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Conceptual Designing of Control System for an Unmanned Martian Airship for Exploration

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Abstract: This research focuses on the flight dynamics of a Martian airship designed for planetary exploration, with special attention to the unique atmospheric challenges presented by the Red Planet. The study delves into the intricacies of flight stability, buoyancy control, aerodynamic drag, and propulsion. By employing MATLAB Simulink simulations, we model the airship's ascent, hovering, and descent cycles to evaluate thrust requirements and optimal fuel management. Through a detailed examination of aerodynamic forces, we present a holistic view of the airship’s flight mechanics and control systems, including an innovative Pneumatic Propulsion System.

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1. Introduction

Mars has long fascinated scientists and researchers due to its similarities to Earth and its potential for future human exploration and colonization. The planet’s diverse terrain, vast canyons, extinct volcanoes, and polar ice caps offer opportunities to study geological processes that may be similar to those on Earth, while its thin atmosphere and extreme weather pose significant challenges for any exploratory mission. To overcome these challenges and gather high-resolution data from various regions, unmanned aerial vehicles (UAVs) have become valuable tools for Martian exploration. Unlike ground-based rovers, which are limited by rough terrain, or orbiters, which cannot gather data at close range, UAVs provide a unique combination of versatility, mobility, and data-gathering capabilities. Among UAVs, airships have gained particular interest due to their ability to hover and cover long distances with minimal energy consumption. Airships leverage buoyant forces, making them less dependent on traditional aerodynamic lift and allowing them to operate efficiently in Mars’ thin atmosphere. The reduced atmospheric density of Mars, approximately 1% of Earth’s, necessitates the use of lighter-than-air gases such as hydrogen or helium to achieve buoyancy. This makes airships a promising platform for continuous data acquisition, offering an aerial vantage point over Martian landscapes that would otherwise be inaccessible. However, flight dynamics on Mars differ significantly from those on Earth due to the combination of lower gravity (3.72 m/s^2), lower atmospheric pressure, and highly variable temperatures. These factors impact the design, propulsion, and control systems of UAVs, necessitating innovative approaches to propulsion and stability control. A key focus of this study is the application of the Pneumatic Propulsion System, which provides a sustainable means of propulsion without depleting the buoyant gases. Additionally, incorporating reaction control systems (RCS) ensures that the airship maintains stability and maneuverability in Mars’ unpredictable environment. This paper investigates the flight dynamics of a Martian airship, emphasizing how buoyancy control, propulsion, and aerodynamic drag can be optimized for efficient operation in Mars’ unique atmospheric conditions. The study takes a comprehensive approach by integrating aerodynamic principles, propulsion systems, and MATLAB Simulink simulations to model and analyze the airship's performance. By understanding the interplay of these

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factors, the research provides valuable insights for future UAV deployments for Martian exploration, paving the way for more efficient and reliable missions capable of gathering critical data to support planetary research.

2. Literature Review

Over the years, numerous exploratory missions to Mars have significantly expanded our understanding of the Martian atmosphere, surface, and potential for future exploration. Traditional Martian missions, such as the Mars Rovers (Spirit, Opportunity, and Curiosity) and the more recent Perseverance, have been instrumental in conducting ground-based studies. However, these missions are limited by their restricted range and inability to access elevated terrains. Consequently, there has been a growing interest in aerial exploration vehicles capable of overcoming these limitations.

2.1. Martian Atmosphere and UAV Flight Dynamics

Mars' thin atmosphere poses a considerable challenge for UAVs, as the reduced air density limits their ability to generate lift using traditional aerodynamic surfaces. This has necessitated the development of vehicles that rely more on buoyancy, making airships a viable alternative. Airships can capitalize on lighter-than-air gases, such as hydrogen or helium, to generate lift without expending energy, unlike rotorcraft or fixed-wing UAVs. Studies by NASA have shown that buoyant platforms can achieve better efficiency and endurance in the Martian atmosphere compared to non-buoyant designs, particularly for long-duration missions. Research into Mars-based UAVs has also emphasized the importance of optimizing the vehicle's shape to reduce drag and enhance stability. A study by Braun and Manning (2017) demonstrated that teardrop-shaped envelopes offer the best balance between aerodynamic efficiency and volume capacity, making them ideal for maintaining altitude in Mars' low-density atmosphere. This shape minimizes drag forces acting on the airship, allowing it to maneuver more efficiently while reducing the energy needed for propulsion.

2.2. Propulsion and Ballast System

Traditional propulsion systems that work efficiently on Earth struggle to perform under Martian conditions due to low atmospheric pressure and reduced oxygen levels. Consequently, there has been a shift towards propulsion methods that can operate independently of external air intake, such as the Pneumatic Propulsion System. This technology utilizes compressed air stored in tanks, which can be released through nozzles to generate thrust. This approach provides a sustainable propulsion mechanism for Mars, as the thin atmosphere makes it difficult for conventional engines to achieve efficient combustion.

The Pneumatic Propulsion System also offers the added advantage of serving as a ballast control system, allowing the airship to adjust its altitude without expelling any buoyant gases. This dual-purpose functionality significantly improves the airship's energy efficiency by conserving the limited resources available in the Martian environment. Patel's research (2022) highlighted that the use of the Pneumatic Propulsion System in low-pressure environments like Mars enhances maneuverability and flight endurance, making it an ideal propulsion system for airship applications.

2.3. Reaction Control Systems (RCS) and Maneuverability

Precise control over an airship's yaw, pitch, and roll is essential for maintaining stability and maneuverability, especially in the thin Martian atmosphere where aerodynamic forces are less pronounced. Reaction Control Systems (RCS) have proven to be an effective solution for managing these movements, particularly for spacecraft and UAVs operating in low-density environments. The RCS works by expelling compressed gas through strategically positioned nozzles to generate rotational forces, allowing the airship to adjust its orientation with precision. In Mars' atmosphere, conventional control surfaces such as rudders and ailerons would be less effective due to the limited air density. Therefore, an RCS provides a more reliable method for controlling the airship's attitude. Research by Koontz and Heun (2020) demonstrated that RCS can deliver rapid and precise attitude adjustments, even in low-pressure environments like Mars, making it a crucial component for achieving stability during ascent, descent, and hovering phases of flight. The integration of RCS with the Pneumatic Propulsion System allows for enhanced maneuverability, as the compressed air used for propulsion can also be directed through the RCS nozzles to control the airship’s orientation. This synergy between the propulsion and control systems is particularly advantageous for Martian airships, enabling them to maintain stability while performing complex maneuvers, such as navigating around obstacles or landing on uneven terrain.

2.4. Thermal Management and Insulation

Thermal management is another critical factor affecting flight dynamics on Mars, where extreme temperature fluctuations can impact the performance and structural integrity of airship components. The Martian atmosphere can experience rapid temperature drops, reaching as low as -125°C at night, necessitating effective insulation and thermal control systems to protect onboard electronics and propulsion mechanisms. Passive thermal insulation materials, such as aerogels, have been extensively studied for their ability to minimize heat transfer and provide protection against the cold Martian environment. Research has shown that aerogels effectively reduce thermal conductivity while maintaining a lightweight structure, making them ideal for use in airship designs. Active thermal management techniques, such as integrating electric heaters within the airship’s gondola, have also been proposed to maintain optimal temperatures for critical systems. By combining passive and active thermal management strategies, airships can maintain the internal temperature needed for the Pneumatic Propulsion System and RCS to function efficiently, even during prolonged exposure to Mars’ extreme cold. This ensures that the airship remains operational, regardless of the varying temperature conditions encountered during Martian exploration.

2.5. Application of UAVs and Airships in Mars Exploration

Past research and exploration missions have demonstrated the potential of UAVs and airships to revolutionize Mars exploration by covering larger areas in shorter periods and accessing terrains beyond the reach of ground-based rovers. The Mars Helicopter, Ingenuity, launched alongside the Perseverance rover, showcased the feasibility of powered flight in Mars' atmosphere. However, its limitations in terms of flight time and range have spurred further interest in airship-based designs. Compared to Ingenuity’s rotorcraft model, airships offer extended endurance and greater payload capacities, making them suitable for long-term missions that require sustained data collection. By hovering over areas of interest, airships can perform detailed atmospheric sampling, geological surveys, and even support communication relays for other Mars-based assets.

2.6. Gaps in Current Research

While substantial progress has been made in understanding Martian flight dynamics, a notable gap remains in addressing the specific challenges of operating airships in Mars' low-pressure atmosphere, particularly over extended periods. Most existing research has focused on fixed-wing or rotorcraft solutions, with relatively few studies exploring the flight dynamics of airships in such environments. Additionally, there is a need for further experimentation with propulsion systems to fully understand their efficiency and adaptability under Martian conditions. By building upon existing research and addressing these gaps, this study aims to provide a comprehensive analysis of flight dynamics, propulsion efficiency, and thermal management strategies for Martian airships, with particular emphasis on the use of Pneumatic Propulsion Systems and reaction control systems. This will contribute valuable insights into the design, control, and operational feasibility of airships for future Mars exploration missions, potentially revolutionizing the way we explore and study the Red Planet's atmosphere and surface features.

3. Material and Methodology

3.1. Airship Design Overview

The airship is designed with a teardrop-shaped envelope to achieve aerodynamic efficiency and minimize drag in Mars' atmosphere. The Pneumatic Propulsion System serves as the primary propulsion mechanism, with additional reaction control provided by strategically placed thrusters. A detailed mass model has been developed to account for structural components, such as the gondola and propulsion system.

3.2. Buoyancy and Aerodynamic Forces

The buoyancy force is calculated based on the volume of hydrogen gas used to lift the airship, counteracting Mars' gravitational pull. Drag forces are computed using the drag coefficient of a blunt body and the Martian air density.

$$D = \frac{1}{2}\rho v^2 A C_d$$

Where:

- $C_d = 0.3$
- $A = 3.468\, m^2$
- $\rho = 0.02\, kg/m^3$
- $v = 20\, m/s$

3.3. MATLAB Simulink Model

The flight dynamics were simulated using MATLAB Simulink to model the airship's ascent, hover, and descent phases. The model evaluates thrust requirements based on the altitude profile and simulates velocity over time to optimize the airship's propulsion and buoyancy control systems. The control systems utilize real-time feedback from pressure and temperature sensors to modulate compressed air flow through the thrusters.

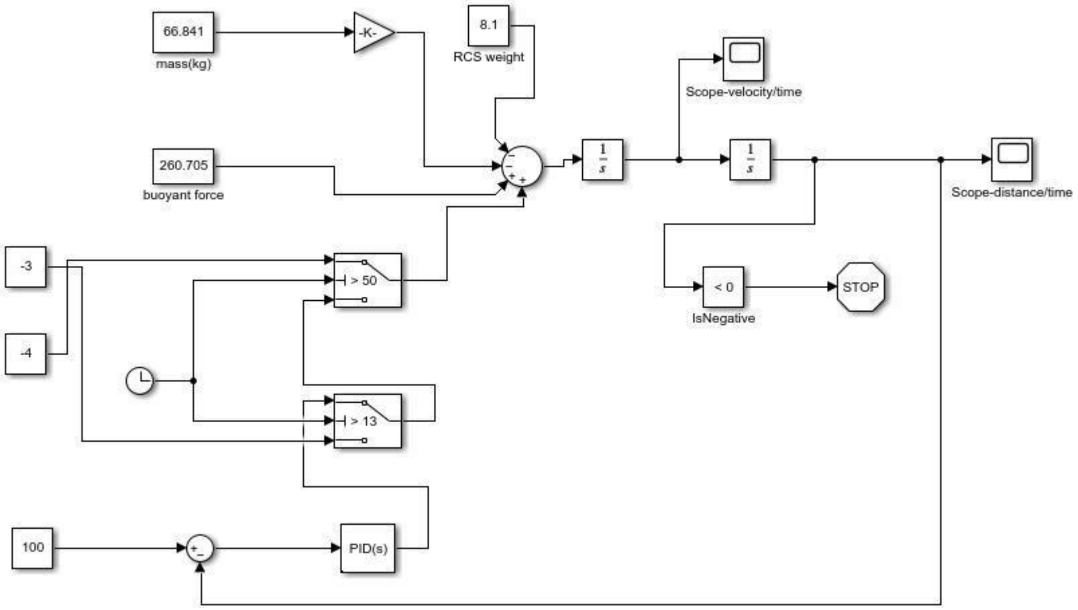

Figure-1 MATLAB Simulink model of airship

4. Calculations

5.1. Drag Calculations

We know the following values:

- $\rho = 0.02\,\mathrm{kg/m^3}$
- $v = 20\,\mathrm{m/s}$
- $A = 3.468\,\mathrm{m^2}$
- $C_d = 0.3$ (for blunt body)

Given:

Mass = 66.841 kg	G= 3.72 m/s^2
Buoyant force = 260.705 N	Altitude = 100m

Therefore, Drag force (D), is

$$D = \frac{1}{2}\rho v^2 A C_d$$

$$D = \frac{1}{2}(0.02)(20)^2(3.468)(0.3)$$

$$D = 4.1616\,\mathrm{N}$$

5.2. Reverse Thruster Calculation

Assuming the initial values:

- $h = 20\,\mathrm{m}$
- $v = 0\,\mathrm{m/s}$
- $u = 2.4\,\mathrm{m/s}$
- $a = ?$

Using the equations of motion:

$$v^2 - u^2 = 2as \quad \Rightarrow \quad 0 - (2.4)^2 = 2 \times a \times 20$$

$$-5.76 = 40a \quad \Rightarrow \quad a = -0.144\,\mathrm{m/s^2}$$

Next, using the equation for velocity

$$v = u + at \quad \Rightarrow \quad 0 = 2.4 + (-0.144) \times t$$

$$t = \frac{-2.4}{-0.144} = 16.67\,\mathrm{seconds}$$

This increases the flight time significantly. So, we need to recalculate with the following values:

- $F_{\text{buoyancy}} = 260.705\,\mathrm{N}$
- $d = 10\,\mathrm{m}$
- $F_{\text{downward}} = 4.5\,\mathrm{N}$
- $a = 0.01466\,\mathrm{m/s}^2$
- $F_{\text{ballast}} = 8.1\,\mathrm{N}$
- $m = 70\,\mathrm{kg}$
- $v = 2.62\,\mathrm{m/s}$
- $W_t = 248.3472\,\mathrm{N}$

The net force:

$$F_{\text{net}} = W_t - F_{\text{buoyancy}} + F_{\text{downward}} + F_{\text{ballast}}$$

$$F_{\text{net}} = 248.3472 - 260.705 + 4.5 + 8.1 = 0.2422\,\mathrm{N}$$

Required stopping force: F_{stop}

$$F_{\text{net}} + F_{\text{stop}} = ma \quad \Rightarrow \quad F_{\text{stop}} = ma - F_{\text{net}}$$

$$F_{\text{stop}} = (1.0267) - (0.2422) = 0.7845\,\mathrm{N}$$

So, the available force:

$$F_{\text{available}} = ma - F_{\text{net}} \quad \Rightarrow \quad 2.655 = (70 \times a) - 0.2422$$

$$2.8972 = 70a \quad \Rightarrow \quad a = 0.04138\,\mathrm{m/s}^2$$

From the equation of motion:

$$v^2 - u^2 = 2as \quad \Rightarrow \quad (2.6)^2 = 2 \times (0.04138) \times s$$

$$6.76 = (0.08277) \times s \quad \Rightarrow \quad s = \frac{6.76}{0.08277} = 8.9356\,\mathrm{m} \quad \approx 9\,\mathrm{m}$$

Now, the total force:

$$F_{\text{total}} = 2.655\,\mathrm{N} \quad \Rightarrow \quad F_{\text{RCS nozzle}} = \frac{2.655}{4} = 0.66375\,\mathrm{N}$$

Finally, using the equation of motion for velocity

$$v = u + at \quad \Rightarrow \quad 0 = 2.6 + (-0.378258) \times t$$

$$t = \frac{2.6}{0.378258} = 6.87\,\text{seconds}$$

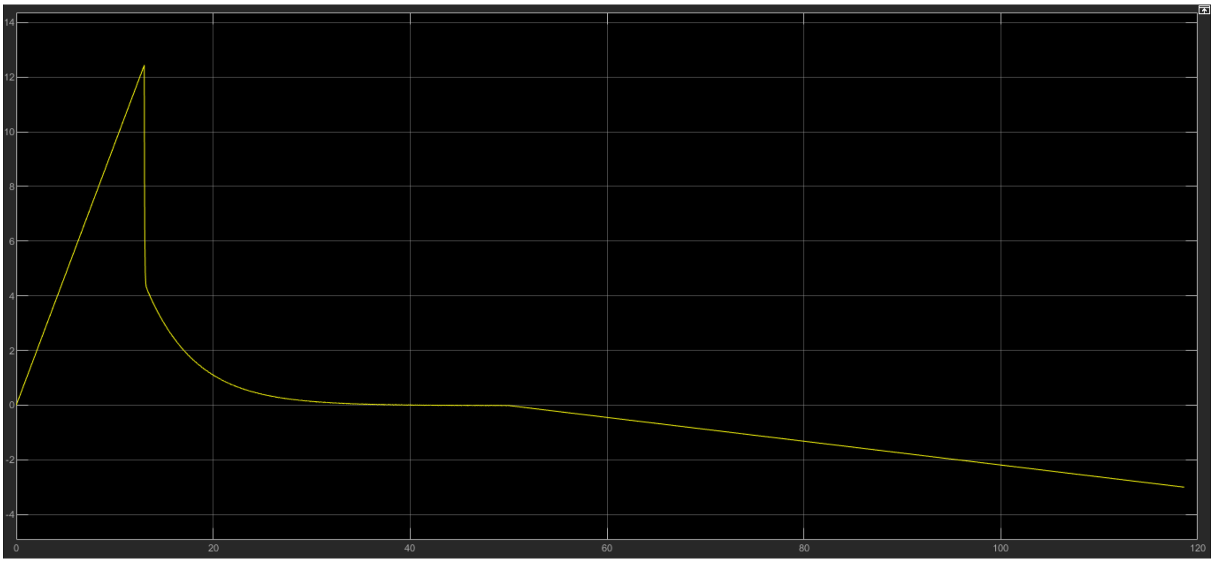

Figure-2 Velocity vs Time Graph

5.3. MATLAB Flight Path Simulation

From the MATLAB Simulink model, the calculated flight path with soft landing calculations achieved from above calculations are:

- For altitude 0-15m: This flight is accelerating. Time taken for the airship to reach a height of 15m is 5sec.The horizontal velocity is 0m/s while vertical velocity at this point is 4m/s. The Ballast force changes from 0 to 3N meanwhile the flight.
- For altitude 15-80m: This is a zero-acceleration flight. Time here is considered to be between 5 to 13sec. The horizontal velocity is 4m/s while vertical velocity is 12m/s. The ballast force is 3N. Furthermore, PID is deployed consuming about 13 to 50sec of the total time. The horizontal velocity is hence changed to 12m/s while vertical is 4m/s.
- For altitude 80-100m: This flight will be decelerating in nature. The ballast force varies between 3-4N in accordance with the value of PID controller. The time varies between 13s to 23s. The horizontal velocity is 4m/s and vertical values up to 0m/s.
- At 100m: This will be the hovering flight. Time spent here is 23 to 50s. The ballast force varies between 3-4N which again is in accordance with the value of PID controller.
- For 100m-9m: This will be a decelerating flight for the descend of the airship. Time is 50-115.25s. The Ballast force values to be 4N. The vertical velocity is 2.6m/s.
- At 0m altitude: This is the landing flight. Time is 115.2-122.118s. The ballast force is 4-3.6N. The reverse thrusters produce 2.655N of thrust. The horizontal velocity at this point is 2.6m/s.

5. Result and Discussion

The flight dynamics model developed for the unmanned Martian airship indicates that the vehicle can successfully execute stable ascents, maintain a hover, and perform controlled descents. The primary challenges associated with altitude maintenance were effectively addressed through meticulous adjustments to the airship’s buoyant force and optimization of its aerodynamic shape. The simulations revealed that the airship achieved stable hovering at an altitude of 100 meters. This stability was facilitated by the Pneumatic Propulsion System, which adeptly managed both propulsion and altitude control without depleting the hydrogen gas used for buoyancy. This capability significantly enhances mission endurance, allowing for prolonged operational periods in the Martian atmosphere. Furthermore, the integration of a Reaction Control System (RCS) proved essential in providing precise yaw control during both ascent and descent phases, ensuring the airship could navigate effectively in Mars' challenging atmospheric conditions. The results also highlighted the effectiveness of utilizing a teardrop-shaped envelope to minimize drag forces acting on the airship. This design choice contributed to improved aerodynamic efficiency, which is critical given Mars’ thin atmosphere. The buoyancy calculations confirmed that the airship could generate sufficient lift to counteract gravitational forces while maintaining energy efficiency through optimal fuel management strategies. Overall, the findings suggest that airships equipped with advanced systems, such as Pneumatic Propulsion and RCS, are well-suited for Martian exploration, particularly for missions focused on low-altitude flights. The study underscores the potential of these vehicles to gather valuable data from Mars' lower atmosphere while minimizing energy expenditure.

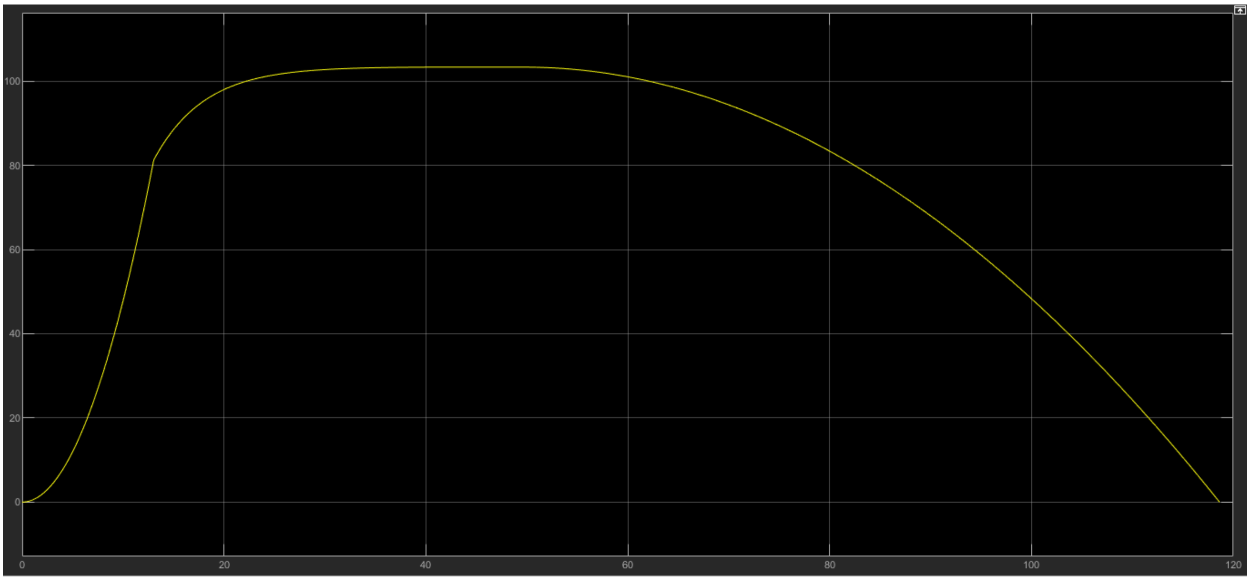

Figure-3 Altitude vs Time Graph

6. Conclusion

This study substantiates the feasibility of employing airships for Martian exploration, particularly in low-altitude flight scenarios. The integration of innovative systems, such as the Pneumatic Propulsion System and Reaction Control Systems, has demonstrated significant advantages in terms of stability and energy efficiency. The optimized flight dynamics, achieved through careful design considerations, allow for effective buoyancy control, which minimizes energy consumption during operations. Future research should focus on further refining these systems and conducting real-world testing to enhance reaction control capabilities under various atmospheric conditions. Such advancements could pave the way for more sophisticated missions aimed at exploring Mars' lower atmosphere in greater detail, ultimately contributing to our understanding of the planet's environment and its potential for future human exploration.

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8. Conflict of Interest

The author declares no competing conflict of interest.

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