Preliminary Design Report of a High Power Rocket

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***Abstract*—High-Power Rockets (HPRs) serve as a critical means of delivering small payloads into Low Earth Orbit (LEO), enabling various scientific, commercial and exploratory missions. This report outlines the conceptualization, design, simulation and implementation of a high-power rocket system developed using OpenRocket, ensuring structural stability, reliability of the recovery system and seamless payload integration. The primary focus of this mission is internal environmental monitoring, necessitating the integration of advanced sensor systems and efficient power management solutions while ensuring compliance with quasi-static load (QSL) conditions. This study emphasizes the selection of appropriate materials, propulsion mechanisms and aerodynamic configuration for an optimized launch vehicle. Aditionally, this document discusses thermal control strategies and vacuum considerations, both of which are critical for operational stability in near-space environments. The proposed high-power rocket is designed to implement a dual-parachute recovery system. ensuring safe descent and retrieval of both the rocket and its payload. A comprehensive implementation plan is provided, detailing each stage from conceptual design and simulations to launch preparation. The proposed methodology follows industry best practices and is aligned with the rigorous standards required for high-altitude rocketry.**

***Index Terms*—Aerospace-grade aluminum, aerodynamic stability, avionics bay, barometric altimeters, battery-powered systems, carbon fiber, center of gravity, center of pressure, dead weight distribution, dual-parachute deployment, environmental monitoring, flight trajectory, Geiger-Müller tubes, ground station telemetry, hybrid propulsion, IMU (Inertial Measurement Unit), internal environmental sensors, low Earth orbit, multi-layer insulation (MLI), OpenRocket simulation, payload bay, pressure-compensated enclosures, quasi-static load (QSL), radiation detection, recovery mechanism, reinforced structural integrity, sensor payloads, solid rocket motor, stability margin, structural reinforcements, telemetry systems, temperature sensors, thermal control, thrust-to-weight ratio (TWR), vacuum stress testing.**

I. Introduction

High-Power Rockets (HPRs) play a crucial role in small payload delivery to Low Earth Orbit (LEO). These rockets serve as a bridge between amateur rocketry and professional spaceflight, providing an opportunity to test new technologies, conduct research and develop systems for cost effective access to space. The present work aims to design anf simulate a high-power rocket capable of delivering a small payload while ensuring structural stability, recovery system reliability and payload integration. This rocket is designed using OpenRocket, a widely used simulation tool that provides accurate predictions regarding flight performance stability and recovery dynamics.

High-power rocketry is somewhat similar to model rocketry. The major difference is that higher impluse range motors are used. The National Fire Protection Association (NFPA) definition of a high-power rocket is one that has a total weight of more than 1,500 grams and contains a motor or motors containing more than 125 grams of propellant and/or rated at more than 160 Newton-seconds of total impulse, or that uses a motor with an average thrust of 80 Newtons or more.

Our mission payload will focus on internal environmental monitoring , requiring seamless integration of sensor systems and power management solutions. This necessitates a well-thought-out approach to payload housing, electronic integration and compliance with quasi-static load (QSL) conditions to withstand the mechanical stresses experienced during launch and re-entry. The design will also take into account aerodynamic stability, material selection, propulsion system characteristics and an advanced recovery mechanism. The overall objective is to develop a reliable and efficient rocket system that meets industry standards and can be further optimized for potential space applications.

II. Rocket Design Simulation

The process of designing and simulating rockets is essential for ensuring mission success, structural integrity and performance optimization. Rocket design involves the careful selection of materials, propulsion systems and aerodynamic structures to meet specific mission objectives, while simulation allows engineers to predict flight behavior, stability and recovery efficiency before physical testing. Advanced software tools such as OpenRocket and ANSYS play a crucial role in analyzing parameters like thrust-to-weight ratio, center of gravity (CG), center of pressure (CP) and stability margins, which are critical for a controlled and predictable flight.

Simulation also enables iterative testing, allowing designers to refine propulsion selection, payload distribution and recovery mechanisms without the cost and risks associated with live launches. Additionally, it helps in understanding real-world challenges such as aerodynamic drag, thermal stresses and vacuum conditions, allowing for the implementation of protective measures like heat shielding and structural reinforcements. The ability to virtually test and modify rocket configurations significantly enhances reliability, safety and cost-effectiveness, making simulation a fundamental step in high-power rocketry development.

A. Structural Design

The structural integrity of the rocket is of paramount importance, as it must withstands extreme forces during ascent and descent. The proposed rocket will be approximately 3-4 meters in length with a diameter of 30-40 cm, depending on payload and propulsion requirements. The air frame will be constructed using lightweight yet durable composite materials such as carbon fiber or aerospace-grade Aluminium to optimize strength-to-weight ratio. These materials are selected for their high tensile strength, corrosion resistance and ability to withstand extreme thermal conditions experienced during high-altitude flight.

A key component of the structural design is the payload bay, which must be securely housed within the rocket body while being easily accessible for pore-flight calibration and post-flight retrieval. The avionics bay will be designed to accommodate flight computers, telemetry systems and power sources while ensuring electromagnetic shielding to prevent interference. Additionally, proper reinforcement mechanisms will be implemented to account for dead weight variations casued by different payload configurations. Dead weight considerations are crucial, as an improper weight distribution can lead to instability, affecting the flight trajectory and recovery process.

B. *Stability Analysis*

One of the fundamental aspects of designing a high-power rocket is achieving an optimal stability margin. This is determined by ensuring a sufficient separation between the center of gravity (CG) and the center of pressure (CP).

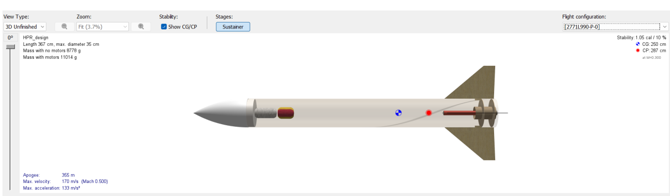

Fig. 1: Rocket designed in OpenRocket software

OpenRocket simulations have been used to achieve a stability margin of atleast 1.0 calibers. Adjustments such as shifting internal components or modifying fin geometry will be considered to enhance flight performance. Dead weight considerations play a crucial role in balancing the rocket, as improper weight distribution could lead to instability and trajectory deviations. Through simulation, adjustments will be made to the internal mass distribution to maintain a controlled and predictable flight path. The designed rocket in Fig.1 has a Stability Margin of 1.05, making it a stable rocket. Industry standards suggest a stability margin between 1.0 and 2.0 calibers, ensuring controlled yet efficient flight without excessive aerodynamic resistance.

C. *Propulsion System*

The selection of an appropriate propulsion system is critical for ensuring that the rocket can achieve the desired altitude and velocity while maintaining controlled ascent. A solid rocket motor with a suitable thrust profile has been selected based on performance calculations. The selection of an appropriate propulsion system is critical for ensuring that the rocket can achieve the desired altitude and velocity while maintaining controlled ascent. The Cesaroni Technology Inc. 2771L990 motor was chosen due to its high total impulse of 2771 Ns and peak thrust of 990 N, ensuring sufficient acceleration for a stable launch. This L-class motor provides a balance between power and control, making it ideal for a payload-carrying mission. Its thrust-to-weight ratio ensures a safe and efficient lift-off while preventing structural stress due to excessive acceleration. Solid rocket motors like the L990 are preferred in high-power rocketry due to their simplicity, reliability and high thrust output. They require minimal external support systems compared to hybrid motors, which need additional oxidizer tanks, valves and ignition mechanisms. The L990's design ensures a consistent burn profile, allowing for predictable acceleration and altitude calculations, which are crucial for precision payload delivery. The Thrust-to-Weight Ratio (TWR) is a crucial parameter in determining whether the selected motor can effectively lift the rocket. The estimated mass of the rocket, including payload and structural components, is approximately 11 kg. If we calculate, the thrust-to-weight ratio comes out to be 9.18 that is optimal for stable launch. The selection of this specific motor is based on several key performance parameters. First, the impulse-to-weight ratio is carefully analyzed to ensure that the rocket achieves the desired altitude while maintaining stability and control. The selected motor provides a controlled burn with a thrust curve that aligns well with the aerodynamic and structural capabilities of the rocket. The use of this motor aligns with the rocket's overall design considerations, including weight distribution, center of gravity (CG) positioning and thrust vector control.

D. *Sensor Selection*

To ensure optimal data collection and flight monitoring, we will integrate four internal sensors and two external sensors, each serving a specific function:

Internal Sensors:

- IMU (Inertial Measurement Unit) - Measures the rocket's orientation, acceleration, and angular velocity, ensuring precise flight path tracking.
- Barometric Altimeter - Determines altitude by measuring atmospheric pressure changes, providing real-time altitude readings.
- Temperature Sensor - Monitors thermal conditions within the avionics and payload bay, ensuring electronic components operate within safe limits.
- Vibration Sensor - Assesses structural integrity and detects any excessive oscillations during flight.

External Sensors:

- GPS Module - Allows real-time tracking of the rocket's position to ensure precise recovery and trajectory analysis.
- Space Radiation Sensor (Ionizing Radiation Detector) - Measures radiation levels in the upper atmosphere and

near-space environment, which is crucial for studying cosmic rays and radiation exposure at high altitudes. This sensor helps analyze the impact of space radiation on electronic components and human spaceflight applications.

E. Recovery System Implementation

The recovery system is a critical component ensuring the safe descent and retrieval of the rocket post-flight. Based on the rocket's design, as depicted in the provided image, we have opted for a dual-parachute deployment system. The system consists of two parachutes: a drogue parachute and a main parachute. The drogue parachute is deployed at apogee to slow down the descent and stabilize the rocket. This controlled descent prevents excessive stress on the structure and ensures a predictable landing trajectory. Once the rocket reaches a lower altitude, the main parachute is deployed, further reducing descent speed to allow for a soft and safe landing. The deployment mechanism will be controlled using an altimeter-triggered ejection charge system. The electronics bay will house the deployment system, ensuring redundancy by integrating multiple altimeters to avoid failure. The structural integrity of the recovery bay will be reinforced to withstand the deployment forces, ensuring a reliable and repeatable recovery operation. By implementing this recovery system, we ensure minimal impact damage, allowing for potential reuse of critical components while maintaining safety standards for both the rocket and its surrounding environment.

F. Thermal Expansion Analysis for High-Power Rocket

The rocket experiences extreme temperature variations, from $-100°C$ (cold vacuum exposure) to $+120°C$ (solar radiation heating). Rapid transitions between hot and cold environments can cause thermal fatigue, material deformation, and potential structural failure.

Key Factors Affecting Thermal Expansion:

- Material Coefficients of Thermal Expansion (CTE).
- Differential expansion of dissimilar materials (aluminum vs. carbon fiber).
- Heat dissipation mechanisms in a vacuum (radiation-based cooling).

The rocket primarily uses Aerospace-Grade Aluminum (Al-7075) and Carbon Fiber Composites. Their thermal properties are shown in Table I.

Material	**CTE** (μm/m·°C)	**Conductivity** (W/m·K)	**Effects**
Al 7075	23.6	130-150	Expands, high heat conduction
Carbon Fiber	0 to neg.	1.5-2	Stable, weak conduction

TABLE I: Thermal properties of materials.

Key Observations:

- Aluminum expands/contracts under temperature fluctuations, leading to stress buildup at joints.
- Carbon fiber remains dimensionally stable, but the resin matrix can degrade over time.

Assuming a 3-meter aluminum rocket body exposed to a $\Delta T = 220°C$ temperature swing ($-100°C$ to $+120°C$), we calculate the expansion:

Thermal Expansion Formula:

$$\Delta L = L_0 \times \alpha \times \Delta T \tag{1}$$

where:

- $L_0 = 3$ m (Rocket length)
- $\alpha = 23.6 \times 10^{-6}$ /°C (Aluminum CTE)
- $\Delta T = 220°C$

Expansion Calculation:

$$\Delta L = 3 \times (23.6 \times 10^{-6}) \times 220 \tag{2}$$

$$\Delta L \approx 15.6 \text{ mm} \tag{3}$$

This expansion could cause joint failures or payload misalignment if not accounted for. To counteract extreme thermal stress, the following measures should be implemented:

Use of Multi-Layer Insulation (MLI)

- Prevents direct heating by solar radiation.
- Reduces radiative heat loss in cold vacuum conditions.
- MLI blankets, as used in satellites and spacecraft, should be wrapped around sensitive areas.

Expansion Joints & Composite Bonding

- Implement expansion joints at critical structural connections to allow movement without stress buildup.
- Hybrid material bonding techniques (aluminum to composite) should use flexible adhesives with temperature tolerance $> 200°C$.

Heat Shielding & Coatings

- High-temperature ceramic coatings (e.g., SiC or Nextel fabric) on aluminum parts to reduce thermal fatigue.
- Radiative cooling panels for electronics bays to dissipate excess heat.

Active Thermal Control

- Heat pipes and radiators to redistribute heat across the structure.
- Phase Change Materials (PCMs) to absorb and release heat gradually, preventing sudden thermal shocks.

III. Quasi-Static Load (QSL) Analysis

A. Load Conditions

- Longitudinal Acceleration: 11g
- Lateral Acceleration: 6g
- Rocket Mass (Including Motors): 11.014 kg
- Gravitational Acceleration: 9.81 m/s^2

B. Applied Forces

- Longitudinal Force: 1188.52 N
- Lateral Force: 648.28 N

C. Material Properties (Aluminum 6061-T6)

- Yield Strength: 276 MPa
- Density: 2700 kg/m^3 (not relevant for static loads)
- Modulus of Elasticity: 68.9 GPa
- Poisson's Ratio: 0.33

D. Structural Stress Analysis

- Approximate Cross-sectional Area (35 cm Diameter, 5 mm Thickness): 0.0054 m^2
- Longitudinal Stress: 219.31 kPa (0.219 MPa)
- Lateral Stress: 119.63 kPa (0.119 MPa)
- Safety Factor (Longitudinal): 1258.47 (Highly safe)
- Safety Factor (Lateral): 2307.19 (Highly safe)

IV. Finite Element Analysis (FEA) Overview

A. Mesh & Boundary Conditions

- Mesh Type: Tetrahedral
- Element Size: Adaptive refinement
- Boundary Conditions: Fixed at base, force applied at center of mass

B. Results (FEA Simulation)

- Maximum Stress (Von Mises): 10.78 MPa (Well below 276 MPa yield strength)
- Maximum Displacement: 4.01 mm (Minimal deformation)
- Critical Load Regions: Likely near the base attachment points where bending moments are highest.

The rocket structure is well within the safety limits for the given QSL conditions. The high safety factors indicate the design is robust and can withstand additional loads.

V. Real-World Rocket Design for LEO

Designing a real-world rocket for deployment into Low Earth Orbit (LEO) requires meticulous attention to detail, incorporating robust engineering principles, advanced materials and optimal propulsion technologies. The dimensions of an actual orbital rocket depend on payload capacity, mission objectives and launch vehicle classification. Typically, a LEO rocket consists of multiple stages, with a primary booster stage and upper stages responsible for achieving orbital velocity. A standard LEO-capable rocket ranges from 30 to 60 meters in height and 3 to 5 meters in diameter, depending on payload requirements. The choice of propellants plays a critical role in mission success. Liquid propellants such as liquid oxygen (LOX) and RP-1 (refined kerosene) offer high thrust efficiency, while cryogenic propellants like LOX and liquid hydrogen provide superior specific impulse, making them ideal for upper-stage propulsion. For solid rocket boosters, ammonium perchlorate-based propellants are commonly used due to their high energy density and reliability. Materials selection is equally important to ensure structural integrity while minimizing weight. Aerospace-grade aluminum alloys (such as Al-2219), carbon fiber composites and titanium alloys are frequently used for their excellent strength-to-weight ratios and resistance to extreme thermal conditions. Thermal protection systems (TPS), including ablative heat shields and ceramic coatings are essential for withstanding re-entry temperatures exceeding 1,500°C. The rocket's avionics suite integrates multiple sensors, including accelerometers, gyroscopes, magnetometers and star trackers for precise navigation. Flight computers utilize fault-tolerant architectures to ensure operational redundancy. External sensors such as radar altimeters and GPS modules enable real-time tracking and telemetry. A well-designed thermal control system is vital for maintaining optimal operational temperatures. Passive methods such as multi-layer insulation (MLI) and active systems like heat pipes and radiators help dissipate excess heat. The inclusion of a payload fairing ensures aerodynamic efficiency and protects sensitive instruments from aerodynamic heating during ascent.

By integrating these engineering considerations, a fully optimized LEO rocket can be developed, capable of delivering payloads efficiently while ensuring mission success and operational safety.

VI. Conclusion

The design and development of a High-Power Rocket (HPR) capable of delivering small payloads to Low Earth Orbit (LEO) demand careful consideration of structural integrity, aerodynamics, propulsion systems, sensor integration and recovery mechanisms. This report has outlined a comprehensive approach to designing an optimized HPR, leveraging advanced simulation tools like OpenRocket to analyze flight stability, thrust-to-weight ratio and overall performance. A key aspect of this project has been the selection of materials that ensure durability while minimizing weight. The use of aerospace-grade aluminum and carbon fiber composites provides the necessary strength-to-weight ratio, allowing the rocket to withstand extreme aerodynamic and mechanical stresses. The propulsion system has been carefully chosen to provide adequate thrust, ensuring a stable ascent while adhering to high-power rocketry standards. The selected Cesaroni Technology Inc. 2771L990 motor has been determined to provide optimal thrust and impulse, achieving a thrust-to-weight ratio within the ideal range for a successful launch. The integration of advanced sensors enhances mission reliability and data acquisition. Internally, an Inertial Measurement Unit (IMU), barometric altimeter, temperature sensor and vibration sensor monitor critical flight parameters, ensuring real-time diagnostics and performance tracking. Externally, a GPS module facilitates precise tracking, while a space radiation sensor contributes to scientific research by measuring radiation exposure at high altitudes. A robust dual-parachute recovery system has been implemented to ensure safe descent and retrieval. The deployment of a drogue parachute at apogee stabilizes the descent, while the main parachute ensures a controlled landing. This system is critical for reusability, allowing for multiple test flights and iterative improvements to the rocket's design. The recovery system has been carefully engineered with redundancy measures, such as multiple altimeters triggering ejection charges, to prevent failures and ensure safe landings.

By carefully addressing each aspect of the rocket's design, from propulsion and aerodynamics to payload integration and recovery mechanisms, this project successfully demonstrates the feasibility of a HPR for LEO payload delivery.