Design of a Launchable Remote-Controlled Rover and Protective Aeroshell

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Planetary rovers, vehicles that can traverse challenging terrain, have excelled in their exploration missions to other celestial bodies. They have been especially suitable for exploring Mars, as rovers such as Opportunity and Perseverance have collected valuable geological, atmospheric, seismic, and magnetic information from the Martian surface. Rovers will remain vital in future space exploration missions, and it is necessary to understand their design and functionality. This paper focuses on the design and prototyping of a miniature rover that can survive the rough Martian terrain while collecting and submitting environmental data for scientific analysis. The proposed design is based off proven Martian rover designs by NASA. To protect the vehicle from the typical atmospheric entry conditions encountered by mars missions, the rover is contained within a protective aeroshell. The proposed design enables the aeroshell to be mounted to and deployed from an amateur rocketry booster, so its functionality can be tested. The aeroshell protects the rover during descent before detachment and is representative of an entry vehicle undergoing aerobraking. Once landed and removed from the entry vehicle, the rover is self-powered through solar panels and controlled remotely by an operator. Its chassis design gives it the ability to withstand relatively large inclinations while not relying on spring suspension, allowing it to traverse Mars-like terrain. The rover contains a camera that can record HD video of its surroundings and transmit the video to an external receiver. The proposed rover and aeroshell designs may provide insight and lessons learned into Martian rover and entry-vehicle design and could be applied to future rover missions.

I. Nomenclature

CAD	=	Computer-Aided Design
ESA	=	European Space Agency
FEA	=	Finite Element Analysis
ISAS	=	Institute of Space and Astronautical Science
JAXA	=	Japanese Space Agency
JPL	=	Jet Propulsion Laboratory
MJF	=	Multi-Jet Fusion
MF	=	Mineral-Filled
MMX	=	Martian Moons Exploration
MOXIE	=	Mars Oxygen In-Situ Resource Utilization Experiment
NASA	=	National Aeronautics and Space Agency
PA	=	Polyamide
SLS	=	Selective Laser Sintering

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II. Introduction

Planetary rovers have been crucial in missions to other celestial bodies such as Mars over the last 30 years. They can collect a wide variety of surface information, such as atmospheric, seismic, environmental, and geological data and transmit that data back to Earth. They can traverse challenging terrain and move from location to location to collect a wider variety of data, while protecting their instruments and electronics with a rigid structure. Planetary rovers will continue to play a key role in space exploration, as they are currently collecting valuable data that will help regulate the scope of future missions and provide a deeper understanding of the solar system. And as their role expands, rover designs must constantly evolve to expand their range of capability.

NASA has a long history of sending rovers to Mars. Through the efforts of Sojourner, Spirit, Opportunity, and Curiosity, NASA has collected and analyzed a large amount of data from the Martian surface. Today, NASA's Perseverance rover is exploring the history of the Jezero crater, a 45 km diameter crater and location of an ancient delta and lake basin on the Martian surface [1]. The crater contains sediments, assumed to be river deposits along the delta and lake basin as early as 3.6 billion years ago [2]. Perseverance is also investigating one-meter-wide boulders high up within Jezero crater, potentially indicating the existence of floods on ancient Mars [3]. This research advances NASA's mission of confirming the existence, and extent, of water on ancient Mars, building on the work of Spirit and Opportunity, and has opened discourse into the potential of life on Mars [3]. Another key objective of Perseverance's mission is to extract oxygen from the Martian atmosphere. Engineers at NASA's Jet Propulsion Laboratory (JPL) developed the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) instrument to extract oxygen from air on Mars. By having the ability to produce oxygen on Mars, NASA can reduce the oxygen payload weight for crewed missions [4]. During its' first operation, MOXIE successfully produced around 5 g of breathable oxygen, or around 10 minutes' worth for an astronaut [4]. Thanks to the success of the instrument, NASA wants to utilize similar technology when humans make their journey to the red planet [4].

Other space agencies are also designing planetary rovers and sending them to celestial bodies. In June 2020, along with Perseverance, China's Tianwen-1 mission marked China's first mission to Mars and attempts to gather pertinent atmospheric, gravitational, and geological information [5]. More specifically, the rover used in the Tianwen-1 mission will investigate the topography, soil composition, and water-ice distribution of Martian surface materials [5]. The Rosalind Franklin, a rover jointly designed by the ESA and Roscosmos, pledging to be a "fully fledged automated laboratory on Mars" according to ESA astronaut Tim Peake (Dickinson, 2023) [6]. It will provide spectroscopy, advanced radar, and a 2 m drill for its' research efforts [6]. It was supposed to launch in 2022; however, after the partnership between the ESA and Roscosmos was cancelled, the launch date has been pushed back to 2028 [7]. The Japanese Space Agency (JAXA) plans to send a lander to Mars' moon Phobos as part of the Martian Moons Exploration (MMX) mission in 2026, with the goal being to collect samples from Phobos to return to Earth [8]. These missions highlight the continued effectiveness of planetary rovers and highlight the importance of the design.

NASA has consciously considered the practical applications of small rover counterparts, whether to expand the scientific discovery possibilities of Martian and lunar missions or enabling missions to other celestial bodies such as asteroids and comets. In 1997, Japan's Institute of Space and Astronautical Science (ISAS) announced their MUSES-C or Hayabusa mission. Set to launch in 2002, MUSES-C would attempt to gather samples from a nearby asteroid called Nereus to provide insight into the formation of the inner planets [9]. For this mission, NASA pledged to contribute a one-kilogram robotic rover to collect images and spectral data on the surface of Nereus titled MUSES-CN [9]. However, NASA cancelled the project in 2000 [10]. More recently, NASA created Ingenuity, a small 1.8-kilogram autonomous helicopter that accompanies Perseverance on Mars. During Ingenuity's lifetime, it has been key in expanding the capabilities of Perseverance's mission. Its' scouting capabilities have both guided Perseverance and acquire aerial images of the surrounding terrain, while it set a benchmark for aerial performance in the Martian atmosphere [3,11]. Sadly, after three years and 72 flights, it is no longer operational [11].

The team believes that small rovers will become essential for future space exploration missions. Their smaller size makes them highly preferable for certain missions. They can traverse the surface of asteroids and transmit data to help design asteroid mining technology, an industry of the future. They can land on interesting celestial objects such as comets and collect important scientific data from them. They can drive into small spaces that larger rovers cannot collect scientific data. Finally, they could be used as a counterpart to a larger rover to expand the reach of a mission. For these reasons, the team decided to build one of these small rovers, see what challenges will arise, and test its' potential capabilities.

III. Problem Set-Up

This paper focuses on the design and development of a remotely operated rover deployed from an aeroshell. There are several key requirements that guide the design and development of the rover and its deployment system throughout this project. Key requirements are modeled after those of NASA's nanorover tasks. "The Nanorover Technology Task is a technology development effort to create very small (10-100s of grams) but scientifically capable robotic vehicles for planetary exploration, which can easily fit within the mass and/or volume constraints [10]." Requirements specific to this project include the need for the rover to be remotely operated and solar-powered, as well as its ability to traverse 50 m over Mars-like terrain. The rover must also be equipped with video recording capabilities to capture its environment during operation. Additionally, the aeroshell must protect the rover for at least 5 s after deployment from the booster.

As discussed, deployment is being done in conjunction with two separate teams creating boosters. The deployment of the rover from the booster must be compatible with both interfaces and must be robust enough to withstand the forces and conditions experienced during launch and deployment because "once the rover is dropped from the spacecraft, it is expected to bounce a few times before coming to rest on the surface" (Litwin & Wilcox, 2000) [12]. It also needs to provide a secure connection between the booster and the rover, ensuring that the rover is released at the correct time and in the proper orientation for its mission.

Another set of requirements that come almost directly from those of NASA's nanorover are the electrical requirements. According to NASA, "the solar powered rover will move around the surface of 1989ML collecting imagery data, which are complimentary to the spacecraft investigation" (Litwin & Wilcox, 2000) [12]. These electrical requirements include designing a solar power system that can efficiently capture and store enough energy to power the rover's operations. Additionally, the rover's electrical system must be robust enough to manage the demands of its various components, such as the propulsion system, communication system, and other various instruments. Ensuring that the electrical system meets these requirements is crucial for the rover to successfully conduct its mission on Mars-like terrain.

This then leads to arguably the largest design guiding requirements: size and weight. These requirements imposed by the booster team present significant challenges for rover design. The rover must fit within the confines of the booster fairing, which is cylindrical with a 101.6 mm (4 in) diameter and a height of 101.6 mm as well. Additionally, the rover must meet certain weight restrictions to ensure the stability and safety of the booster during launch and deployment. This weight requirement was given to be 350 g. Balancing the need for a robust and capable rover with the constraints imposed by the booster team requires innovative design solutions that involve trade-offs in terms of materials, components, and functionalities.

The final constraints of this project include financial and time constraints. The budget allocated for the project was $1,250 dictating available materials, components, testing, and other project decisions. Managing costs effectively is crucial to ensure that the project stays within budget while meeting all requirements and objectives. Time constraints are also a key consideration, with deadlines set for various milestones and the final completion of the project. Efficient project management, including scheduling, resource allocation, and risk mitigation, is essential to meet these time constraints and deliver the project by the end of the spring semester.

IV. Detailed Design

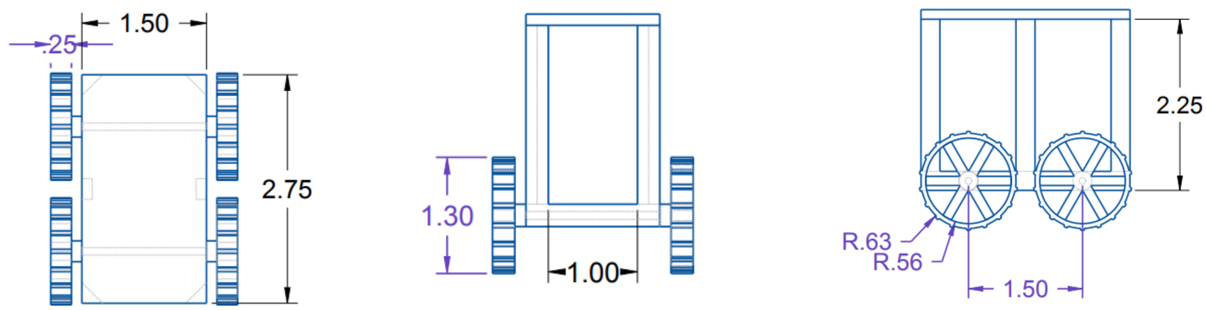
The detailed design portion of this paper focuses on the specific technical aspects of the rover and its deployment system. This section discusses the engineering principles and calculations used to design the rover's structure, propulsion, power systems, communication systems, and other key components. It also addresses the design of the interface between the rover and the booster, ensuring a secure and reliable connection during launch and deployment. The detailed design considers the size and weight constraints imposed by the booster team, as well as the need for the rover to withstand the harsh conditions of Mars-like terrain. Through rigorous analysis and testing, the detailed design aims to ensure that the rover meets all requirements and is capable of successfully completing its mission.

A. Rover Design

The design of the rover is a critical aspect of the project, aiming to create a robust and functional vehicle capable of operating on Mars-like terrain. The rover's structure must be lightweight, but able to withstand the forces experienced during launch and deployment. The propulsion system must provide sufficient power and control for the rover to traverse the 50 m distance required. Additionally, the power system must be dependable and efficient, utilizing solar power to sustain the rover's operations. The communication system is vital for remote operation, enabling real-time control and data transmission. Each of these subsystems must be designed to work as a unit to ensure a successful mission.

The rover structure has been through many iterations already and is continuously being updated. Models of the structure have been done in CAD software such as Creo-Parametric, as well as Catia V5. Most design changes have been made continuously to save weight, being that this is the one of the driving design requirements. Fig.1 shows the preliminary design, with dimensions being shown. The aeroshell that will house the designed rover is a cylinder with

4” in diameter as well as 4” in height. This design will be discussed in a later section, but these dimensions guide the design of the rover.



a) Top View of Rover **b) Front View** **c) Side View**

Fig. 1. Dimensions of the rover body in inches.

Due to the weight and functionality requirements, the material selection is paramount in the design process. The chosen material must be lightweight, stiff, durable, economical, and easy to manufacture. It must also have a high enough strength-to-weight ratio to adequately support the weight of the rover. Nylon-based plastics are perfect for the mission. They are extremely lightweight, with some densities ranging from 1.0-1.3 g/cm^3, and less than half as dense as Aluminum 6061 (2.7 g/cm^3) [13,14]. They offer adequate strength, with a tensile modulus usually around 1.5-2.5 GPa. They can easily be 3D printed, making them more economical than other materials. As a bonus, nylons offer great heat resistance for plastics between 100-500 °C (212-932 °F) [14]. The environment is also a concern, and nylons can have long lifespans and are easily recyclable [14].

The chosen material for the rover is PA650 (Nylon 12), a nylon-based plastic produced by SLS [15]. Its biggest advantage is an extremely low density of 1.02 g/cm^3. With a tensile modulus of 2000 MPa ± 200 MPa in the x-y plane, 1900 MPa ± 200 MPa in the z-plane, and an ultimate tensile strength of 50 MPa ± 4 MPa in the x-plane and 42 MPa ± 5 MPa in the z-plane [15], it is strong enough to support the rover as shown later. It exhibits high toughness while being moderately priced and easy to process. PA650 also boasts a relatively low water absorption rate among nylons of 0.5% ± 0.2% at room temperature, which will help on a rainy day [14,15]. However, there are some drawbacks. PA650 is not as stiff as other nylons, although its’ stiffness should suffice for the project. Its’ maximum heat resistance of 177°C (350°F) also is not as high as other nylons [13,14], but this should not be important for the rover. Overall, PA650 is a well-rounded material well-suited for rover design.

Electrical systems for the rover have started being designed based on requirements to fit inside of the rover housing. The electrical systems on the rover play a crucial role in its operation and functionality. These systems are responsible for powering various components of the rover. The layout of these systems can be seen in Fig.2, with connections also being shown. Everything in the electrical system connects back to the main computer. Onboard the rover it is planned to have a Raspberry Pi Pico as the main microcontroller, with two motors for rover control, a transceiver to receive commands, a camera to receive visual data to be controlled remotely, batteries to power the entire rover, as well as solar panels to provide power to the batteries. All these components need to fit within the 38.1 mm x 69.85 mm x 57.15 mm (1.5 in x 2.75 in x 2.25 in) housing. The weight of these components must remain lightweight due to the weight constraints given. Weights of all individual components can be seen in Table 1. As seen, most of the weight goes to the structure of the aeroshell and rover, with a total weight of 280.59 g estimated. This leaves 69.41 g of weight that is not being used. This padding may be used int the case of design changes in the structure or electrical systems in the future. Booster teams also have leftover weight allotted to ensure weight does not inhibit the success of the launch.

Table 1. Weight of Individual Components.

Item	Mass (g)
Micromotor with Gearbox	11.05
Lithium-Ion Battery	26.00
Arducam Mini Module Camera	22.97
Raspberry Pi Pico W	17.80
Receiver (remote)	7.00
Solar Panels	9.00
Parachute	42.00
Aeroshell	89.00
Wheels	8.00
Rover Body	26.72
Total	280.59

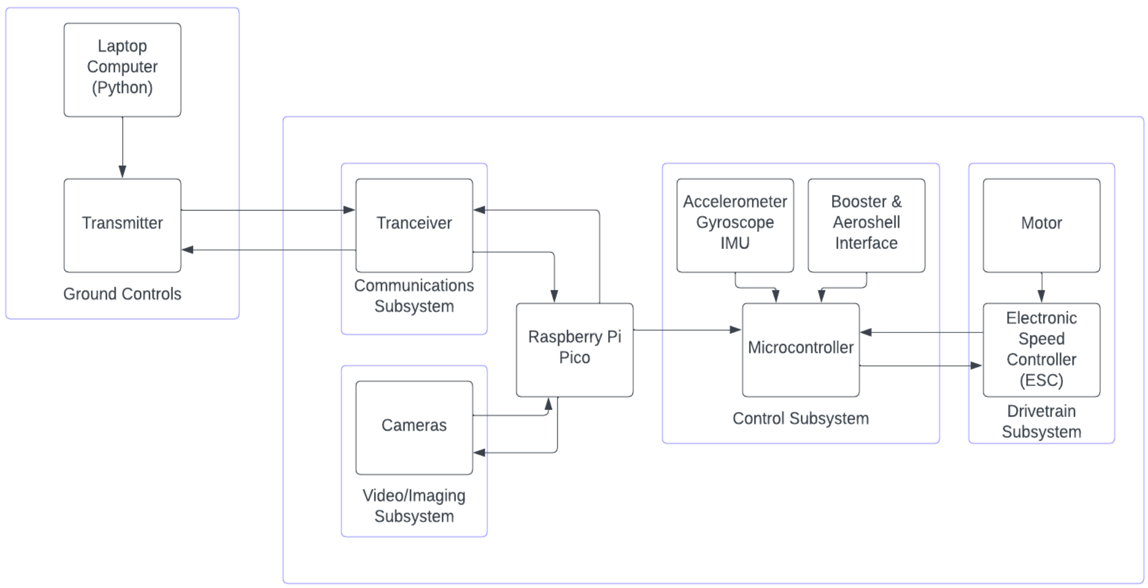


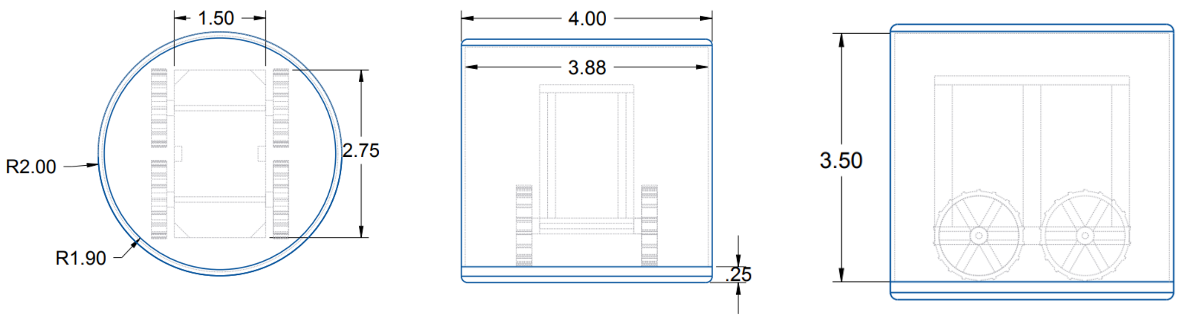
Fig. 2. Functional block diagram explaining the connection of electrical systems to the main computer.

B. Aeroshell Design

An aeroshell is crucial for reentry vehicles primarily because it protects the payload from the intense heat generated during reentry into Earth's atmosphere. The aeroshell holds the rover inside of it as shown in Fig.3. As a spacecraft returns from space, it encounters extreme temperatures caused by the compression of air in front of it. Without a protective shell, the spacecraft's surface would be subjected to temperatures reaching several thousand degrees Celsius, leading to structural damage or destruction. The aeroshell serves as a heat shield, dissipating and deflecting the heat away from the spacecraft's delicate internal components. Additionally, it helps to stabilize the spacecraft's descent trajectory by creating aerodynamic drag, ensuring a controlled and safe reentry into the atmosphere. Overall, the aeroshell plays a critical role in ensuring the survival of the spacecraft and its payload during the challenging phase of atmospheric reentry.

As with the rover, material selection is important for the design of the aeroshell. The bottom plate of the aeroshell will serve as a heat shield for the shell, making heat resistance properties important. It will also support the entire weight of the rover during descent, forcing the selection of a stiff, strong material. Once again, nylon-based plastics are well-suited for this application. The choice of material for the aeroshell is PA12 Mineral-Filled (PA12-MF), a nylon material constructed with a 25% mineral fill produced by SLS [16]. With a tensile modulus of 3100 MPa ± 400 MPa in the x-y plane, 2500 MPa ± 200 MPa in the z-plane, and an ultimate tensile strength of 38 MPa ± 5 MPa in the x-plane and 32 MPa ± 7 MPa in the z-plane [16], it is strong enough to support the rover as shown later while having a great stiffness property. But PA12-MF's main advantage compared to PA650 is its very consistent heat deflection temperature, only varying from 184°C (363°F) to 179°C (354°F) between 0.46 MPa and 1.82 MPa [15,16]. This ensures that the shell can deflect the heat coming from the booster engine. The rest of the aeroshell will be made of PA12 Black, a nylon produced by MJF. It still exhibits a high heat deflection temperature of 175°C (374°F) at 0.46 MPa and 95°C (203°F) at 1.82 MPa [17]. It is not as stiff as PA12-MF with a tensile modulus of 1900 MPa ± 200 MPa in all planes, but it is extremely lightweight with a density of just 1.01 g/cm^3 [16,17].

Since it is not practical to physically test reentering an atmosphere, the aeroshell will be tested in two parts. First, detailed computer simulations will be run to mimic the reentry aspect of the mission. This will show that the rover design and structure will survive reentering the atmosphere. The second part will test the design of the rover after reentry. To simulate this, the aeroshell will be launched in a rocket booster that flies to 100 m. After the aeroshell is deployed, it must protect the rover cargo for at least 5 s to simulate that it will hold through reentry. The aeroshell then will release a parachute to slow its descent. After landing, it will allow the rover to safely exit and conduct its mission after being detached via a spring-lock system.



a) Top View of Aeroshell **b) Front View** **c) Side View**

Fig. 3. Dimensions of the aeroshell in inches.

C. Computer Simulations

Computer simulations are the primary method of testing the rover and aeroshell structurally. Testing design strengths through computer simulations has become an indispensable tool for this project. By utilizing reliable software, engineers can model complex structures and systems to predict their behavior under different conditions without the need for costly physical prototypes. These simulations allow engineers to assess the performance of a design in terms of stress, strain, deformation, and other critical parameters. Moreover, computer simulations offer the flexibility to simulate extreme conditions that might be challenging or even impossible to replicate in physical tests. Engineers can subject their designs to simulated environments such as high temperatures, pressures, or dynamic forces to evaluate their performance under extreme scenarios. This capability is particularly valuable in the reentry aspect of the mission. Additionally, simulations allow for rapid prototyping and design iteration, significantly reducing development time and cost. By refining designs virtually before physical production, engineers can ensure that the final product meets or exceeds performance requirements while minimizing the risk of failure.

For rovers, these simulations provide crucial insights into the rover's capabilities and limitations, guiding design modifications to optimize performance for specific mission objectives. Similarly, computer simulations play a vital role in testing aeroshell designs for spacecraft reentry. FEA, for instance, enables engineers to break down a structure into small, manageable elements and analyze how each element responds to various loads and boundary conditions. Through FEA, engineers can identify potential weak points in a design and iteratively refine it to enhance strength and durability. By simulating Earth's, or other planet's, atmosphere, engineers can assess the effectiveness of different aeroshell shapes, materials, and thermal protection systems in withstanding the extreme conditions of reentry. These simulations allow engineers to refine aeroshell designs to ensure the safe delivery of payloads while minimizing weight and cost.

Simulations of the stresses and deformation of critical rover and shell structural components were completed using Abaqus, a FEA software used in industry for several decades. The critical structural components are the base plates of both the rover and aeroshell, as these bodies will bear the most weight among the components. The base plate of the rover was tricky to simulate because of the unusual geometry thanks to the cut-out cylinders designed for the wheel axles. This required the creation of a tetrahedral mesh with over 72,000 elements. The weight of the electrical components was simulated by placing a concentrated force at 9 different locations, with a 250 g weight being distributed at every node after being multiplied by the acceleration due to gravity (9.81 m/s^2). The weight of the beams within the structure were also simulated by placing a weight of 50 g distributed across each of the beam locations. The stress and deformation of the bottom plate are shown in Fig.4 and Fig.5. The edges of the cylindrical cut-outs are under the most stress with a maximum of 3.314 MPa. The corners of the plate also display a higher stress value compared to the rest of the body. Fig.5 displays the deformation of the body, and the center displays the highest displacement at 0.023 mm. Both the stress and displacement values are acceptable for the structure.

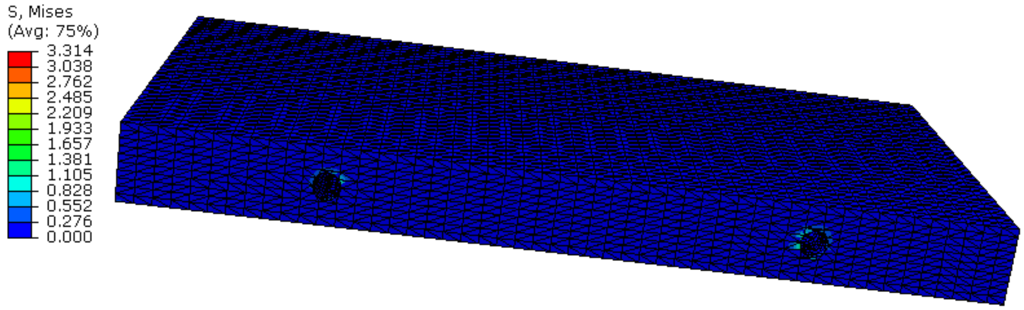


Fig. 4. Simulation of stress on the bottom plate of the rover in MPa.

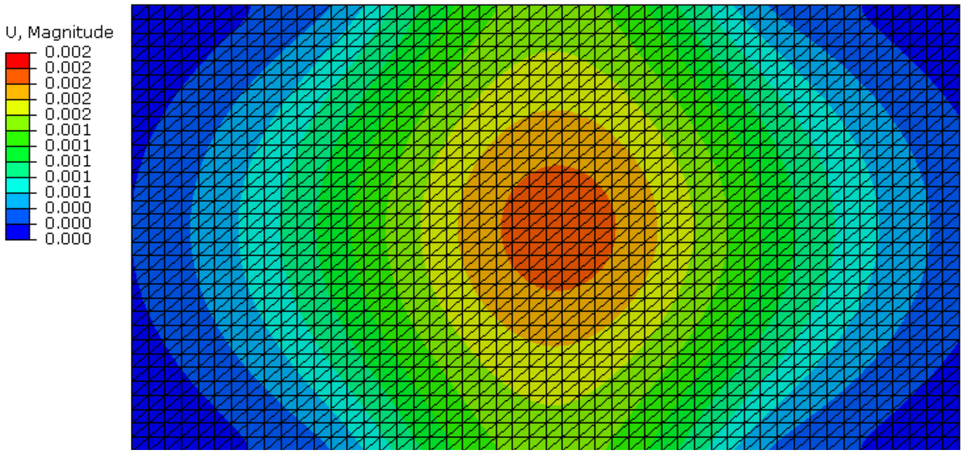
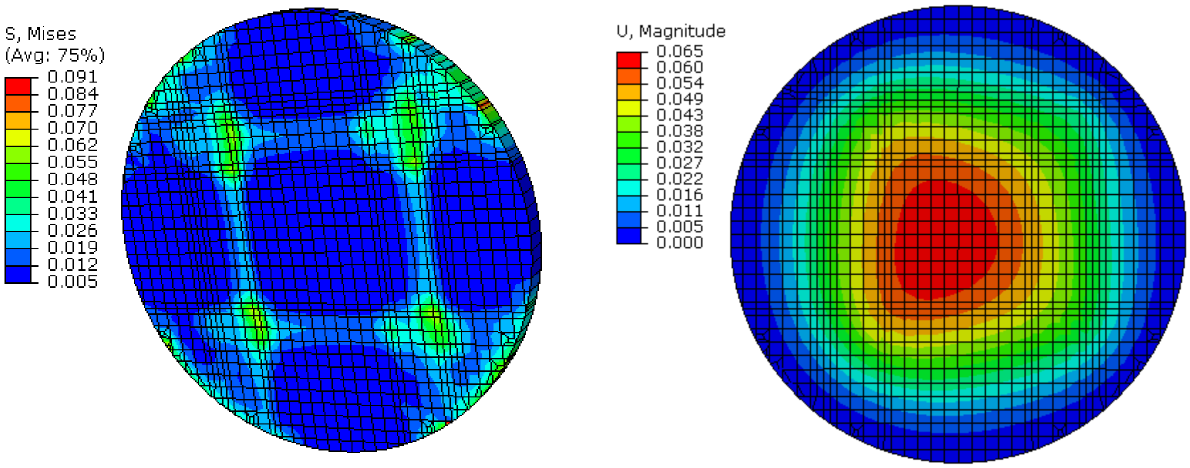


Fig. 5. Simulation of deformation on the bottom plate of the rover in mm.

The analysis of the shell plate was much more straight-forward due to its simple geometry. The weight of the rover inside of the shell was simulated by placing an equivalent force at the four-wheel positions. The stress and deformation of the shell plate are shown in Fig.6. The stress model of the shell plate shows a maximum stress of 0.091 MPa at the edges of the plate with notable stress locations at the wheel locations. The deformation model displays the displacement of the plate, and it shows a maximum displacement of 0.065 mm at the center of the plate. Both the stress and displacement values are acceptable for the structure.



a) Stress in MPa **b) Deformation in mm**

Figure 6. FEA simulations on the bottom plate of the aeroshell.

V. Conclusion

The team believes that small rovers can feasibly be designed at a much lower cost than a standard planetary rover. The largest challenge faced when designing the rover was the size and weight restrictions. This forces the use of lightweight materials and microelectronics, creating a challenge when these components also must be high-performance to satisfy the demands of the mission. Other challenges include the design of detachment mechanisms and power generation, as these must also be lightweight and are crucial to mission performance. It is important to run computer simulations of the structural analysis before finalizing the design to ensure the proper effectiveness of structural parts and visualize potential weaknesses in the design. Future work will include the assembly of the rover and aeroshell, along with any revisions to the proposed design that may entail.

The need and uses for nano-sized rovers are ever present as humanity continuously explores the solar system. By being no longer than a few inches and being equipped with sensors, cameras, and propulsion systems, they can traverse terrains inaccessible to conventional rovers, exploring crevices, tunnels, and other confined spaces with ease. Their compact size and low cost make them ideal for missions requiring expansive examination of a planetary surface, such as scouting for signs of life on a distant planet. Instead of one larger rover, dozens of smaller rovers can take its' place to explore an environment more efficiently. A smaller rover can also accompany a much larger one and perform a different aspect of the mission, increasing the scope of the mission and providing more data. Despite their smaller stature, nano rovers pack a punch in terms of scientific capability, opening new frontiers in exploration and discovery across the cosmos.

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