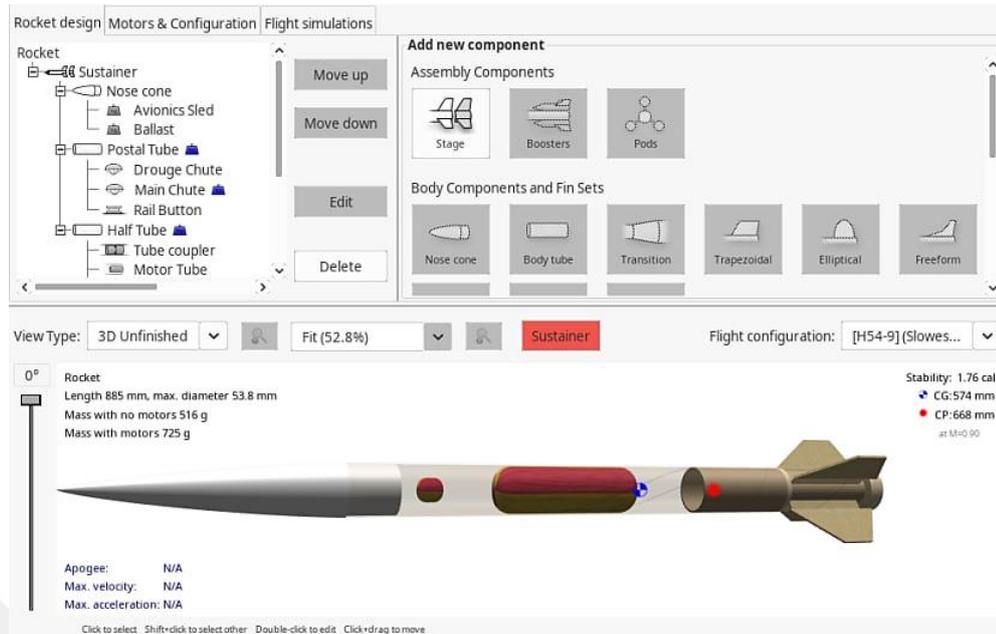


Figure 2.2 Open Rocket Simulation Environment

Gazebo: A 3D robot simulator that integrates with ROS (Robot Operating System). It provides a realistic physics engine for simulating the dynamics of rockets in a virtual environment. Gazebo offers a wide range of applications for sensor data integration and robotic simulations.

COMSOL Multiphysics: This software allows for the modeling of various physical phenomena and is suitable for simulating thermal, structural, and fluid dynamics interactions during rocket landings. Users can analyze multiple physics scenarios together to evaluate overall system performance.

Unity 3D: Known primarily for game development, this engine can also be utilized for rocket simulations. Unity offers a powerful platform for creating real-time graphics and interactive simulations. Users can combine visual and simulation experiences to present rocket landings in an engaging and realistic manner. Additionally, it provides opportunities for virtual reality (VR) and augmented reality (AR) applications, adding an innovative dimension to training and simulation processes.

2.3.3 Simulation Approaches

Various simulation approaches can be employed to study rocket landings. These include:

Numerical Simulations: These methods involve solving mathematical models representing physical dynamics, often utilizing finite element analysis (FEA) and finite volume methods (FVM). They are used to investigate the aerodynamic and structural behavior of rockets.

Real-Time Simulations: These simulations allow for the interactive testing of control algorithms under various conditions. Models integrated with real-time data enable the dynamic evaluation of landing strategy performances.

Monte Carlo Simulations: This statistical method helps analyze the probabilities of success by simulating numerous random variables across landing scenarios. It is particularly beneficial in situations with high uncertainty.

Agent-Based Modeling: This technique simulates the behavior of individual components (e.g., rocket systems, environmental factors) to understand their interactions. Such models are useful for analyzing strategies that affect landing outcomes.

2.3.4 Hardware and Software Integration

The integration of hardware and software is a technique that combines hardware with simulation software. In the context of rocket landings, this method allows for the merging of real control systems with virtual models. This enables engineers to validate and test control algorithms against real-time scenarios.

2.3.5 Challenges in Rocket Landing Simulations

While simulation technologies offer significant advantages, they also present several challenges:

Model Accuracy: It is crucial to create models that accurately represent the complex dynamics of rocket landings. Simplifications or inaccuracies in the model can lead to misleading results.

Computational Resources: High-quality simulations often require substantial computational power and time, potentially limiting the number of scenarios that can be tested.

Verification and Validation: Ensuring that simulation results are consistent with real-world data is critical. This necessitates comprehensive verification and validation processes, which can be time-consuming.

2.3.6 Conclusion

Simulation technologies are indispensable tools for understanding and optimizing rocket landings. By providing a safe and cost-effective environment to test various scenarios, these technologies enhance the safety and reliability of rocket missions. Future advancements, particularly in real-time capabilities and model accuracy, will further improve the effectiveness of rocket landing simulations. As the space industry continues to evolve, the role of simulations in successful and secure rocket landings will remain a critical area for research and development.

CHAPTER 3

THEORITICAL BACKGROUND

3.1 Physical Dynamics of the Rocket

The vertical landing of rockets is becoming increasingly important in space exploration and commercial space transport. Controlling the landing of a rocket involves not only advanced technology but also a thorough understanding of the physical forces at play. During a vertical descent, rockets are influenced by various forces such as gravity, atmospheric drag, thrust, and other environmental factors. In this article, we will explore the primary physical forces that rockets encounter during vertical landing[10].

3.1.1 Gravitational Force

The most fundamental force affecting rockets during vertical descent is gravity. As a rocket descends toward the Earth's surface, gravity constantly applies a downward acceleration. The gravitational force depends on the rocket's mass and is expressed by the following equation:

Table 3.1 Gravitational Force Equation

$F = m \times g$	<i>F</i> is the gravitational force (in Newtons)
	<i>m</i> is the rocket's mass (in kilograms)
	<i>g</i> is the gravitational acceleration (approximately 9.81 m/s ² on Earth)

Gravity accelerates the rocket downward, and without counteracting this force, the rocket would accelerate uncontrollably, resulting in a crash. To ensure a safe landing, the rocket must generate a counteracting thrust force to slow its descent [11].

3.1.2 Atmospheric Drag

Atmospheric drag is the resistance a rocket experiences as it moves through the Earth's atmosphere. As the rocket descends, it collides with air molecules, creating a drag

force that opposes its motion. The magnitude of this drag force depends on the rocket's speed, its surface area, and the air density. The equation for drag force is:

Table 3.2 Atmospheric Drag Equation

$F_d = \frac{1}{2} \rho v^2 C_d A$	<i>F_d</i> is the drag force (in Newtons)
	<i>ρ</i> is the air density (in kg/m ³)
	<i>v</i> is the rocket's velocity (in m/s)
	<i>C_d</i> is the drag coefficient
	<i>A</i> is the cross-sectional area of the rocket (in m ²)

As the rocket approaches the surface, the increasing air density amplifies the drag force, which helps to decelerate the rocket. However, this force varies as the rocket passes through different altitudes, making it a dynamic component that must be managed throughout the descent[12].

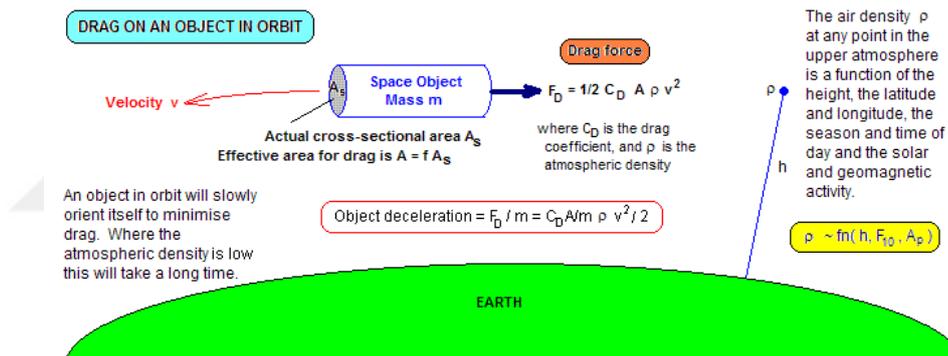


Figure 3.1 Atmospheric Drag [13]

3.1.3 Thrust Force

Thrust is one of the most critical forces in the vertical landing of rockets. The rocket's engines produce thrust, which counteracts gravity and slows the rocket's downward motion. Thrust is generated by the rapid expulsion of combustion gases from the rocket's engines, as described by Newton's third law of motion:

Table 3.3 Thrust Force Equation

$F_t = \dot{m} v_e$	<i>F_t</i> is the thrust force (in Newtons)
	<i>ṁ</i> is the mass flow rate of the expelled fuel (in kg/s),
	<i>v_e</i> is the exhaust velocity (in m/s).

In vertical landing, thrust must be carefully adjusted to ensure the rocket does not descend too quickly or rise uncontrollably. Precision in regulating thrust is essential for a safe, soft landing.

3.1.4 Aerodynamic Forces and Stability

Aerodynamic forces arise from the interaction between the rocket's surface and air molecules. These forces can influence the rocket's stability during descent. The primary aerodynamic forces include,

Lift Force: Under certain conditions, lift can develop due to the rocket's shape and velocity. While lift is typically associated with horizontal flight, it can affect the rocket's stability during vertical descent.

Lateral Wind Forces: Side winds can introduce lateral forces that push the rocket off course during landing. Managing these forces is crucial to maintaining landing accuracy.

3.1.5 Kinetic and Potential Energy

During a vertical descent, the rocket's kinetic and potential energy constantly shift. At higher altitudes, the rocket possesses significant potential energy due to its height. As it descends, this potential energy converts into kinetic energy, increasing the rocket's velocity. The equation for kinetic energy is:

Table 3.4 Kinetic Energy Equation

$E_k = \frac{1}{2} m v^2$	<p>E_k is the kinetic energy (in Joules)</p> <p>m is the rocket's mass (in kilograms)</p> <p>v is its velocity (in m/s)</p>
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The engines must counteract this energy transformation by reducing the rocket's kinetic energy to ensure a controlled descent. Managing this balance of energy is key to a successful landing.

3.1.6 Reaction Forces from the Landing Surface

The surface onto which the rocket lands also plays a role in the dynamic forces at work. The characteristics of the landing surface, such as its rigidity, incline, and structure, can influence the rocket's touchdown. When the rocket makes contact with the ground, reaction forces from the surface counter the rocket's downward motion. A smooth, even surface helps distribute these forces evenly, ensuring a stable landing.

3.1.7 Conclusion

The vertical descent of rockets is a complex interplay of various physical forces, including gravity, atmospheric drag, thrust, and aerodynamic effects. Understanding the dynamics of these forces is essential for developing effective landing strategies. The combination of precise thrust control, aerodynamic management, and energy regulation ensures that modern rockets can achieve soft, controlled landings. Advances in simulation technology and engineering solutions have further enhanced our ability to analyze and optimize these forces, paving the way for safer and more efficient vertical landing systems.

3.2 Overview of Rockets

Rockets are complex vehicles that serve a variety of purposes, and their physical structure can be broken down into several main components. The primary sections include the nose cone, the body, and the fins. The nose cone, located at the top, is typically aerodynamic, designed to minimize air resistance during flight. In some cases, the nose may house important instruments or equipment, such as sensors, navigation systems, or even payloads like satellites or scientific instruments. The body, or fuselage, is the central part of the rocket, often containing fuel tanks, internal systems, and support structures for the payload. It is designed to be strong and lightweight, often made from advanced materials like aluminum alloys or carbon composites to endure the immense pressures and stresses experienced during launch and flight[14].

The fins, typically located near the base of the rocket, help stabilize the vehicle in flight. They are especially crucial during the initial ascent through the atmosphere,

where aerodynamic forces play a significant role in maintaining a stable trajectory. The fins may be fixed or adjustable, with some modern rockets utilizing sophisticated control surfaces that can be moved by onboard systems to correct the rocket's flight path dynamically.

In addition to these structural components, rockets are equipped with a propulsion system that drives them skyward. This propulsion system is centered around the motor section, which houses the engines and fuel delivery mechanisms. Rockets may use either solid or liquid fuel, depending on their design and mission requirements. Solid rocket motors are simpler and typically used in booster stages or smaller rockets, while liquid-fueled engines are more complex but offer greater control and efficiency, especially for long-duration missions.

At the heart of the propulsion system is the nozzle, a critical component that directs the flow of exhaust gases to generate thrust. The shape and design of the nozzle are crucial for optimizing performance, ensuring that the rocket maximizes its acceleration and efficiency during flight. The control of thrust is managed by the nozzle in conjunction with the avionics systems, which monitor and adjust the rocket's performance in real time. These avionics systems include sensors, flight computers, and navigation equipment that allow the rocket to follow a precise trajectory, making necessary adjustments along the way.

Depending on the mission, a rocket may also carry a payload, which could range from scientific instruments and communication satellites to more specialized cargo such as humans, space exploration rovers, or even explosives for military purposes. Payloads are typically housed in a separate section at the top of the rocket and are carefully integrated into the design to ensure they reach their intended destination safely and efficiently. The payload capacity and configuration of a rocket often dictate its overall design and launch profile, making it a key consideration in mission planning[15].

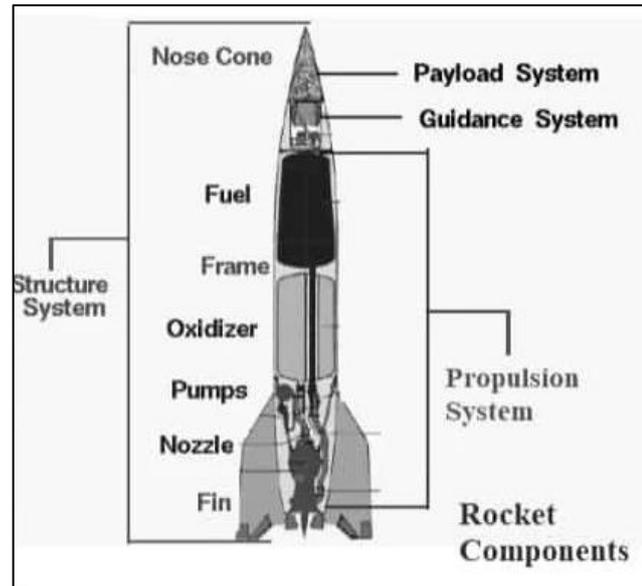


Figure 3.2 Basic Hybrid Rocket Parts

3.2.1 Nose Cone

The nose cone is an essential structural element located at the very front of the rocket. Its primary role is to enhance the aerodynamic efficiency of the rocket as it travels through the atmosphere. This is achieved by minimizing air resistance, also known as drag, which can significantly slow down the rocket if not properly managed. The aerodynamic shape of the nose cone allows the rocket to cut through the air more smoothly, reducing the amount of force acting against its forward motion. This reduction in drag is crucial for allowing the rocket to reach high speeds, which is often a necessary condition for successful space missions or even for military or commercial uses such as satellite launches[16].

In addition to its aerodynamic benefits, the nose cone also serves as a protective structure. It shields the delicate payload housed within the rocket from the intense forces and environmental conditions experienced during the initial stages of launch and the passage through the atmosphere. These forces include high temperatures due to air friction, as well as significant pressures caused by rapid changes in altitude and speed. Without the protective barrier provided by the nose cone, the sensitive equipment, instruments, or human passengers inside the payload would be at risk of damage.

The design of the nose cone is a highly specialized process, tailored to the specific mission requirements and performance goals of the rocket. There are several standard types of nose cone shapes, each offering unique aerodynamic properties. One of the most common is the Tangent-Ogive shape, which is designed for minimal drag at high speeds. This design is often used in rockets where reaching high velocities in a short amount of time is critical. The smooth curvature of the Tangent-Ogive shape helps the air flow over the rocket without creating significant turbulence, thereby reducing drag.

Another common design is the Elliptical nose cone, which features a more rounded profile. This shape is often preferred in subsonic and transonic flight regimes, where the airflow is not as extreme as it is in supersonic conditions. The Elliptical design provides a balance between aerodynamic efficiency and ease of manufacturing, making it suitable for a wide range of rocket types, especially those used for atmospheric flight or launching lighter payloads.

The Parabolic nose cone is another popular design, known for its effectiveness at even higher speeds, including supersonic and hypersonic flight. The Parabolic shape tapers more sharply towards the tip, allowing it to better handle the shock waves that form when a rocket surpasses the speed of sound. This design is particularly beneficial for long-range missiles or space-bound rockets, where maintaining high speeds while minimizing air resistance is essential for success.

Additionally, modern rockets may incorporate advanced materials into the construction of the nose cone, such as lightweight composites, ceramics, or heat-resistant alloys. These materials not only help to reduce the overall mass of the rocket, allowing for greater payload capacity, but they also provide enhanced protection against the extreme temperatures generated during high-speed flight. For example, in missions where re-entry into Earth's atmosphere is required, such as crewed space missions, the nose cone is often equipped with specialized thermal protection systems to prevent burning up due to intense frictional heating.

In some cases, the nose cone is also designed to detach or jettison during different stages of the flight, revealing the payload inside once the rocket has passed through the densest layers of the atmosphere. This further reduces the weight and drag,

improving the rocket's overall performance as it continues its journey into space. Depending on the mission, the nose cone may house communication arrays, scientific instruments, or even crew capsules, making it a critical part of the rocket's overall design..

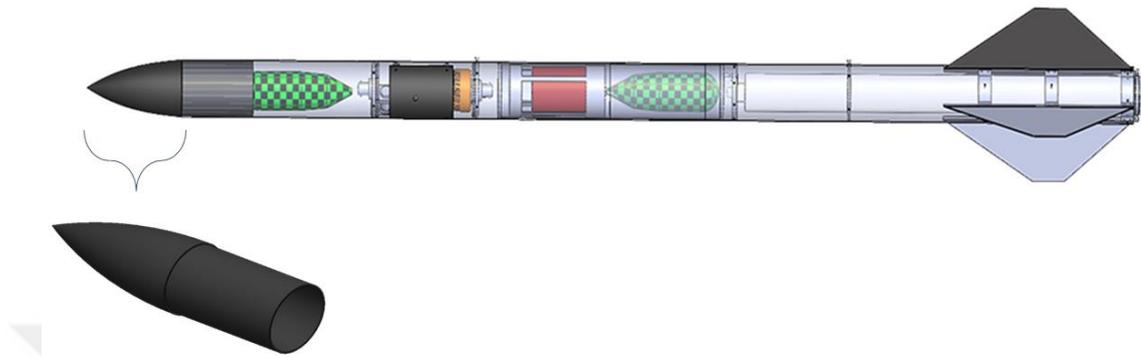


Figure 3.3 Simple Rocket Design, Rocket Nose Cone

3.2.2 Rocket Body

The body of the rocket forms the main structure that holds all the other physical components together. It is responsible for maintaining the rocket's structural integrity, which is crucial for ensuring proper flight. Given the intense forces and environmental conditions the rocket is subjected to during launch and flight, the body must be durable and robust. It acts as the primary frame supporting the internal systems, fuel tanks, engines, and payload, allowing the rocket to function as a cohesive whole.

During launch, the thrust generated by the rocket motor typically acts on the entire body. This thrust accelerates the rocket upwards through the atmosphere, while also testing the body's structural strength. Proper transmission of this thrust is essential for the rocket to maintain a stable trajectory and follow its planned flight path. The body must withstand not only the powerful thrust generated by the engines but also external forces like gravity, atmospheric pressure, and air drag, all while maintaining structural integrity.

The body is usually made from lightweight yet strong materials. Aluminum alloys, titanium, carbon fiber composites, and other advanced materials are commonly used

in modern rocket bodies. These materials help keep the weight of the rocket to a minimum while ensuring it remains structurally sound. A lighter body allows for more fuel and payload to be carried, thereby increasing the rocket's range and capacity. The body's design is typically aerodynamically optimized, minimizing air resistance to maximize acceleration and fuel efficiency.

In addition to being a structural frame, the body also serves to carry and protect other critical components. Inside the body, fuel tanks, engines, avionics systems, and other equipment are housed. The body ensures these components are securely mounted and able to withstand extreme pressures, vibrations, and temperature fluctuations during flight. The robust structure of the body guarantees that these systems function properly, and that the payload is transported safely.

Depending on the mission requirements, the rocket's body may consist of multiple sections. For instance, in multi-stage rockets, each stage has its own body section, and these sections separate as each stage is completed. The modularity of the body enhances the rocket's efficiency, as each stage is jettisoned after use, reducing weight and allowing the remaining sections to reach higher speeds.

In some cases, the rocket's body is designed with reusability in mind. This is a key feature in modern rockets like SpaceX's Falcon series. The body is built to withstand re-entry into the atmosphere and vertical landing so that it can be reused in future launches. This reduces costs and marks a significant step toward a more sustainable space program.

The body also provides protection against external factors. As the rocket ascends into higher altitudes, it encounters extreme temperatures and pressure differences. The body must be able to withstand these conditions to ensure the rocket and its payload can successfully complete the mission. In some cases, the body also serves as a housing area for landing systems, such as landing legs or parachutes.

In conclusion, the rocket's body is not only a structure that holds all components together but also balances all the forces encountered during flight, optimizes

aerodynamic performance, and protects critical systems. The durability and lightness of the body play a vital role in the success of modern rocket technology[17].

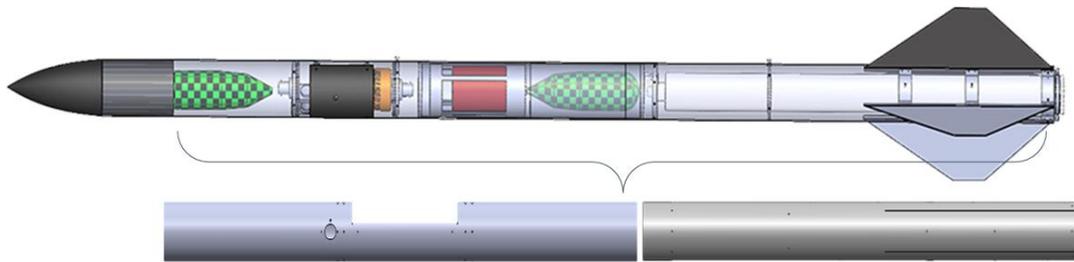


Figure 3.4 Simple Rocket Design, Rocket Body

3.2.3 Fins

Fins are aerodynamic surfaces located at the rear of the rocket and play a crucial role in the overall stability and control of the vehicle during flight. These surfaces are designed to ensure that the rocket remains stable as it moves through the atmosphere, preventing unwanted spinning or veering off course. Stability is a key factor in rocket performance, especially during the initial stages of flight when the rocket is accelerating through the atmosphere and subjected to various forces like wind, drag, and gravity. Without fins or similar stabilizing elements, the rocket's flight path could become erratic, making it difficult to reach its intended destination.

Fins are designed to control specific types of movement, particularly yaw and pitch. Yaw refers to the side-to-side movement of the rocket, while pitch refers to its up-and-down movement. By controlling these movements, the fins help to keep the rocket aligned with its intended trajectory. This ensures a smooth flight, allowing the rocket to efficiently reach higher altitudes or even enter space without unnecessary deviations from its course.

In many rockets, the fins are movable, functioning as active control surfaces that adjust in response to real-time data collected by the rocket's onboard navigation systems. These systems continuously monitor the rocket's position and orientation, sending signals to the fins to make slight adjustments as needed. For example, if the rocket begins to drift slightly off course due to atmospheric conditions or mechanical

disturbances, the fins can be angled in a way that corrects the trajectory and brings the rocket back on track. This type of active control is essential for precision in space missions or military applications where the rocket needs to follow a specific flight path with minimal margin for error.

In addition to controlling yaw and pitch, fins help counteract the forces of drag, which are most prominent during the rocket's ascent through the lower layers of the atmosphere. By providing a stabilizing force, fins reduce the likelihood of the rocket experiencing excessive drag-induced vibrations or turbulence. This helps maintain the integrity of the rocket's structure and ensures that it flies as efficiently as possible.

There are several different designs for fins, each optimized for different flight conditions and rocket types. One common design is the triangular fin, which is simple and effective in providing stability at subsonic speeds. Triangular fins are often used in smaller rockets or rockets that do not require complex control systems. These fins are fixed and provide passive stabilization by creating aerodynamic forces that naturally keep the rocket aligned[18].

For rockets that travel at supersonic or hypersonic speeds, more sophisticated fin designs are needed. Delta fins or swept-back fins are commonly used in such cases because they provide better control at higher velocities. These fins are typically larger and have a more pronounced angle, allowing them to handle the intense aerodynamic forces that come with high-speed flight. Additionally, these fins are often constructed from advanced materials like carbon composites or heat-resistant alloys, which help them withstand the extreme temperatures generated by friction with the air at such high speeds.

In some modern rockets, the fins are not only used for in-flight stability but also play a role in re-entry and landing. For example, in reusable rockets like SpaceX's Falcon 9, grid fins are deployed during re-entry to help guide and stabilize the rocket as it descends back to Earth. These grid fins, which are more intricate and complex in design than traditional fins, act like aerodynamic brakes, allowing the rocket to control its descent and position itself correctly for a safe landing. This ability to reuse rockets

has revolutionized the aerospace industry, and fins have been a key component in enabling such advancements.

Overall, fins are an integral part of a rocket's design. They work in conjunction with other control systems, such as gyroscopes and thrust vectoring, to ensure that the rocket flies smoothly and reaches its target destination. Whether they are fixed or movable, fins play a vital role in maintaining stability, controlling direction, and ensuring the overall success of the mission.

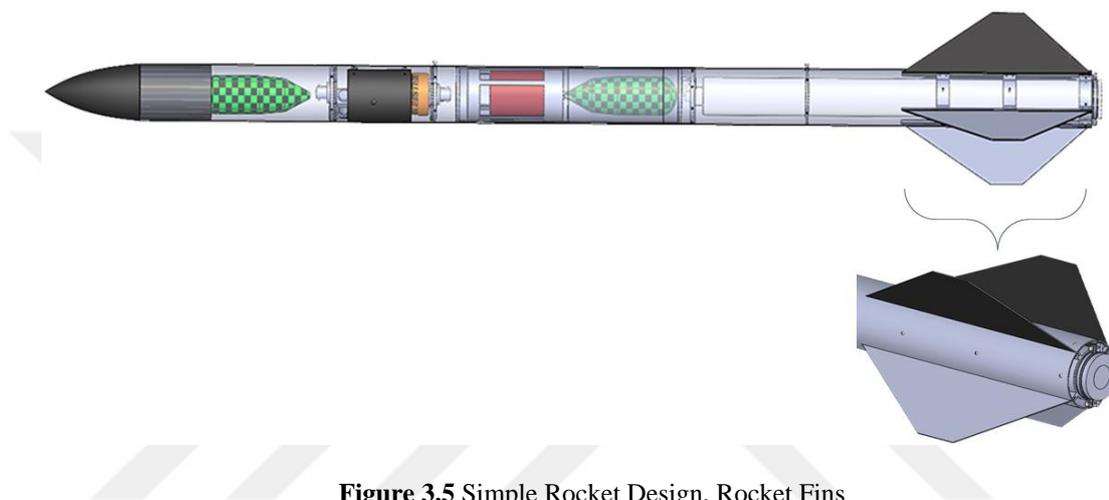


Figure 3.5 Simple Rocket Design, Rocket Fins

3.2.4 Engine

A rocket engine is an advanced and highly complex device that generates the immense thrust required to propel a rocket into space or through the atmosphere. It stands as one of the most crucial components of a rocket, responsible for converting stored energy in the form of fuel into kinetic energy, allowing the rocket to overcome Earth's gravity and reach its intended destination. The primary function of a rocket engine is to produce thrust, which it achieves by either burning fuel in a chemical reaction or expelling a reaction mass at incredibly high speeds. This process is rooted in Newton's third law of motion, which states that for every action, there is an equal and opposite reaction. In the context of a rocket engine, the high-speed ejection of exhaust gases out of the engine nozzle creates a reactive force in the opposite direction, pushing the rocket forward.

The working principle of a rocket engine is based on the controlled combustion of fuel, typically a combination of propellant chemicals such as liquid oxygen (oxidizer) and kerosene (fuel), or in some cases, hydrogen and oxygen for more advanced engines. This fuel mixture is ignited within the combustion chamber, producing extremely high-temperature gases. These gases expand rapidly and are forced out through the engine's nozzle at supersonic speeds, generating the thrust necessary to launch the rocket. The precise engineering of the combustion chamber and nozzle is critical for ensuring that the exhaust gases are expelled efficiently, maximizing thrust while minimizing waste.

Rocket engines are categorized into different types, depending on the nature of the propellant used and the method of expelling reaction mass. The most common type is the chemical rocket engine, which relies on the chemical energy stored in propellant fuel. Chemical rockets are further divided into liquid and solid rocket engines, each with its specific applications and benefits[19].

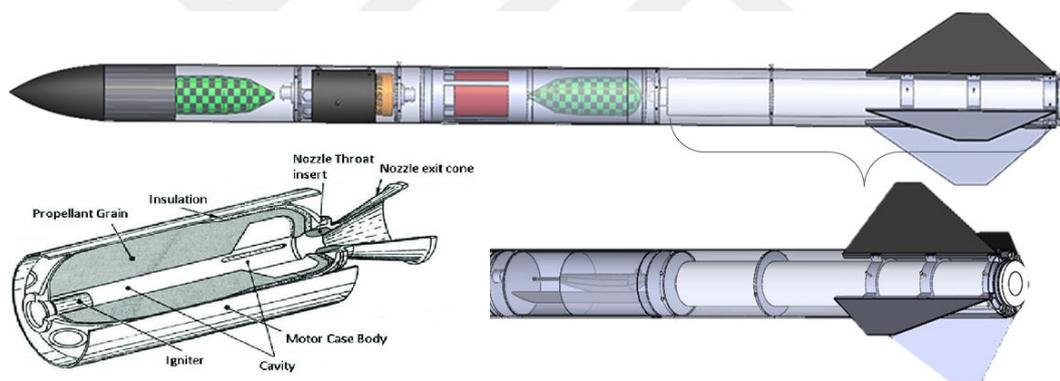


Figure 3.6 Simple Rocket Design, Solid Rocket Engine

3.2.5 Avionics & Guidance

The term "avionics" refers to the electronic control systems of a rocket, encompassing a wide range of critical subsystems that work together to ensure the rocket's proper functioning during flight. These systems are not just passive instruments but are at the core of the rocket's ability to navigate, control, communicate, and respond to changing conditions in real-time. The avionics systems include computers, sensors,

communication devices, and navigation systems, all of which play an essential role in the successful execution of the rocket's mission.

At the heart of a rocket's avionics is its flight computer, which acts as the brain of the entire system. This computer is responsible for processing vast amounts of data collected from onboard sensors and external sources, making split-second decisions that affect the rocket's flight path, orientation, and operation of other subsystems. The flight computer runs sophisticated algorithms that control key functions such as guidance, navigation, and control (GNC), which ensure that the rocket remains on course, compensating for any deviations that may arise during the ascent or descent phases.

One of the primary functions of avionics systems is data collection. A variety of sensors installed throughout the rocket continuously gather data on various parameters, including altitude, velocity, pressure, temperature, and structural stress. These sensors also measure the rocket's attitude, or orientation in space, which is crucial for maintaining a stable flight trajectory. Data from gyroscopes, accelerometers, and inertial measurement units (IMUs) is fed into the flight computer to determine the rocket's precise position and velocity at any given moment. By continuously monitoring these parameters, the avionics system ensures that the rocket stays on its designated flight path, making adjustments when necessary to account for environmental factors such as wind, atmospheric drag, or variations in engine performance.

One of the most important tasks performed by the avionics system is guidance. The guidance system is responsible for determining the optimal flight trajectory to ensure that the rocket reaches its target, whether that target is a specific orbit, a lunar landing site, or a rendezvous point in deep space. The guidance algorithms take into account factors like fuel efficiency, aerodynamic forces, and gravitational influences, calculating the necessary adjustments to the rocket's course to ensure mission success. This process is dynamic, requiring constant updates and recalculations as the rocket moves through different phases of flight and encounters varying conditions.

The navigation system within the avionics suite works hand-in-hand with guidance, providing the flight computer with real-time data on the rocket's current position, speed, and orientation. Navigation systems typically rely on a combination of inertial navigation (which uses accelerometers and gyroscopes to track the rocket's movement) and external reference systems such as GPS or ground-based tracking stations. These systems are vital for determining where the rocket is in relation to its planned flight path and making sure it is heading in the right direction. In some missions, particularly those involving space exploration, onboard navigation systems may also need to perform advanced calculations to account for gravitational assists from planets or moons, adjusting the rocket's trajectory accordingly.

Another critical function of the avionics system is control. The control systems govern how the rocket responds to the data collected by the sensors and guidance algorithms. One of the key control mechanisms is thrust vectoring, where the rocket's engines are swiveled or gimballed to change the direction of the thrust, allowing the rocket to adjust its trajectory without the need for additional fuel or mechanical devices. By altering the angle of the engine nozzles, the control system can correct for minor deviations in the rocket's course or stabilize it during challenging maneuvers. In addition to thrust vectoring, control surfaces such as fins (on atmospheric rockets) or reaction control systems (RCS) (on spacecraft) may be used to fine-tune the rocket's flight path.

The avionics system also plays a vital role in communication, ensuring that the rocket remains in contact with ground control throughout the mission. The communication system sends and receives data between the rocket and mission control, allowing engineers to monitor the rocket's performance and health in real-time. This communication link is critical for sending telemetry data, which provides a detailed report on the rocket's various subsystems, including the status of the engines, fuel levels, structural integrity, and environmental conditions. Telemetry is essential not only for monitoring the rocket's current state but also for making crucial decisions in real time, such as whether to continue the mission or initiate an abort if something goes wrong.

The ability to make corrective actions is another essential feature of the avionics system. During flight, there are many factors that can cause the rocket to deviate from

its intended path, such as unexpected winds, engine fluctuations, or mechanical malfunctions. When the avionics system detects such deviations, it quickly makes adjustments to correct the rocket's course, whether by altering the thrust, changing the angle of control surfaces, or modifying the flight trajectory. These corrective actions are typically carried out autonomously by the flight computer, although they can also be directed by ground control in more complex missions.

In modern reusable rockets, avionics systems have become even more advanced, enabling autonomous landing and reusability. For instance, in rockets like SpaceX's Falcon 9, the avionics systems not only guide the rocket into space but also help it return to Earth for a controlled landing. During re-entry and descent, the avionics systems manage a series of complex maneuvers, using data from onboard sensors and external tracking to adjust the rocket's position and attitude. This precision allows the rocket to land vertically on a designated platform, a feat that was once considered impossible in the world of rocketry.

In conclusion, avionics are the essential electronic systems that manage data collection, control, guidance, navigation, communication, and corrective actions during a rocket's flight. These systems ensure that the rocket stays on course, communicates with ground control, and performs the necessary maneuvers to complete its mission successfully. Whether it's launching into orbit, landing on another planet, or returning to Earth, the avionics system is the backbone of modern rocketry, making complex space missions possible through its advanced control and data-processing capabilities.

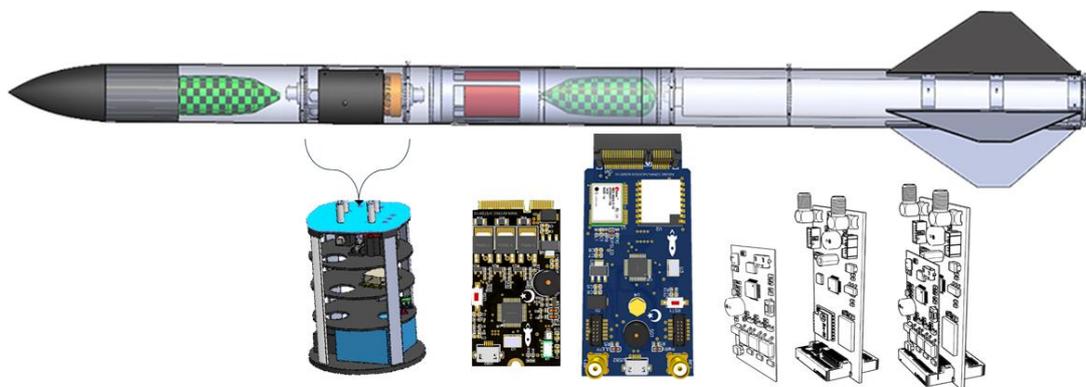


Figure 3.7 Simple Rocket Design, Rocket Avionics System

3.2.6 Payload

The payload in rockets refers to the primary load or cargo that the rocket is designed to transport and deliver to a specific destination, which can be in space, orbit, or another planetary body. The payload is the central reason for the rocket's mission, and its contents can vary widely depending on the mission's objectives, the type of rocket, and the destination. Payloads generally consist of devices, instruments, equipment, and sometimes even living organisms, such as astronauts or biological samples. The payload represents the functional part of the mission, while the rocket itself is the delivery system designed to carry and deploy this valuable cargo[20].

There are several categories of payloads, each designed for a specific purpose, such as scientific research, communication, military applications, and human space exploration. In scientific missions, payloads may include a variety of research instruments and sensors. These could range from telescopes and cameras for observing distant celestial bodies to spectrometers and particle detectors that analyze space dust, radiation, or the chemical composition of other planets and moons. A famous example of a scientific payload is the Hubble Space Telescope, which was deployed into orbit by the Space Shuttle and has provided humanity with some of the most detailed images of the universe ever captured. Other examples include probes like the Voyager and Cassini missions, which carried scientific instruments to study planets, moons, and other celestial phenomena.

For communications purposes, rockets often carry satellites as payloads. Communication satellites are launched into orbit to provide telecommunication services, enabling activities like global internet coverage, TV broadcasts, GPS services, and long-distance phone calls. These satellites play an essential role in modern society, supporting industries such as telecommunications, navigation, weather forecasting, and global positioning systems. Once in orbit, these satellites may remain operational for years, facilitating global connectivity and data transmission.

Another type of payload is the military payload, which includes satellites and other equipment designed for defense purposes. These payloads can carry reconnaissance satellites used for intelligence gathering, surveillance, and tracking of potential threats.

Military payloads may also include early-warning satellites that detect missile launches or advanced communication satellites that ensure secure communication between military forces around the world. In some cases, rockets may also carry ballistic missiles or other types of military hardware as part of strategic defense initiatives.

Space exploration missions designed to reach other planets, moons, or asteroids often carry space probes as payloads. These probes are unmanned spacecraft that carry scientific instruments to explore and collect data from other parts of the solar system. For example, the Mars rovers, such as Curiosity and Perseverance, were payloads delivered by rockets to Mars, where they continue to perform geological surveys and search for signs of ancient life. These payloads play a critical role in expanding our understanding of the universe, gathering valuable information about the conditions and resources available on other celestial bodies.

In missions involving human spaceflight, the payload often consists of crewed capsules, designed to safely transport astronauts into space and, in some cases, bring them back to Earth. Human-rated payloads are among the most complex types of payloads, as they must ensure the safety and well-being of the astronauts aboard while providing the necessary life support, protection, and equipment for the mission. Crewed capsules, such as the Apollo Command Module, Space Shuttle, and modern vehicles like SpaceX's Crew Dragon, have been used for missions to low-Earth orbit (LEO), the International Space Station (ISS), and even the Moon. These capsules are equipped with life-support systems, radiation shielding, communication equipment, and supplies to support human life for extended periods in the harsh environment of space.

Payloads for crewed missions often include scientific equipment for conducting experiments in space. On the International Space Station (ISS), astronauts perform numerous scientific experiments in the unique microgravity environment, which provides opportunities to study everything from materials science to human biology in conditions that cannot be replicated on Earth. These experiments can help advance medical research, improve industrial processes, and contribute to our understanding of how living organisms function outside of Earth's gravity.

One important consideration when designing a payload is its mass and volume. Every rocket has a maximum payload capacity, which refers to the amount of weight it can safely carry into space. Exceeding this capacity can compromise the rocket's ability to reach its target orbit or destination, so payload engineers must carefully calculate the mass of all instruments, equipment, and other components to ensure they stay within the limits. Payloads are often housed in the payload fairing, a protective casing that shields them from aerodynamic forces and extreme temperatures during launch. Once the rocket reaches a certain altitude, the payload fairing is jettisoned, and the payload is exposed to the space environment.

Payload integration is another critical phase in a mission's development, during which the payload is carefully attached to the rocket. Engineers must ensure that the payload is securely fastened and that all systems, including power, communication, and deployment mechanisms, are properly connected and tested. Any failure during this phase can jeopardize the entire mission. For example, the James Webb Space Telescope, one of the most sophisticated scientific payloads ever developed, underwent rigorous testing and integration procedures before being launched to ensure it would function correctly once deployed in space.

The deployment of the payload is a carefully orchestrated process. Once the rocket has reached its destination, whether it be in low Earth orbit, geostationary orbit, or beyond, the payload is released or deployed. In the case of satellites, they are carefully positioned in their desired orbit, where they will begin their operational tasks. In other missions, such as landing on the Moon or Mars, the payload is designed to descend from the rocket and land safely on the surface of the celestial body.

Modern payload designs also focus on sustainability and reusability. With the advent of reusable rocket technology, such as SpaceX's Falcon 9, payloads are often designed to be compatible with these systems, allowing for multiple launches and reducing costs. Additionally, efforts are being made to minimize space debris, with payloads equipped with deorbit systems that guide them to burn up in the atmosphere after their mission is complete, reducing the long-term impact on the space environment.

In summary, the payload of a rocket is the cargo it carries to fulfill the mission's primary objective. Whether it's delivering scientific instruments, communication satellites, military equipment, space probes, or crewed capsules, the payload is the central component of the mission. The design, integration, and deployment of payloads require precision engineering, careful planning, and thorough testing to ensure the success of the mission and the advancement of space exploration and technology..

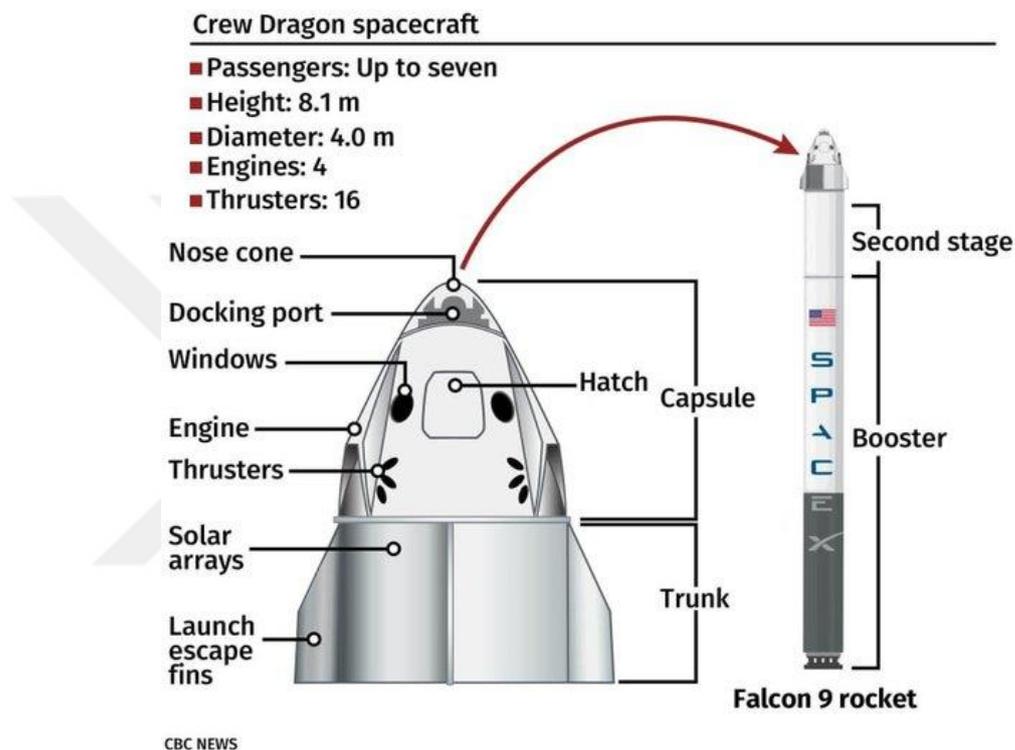


Figure 3.8 SpaceX Falcon 9 Rocket's Dragon Spacecraft Payload [21]

3.3 Types of Rocket Engines

Rocket engines are critical components for space exploration and the launching of aircraft. Designed for various missions and needs, rocket engines are generally classified by the type of fuel they use. These engines are primarily divided into three main categories: solid rocket engines, liquid rocket engines, and hybrid rocket engines. Each type offers distinct advantages and application areas, making them effective for a range of space and aerospace missions.

3.3.1 Solid Rocket Engine

Solid rocket engines are characterized by their use of solid propellants, which consist of a mixture of fuel and oxidizer in a solid state. Once ignited, the combustion process is self-sustaining, meaning that solid rockets do not require any additional mechanisms to maintain thrust. This simplicity makes them highly reliable and easier to handle compared to liquid engines. Common applications of solid rocket engines include military missiles, space launch boosters, and auxiliary engines for spacecraft.

One of the most notable features of solid rocket engines is their high thrust-to-weight ratio, which allows them to generate significant thrust quickly, making them suitable for initial launch phases. They are typically used as booster stages in large launch vehicles, such as NASA's Space Shuttle and the Ariane 5, where they provide the necessary lift during the initial ascent through the atmosphere.

However, solid rocket engines also have limitations. Once ignited, they cannot be shut down or throttled, which means that their burn time is predetermined and cannot be adjusted mid-flight. Additionally, the inability to control thrust means that careful calculations and engineering are necessary to ensure the mission's success.

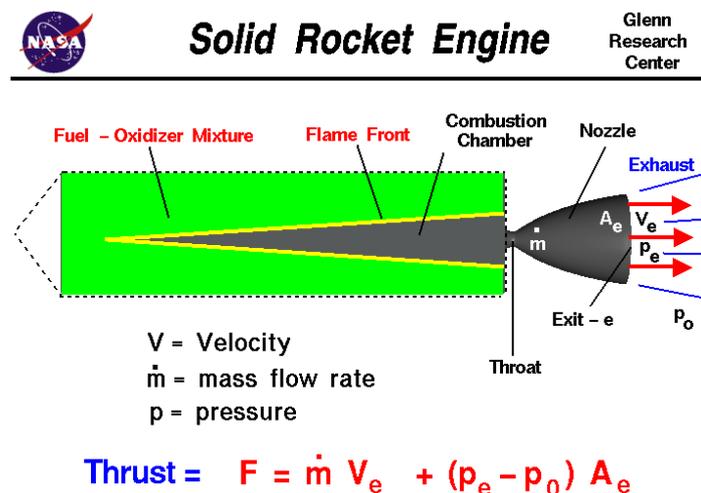


Figure 3.9 Solid Rocket Engine [22]

3.3.2 Liquid Rocket Engine

Liquid rocket engines use liquid propellants that are stored in separate tanks and pumped into the combustion chamber as needed. This design allows for greater control over the thrust produced, making them highly versatile for a variety of missions. Liquid engines can be throttled, shut down, and restarted during flight, providing the flexibility needed for complex missions that may require precise adjustments to flight trajectories.

The most common liquid propellants include combinations of fuels such as kerosene, liquid hydrogen, or hypergolic propellants. Liquid oxygen is frequently used as an oxidizer. Notable examples of liquid rocket engines include the F-1 engines used in the Apollo program and the Merlin engines powering SpaceX's Falcon 9 rockets.

One of the advantages of liquid rocket engines is their efficiency, as they typically provide a higher specific impulse (a measure of efficiency in rocket engines) than solid engines. This makes them ideal for long-duration missions, such as sending payloads to orbit or beyond. However, liquid engines are also more complex and require intricate plumbing systems to handle the cryogenic fuels, which adds to their overall weight and design challenges.

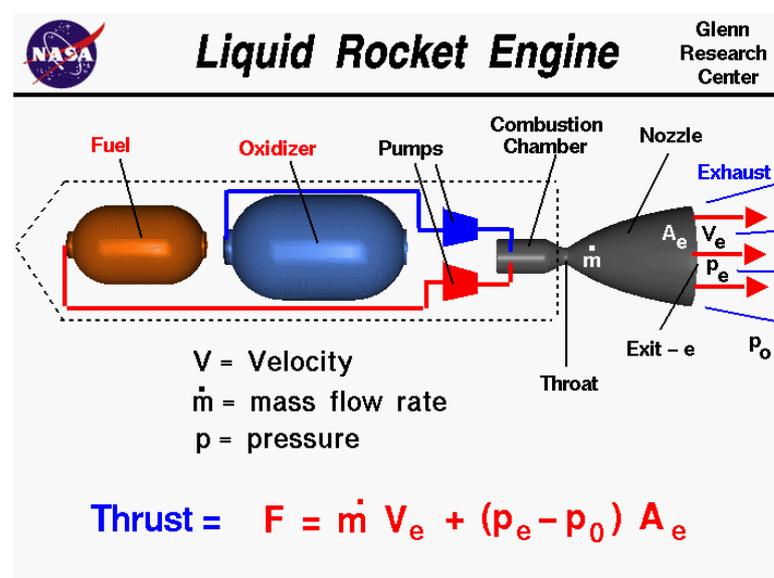


Figure 3.10 Liquid Rocket Engine [23]

3.3.3 Hybrid Rocket Engine

Hybrid rocket engines represent a combination of solid and liquid propulsion systems. These engines utilize a solid fuel grain combined with a liquid oxidizer, allowing for some of the advantages of both types. By using a liquid oxidizer, hybrid engines can be throttled and shut down, providing greater control compared to solid engines while maintaining some of the simplicity of solid propellants.

The use of hybrid rocket engines has been explored in various applications, including suborbital flights, space tourism, and experimental launches. One of the notable advantages of hybrid engines is their safety, as they pose less risk of accidental detonation compared to fully solid engines. Additionally, hybrids can be designed to minimize environmental impacts, with lower emissions compared to traditional solid rockets.

Hybrid engines, however, still face challenges related to the combustion process, which can be less stable than in pure solid or liquid engines. Researchers and engineers continue to develop hybrid technology to enhance performance and reliability, making it a promising area for future advancements in rocketry.

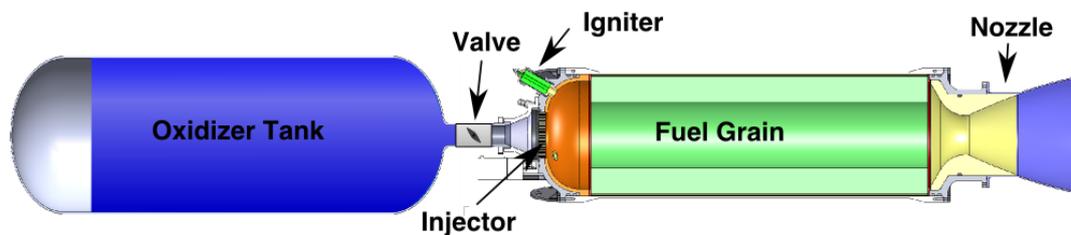


Figure 3.11 Hybrid Rocket Engine [24]

3.3.4 Choosing the Right Engine Type

The choice of rocket engine type depends on various factors, including the mission objectives, payload capacity, and flight profile. For missions requiring quick launches and high thrust, solid rocket engines are often preferred, while missions that demand precision and flexibility benefit from the capabilities of liquid rocket engines. Hybrid engines may serve as an effective compromise, especially for missions with budget constraints or safety considerations.

3.3.5 Conclusion

In conclusion, rocket engines are fundamental to the success of space exploration and aerospace missions. By classifying rocket engines into solid, liquid, and hybrid types, engineers can select the most suitable propulsion systems based on mission requirements and specific operational goals. Each type of engine brings unique benefits and challenges, influencing the design and execution of space missions. As technology continues to advance, the development of more efficient, reliable, and versatile rocket engines will play a crucial role in pushing the boundaries of human exploration beyond Earth and into the depths of our solar system and beyond.

3.4 Rocket Physics & Aerodynamics

To grasp why specific phenomena occur during a rocket launch, it is essential to understand the forces acting on the rocket, their timing, and their underlying causes. Refer to figure for a visual representation of these forces.

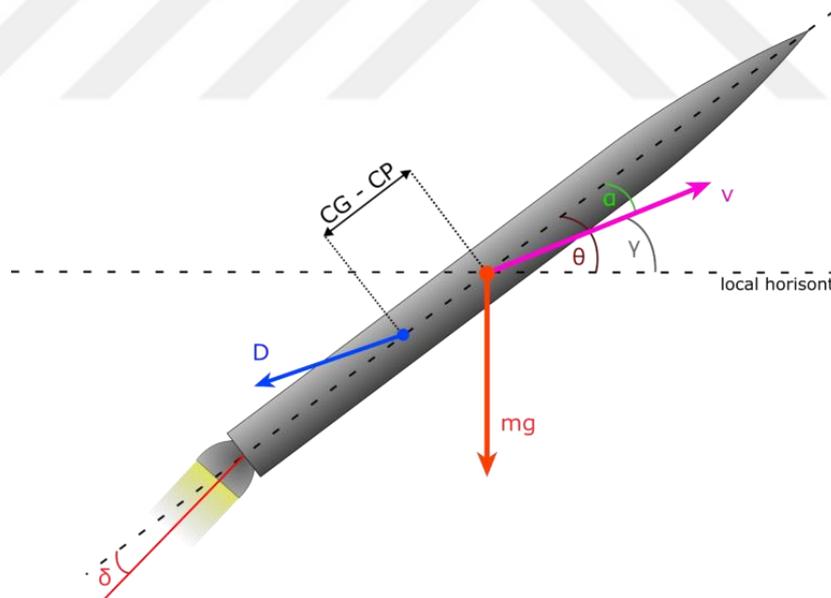


Figure 3.12 Forces Acting on a Rocket [25]

3.4.1 Center of Gravity

The center of gravity is the point where the rocket balances evenly if placed on a finger or similar support. This location signifies the balance point along the rocket's length,

typically aligned with the z-axis of the rocket's coordinate system. The CG is determined by the distribution of mass throughout the rocket, and its position can be influenced by various factors, including the mass of the fuel, payload, and structural components. For an object with a uniform mass distribution, the center of gravity will typically be at its midpoint. However, in rockets, mass distribution can be non-uniform due to the varying densities and configurations of the components[26].

3.4.2 Importance of the Center of Gravity

The CG's position directly affects the rocket's stability. If the CG is too far forward, the rocket may become nose-heavy, leading to pitch instability. Conversely, if the CG is too far aft, the rocket may be tail-heavy, causing it to become unstable and possibly tumble during flight. Achieving a well-balanced CG is crucial for successful rocket launches, as it enables the rocket to follow its intended flight path without excessive corrective maneuvers.

Furthermore, as the rocket burns fuel during ascent, the distribution of mass changes, which can shift the CG. Engineers must account for these changes to ensure that the rocket remains stable throughout its flight profile. Advanced simulations and models are often used to predict how the CG will shift as fuel is consumed, allowing for appropriate design adjustments and flight planning.

3.4.3 Center of Pressure

The center of pressure, on the other hand, is the point along the rocket where the aerodynamic forces are balanced. It is the point at which the total aerodynamic drag force can be considered to act. The CP is critical for understanding how aerodynamic forces will interact with the rocket, particularly during ascent and re-entry. While the CG is concerned with mass distribution, the CP is focused on the distribution of aerodynamic forces acting on the rocket.

The position of the CP can change throughout the flight as the rocket moves through different atmospheric conditions and as the rocket's shape and configuration change (for example, as stages are jettisoned). A rocket is stable when the CP is located below the CG; this configuration creates a restoring moment when the rocket experiences

disturbances, such as wind gusts or changes in angle of attack. If the CP moves above the CG, the rocket may become unstable, leading to potential control issues[27].

3.4.4 Interaction Between CG and CP

The relationship between the CG and CP is fundamental to rocket stability. For optimal performance, the CG should be positioned ahead of the CP to ensure stability. This can be particularly challenging for rockets that experience significant mass loss as they burn fuel or that have movable control surfaces, as these changes can influence the position of both the CG and CP.

Designers often employ various techniques to manage the CG and CP effectively. This can include strategic placement of components, using aerodynamic shapes, and incorporating control surfaces like fins and canards that can help maintain stability by providing additional aerodynamic force. Simulations and computational fluid dynamics (CFD) tools are also employed to model airflow around the rocket and predict how changes to the design will affect both the CG and CP..

3.4.5 Stability

Understanding the positions of the center of gravity (CG) and center of pressure (CP) is critical for assessing rocket stability throughout its flight. These two points are essential to the dynamics of the rocket and play a significant role in ensuring a controlled and successful trajectory.

During flight, a rocket rotates around its center of gravity. This point serves as the balance point of the rocket, where the mass is evenly distributed on either side. As the rocket ascends, gravitational forces act upon this CG, providing a consistent point around which the rocket can maneuver. The stability of the rocket during flight is heavily influenced by the interplay between the CG and the aerodynamic forces acting on the rocket.

Meanwhile, aerodynamic forces such as drag and lift are applied at the center of pressure. The CP is determined by the rocket's shape, design, and configuration, which influence how air interacts with the rocket as it travels through the atmosphere. As the

rocket moves, airflow around it generates these aerodynamic forces, which can cause the rocket to pitch, yaw, or roll, depending on the orientation of the CG and CP.

The relative positions of the CG and CP are paramount in determining the rocket's stability. If the center of pressure is located behind the center of gravity, the rocket is generally more likely to be stable. This configuration provides a natural restoring force; if the rocket experiences any disturbance, the aerodynamic forces will create a moment that pushes it back toward its original flight path. The result is a stable flight behavior, where the rocket can adjust to changes in pitch or angle of attack without losing control.

Conversely, if the CP is ahead of the CG, the rocket may become unstable and uncontrollable. In this scenario, any disturbance or deviation from its intended path could lead to an exacerbation of the pitch or yaw motion, causing the rocket to tumble or spiral. This instability can be particularly dangerous, as it may lead to mission failure or catastrophic failure during ascent or re-entry.

To mitigate the risks associated with an unstable configuration, rocket designers often incorporate control surfaces such as fins, canards, and gimbaled thrust systems. These components help maintain the desired orientation by altering the airflow around the rocket, generating additional aerodynamic forces that can counteract disturbances.

Control surfaces are especially effective in adjusting the position of the effective center of pressure, allowing for greater stability during flight. For example, if the rocket begins to yaw due to a lateral wind gust, the control surfaces can be adjusted to generate a corrective aerodynamic force, realigning the rocket with its intended trajectory. The design of these surfaces is carefully calibrated to ensure they work harmoniously with the rocket's CG and CP throughout various flight phases.

Another critical factor to consider is the dynamic nature of both the CG and CP during flight. As the rocket burns fuel, its mass distribution changes, which can shift the position of the CG. This shift can alter the stability characteristics of the rocket throughout its ascent. Engineers must account for these changes when designing the rocket and planning its trajectory.

For example, as the lower stages of a multi-stage rocket are jettisoned, the mass of the remaining stages decreases, which can lead to a rearward shift in the CG. At the same time, the CP can also shift based on the rocket's aerodynamic profile at different stages of the flight. Engineers use simulations and real-time telemetry data to monitor the CG and CP during flight, allowing for adjustments to be made if necessary.

Advanced stability analysis techniques, including computational fluid dynamics (CFD) simulations and flight dynamics modeling, allow engineers to predict how changes in design or conditions will affect the CG and CP. By simulating various flight scenarios, engineers can identify potential stability issues before launch, making necessary design adjustments to ensure that the rocket will perform as expected.

In addition to simulations, real-time data collection during flight can inform engineers about the actual performance of the rocket. Telemetry systems provide valuable data on the rocket's orientation, velocity, and environmental conditions, which can be used to assess stability and make corrections if needed.

In conclusion, the positions of the center of gravity (CG) and center of pressure (CP) are critical for assessing and ensuring rocket stability during flight. The relationship between these two points influences how the rocket responds to aerodynamic forces and gravitational effects, directly impacting its ability to maintain a controlled trajectory. Understanding this relationship allows engineers to design rockets that are not only capable of reaching their destinations but also stable and controllable throughout their flight paths. As rocket technology continues to advance, ongoing research and development efforts will focus on optimizing the interactions between CG and CP, enhancing the safety and effectiveness of space missions.

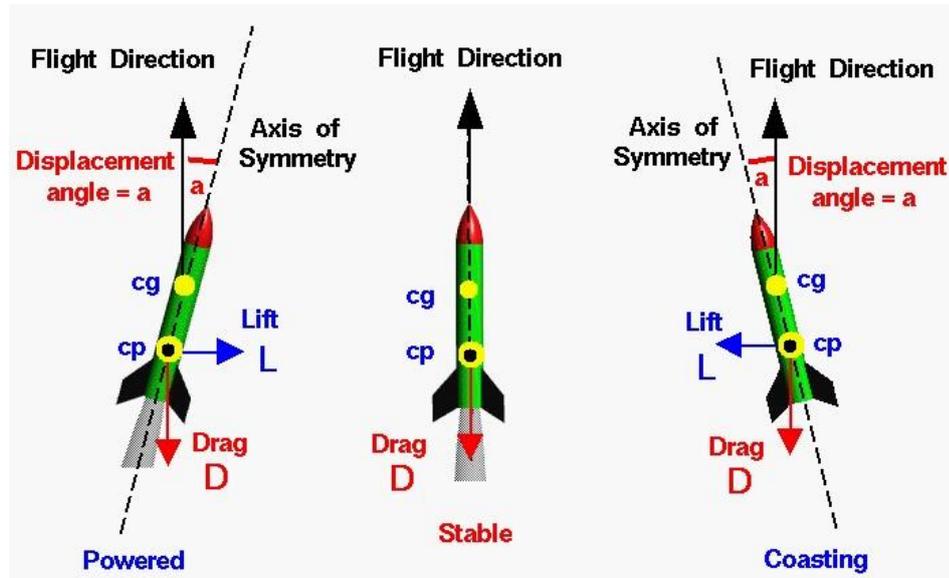


Figure 3.13 Rocket Stability [28]

3.5 Control Theory

The successful landing of vertical descent rockets relies heavily on advanced control algorithms. During landing, rockets encounter various physical forces, system complexities, and dynamic environmental variables, which demand precision and accuracy in the control algorithms governing the descent. This is where control theory becomes essential, offering a mathematical framework to ensure the rocket's stability and landing accuracy. In this article, we will delve into the theoretical foundations of several key control algorithms, focusing specifically on PID (Proportional-Integral-Derivative), MPC (Model Predictive Control), and DDPG (Deep Deterministic Policy Gradient) algorithms.

Control algorithms used in vertical descent rockets operate by leveraging sophisticated mathematical models and feedback-based control systems. These systems must manage both the internal dynamics of the rocket and external factors, such as gravitational pull, atmospheric conditions, and potential wind resistance, to ensure a controlled and safe descent. Each control approach has its strengths, limitations, and specific use cases, which make it suitable for various aspects of rocket landing.

3.5.1 Model Predictive Control

Model Predictive Control (MPC) is a more advanced and sophisticated control approach, particularly suited for complex systems like vertical landing rockets. MPC operates by predicting the future behavior of the rocket based on a model of the system's dynamics and optimizing the control actions over a given time horizon. The key feature of MPC is its ability to handle multiple inputs and outputs, making it particularly effective in scenarios where the system has to manage several variables simultaneously, such as engine thrust, velocity, and positional accuracy[29].

MPC is especially valuable for rocket landings as it allows for real-time optimization of the control inputs while accounting for system constraints, such as thrust limits or fuel capacity. The algorithm computes the optimal control inputs by solving a constrained optimization problem at every time step, taking into consideration future states of the rocket. By doing so, MPC can prevent potential overshoot or oscillations and ensure that the rocket achieves a precise landing within the allowable parameters.

Despite its strengths, MPC comes with the challenge of high computational demand. The need to solve optimization problems in real-time requires significant processing power, which can be a limiting factor for its use in real-world applications unless advanced onboard computing resources are available. Nevertheless, MPC remains a powerful tool for managing the complexities of modern vertical descent rockets.

Modeling, MPC uses a mathematical model to represent the rocket's dynamics, including its movement, environmental effects, and control parameters.

Objective Function, the algorithm aims to minimize a specific objective function, usually a cost function that includes errors in position, velocity, and acceleration during the descent.

Optimization, MPC optimizes future control actions over a set time horizon. This determines the most suitable control strategy for the rocket's descent.

Real-Time Application, control actions are continuously updated based on model predictions and real-time measurements, allowing the rocket to respond quickly to dynamic changes.

The following MPC control formulas are listed for use in rockets with vertical landing. This information outlines the general flow of the control algorithms. This study is based on these control algorithms.

The dynamics of the rocket are typically described by state equations such as:

Table 3.5 MPC State Equation

$x_{k+1} = Ax_k + Bu_k + w_k$	<p>x_k State vector (e.g., position and velocity)</p> <p>u_k Control Input</p> <p>A and B System matrices</p> <p>w_k Disturbance or noise</p>
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MPC minimizes a specific cost function, which might look like:

Table 3.6 MPC Cost Function

$J = \sum_{k=0}^{N-1} (x_k^T Q x_k + u_k^T R u_k) + x_N^T P x_N$	<p>Q and R Weight matrices for state and control inputs</p> <p>P Terminal weight matrix</p> <p>N Prediction horizon length</p>
--	---

MPC solves the following optimization problem:

Minimize J subject to $x_{k+1} = Ax_k + Bu_k$ and constraints on u_k

3.5.2 Proportional-Integral-Derivative Control

The PID control algorithm is one of the most widely used feedback mechanisms in engineering due to its simplicity and efficiency. It works by continuously adjusting the control input based on three terms: proportional, integral, and derivative. The proportional term addresses the present error (the difference between the desired and actual state), the integral term accounts for the accumulation of past errors, and the derivative term predicts future errors by examining the rate of change.

In the context of vertical rocket landings, PID controllers can regulate thrust to ensure the rocket decelerates smoothly while maintaining stability. By adjusting these three components, the system can correct deviations in position or velocity in real-time, ensuring a balanced descent. However, while PID control is effective in straightforward applications, it can struggle with more complex scenarios involving multiple interacting variables or highly dynamic environmental conditions. As a result, it may not be sufficient for advanced rocketry systems that require more adaptive or predictive control strategies[30].

Proportional, P component addresses a portion of the error that is proportional to the difference between the desired and actual values. It helps bring the system closer to the target quickly.

Integral, I component considers the accumulation of past errors and helps correct persistent errors over time.

Derivative, D component looks at the rate of change of the error and helps prevent the system from overshooting or oscillating, ensuring stable responses.

The following PID control formulas are listed for use in rockets with vertical landing. This information outlines the general flow of the control algorithms. This study is based on these control algorithms.

The control input u_t is computed as:

Table 3.7 PID Control Input Equation

$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$	<p>$e(t)$ Error signal (desired value – measured value)</p> <p>K_p Proportional gain</p> <p>K_i Integral gain</p> <p>K_d Derivative gain</p>
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Error signal and integral term are used for control actions:

Table 3.8 PID Error Signal & Integral Term

<p>Error: $e(t) = r(t) - y(t)$ Integral Term: $\int_0^t e(\tau) d\tau$</p>	<p>$r(t)$ Reference(desired value)</p> <p>$y(t)$ Actual measured value</p>
--	--

3.5.3 Deep Deterministic Policy Gradient

DDPG is an algorithm rooted in reinforcement learning, specifically designed for continuous action spaces, making it particularly suitable for controlling systems like rockets. DDPG blends ideas from both deep learning and reinforcement learning to create a control system that can learn optimal behaviors through experience. Unlike PID or MPC, which are model-based, DDPG is a model-free algorithm, meaning it doesn't require a pre-built model of the rocket's dynamics. Instead, it learns how to control the system by interacting with the environment and receiving feedback on its performance[31].

In the context of rocket landings, DDPG can autonomously learn to manage the rocket's thrust and orientation during descent by repeatedly simulating landings and adjusting its actions based on the results. Over time, the algorithm becomes proficient in landing the rocket, even under varying conditions, by optimizing its policy—the mapping from states (e.g., velocity, altitude) to actions (e.g., thrust adjustments). One of the key advantages of DDPG is its adaptability; because it doesn't rely on a pre-defined model, it can adapt to new situations or unexpected dynamics, such as sudden changes in wind speed or atmospheric pressure.

However, DDPG has its challenges. It typically requires a large amount of training data and computational resources to achieve optimal performance. Moreover, the training process can be time-consuming, especially when dealing with high-stakes tasks like rocket landings, where safety and accuracy are paramount. Nonetheless, once trained, DDPG can offer flexible and robust control in environments that are too complex for traditional control methods.

Actor-Critic Structure, DDPG uses two separate neural networks: an actor and a critic. The actor learns and applies action strategies, while the critic evaluates the value of these actions.

Deterministic Policy, DDPG employs a deterministic policy to optimize continuous action spaces, aiming to determine the best action for a given state.

Experience Replay, The algorithm stores past experiences in a memory pool and uses this data to improve learning during training.

Target Networks, DDPG uses target networks to stabilize learning by slowly updating versions of the main networks.

The following DDPG control formulas are listed for use in rockets with vertical landing. This information outlines the general flow of the control algorithms. This study is based on these control algorithms.

Actor and critic networks are updated as follows:

The actor network is updated using,

Table 3.9 DDPG Actor Network

$\nabla_{\theta^{\text{actor}}} J \approx \mathbb{E} \left[\nabla_{\theta^{\text{actor}}} \left(Q(s, a; \theta^{\text{critic}}) \right) \right]$	θ^{actor} Actor network parameters $Q(s, a; \theta^{\text{critic}})$ Value function from the critic network
--	--

The critic network is updated using the TD error:

Table 3.10 DDPG Critic Network TD Error

$\delta = r + \gamma Q(s', a'; \theta^{\text{critic}}) - Q(s, a; \theta^{\text{critic}})$ $\nabla_{\theta^{\text{critic}}} \text{Loss} = \nabla_{\theta^{\text{critic}}} (\delta^2)$
δ Temporal Difference (TD) error
γ Discount factor for future rewards

Target networks are updated as:

Table 3.11 DDPG Target Network

$\theta^{\text{target}} \leftarrow \tau \theta^{\text{main}} + (1 - \tau) \theta^{\text{target}}$	τ Target network update rate
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3.5.4 VTVL Rocket Control Algorithms Conclusion

The mathematical and theoretical foundations of control algorithms for vertical descent rockets, such as PID, MPC, and DDPG, each offer unique advantages and limitations depending on the specific requirements of the landing scenario. PID control remains a go-to solution for straightforward and well-understood control problems,

offering simplicity and efficiency. MPC, with its predictive capabilities, is highly effective in managing complex systems and constraints, but it requires significant computational resources. DDPG, leveraging reinforcement learning, represents a modern approach that can adapt to unpredictable environments and complex dynamics, albeit with higher demands for training and data.

Together, these algorithms form the backbone of control systems in vertical landing rockets, enabling precise, safe, and efficient landings in increasingly challenging and dynamic environments. Advances in control theory, along with improvements in computational technology, continue to push the boundaries of what is possible in the realm of autonomous rocket landings, paving the way for future innovations in space exploration and reusable rocket technology.

3.6 Simulation Models, The Theoretical Foundation of Simulations

The development and testing of landing algorithms for vertical landing rockets can be both expensive and risky in real-world scenarios. For this reason, simulations play a crucial role in evaluating the performance of rockets and optimizing control algorithms. Simulations offer a realistic modeling of the physical forces, environmental conditions, and dynamic interactions that rockets encounter during landing, providing a safer, more efficient way to test these complex processes in a virtual environment. This article explores the theoretical background of simulation models used in vertical landing rockets and how they assist in the evaluation of landing algorithms.

3.6.1 The Role of Simulations

Simulation models serve as a mathematical representation of the physical forces and dynamics encountered by vertical landing rockets during descent. These models calculate how different components of the system interact and how control algorithms respond to these interactions. Through simulations, various landing scenarios can be tested in advance, allowing for the optimization of rocket control systems. Furthermore, environmental factors like atmospheric conditions, wind speeds, and

terrain variations can be accurately tested in a simulation environment, ensuring comprehensive testing of landing performance.

3.6.2 Modeling Physical Forces

Vertical landing rockets face numerous physical forces during descent, including gravity, atmospheric drag, aerodynamic forces, and ground effects. Accurately modeling these forces is essential for the simulations to produce realistic results. These forces make it necessary to fine-tune the control algorithms and ensure that the rocket can land safely and precisely.

3.6.3 Simulating Control Algorithms

Simulations play a pivotal role in evaluating the performance of control algorithms used for vertical landing rockets. These algorithms are designed to continuously adjust the rocket's speed, direction, and position during descent to achieve a safe landing. Testing control algorithms in a simulation environment allows engineers to observe how the system performs under various environmental factors and dynamic conditions.

3.6.4 Conclusion

Simulation models are essential for the development, testing, and optimization of landing algorithms for vertical landing rockets. Accurately modeling the physical forces encountered during descent and testing how control algorithms respond to these forces in various environmental conditions ensures both safety and efficiency. The wide range of simulation tools, including MATLAB/Simulink, Unity 3D, Gazebo, and advanced platforms like ANSYS and COMSOL, offer engineers the ability to evaluate and optimize rocket landing systems comprehensively. By using these tools, the space industry can continue to develop safer, more reliable landing systems for reusable rockets, reducing costs and advancing space exploration technology.

CHAPTER 4

VTVL ROCKET PROBLEM STATEMENT & METHOD

4.1 VTVL Rocket Problem Statement

The primary challenges faced in vertical landing rockets involve a range of difficulties related to maintaining both stability and control during descent. Precise control systems are required to ensure that the rocket can land accurately without being affected by external factors such as atmospheric conditions and wind. Fuel management also presents a significant problem; using the correct amount of fuel at the right moment during descent is crucial for controlling the descent speed and achieving a soft landing. Additionally, the thrust of the rocket must be modulated accurately; this requires precise control of the engines to reduce descent speed and prevent the rocket from ascending again.

Another critical issue is ensuring that the rocket reaches the designated landing area with high precision, which necessitates advanced navigation and positioning systems. The rocket must also maintain its structural integrity against the forces experienced during landing; sudden changes in descent speed can create structural stress, testing the durability of components such as landing legs and the chassis. Furthermore, the high heat generated by the engines during landing requires an effective thermal management system. Finally, the rocket must be resilient to potential failure modes and equipped with backup systems for such scenarios. All these factors present significant challenges in the design and operational phases of vertical landing rockets, requiring advanced technological solutions and innovative engineering methods to overcome them.

The primary aim of this study is to compare fuel efficiency and landing accuracy according to various control algorithms.

4.2 VTVL Rocket Landing Algorithms Comparison Method

In this study, I aim to compare different landing control algorithms for vertical landing rockets using the Unity game engine. The algorithms to be examined include PID (Proportional-Integral-Derivative), MPC (Model Predictive Control), and DDPG (Deep Deterministic Policy Gradient). The purpose of this comparison is to determine the impact of each control algorithm on the landing performance of rockets. The primary focus of the study is to evaluate the landing accuracy and fuel consumption performance of rockets when released under identical initial conditions, each governed by one of these control algorithms.

Using Unity as a simulation environment provides a flexible platform to test how these algorithms perform under dynamic flight conditions. The PID controller offers a simple and straightforward approach based on feedback control theory, continuously monitoring and adjusting variables such as speed, position, and thrust to ensure a controlled descent of the rocket. The MPC algorithm, on the other hand, provides a forward-looking perspective by using a model of the rocket's dynamics to optimize a series of future control actions. This algorithm seeks to adjust the rocket's descent path and speed by calculating the effects of future maneuvers. The DDPG algorithm employs deep reinforcement learning techniques, allowing the rocket to learn how to react to environmental conditions during landing. This algorithm offers a high degree of adaptation and learning capability, even in complex and unpredictable landing scenarios.

The study will analyze critical performance metrics such as how each control algorithm ensures rocket stability during descent, responds to unexpected situations, and manages fuel efficiency. This analysis is essential for understanding how precisely the rockets can land at a designated landing area and whether they can achieve a safe landing with minimal fuel consumption. The findings will help determine which control algorithm provides the best performance for vertical landing rockets in specific scenarios. Consequently, the study will offer valuable insights into selecting the most suitable control strategy for future space missions and commercial applications.

This comprehensive analysis aims to provide a deeper understanding of engineering and algorithmic strategies to enhance the performance of vertical landing rockets and maximize the effectiveness of control algorithms.



CHAPTER 5

VTVL ROCKET SIMULATION CALCULATION & RESULT

5.1 Simulation Environment Calculation & Results

In these calculations, a virtual environment created within the Unity game engine was used. Accordingly, the environmental conditions, such as weather, were input into the system. Additionally, the rocket model, rocket engine, fuel amount, and thrust force used across all algorithms were standardized to be the same. Therefore, only the success criteria of the algorithms will be evaluated here.

Pressure: At higher altitudes, air pressure decreases, which can affect rocket engine performance and reduce air resistance, making stabilization during descent more challenging. Lower pressure means less drag on the rocket.

Wind: Wind can cause horizontal drift of the rocket, complicating the landing. Strong winds make it harder to stabilize the rocket and hit the precise landing point.

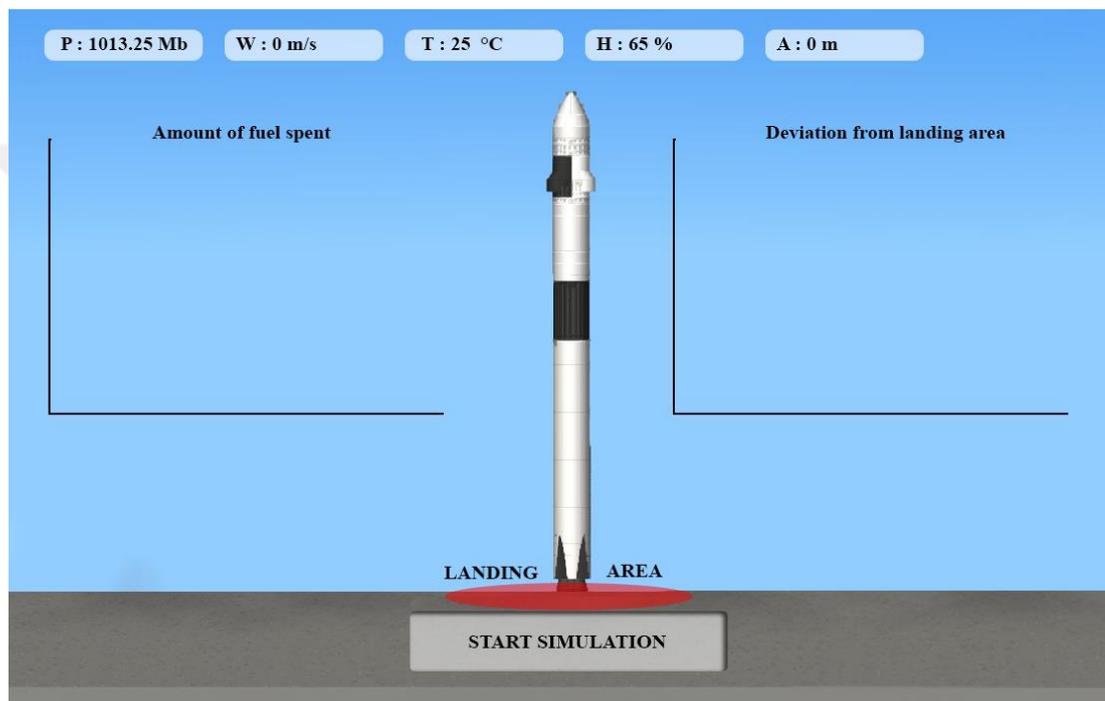
Temperature: Temperature affects engine performance and fuel combustion rates. Extreme temperature differences can lead to variations in thrust during landing, impacting control.

Humidity: Humidity increases air density, which influences the rocket's behavior in the atmosphere. Higher humidity can increase drag, making speed control more difficult during descent.

Altitude: At higher altitudes, air density is lower, impacting the rocket's aerodynamics. Reduced air density makes it harder to slow down the rocket without excessive thrust, requiring more precise engine control during landing.

Table 5.1 Simulation Environment Inputs

Environments Input	Value
Pressure	1013.25 Mb
Wind	0 m/s
Temperature	25 °C
Humidity	65 %
Altitude	0 m

**Figure 5.1** VTVL Rocket Simulation Environment

5.1.1 Graphical Results

In this section, three graphs are presented that demonstrate the performance of each control algorithm. These graphs illustrate outputs such as fuel consumption, landing area deviation, and landing stability. The primary objective of this analysis is to explain which algorithm performs best under the given simulation environment inputs. However, it is important to acknowledge that each algorithm may exhibit different behaviors under varying terrain and weather conditions. One algorithm may outperform the others in specific scenarios, while another may show better results

under different circumstances. Therefore, the results should be evaluated with consideration of the specific strengths and weaknesses of each algorithm.

The data presented in the graphs provide detailed insights into how each algorithm responds under certain parameters. Fuel consumption indicates the efficiency of the rocket during landing and how much energy is expended throughout the descent. Landing area deviation shows the difference between the target landing point and the actual landing location. Landing stability reflects how stable the rocket remains during vertical descent and the overall safety of the landing process. All of these factors are crucial performance indicators that must be considered when assessing the success of a landing algorithm.

Ultimately, it is essential to recognize that the algorithms presented in this study offer various advantages and disadvantages depending on the conditions. For instance, one algorithm may optimize fuel consumption under calm and stable weather conditions, while another may provide more stable landings in challenging weather and terrain. As a result, when evaluating these algorithms, it is crucial to consider not only the current simulation environment but also potential real-world scenarios and conditions. This comprehensive evaluation is critical for determining which algorithm may be more suitable in different situations for future real-world applications..

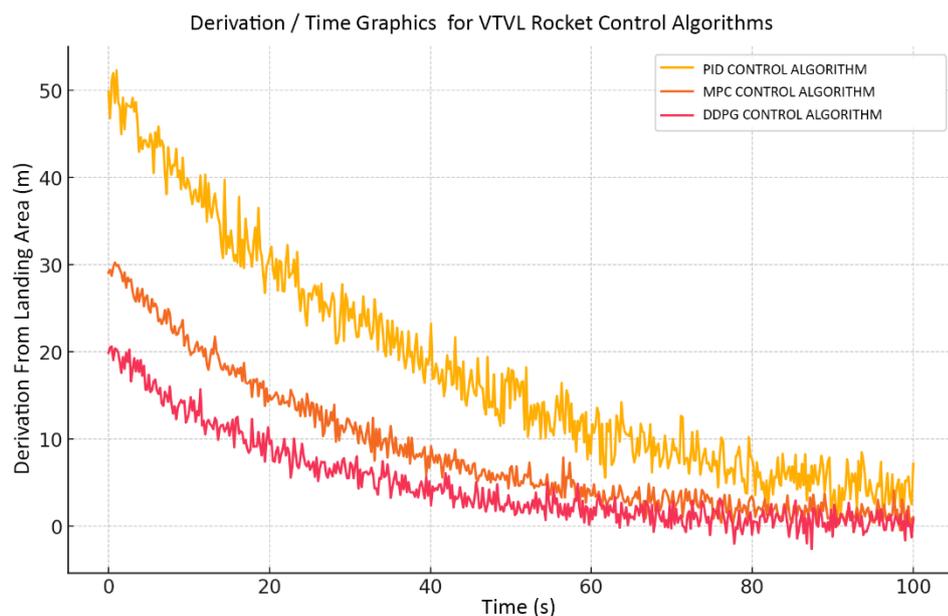


Figure 5.2 Derivation / Time Graphics for VVTL Rocket Control Algorithms

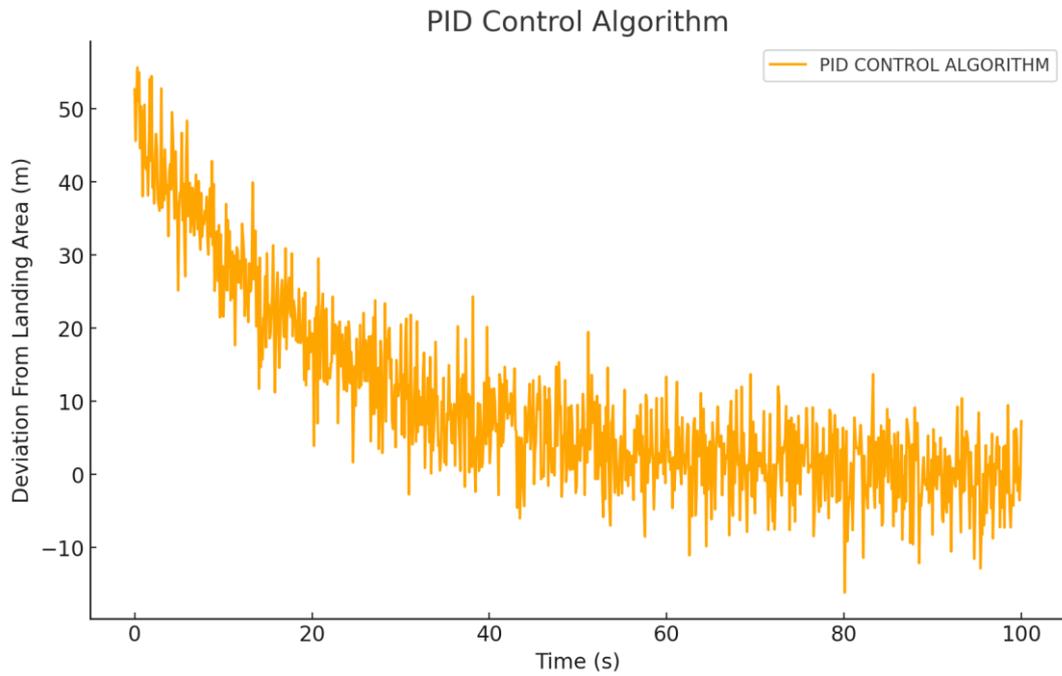


Figure 5.3 Derivation / Time Graphics for VVTL Rocket PID Control Algorithm

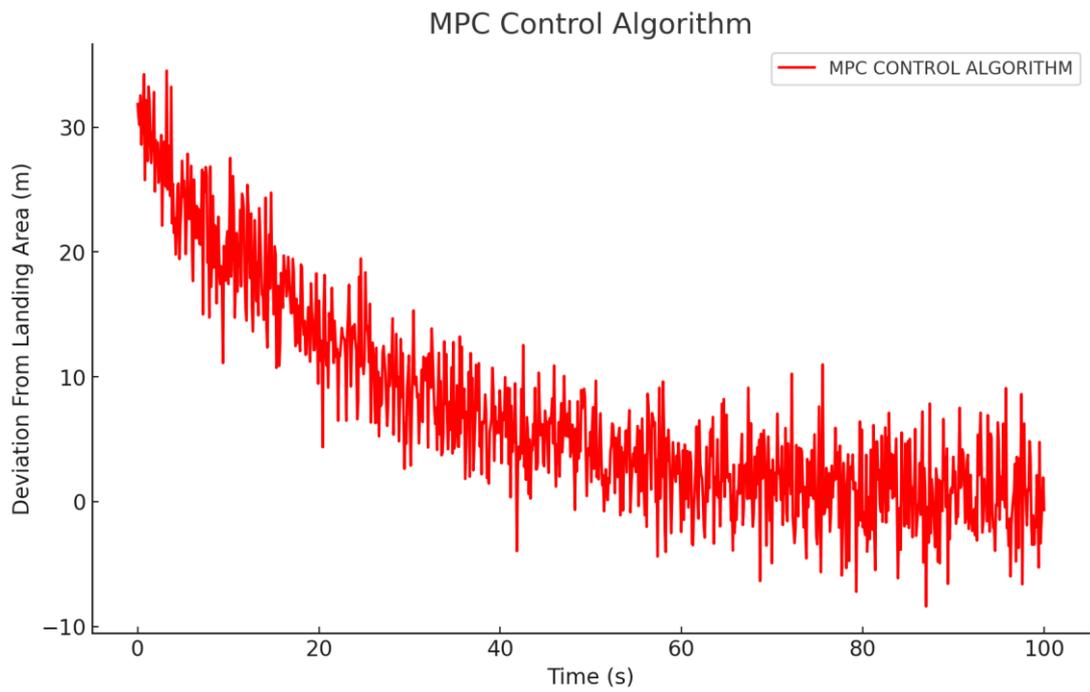


Figure 5.4 Derivation / Time Graphics for VVTL Rocket MPC Control Algorithm

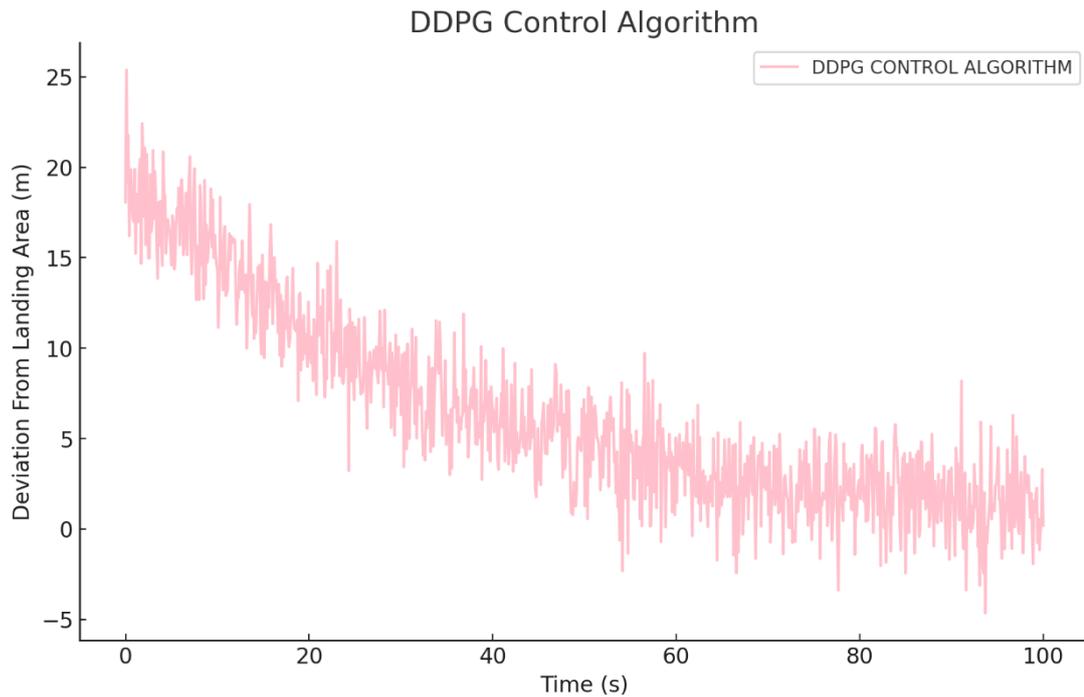


Figure 5.5 Deviation / Time Graphics for VVTL Rocket DDPG Control Algorithm

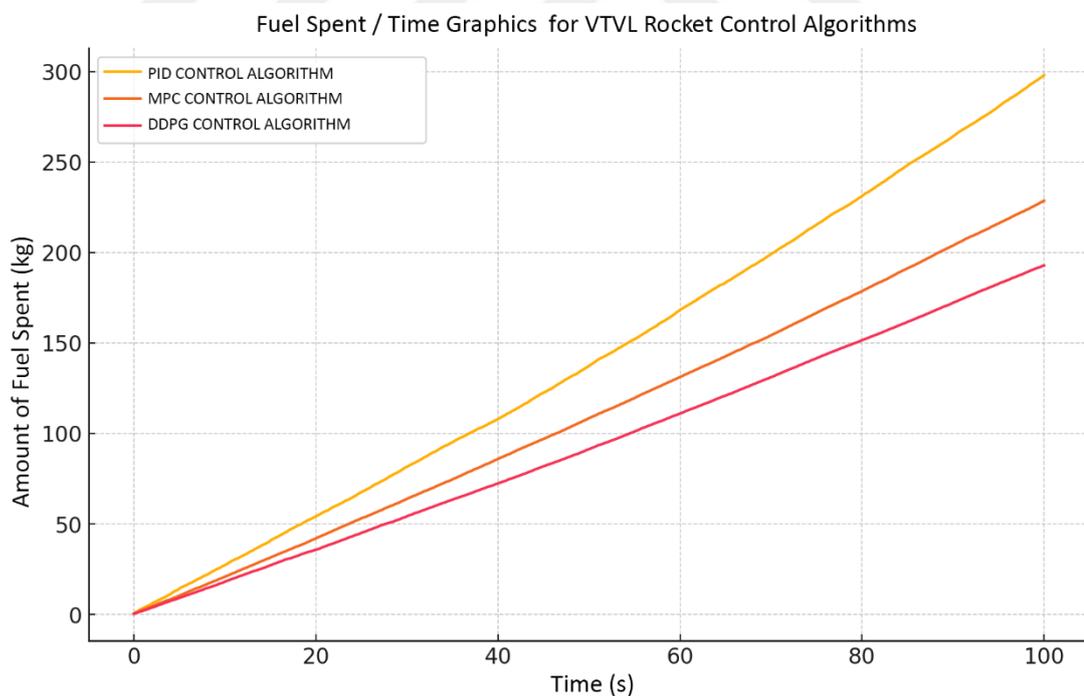


Figure 5.6 Fuel Spent / Time Graphics for VVTL Rocket Control Algorithms

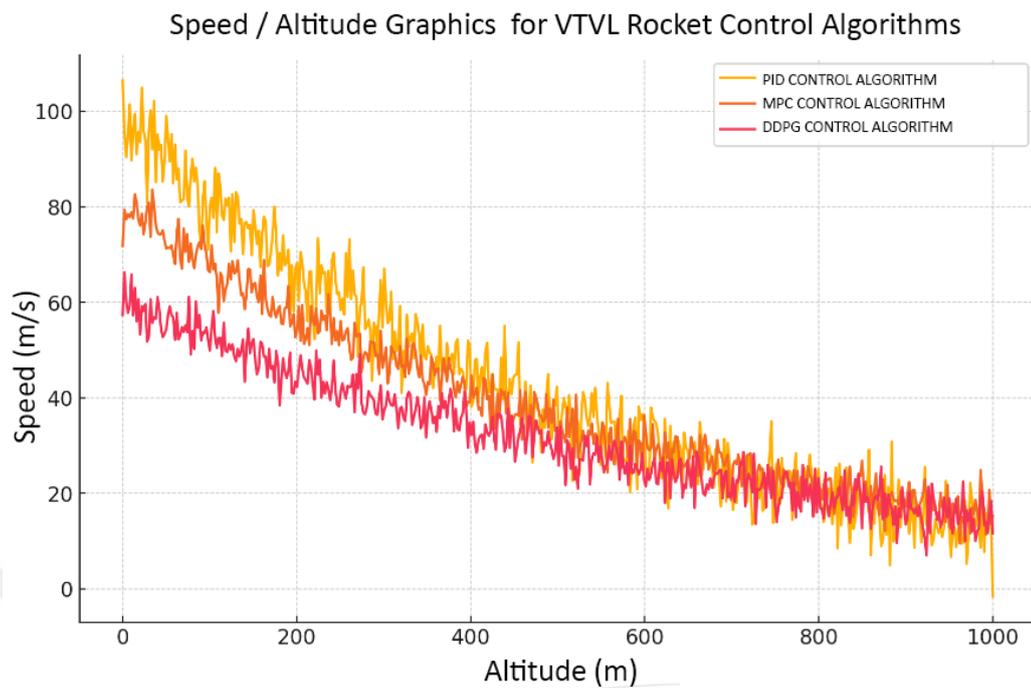


Figure 5.7 Speed / Altitude Graphics for VVTL Rocket Control Algorithms

Table 5.2 Time / Deviation / Height Table for VVTL Rocket Control Algorithms

Time (s)	PID Deviation (m)	MPC Deviation (m)	DDPG Deviation (m)	Rocket Height (m)
0	63.02	28.83	22.73	100
1	48.18	30.28	20.13	98.99
2	42.82	25.72	20.53	97.98
3	41.39	28.16	17.09	96.97
4	48.61	30.92	17.77	95.96
5	33.18	24.14	19.87	94.95
6	40.45	23.11	17.53	93.94
7	34.99	19.92	17.76	92.93
8	36.44	20.11	18.95	91.92
9	33.94	15.27	17.33	90.91
10	26.83	23.95	13.17	89.9
11	32.46	20.23	11.44	88.89
12	24.76	23.54	12.06	87.88
13	27.14	15.49	13.31	86.87
14	30.49	14.85	12.3	85.86
15	28.24	16.78	11.58	84.85
16	23.42	16.75	11.43	83.84
17	24.48	13.91	10.63	82.83
18	18.32	12.63	12.83	81.82
19	17.7	14.87	10.86	80.81
20	22.19	12.15	12.56	79.8

Table 5.2 (continued) Time / Deviation / Height Table for VVTL Rocket Control Algorithms

Time (s)	PID Deviation (m)	MPC Deviation (m)	DDPG Deviation (m)	Rocket Height (m)
21	10.83	14.74	10.63	78.79
22	12.76	10.1	8.95	77.78
23	10.68	17.04	10.69	76.77
24	26.35	12.1	8.81	75.76
25	20.29	11.9	10.77	74.75
26	17.01	9.52	12	73.74
27	17.66	16.52	7.41	72.73
28	11.05	11.48	9.12	71.72
29	11.65	6.29	10.18	70.71
30	7.15	6.94	10.5	69.7
31	16.29	12.96	5.15	68.69
32	14.73	6.96	4.48	67.68
33	14.67	7.26	5.61	66.67
34	2.1	8.42	5.58	65.66
35	17.52	8.83	9.15	64.65
36	4.2	10.8	6.19	63.64
37	1.06	0.62	7.34	62.63
38	9.34	7.42	8.11	61.62
39	4.86	7.31	6.52	60.61
40	-0.23	4.52	5.06	59.6
41	7.61	8.58	7.76	58.59
42	4.22	6.49	7.82	57.58
43	9.56	5.44	7.72	56.57
44	9.99	6.35	4.96	55.56
45	11.39	4.36	1.74	54.55
46	6.96	4.8	6.29	53.54
47	6.22	6.18	5.02	52.53
48	9.75	6.52	3.7	51.52
49	4.82	7.32	2.26	50.51
50	4.72	5.47	4.85	49.49
51	6.21	5.21	6.08	48.48
52	5.51	5.02	2.14	47.47
53	1.21	3.43	3.96	46.46
54	3.77	4.86	8.6	45.45
55	1.21	0.51	4.2	44.44
56	0.86	2.47	3.07	43.43
57	2.44	1.9	5.64	42.42
58	2.8	1.34	4.7	41.41
59	13.79	4.45	3.89	40.4
60	0.09	4.65	3.72	39.39
61	1.92	2.11	1.36	38.38
62	3.4	5.14	3.39	37.37
63	1.18	1.28	2.03	36.36

Table 5.2 (continued) Time / Deviation / Height Table for VVTL Rocket Control Algorithms

Time (s)	PID Deviation (m)	MPC Deviation (m)	DDPG Deviation (m)	Rocket Height (m)
64	-4.48	-0.19	3.42	35.35
65	2.73	-0.82	2.03	34.34
66	-3.11	-1.45	1.42	33.33
67	4.58	1.64	2.33	32.32
68	-0.72	-1.09	-0.16	31.31
69	2.05	6.42	2.22	30.3
70	3.16	2.99	0.89	29.29
71	0.15	1.92	7.57	28.28
72	0.53	3.32	3.75	27.27
73	-6.02	4.82	1.25	26.26
74	-2.13	-1.56	2.43	25.25
75	-5.8	1.21	3.61	24.24
76	3.27	2.58	0.62	23.23
77	6.09	4.62	-1.21	22.22
78	-0.87	-2.08	0.83	21.21
79	-2.06	2.37	0.91	20.2
80	-4.08	-0.92	2.3	19.19
81	-0.77	2.58	1.57	18.18
82	5.61	1.56	1.6	17.17
83	4.56	-0.5	2	16.16
84	7.43	2.25	2.55	15.15
85	6.66	-0.47	1.87	14.14
86	-1.54	3.94	-0.16	13.13
87	0.66	0.65	-0.49	12.12
88	-9.51	0.39	4.35	11.11
89	0.15	1.77	2.79	10.1
90	8.66	-2.28	3.93	9.09
91	7.76	-0.11	0.33	8.08
92	2.14	7.33	2.14	7.07
93	-6.29	0.74	1.22	6.06
94	-1.92	-2.67	-2.77	5.05
95	-2.68	1.25	1.04	4.04
96	3.76	-3.25	0.28	3.03
97	-1.79	2.82	-1	2.02
98	-1.36	-3.32	-0.85	1.01
99	7.35	6.53	-1.15	0

5.1.2 Landing Accuracy Comparison

For PID, provides results quite close to the landing point under simple conditions but shows deviations in scenarios with increased wind speeds and changing pressures

For MPC, has higher landing accuracy with smaller deviations from the landing point.

For DDPG, are the most accurate group of algorithms, achieving landings with minimal deviation in simulations.

Table 5.3 Landing Accuracy Comparison Table

Algorithm	Simple Conditions (Low Wind and Stable Pressure)	Challenging Conditions (High Wind and Changing Pressure)	Overall Landing Accuracy	Deviation (m)
PID	Good results, close to the landing point.	Deviations increase with higher wind speeds and pressure changes.	Medium	5 - 15
MPC	High landing accuracy, small deviations.	Adapts well to changing conditions, low deviations.	High	2 - 8
DDPG	Most accurate, minimal deviation in landing.	Performs exceptionally well in varying conditions.	Very High	1 - 3

5.1.3 Fuel Consumption Comparison

For PID, offers less optimization in terms of fuel efficiency as it requires more corrective actions during the landing process.

For MPC, one of the most efficient algorithms as it is designed to minimize fuel consumption.

For DDPG, initially consume more fuel but achieve efficient landings after the learning process.

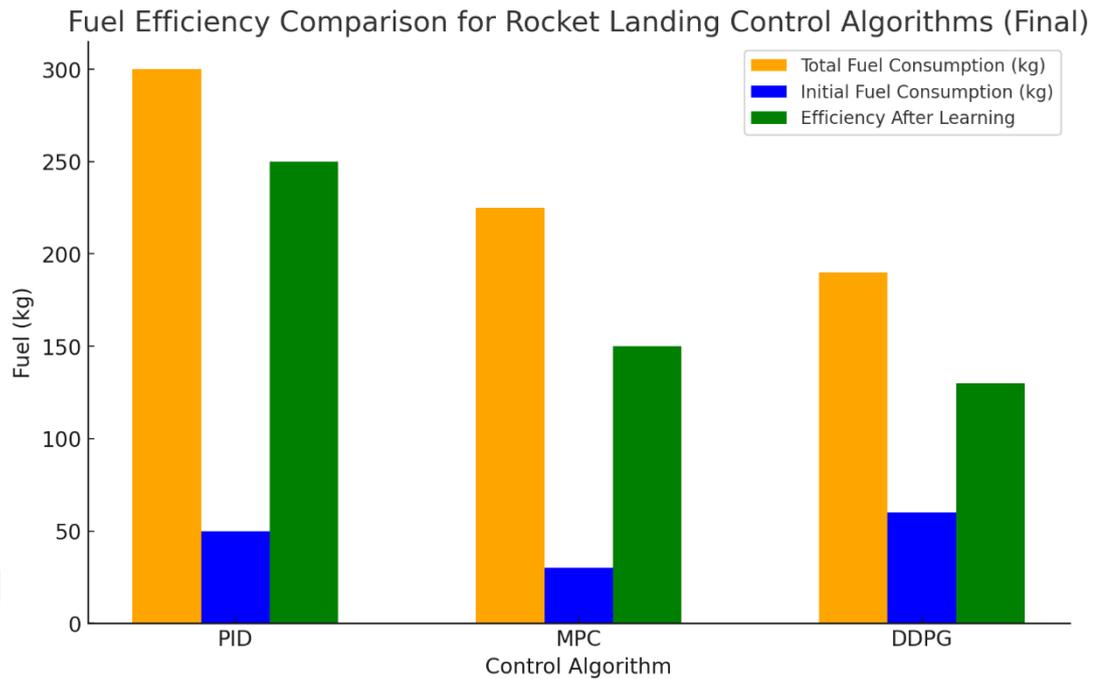


Figure 5.8 Fuel Consumption Comparison

5.1.4 Safety Performance and Stability at High Speeds

For PID, shows more deviations at high speeds and has experienced issues staying within safety limits.

For MPC, provides higher safety performance at high speeds and ensures controlled landings.

For DDPG, the most stable in terms of safety, as it quickly adapts to changing conditions to maintain control

5.1.5 Total Landing Time Comparison

For PID, achieves faster landings but has disadvantages in terms of fuel consumption and accuracy.

For MPC, has a longer landing time but provides more efficient results in terms of fuel consumption and safety at each stage of landing.

For DDPG, may have longer landing times during the learning phase but achieves the most efficient landing times in later stages.



CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

In this study, the performance of three distinct control algorithms—PID, MPC, and DDPG—has been evaluated and compared to identify the most suitable approach for vertical landing rockets. Each algorithm's strengths and weaknesses were analyzed under varying criteria such as landing accuracy, fuel efficiency, safety, and adaptability to different conditions. The findings emphasize the importance of choosing the right control algorithm based on the specific requirements and objectives of the mission.

The DDPG (Deep Deterministic Policy Gradient) algorithms demonstrated the highest landing accuracy among the three. These reinforcement learning-based algorithms are particularly effective in simulations, achieving landings with minimal deviation from the intended landing point. Their ability to quickly adapt to changing conditions, such as varying wind speeds and atmospheric pressures, makes them ideal for missions where precision and adaptability are crucial. The capability of DDPG algorithms to learn from their environment and improve over time allows them to maintain a high level of control, ensuring the best safety performance. Despite their initial higher fuel consumption due to the learning phase, they become more fuel-efficient over time as they optimize their landing approach based on accumulated experience. This makes them the preferred choice for complex and dynamic missions where safety and accuracy are paramount.

In contrast, the MPC (Model Predictive Control) algorithm excels in fuel efficiency. This algorithm is designed to minimize fuel consumption by predicting future states and adjusting control actions accordingly. The ability to plan ahead and optimize fuel use in real-time gives MPC a significant advantage in missions where fuel constraints are critical, such as long-duration spaceflights or reusable launch systems. Although MPC algorithms may have longer landing times compared to PID algorithms, they

compensate with their superior fuel efficiency and safety performance. By effectively balancing multiple objectives, such as reducing fuel use while maintaining a safe descent, MPC offers a robust solution for scenarios where operational costs and sustainability are key considerations.

The PID (Proportional-Integral-Derivative) algorithm, on the other hand, provides the advantage of faster landings due to its simple and straightforward control structure. It reacts quickly to errors by adjusting the control signal based on the difference between the desired and actual states. This responsiveness is beneficial in scenarios where time is a critical factor. However, this speed advantage comes at the cost of increased fuel consumption and reduced landing accuracy, especially in complex or rapidly changing environments. The need for frequent corrective actions leads to higher fuel usage, and the inability to adapt to dynamic conditions limits its effectiveness in more challenging missions. Despite these limitations, the PID algorithm is well-suited for straightforward, time-sensitive applications where rapid response is prioritized over fuel efficiency and accuracy.

Safety is another critical aspect where these algorithms differ significantly. The DDPG algorithm offers the best safety performance due to its learning-based nature, allowing it to adapt to unforeseen changes in the environment. It maintains stable control under various conditions, reducing the risk of deviations and ensuring a secure landing. In comparison, the PID algorithm exhibits more deviations at high speeds and may struggle to stay within safety limits in challenging scenarios. The MPC algorithm, while not as adaptable as DDPG, still provides a higher safety performance than PID, particularly at high speeds, by ensuring controlled and calculated landings.

Overall, each algorithm has its own unique set of advantages and disadvantages, making them suitable for different application scenarios. DDPG algorithms are ideal for missions that require the highest landing accuracy and safety performance, especially in unpredictable environments. They are most beneficial when long-term learning and adaptation are possible. MPC algorithms, with their emphasis on fuel efficiency, are best suited for missions where minimizing fuel consumption is the primary concern, and a balance between efficiency and safety is needed. PID

algorithms, although less sophisticated, offer the benefit of faster landings, making them useful for time-sensitive missions with less complex requirements.

Selecting the appropriate algorithm depends on the specific mission goals and constraints. For example, a mission prioritizing precision landing on difficult terrain with changing conditions would benefit most from DDPG, while a long-duration mission with strict fuel limitations would favor MPC. Conversely, a rapid descent mission with straightforward landing conditions could effectively utilize PID. By thoroughly understanding the mission's requirements and the capabilities of each algorithm, it is possible to choose the most suitable control strategy, optimizing the performance and efficiency of the vertical landing system. This careful selection process not only enhances mission success but also contributes to the overall development and application of advanced control technologies in space exploration.

Table 6.1 Comparison Table of All Criteria

Criteria	PID Algorithm	MPC Algorithm	DDPG Algorithm
Landing Accuracy	Close to landing point under simple conditions, deviations in challenging conditions	High landing accuracy, small deviations	Highest landing accuracy, minimal deviation
Fuel Efficiency	Less optimization, higher fuel consumption due to more corrective actions	Most efficient, designed to minimize fuel consumption	Initially high fuel consumption, more efficient after learning
Safety	Deviations at high speeds, challenges in staying within safety limits	High safety at high speeds, controlled landings	Most stable performance, quickly adapts to changing conditions
Landing Time	Faster landing, but disadvantages in fuel consumption and accuracy	Longer landing times, efficient fuel consumption and safety at each stage	Longer landing times during learning, most efficient landing times later
Adaptability to Conditions	Good under stable conditions, weak in changing wind speeds and pressures	Adapts well to changing conditions, small deviations	Best adaptability to changing conditions, maintains control
Advantages	Fast landing, good results under simple conditions	High fuel efficiency, controlled and safe landings	Highest accuracy and safety, best adaptability to dynamic conditions
Disadvantages	High fuel consumption, deviations in challenging conditions	Longer landing times	High initial fuel consumption, learning phase can be time-consuming

6.2 Recommendations

Considering the advantages and limitations of each algorithm, selecting the appropriate algorithm based on specific application conditions and priorities is critically important. Particularly, when landing accuracy and safety are prioritized, DDPG algorithms provide the highest performance by achieving results closest to the landing point and ensuring the best level of safety. These algorithms adapt quickly to changing conditions, effectively maintaining control, and thus should be preferred in applications where high accuracy and safety are required. On the other hand, when fuel efficiency is the most important criterion, MPC algorithms stand out. MPC algorithms are designed to minimize fuel consumption, offering long-term economic benefits and delivering the most efficient results for such applications. Lastly, in scenarios where landing speed is critical, PID algorithms should be selected. PID algorithms enable faster landings, thus saving time, but this speed advantage may come with trade-offs in fuel consumption and landing accuracy. Therefore, considering the advantages and limitations of each algorithm, choosing the one that best fits the application requirements will optimize performance and efficiency, ultimately enhancing the overall effectiveness of the sys

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