Development of a Remotely Operated Reentry Rover for Planetary Exploration

Guru Dhungel* and Ammar Elkhatib†
University of South Carolina, Columbia, SC, 29201, USA

Wout De Backer#
University of South Carolina, Columbia, SC, 29201, USA

Planetary exploration missions are essential for advancing our understanding of the solar system, yet they face significant challenges in achieving safe atmospheric entry, precise landing, and effective surface mobility. This research addresses these challenges by designing a deployable rover capable of descending from 100 meters and transitioning to surface exploration controlled via Wi-Fi, specifically tailored for Mars-like terrain. The proposed system integrates advanced aerothermal shielding, a controlled descent mechanism, and a terrain-adaptive mobility system. Computational analyses using Abaqus were employed to model aerodynamics, thermal loads, and structural integrity during entry. Guidance, Navigation, and Control (GNC) strategies were developed to enhance landing accuracy and post-landing maneuverability. The rover is designed to withstand the harsh Martian terrain, with a chassis capable of handling large inclinations without relying on spring suspension. It is self-powered through solar panels and equipped with a camera to record and transmit HD video of its surroundings. The aeroshell, designed to protect the rover during descent, is representative of an entry vehicle undergoing aerobraking and can be mounted to and deployed from an amateur rocketry booster for testing. Key results include validated aerodynamic profiles for stable descent, optimized material selections for thermal protection, and performance metrics for mobility under Martian gravity and terrain constraints. This work advances the field of autonomous planetary exploration by bridging entry vehicle dynamics with rover mobility, offering a scalable framework for future missions and improving mission success rates through cost-effective exploration technologies.

---

* Undergraduate Student, Department of Mechanical and Aerospace Engineering, Student Member

† Undergraduate Student, Department of Mechanical and Aerospace Engineering, Student Member

Assistant Professor & Faculty Advisor, Department of Mechanical Engineering, Senior Member

I. Nomenclature

ADEPT = Adaptable Deployable Entry and Placement Technology
CAD = Computer-Aided Design
GNC = Guidance, Navigation, and Control
FEA = Finite Element Analysis
ISAS = Institute of Space and Astronautical Science
JAXA = Japanese Space Agency
JPL = Jet Propulsion Laboratory
MCEC = Molinaroli College of Engineering and Computing
HIAD = Hypersonic Inflatable Aerodynamic Decelerator
MUSES-CN = Mu Space Engineering Spacecraft

MSL = Mars Science Laboratory
MJF = Multi Jet Fusion
NASA = National Aeronautics and Space Agency
PICA = Phenolic Impregnated Carbon Ablator
PLA = Polylactic Acid

II. Introduction

A key component of scientific progress, planetary exploration has provided a greater understanding of extraterrestrial environments. Although rovers have been essential to previous missions, there are still obstacles in the way of a completely integrated strategy for atmospheric entry, accurate landing, and effective surface mobility [1]. To accomplish a safe landing, traditional planetary landing systems, like those used in NASA's Curiosity and Perseverance rovers, depend on a number of separate subsystems, including as parachutes, retro-propulsion, and sky-crane fall techniques [2]. Despite their effectiveness, these approaches have limitations in terms of mass efficiency, terrain adaptation, and scalability for missions in the future that need for more autonomy and payload capacity [3].

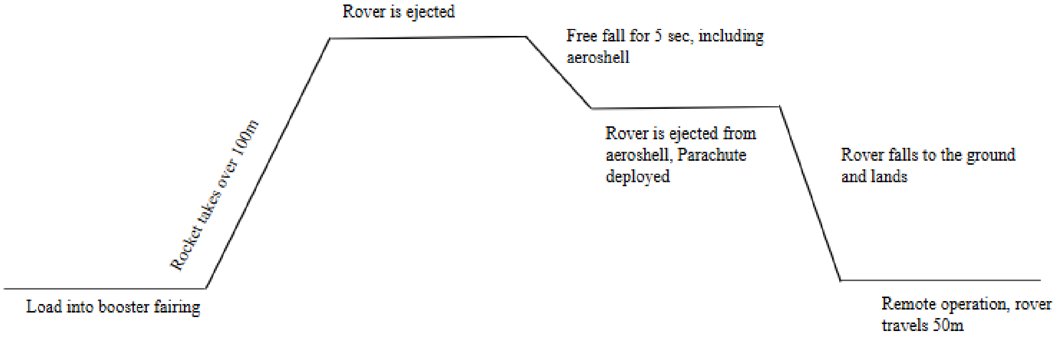


Fig. 1 Mission Profile Diagram

Our research investigates a miniature version of an integrated reentry and mobility system that is intended to be a low-cost, remote-controlled, solar-powered vehicle in order to address these issues. This prototype explores a more cohesive strategy by employing an aeroshell for both atmospheric entry and controlled landing on challenging terrain, in contrast to conventional systems that divide reentry, descent, and landing into discrete stages. To improve landing accuracy and terrain adaptation, the vehicle incorporates lightweight materials and deployable aerodynamic surfaces and is launched from a booster, simulating the dynamics of a planetary drop. [4]. As a scaled-down proof of concept, this study shows how small, inexpensive reentry and mobility devices may be created for upcoming space travel. This research offers important insights into deployable aerodynamic entry systems, energy-efficient surface mobility, and integrated planetary landing technologies, despite operating at a much lower altitude (sub-100m) and decreased size (<500g total mass)[5].

A. Background and Motivation

Traditional planetary landing systems employ rigid aeroshells and parachute-assisted descent mechanisms to achieve controlled entry and landing. NASA's Curiosity and Perseverance rovers, for example, utilized a sky-crane system for final descent and deployment [6]. While effective, these methods have limitations in scalability, mass efficiency, and precision landing. Moreover, Martian surface conditions, characterized by low gravity, high radiation, and rough terrain, present additional challenges for mobility systems. To address these challenges, deployable aerodynamic entry systems have been explored as an alternative approach. Studies on deployable heat shields and aerobraking mechanisms have demonstrated significant potential for reducing structural mass and increasing drag for controlled descent [7]. Fedele et al. investigated a mechanically deployable heat shield for Earth reentry capsules, validating its aerothermal performance through Plasma Wind Tunnel testing. Similarly, NASA has explored inflatable reentry vehicles, such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD), which offers a scalable solution for atmospheric entry [8].

Mars exploration has evolved significantly since the Pathfinder, Opportunity, and Curiosity missions, with each iteration introducing enhanced mobility and scientific tools [9]. China's Tianwen-1 mission incorporated ground-penetrating radar (RoSPR), providing insights into Martian subsurface structures [10]. the effectiveness of radar-based imaging for terrain assessment, facilitating better mobility planning for future rovers [11]. Additionally, Trunins et al. explored micro-rover mobility systems, highlighting the importance of multi-mission payload integration [12]. The growing need for precision landing technologies has driven significant research into aeroshell-based entry systems. For instance, Braun and Manning (2006) reviewed advancements in Mars entry, descent, and landing technologies, emphasizing the development of aeroshell-based systems to achieve higher precision in landing [4]. Additionally, Zou et al. (2021) highlighted the critical importance of accurate orbital insertion and landing site selection in China's Mars 2020 mission, detailing the Guidance, Navigation, and Control (GNC) system design implemented to ensure precise landing [13]. Recent research on deployable aeroshells for sample return missions further underscores the value of adaptive reentry strategies in planetary exploration [14].

B. Objectives and Contributions

This study proposes a remotely operated reentry rover designed to transition from descent to remote surface exploration, specifically optimized for Mars terrain. The rover is deployed by a booster developed by a collaborative team at an altitude of over 100 meters, followed by a 3-second free fall before the reentry rover is released from the aeroshell. The system is engineered to achieve a safe landing and demonstrate mobility on Mars-like terrain, with the rover capable of traversing up to 50 meters post-landing. Key contributions include a deployable aerothermal shielding system that minimizes mass while ensuring thermal protection, an adaptive mobility chassis capable of navigating Martian terrain without reliance on suspension mechanisms, and a precision landing strategy incorporating Guidance, Navigation, and Control (GNC) algorithms for descent accuracy and post-landing maneuverability[15]. The rover's design has been validated through Abaqus simulations, which evaluate aerodynamics, thermal resilience, and structural integrity. Additionally, the aeroshell functions as a deployable aerobraking system, tested in an amateur rocketry environment to validate descent control [16]. The remainder of this paper is organized outlining the problem set-up, detailing the key challenges associated with reentry rover deployment and Mars exploration, in-depth analysis of the detailed design and computer simulation, focusing on engineering methodologies, mobility solutions, and structural integrity.

III. Requirements and Constraints

Strict weight and size restrictions must be taken into consideration while designing a reentry rover for Mars exploration to guarantee compatibility with the launch vehicle and mission goals. The booster fairing, which is cylindrical and has a diameter of around 10cm and a height of roughly 15cm, must accommodate the rover. To ensure the stability and security of the rocket during launch and deployment, the rover's weight is also limited to about 500 grams. It takes creative design solutions that involve trade-offs in materials, components, and functionality to balance the requirement for a sturdy and competent rover within these limitations. The objective of this project is to design, manufacture, test, and operate a remotely controlled entry vehicle for a Mars lander mission simulation shown in Figure 1. The entry vehicle will consist of a rover and a protective aeroshell, functioning as a payload that interfaces with a booster developed by another team. Key performance requirements include: Ensuring the aeroshell protects the rover for at least 3 seconds post-deployment and complies with booster fairing constraints. Enabling the rover to traverse 50 meters over Mars-like terrain autonomously while capturing video footage. Powering the rover with a solar-based energy system capable of daytime operation and automatic reconnection after nightly shutdown. The ultimate goal is to deliver a functional and innovative entry vehicle system that meets all technical, operational, and regulatory requirements.

The design and deployment of a reentry rover for Mars exploration present several engineering challenges, particularly concerning safe atmospheric entry, controlled descent, and mobility upon landing. One of the fundamental considerations is the size and mass constraints imposed by the aeroshell and booster system. Unlike prior missions such as NASA's Mars Science Laboratory (MSL) Curiosity rover, which utilized a 4.5-meter diameter aeroshell to accommodate the rover and ensure aerodynamic stability and thermal protection during entry, this project is constrained to a total mass of 500 grams and a compact size of 10 cm in width, length, and height, encompassing both the aeroshell and the rover. The aeroshell must balance aerodynamic performance and thermal protection, similar to the 70-degree sphere-cone configuration used in MSL, which effectively reduced thermal loads and enhanced stability. These materials will be considered for integration into the proposed reentry rover. These stringent limitations necessitate innovative design solutions to achieve the required functionality within such a small form factor.

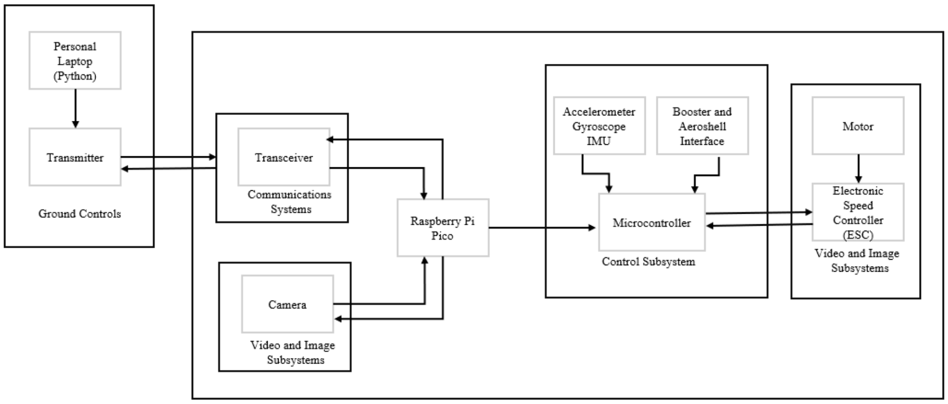


Fig. 2 Functional block diagram explaining the connection of electrical systems to the main computer

The electrical requirements for the rover are influenced by design considerations from NASA's MUSES-CN nano-rover mission. The MUSES-CN rover was designed to be solar-powered, enabling it to traverse the surface of an asteroid and collect imagery data to complement spacecraft investigations [17]. Similarly, our rover's electrical system must efficiently capture and store solar energy to power its operations. This includes managing the energy demands of critical components such as motors for wheel propulsion, cameras for imaging and terrain analysis, and actuators for parachute deployment. Ensuring a robust and efficient electrical system is crucial for the rover to successfully conduct its mission on Mars-like terrain, where reliable power management is essential for sustained mobility and scientific functionality.

Once deployed from the booster, the rover must successfully land and navigate 50 meters over Mars-like terrain, aligning with previous rover mission requirements [18]. The mobility system must be designed to handle rough terrain and inclines, similar to the Spirit and Opportunity rovers, which utilized independent suspension systems to traverse rocky surfaces [19]. Deployment is being carried out collaboratively by two teams developing separate boosters. The rover's deployment mechanism must be compatible with both booster interfaces and robust enough to endure the forces and conditions during launch and deployment. As noted by Sako, B. H. et al. the rover is expected to bounce several times upon landing before settling on the surface [20]. Additionally, the system must ensure a secure connection between the booster and the rover, enabling timely release and proper orientation for mission success. The final consideration is the electrical and operational constraints of the system. The rover will be solar-powered, in line with previous NASA missions, ensuring continuous operation in the harsh Martian environment. The electrical system must efficiently manage power for propulsion, communication, and scientific payloads, while maintaining a lightweight structure to comply with booster weight limitations.

There are major time and money restrictions on the project. With a $1,250 budget, choices on components, materials, testing, and other areas need to be carefully considered in order to guarantee that the project stays within its means while accomplishing its objectives. Achieving a balance between price and quality requires effective cost management. Furthermore, effective project management is necessary due to the tight deadlines for milestones and ultimate completion, which are established for the conclusion of the spring semester. To guarantee on-time delivery and effective project execution, this entails meticulous planning, resource allocation, and proactive risk reduction.

IV. Detailed Design

The Detailed Design section covers the technical details of the rover and its deployment system. It also highlights the engineering calculations and concepts that go into designing the rover's body, including its wheel and chassis, propulsion, power, and communication systems. Since it ensures a secure and reliable connection during launch and deployment, the interface between the rover and the launcher is a key focus area. During the design stage, the launcher team's weight and size constraints are carefully taken into account, as is the need for the rover to endure the harsh conditions of Mars-like terrain. Through careful research and testing, this complex design aims to ensure that the rover meets all mission requirements and can achieve its objectives.

A. Rover Design

The design of the rover is the foundation of the project and must be meticulously approached in order to produce an efficient vehicle that can traverse terrains akin to Mars. To endure the harsh pressures of launch and the unpredictability of deployment, the structure must be light yet sturdy. To push the rover across the 50-meter distance as efficiently as possible, the propulsion system should deliver adequate torque and be easily controlled. To reduce risk of power loss, solar panels are utilized for added power supply and efficiency in addition to the on-board battery pack. Additionally, the rover will be controlled with a Raspberry Pi Pico and a DC motor driver controller board which will aid in maintaining the rover's trajectory as well as keeping a fairly straight and efficient path over the terrain.

Property	Value
Ultimate Strength	37 MPa
Density	0.89 g/cm^3
Strength to Weight Ratio	Moderate
Machinability	High Machinable/weldable
Cost	Moderate
Availability	Available in United States Industrial Market

Table 1 Material Selection: Carbon Fiber, Polypropylene (PP)

Numerous modifications have been made to the rover's construction, which are still being improved. Design models have been created using Abaqus for simulations and Autodesk Fusion 360 for drawing. Weight reduction is the major focus of ongoing modifications since it continues to be a top design priority. The initial design, including dimensions, is shown in Figure 3.

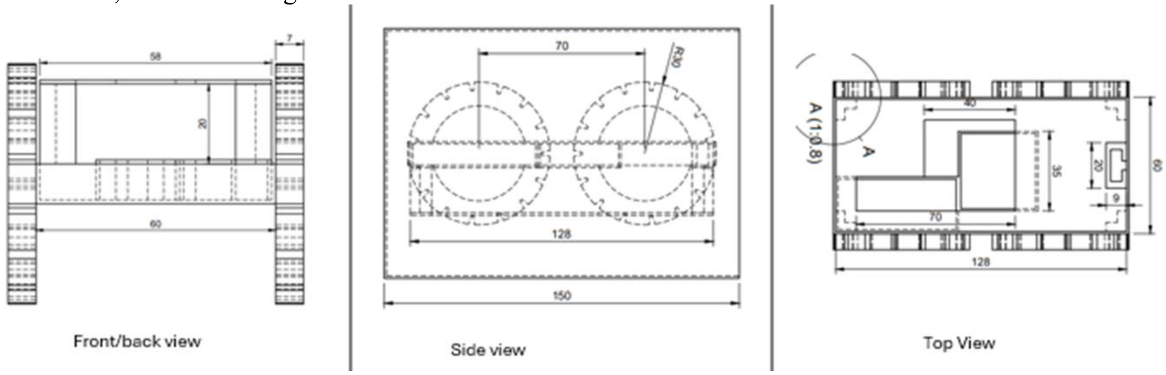


Fig. 3 Rover Views

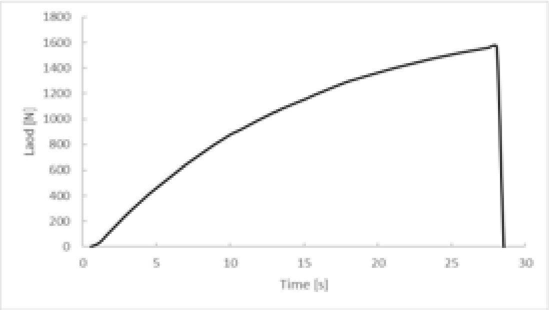
The rover will be housed in a cylindrical aeroshell that is about 10.5cm in diameter and 15cm high. These dimensions are crucial in determining how the rover develops, even though this design will be examined in more depth later. By tackling constraints that traditional vehicle designs are unable to overcome, the rover's design aims to allow it to navigate rocky and uneven terrain. The main objective is to design a rover with a mechanism that works well and gets rid of the problems with existing versions. Because of the limited weight, size, and dimensions, the rover's design needs to be exactly in line with these requirements. Furthermore, the Booster team's ability to incorporate the rover into their system is the only thing that will determine if it is successfully launched into orbit. This emphasizes how crucial it is to coordinate closely and strictly adhere to the set criteria in order to guarantee the rover's compatibility and mission readiness.

Material Specification	Carbon Fiber
Type of Channel Used	Polypropylene
Thickness	1cm
Chassis Dimensions	6*13 cm

Table 2 Plate Specifications

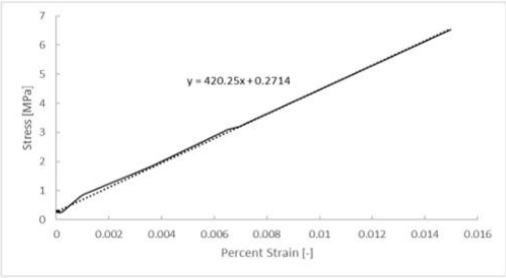
The strength and performance of a vehicle are critical factors in determining its reliability. To enhance the rover's performance, selecting a cost-effective material with an excellent strength-to-weight ratio is essential during the design and manufacturing of the chassis. Several factors were evaluated, including yield strength, density, strength-to-weight ratio, cost, and material availability. After thorough analysis, the options were narrowed down to graded aluminum and composite materials. Although aluminum alloy exhibits greater ductility and plastic deformation capabilities compared to carbon fiber, carbon fiber was ultimately chosen for this project due to its superior strength-to-weight ratio and stiffness, which align with the stringent weight constraints [21]. The decision was based on the evaluation criteria outlined in Table 2.

Carbon fiber composites were chosen for this project due to their exceptional strength-to-weight ratio, corrosion resistance, and durability, which are critical for the rover's lightweight and high-performance requirements. Carbon fiber is composed of thin, strong crystalline filaments of carbon, offering superior stiffness and tensile strength compared to traditional materials like aluminum [21]. It is widely used in aerospace and space applications due to its ability to withstand extreme conditions while maintaining structural integrity. Common variations include unidirectional, woven, and multidirectional carbon fiber laminates, each tailored for specific load bearing and flexibility requirements. These properties make carbon fiber an ideal material for the rover's chassis and structural components, ensuring reliability and efficiency in harsh environments.



Load Testing of Carbon Fiber Polypropylene Test Strip. Fracture occurred at 1568 N

Fig. 4 Load Analysis [22]



Tensile Modulus Testing of Carbon Fiber Polypropylene Test Strip

Young's Modulus, E = 420.5 MPa

Fig. 5 Stress Analysis[22]

The load and tensile testing curves for the carbon fiber polypropylene test strip provide valuable insights into the material's mechanical properties. The load testing curve indicates that the test strip fractured at a maximum load of 1568 N, demonstrating its strength under tension. The tensile stress-strain curve, represented by the equation $y = 420.25x + 0.2714$, reveals a Young's Modulus (E) of 420.5 MPa, which indicates the material's stiffness and ability to resist deformation under stress, figure 4. These results suggest that the carbon fiber polypropylene composite has a balanced combination of strength and flexibility, making it suitable for applications requiring durable and lightweight materials. The research conducted by the team from California Polytechnic State University, as detailed in their Mars Rover Structure Final Design Review, provides a comprehensive analysis of these properties, contributing to the understanding of carbon fiber composites in structural applications [22].

B. Aeroshell Design

For reentry vehicles, the aeroshell is a critical component designed to protect the payload from the extreme thermal and mechanical stresses encountered during atmospheric entry. The aeroshell (10.5cm radius and 15cm height) encloses the rover, as illustrated in figure 6, and serves two primary functions: thermal protection and aerodynamic stability. During reentry, the compression of atmospheric gases in front of the spacecraft generates temperatures as high as several thousand degrees Celsius. Without the aeroshell's heat shield, these extreme temperatures could cause structural failure or complete destruction of the vehicle. The aeroshell mitigates this by absorbing and dissipating heat away from the spacecraft's sensitive internal components, ensuring their survival. Additionally, the aeroshell's shape generates aerodynamic drag, which stabilizes the descent and enables a controlled reentry trajectory.

In the design of aeroshells for planetary entry and high-speed atmospheric missions, researchers have explored a variety of high-temperature materials that offer thermal protection, structural integrity, and mass efficiency. Collins et al. [23] investigated high-temperature adhesives, composites, and ablative thermal protection system (TPS) materials to reduce aeroshell mass by up to 30% while maintaining structural integrity at temperatures up to 400°C. Their study identified polymer-matrix composites (PMCs) such as RP46 and AFRPE-4, which retain 75% of their tensile strength at 315°C, and high-temperature adhesives like Cytec FM 680-1, which maintains 77% of its strength at 315°C. These materials were deemed suitable for deep-space missions and high-speed re-entry vehicles, where extreme heat and mechanical loads are encountered.

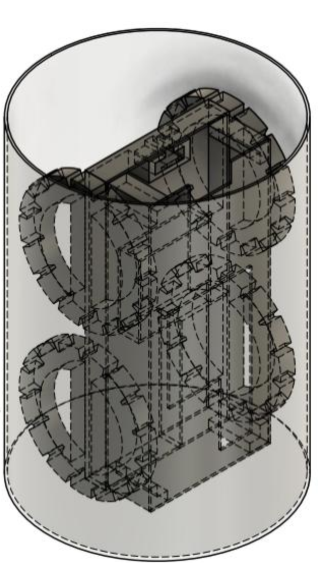


Fig. 6 Rover inside Aeroshell

Similarly, Timothy J. Collins and his team at NASA Langley [24] focused on aeroshell mass reduction using lightweight ablative materials, including silicone-based (SRAM-14, SRAM-17, SRAM-20) and phenolic-based (PC-20) ablators. Their results showed that increasing the bondline temperature tolerance from 250°C to 400°C allowed for a 30% reduction in TPS thickness, optimizing the payload capacity of spacecraft intended for Mars and deep-space landers. On the other hand, studies on functionally graded thermal protection materials (FGM) for reusable launch vehicles (RLVs) [25] utilized NiCrAlY and Yttria-Stabilized Zirconia (YSZ) coatings to enhance oxidation resistance and reduce thermal stresses, demonstrating higher durability in extreme entry conditions.

Recent advancements in aeroshell technology have focused on improving thermal protection and aerodynamic efficiency. For example, deployable aeroshells, such as the Adaptable Deployable Entry and Placement Technology (ADEPT), have been developed to enhance performance during reentry by adjusting their shape and surface properties dynamically [26]. Furthermore, materials like Phenolic Impregnated Carbon Ablator (PICA) and Carbon-Carbon composites have been widely used in aeroshell construction due to their excellent thermal resistance and lightweight properties, as demonstrated in missions like NASA's Mars Science Laboratory (MSL) [27]. The aeroshell is indispensable for ensuring the survival of the spacecraft and its payload during the demanding reentry phase, solidifying its role as a cornerstone of planetary exploration missions. Its dual functions of thermal protection and aerodynamic stability are critical for overcoming the extreme conditions of atmospheric entry, enabling successful missions to destinations like Mars and beyond.

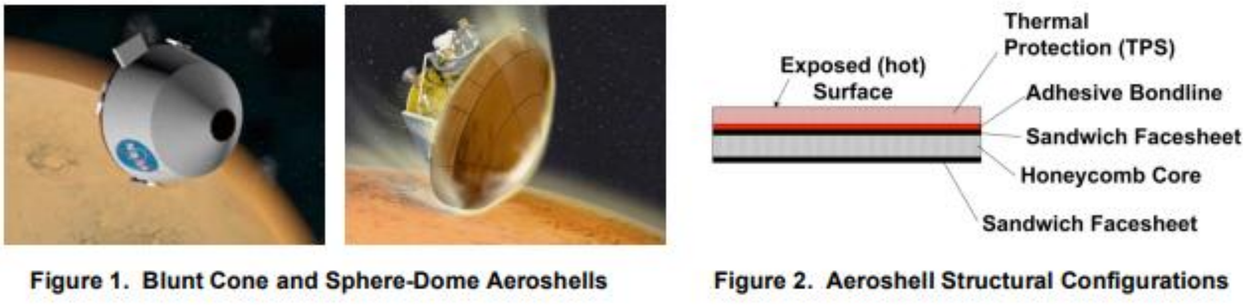


Figure 1. Blunt Cone and Sphere-Dome Aeroshells

Figure 2. Aeroshell Structural Configurations

Fig. 7 Aeroshell Configuration [23]

While these materials provide excellent thermal resistance and durability, they are not necessary for low-altitude applications. For this project, where the aeroshell will operate below 100 meters, carbon fiber was selected due to its lightweight nature, ease of fabrication, and high strength-to-weight ratio. Given that the total system weight is limited to 500 grams, including the rover, carbon fiber provides sufficient mechanical strength without adding unnecessary mass. Unlike ablative or refractory materials, which are crucial for planetary entry missions, carbon fiber is well-suited for low-altitude operations, ensuring efficient deployment and maneuverability within the mission’s constraints. The aeroshell will feature a hinged design with a spring-loaded mechanism to release the door, allowing for rapid and reliable deployment of the rover upon reaching the target altitude.

C. Computer Simulation

A key instrument for assessing the rover and aeroshell's performance and structural soundness is computer simulation. Without requiring actual prototypes, engineers may examine stress distribution, deformation, and overall durability under a range of environmental conditions by utilizing sophisticated simulation software. Extreme conditions that would be impossible or expensive to reproduce in real-world tests, such as high temperatures, changes in air pressure, and impact forces, can be tested under these simulations. By dissecting intricate structures into smaller parts, Finite Element Analysis (FEA) is essential to this process because it enables accurate assessment of how various configurations and materials react to applied stresses. While maintaining structural efficiency, this iterative process aids engineers in improving durability, identifying weak places, and refining the design. Computational simulations can help with design optimization and quick prototyping, which reduces development costs and increases the chance of mission success. Engineers may evaluate the efficacy of alternative aeroshell designs and thermal protection systems by simulating different planetary atmospheres. This ensures that payloads are protected during their mission while retaining lightweight and economical configurations.

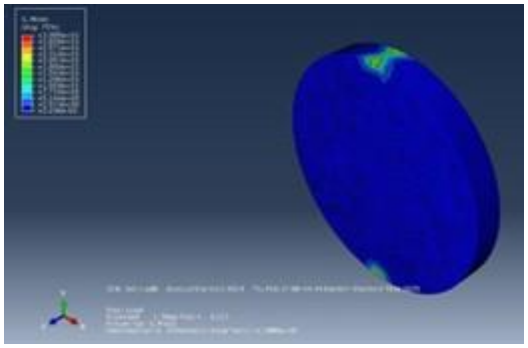


Fig. 7 Mises Stress Analysis

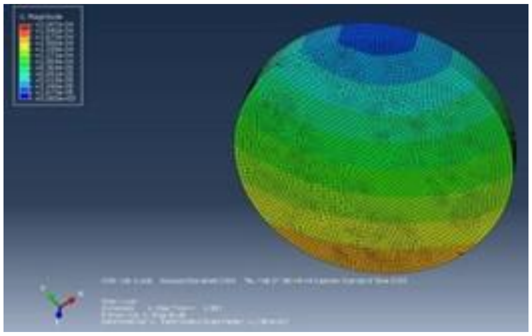


Fig. 8 Magnitude of the Deflection

In this simulation, we analyzed a 30 mm radius rover wheel under a 20 N load, which is significantly higher than the actual weight of the rover, which does not exceed 500 grams. This means the applied load is much greater than what the wheel would typically experience in real-world conditions, allowing us to test its durability under extreme forces. To ensure precision in capturing the stress and deformation distribution, we used a Hex mesh with 24,458 elements, enabling an accurate structural analysis. In finite element analysis (FEA), using a hexahedral (hex) mesh is beneficial because of its higher accuracy and computing efficiency. Hex elements frequently produce more accurate results with fewer components, especially when organized. The von Mises stress distribution highlights the most critical stress areas, with a maximum recorded stress of 30.85 MPa, as seen in Figure 8. The red-highlighted regions in this figure indicate potential high-strain areas, helping us refine the design for durability.

Alongside stress analysis, we also examined deflection, which plays a crucial role in evaluating the wheel's structural integrity and long-term performance. The maximum deflection recorded was 0.0002007 m $(2.007E-04\ m)$, a minimal value that confirms the wheel can withstand forces well beyond what it would typically endure on the rover. Figure 9 illustrates this deflection, highlighting the areas of highest displacement. Given that the wheel remains structurally sound even under loads far exceeding the rover's actual weight, this design is highly suitable for the rover, ensuring reliable performance, minimal wear, and optimal durability in real-world applications.

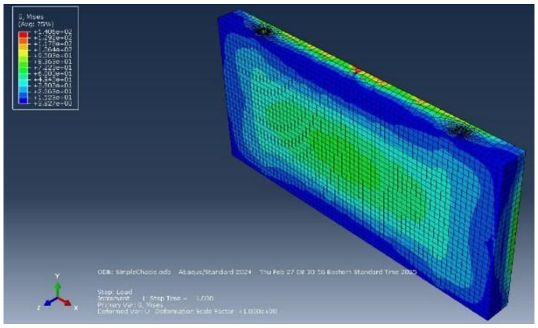


Fig. 9 Rover Chassis Mises Stress

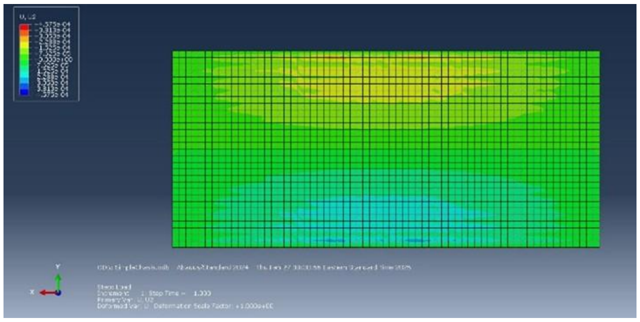


Fig. 10 Magnitude of the Deflection

The rover chassis, measuring 60*130 mm, is designed to handle a 15 N load, with a Hex mesh of 20,070 elements ensuring a detailed and accurate analysis. This study helps us understand how the chassis distributes stress and deforms under real-world conditions, making sure it remains strong yet lightweight for optimal performance. The results show that the maximum von Mises stress reaches 140.6 MPa, highlighting the areas where the chassis experiences the most strain. These high-stress zones, marked in red on the stress map, indicate potential weak points that might need reinforcement to improve durability.

When looking at deformation, the chassis experiences a maximum deflection of 0.0004575 m $(4.575E-4\ m)$ in the X and Y directions. This means that under load, the chassis flexes slightly but not enough to compromise its structure. The deflection map visually pinpoints where the most movement occurs, guiding us in refining the design to keep it rigid yet efficient. These findings confirm that the chassis can withstand operational forces without excessive bending, making it a reliable and well-optimized structure for the rover.

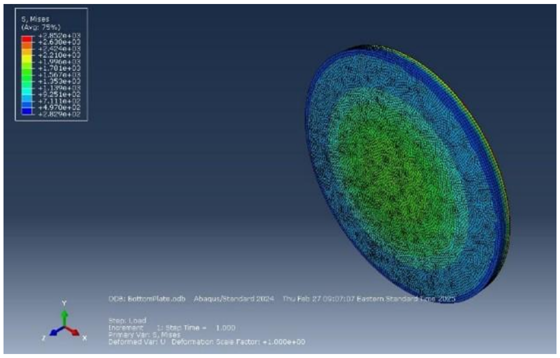


Fig. 11 Aeroshell base plate mises stress

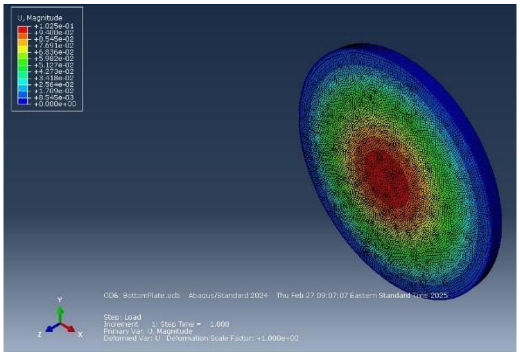


Fig. 12 Magnitude of the Deflection

The aeroshell bottom plate, with a radius of 50.25 mm, was analyzed under a 20 N load using a Hex mesh with 54,480 elements to evaluate its ability to withstand mechanical and aerodynamic forces. Considering that our rover's maximum weight is only 500 grams, the applied load in this simulation is significantly greater than what the plate will experience in real-world conditions. The results indicate a maximum von Mises stress of 2,852 MPa, with high-stress regions highlighted in red on the stress map. These areas represent potential weak points that may require design modifications, material reinforcements, or structural optimizations to improve durability and ensure long-term reliability. Beyond stress distribution, the study also examines how much the plate bends under load, showing a maximum deflection of 0.1025 m. Since the applied force is much higher than what the aeroshell would typically encounter, this deformation provides a worse-case scenario assessment of the structure's flexibility.

During the simulation process in Abaqus, there was no available option to define carbon fiber materials, so PLA (Polylactic Acid) plastic was chosen instead. While PLA is commonly used in 3D printing and prototyping, it is significantly weaker and more flexible compared to carbon fiber composites, which are known for their high tensile strength, superior stiffness, and better mechanical performance under load [28]. Since our rover is expected to operate in environments where structural integrity and durability are crucial, using carbon fiber instead of PLA would provide a more realistic and optimized design. Carbon fiber's ability to withstand higher tensile forces and its lower deformation under stress would drastically improve the strength-to-weight ratio, making the components more resilient and better suited for real-world applications.

V. Conclusion

Our remotely operated reentry rover demonstrates that a lightweight, reasonably priced planetary exploration device that can survive the demanding circumstances of space-like missions may be designed. We examined the rover's deformation under realistic loads, stress distribution, and structural integrity using Finite Element Analysis (FEA) simulations in Abaqus. The findings demonstrate that the wheel, chassis, and aeroshell bottom plate can withstand loads far higher than the 500 grams of the rover itself, guaranteeing its dependability and durability under real-world circumstances.

Choosing the right material was one of the most difficult things since we had to ensure it would be lightweight and strong enough to endure the pressure and movement in the rocket during launch. As such, we selected carbon fiber infused PLA as our print material for high stress parts like the chassis. However, representing this material in Abaqus proved to be difficult so we settled for normal PLA in our simulations. But since carbon fiber is known to be far stiffer and stronger, our real rover will perform considerably better than our calculations indicate. Additionally, our aeroshell design performed well in simulations, demonstrating that it offers protection during descent in addition to aerodynamic stability.

In the future, we'll concentrate on hardware assembly, practical testing, and improving our simulations using more accurate material models. We will have a better understanding of the rover's movement and deployment in practice if we test it on terrain similar to Mars. This research builds the foundation for future low-cost planetary exploration rovers by combining lightweight materials, clever structural design, and autonomous operation. This brings us one step closer to increasing the accessibility and effectiveness of space exploration.

Funding Source

All funding for this project was provided by the University of South Carolina, with a total of $1,250 allocated from the Molinaroli College of Engineering and Computing (MCEC).

References

[1] Braun, R.D. and R.M. Manning, *Mars Exploration Entry, Descent, and Landing Challenges.* Journal of Spacecraft and Rockets, 2007. **44**(2): p. 310-323.
[2] Arvidson, R.E., et al., *Mars science laboratory curiosity rover megaripple crossings up to sol 710 in gale crater.* Journal of Field Robotics, 2017. **34**(3): p. 495-518.
[3] Farley, K.A., et al., *Mars 2020 mission overview.* Space Science Reviews, 2020. **216**: p. 1-41.
[4] Braun, R.D. and R.M. Manning. *Mars exploration entry, descent and landing challenges*. in *2006 IEEE Aerospace Conference*. 2006. IEEE.
[5] Seltner, P.M., S. Willems, and A. Gülhan, *Aerodynamic coefficients of free-flying cubes in hypersonic flowfield.* Journal of Spacecraft and Rockets, 2019. **56**(6): p. 1725-1734.
[6] Laboratory, N.J.P. *Here's How Curiosity's Sky Crane Changed the Way NASA Explores Mars*. 2024 [cited 2025 February 21]; Available from: https://www.jpl.nasa.gov/news/heres-how-curiositys-sky-crane-changed-the-way-nasa-explores-mars/.
[7] Roldugin, D. and P. Testani, *Spin-stabilized satellite magnetic attitude control scheme without initial detumbling.* Acta Astronautica, 2014. **94**(1): p. 446-454.
[8] Ikeya, K., et al., *Significance of 3U CubeSat OrigamiSat-1 for space demonstration of multifunctional deployable membrane.* Acta Astronautica, 2020. **173**: p. 363-377.
[9] Sun, V.Z., et al. *Evolution of the Mars 2020 Perseverance Rover's Strategic Planning Process*. in *2024 IEEE Aerospace Conference*. 2024. IEEE.
[10] Chen, R., et al., *Martian soil as revealed by ground-penetrating radar at the Tianwen-1 landing site.* Geology, 2023. **51**(3): p. 315-319.
[11] Zhou, R., et al., *Predicting terrain mechanical properties in sight for planetary rovers with semantic clues. arXiv 2020.* arXiv preprint arXiv:2011.01872.
[12] Trunins, J., A. Curley, and B. Osborne, *Design of a mars rover mobility system.* Journal of the British Interplanetary Society, 2012. **65**: p. 87-97.
[13] Huang, X., et al., *The Tianwen-1 guidance, navigation, and control for Mars entry, descent, and landing.* Space: Science & Technology, 2021.
[14] Dimino, I., et al., *A Morphing Deployable Mechanism for Re-Entry Capsule Aeroshell.* Applied Sciences, 2023. **13**(5): p. 2783.
[15] Epp, C.D. and T.B. Smith. *Autonomous precision landing and hazard detection and avoidance technology (ALHAT)*. in *2007 ieee aerospace conference*. 2007. IEEE.
[16] Loewer, M., et al. *Design of a Launchable Remote-Controlled Rover and Protective Aeroshell*. in *2024 Regional Student Conferences*. 2024.
[17] Jones, R. and B. Wilcox, *The MUSES CN rover and asteroid exploration mission.* 2000.
[18] Carsten, J., et al. *Global path planning on board the mars exploration rovers*. in *2007 IEEE Aerospace Conference*. 2007. IEEE.
[19] Lindemann, R.A. and C.J. Voorhees. *Mars Exploration Rover mobility assembly design, test and performance*. in *2005 IEEE International Conference on Systems, Man and Cybernetics*. 2005. IEEE.
[20] Sako, B., et al., *Derivation of atmospheric gust-forcing functions for launch-vehicle loads analysis.* Journal of Spacecraft and Rockets, 2000. **37**(4): p. 434-442.
[21] Mouritz, A.P., *Introduction to Aerospace Materials*. 2012: Woodhead Publishing.
[22] Nikcevich, E., et al., *Mars Rover Structure.* 2022.
[23] Collins, T.J., et al. *High-temperature structures, adhesives, and advanced thermal protection materials for next-generation aeroshell design*. in *Spacecraft Propulsion Subsommittee Joint Meeting*. 2005.
[24] Congdon, W., D. Curry, and T. Collins. *Response modeling of lightweight charring ablators and thermal radiation testing results*. in *39th AIAA/ASME/SAE/ASEE joint propulsion conference and exhibit*. 2003.
[25] Baluragi, H., et al., *Development of functionally graded coating material for metallic thermal protection system of reusable launch vehicle.* Transactions of the Indian Institute of Metals, 2011. **64**: p. 471-481.
[26] Hwang, J.T., et al., *Large-scale multidisciplinary optimization of a small satellite's design and operation.* Journal of Spacecraft and Rockets, 2014. **51**(5): p. 1648-1663.
[27] Laub, B., & Venkatapathy, E., *Thermal Protection System Technology and Facility Needs for Demanding Future Planetary Missions*, in *International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*. 2003: Lisbon, Portugal.
[28] Bodaghi, M., et al., *3D/4D printed bio-composites reinforced by bamboo charcoal and continuous flax fibres for superior mechanical strength, flame retardancy and recoverability.* Polymer Testing, 2025: p. 108709.