

**A Novel Self-Extricating Mechanism for Martian Planetary Exploration Rovers**

**Grant Proposal**

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### **Executive Summary**

The goal of this research project is to make planetary rovers independent of mission control in the event that they are stuck in the loose Martian terrain. The design does this by introducing a variable geometry wheel for rovers, that essentially uses live data from the wheel's sinkage and slippage to adjust the wheel's width and force applied on the terrain. This improves the vehicle's traction on the terrain, allowing it to move out of a sand trap. A low fidelity prototype of this design was created to verify if the locomotion performance truly improves when the contact area between the wheel and the terrain is increased. This prototype design passively changed its geometry with the terrain with the use of a flexible material for its circumferential surface. This design was tested on sandy terrain where the sinkage and slippage of the vehicle was measured. The results from the prototype were then compared to the slippage and sinkage of a vehicle with rigid wheels to mimic traditional rover wheels. The prototype design only showed a slippage of 48% while the rigid wheel had a slippage of 100%. Furthermore, the rigid wheel sunk 11mm into the sand during one of the tests. This experiment shows that flexible wheels work better than rigid wheels on granular terrain, helping lay the foundation for a more active and autonomous design.

*Keywords:* planetary rovers, sinkage, slippage, autonomous, wheel design, extrication

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### **General Information about the Martian Landscape**

Mars's terrain is geologically diverse, containing features such as rugged highlands, smooth lowlands, cratered plains, cones, troughs, ridges, impact craters, etc. (Zhao et al., 2021). Dust storms caused by strong winds are also very common, picking up fine Martian dust and particles. The Martian soil is primarily composed of fine particles of iron-rich volcanic rock, giving the planet its signature reddish color due to iron oxide. Its soil consists of silicates, sulfates, perchlorates, and some traces of salt. The gravity of this planet is around 38% of Earth's, making the regolith loose and fluffy, reducing particle compaction and surface cohesion. Common obstacles for these rovers include sand traps, slopes, rocks, and sand dunes. The combination of a diverse, rocky terrain with soft sand makes it easy for the wheels of a planetary rover to get damaged and/or sink into the Martian soil.

### **Rover Mobility and Mechanical Design**

Mobility is essential to the success of planetary rover missions, allowing the rovers to navigate to different parts of the planet for in-situ observation. Getting stuck in the Martian terrain can lead to the end of a rover's mission. These embedding events are caused when the rover experiences significant amounts of sinkage and slippage. Sinkage is defined as the degree to which a wheel sinks into soft soil, and slippage is defined as the difference between the distance the rover wheels were supposed to travel and the actual distance it moved. Traction is another key property needed by rovers, as it allows them to grip onto a surface and propel itself forward; however, it can also cause an increase in the slippage of a vehicle on loose terrain (Girija et al., 2023). This effect can be reduced by increasing the rover's contact area with the surface, by either increasing the width of the vehicle's wheels (Hu et al., 2024) or by making the wheels conform to the surface (Girija et al., 2023). Increasing a wheel contact area with the surface allows the vehicle to distribute its load over a larger area.

Typical Martian rovers consist of a six-wheeled rocker-bogie suspension (Shrivastava et al., 2020), which is a type of suspension system that uses springs and dampers, allowing rovers to keep all their wheels on the ground when traversing rough terrain. Rover wheels usually include parallel grousers (Nagaoka et al., 2020), or

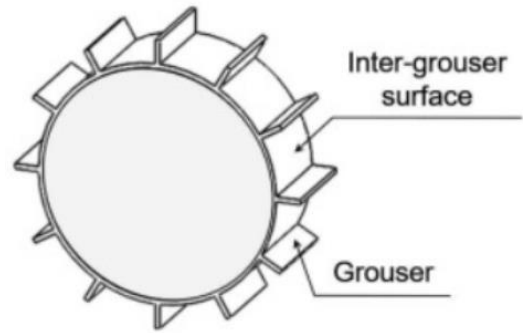


Figure 7: *Schematic Diagram of Wheel*. This image shows a diagram of a wheel with parallel grousers.

outward protrusions along the side edge of a wheel that increase traction on loose soil. Both Spirit and Perseverance are examples of rovers that have parallel grousers, as shown in Figure 7, and a rocker-bogie suspension system (National Aeronautics and Space Administration, 2003).

### **Current Extrication Methods and Their Limitations**

When rovers get stuck on another planet, extrication methods rely heavily on human commands sent from mission control on Earth; however, this has proven to have low success rates and higher costs (Yang et al., 2025) because of the time delay when relaying commands and lack of situational awareness. It takes 4 - 24 minutes for radio signals to travel from Earth to Mars, causing a 8 – 48 minute delay in the command and response. Limited visibility of the rover's surroundings can cause its condition to deteriorate further. The Spirit Mars Exploration Rover prematurely ended its mission when it got stuck in a Martian sand trap (Jet Propulsion Laboratory, 2009). Ground-based extrication methods were employed but proved ineffective in this situation. A built-in autonomous self-recovery system would allow future rovers to detect immobilization and recover independently, without the intervention of mission control.

### **Competitor Analysis**

Currently, many major space exploration companies are in the process of developing alternative wheel designs or improving traditional rover wheels to help planetary rovers better adapt to granular terrain. Some examples include NASA's Shape Memory Alloy tires and the Tensegrity Robot tires

developed by the Adaptive Robotics Laboratory, both of which look at deformable tires that can adapt to the dynamic Martian terrain. Georgia Institute of Technology has also developed a more active method of locomotion, where their rover's wheels are attached to appendages that allow the rover to lift and wiggle its wheels, helping it extract itself from sand traps. However, in the event of an embedding in the Martian surface, these locomotion methods would still rely on commands from ground control to be activated, which has proven to be largely ineffective. While my project will look at similar deformable wheel designs, the primary focus will be on making the extrication method autonomous, allowing the rover to operate independent from mission control and increasing the lifespan of future in-situ Mars exploration missions.

### **Section II: Specific Aims**

This proposal's objective is to create an autonomous extrication mechanism for planetary rovers, that is applicable in various states of embedding in the Martian soil. Due to the diverse terrain of Mars and its loose soil, planetary rovers often tend to get stuck in the Martian surface. In these embedding events, the only current method of extracting these rovers is by initiating rover maneuvers controlled by ground-control on Earth, which doesn't display a high success rate due to the time delay in communicating with technology on Mars and the rover operator's lack of situational awareness. An extrication method built into the planetary rover would allow it to extract itself out of these situations independently, ensuring that it isn't completely reliant on mission control.

Our long-term goal is to make planetary rovers more self-sustaining, thus increasing their lifespan, and gathering more data from Mars at a cheaper cost.

**Specific Aim 1:** Reduce planetary rover dependence on ground-control and human intervention in the event that they get immobilized due to the Martian terrain.

**Specific Aim 2:** Decrease the amount of slippage and sinkage experienced by planetary rovers that could lead to severe embedding conditions.

**Specific Aim 3:** Extension of planetary rover operational lifetimes by making them less susceptible to embedding events, thus increasing the amount of surface covered and data collected by a single rover.

The expected outcome of this work is the development of a functional prototype of a rover that can detect when the rover is immobilized and react accordingly. The experimental results should show an improvement in the overall mobility of the rover with the extrication mechanism than compared to the same rover with the mechanism turned off.

### **Section III: Project Goals and Methodology**

#### **Relevance/Significance**

Martian planetary rovers encounter complex terrain, such as sand dunes, loose soil, rocky terrain, and sand traps, which pose a significant threat to mission success. The permanent immobilization of the Spirit rover due to a Martian sand trap and other similar events, such as the embedding of Opportunity while it was trying to traverse a sand dune, emphasizes the ineffectiveness of ground-based rescue attempts. Developing an autonomous extrication method that addresses these critical situations would help prevent such incidents from occurring in the future.

#### **Methodology**

##### ***Prototype Design:***

This project started by sketching 5 extrication mechanisms. These were then evaluated on decision matrix based on prior research and literature reviews. The criteria used to score these designs were complexity, weight, feasibility, potential damage done to rover, and adaptability in various situations. This highest scoring mechanism was a variable geometry wheel that decreases the pressure it applies to the loose Martian terrain, by varying its contact force and area. This wheel works based on

the principle  $\text{Pressure} = \text{Force}/\text{Area}$ . The more pressure a rover's wheels exert on a granular terrain, such as the loose soil of Mars, the more the terrain deforms underneath it, causing high amounts of sinkage and slippage in the vehicle. The extrication method involves creating a wheel that can decrease the force it exerts on a terrain by decreasing its stiffness and increasing its contact area with the terrain by increasing its width.

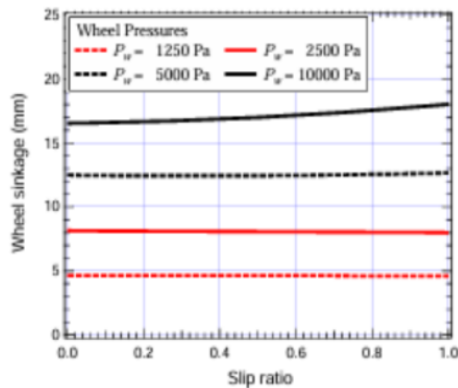


Figure 1: *Wheel sinkage with varied wheel pressure from Ishigami et al. (2011)*. The graph shows the sinkage of wheels at different air pressures, at different slip ratios. These numbers were calculated based on a simulation.

Figure 1 shows how a flexible wheel's pressure affects the amount of sinkage it experiences at different slip ratios on rough terrain. Sinkage is not affected by the slip ratio, until the point where the wheel is completely rigid at 10,000 Pa. The wheel that applied a pressure of 1250 Pa on the surface experienced around 5 mm of sinkage, and as the pressure increases, so does the sinkage. When the wheel was made rigid, its sinkage increases with the slip ratio

instead of remaining constant, as we saw with the lower wheel pressures. According to the article, this is because a wheel with lower pressure is more deformable, resulting in a larger flat section of the wheel that touches the ground. This verifies that reducing a wheel's pressure will improve its mobility on sandy terrain.

Figure 2 shows the velocity of robots designed to move on sandy terrain with the aid of origami wheels, when set at certain rotational velocities. The graph also shows this relationship when the wheel was set at different widths. Increasing the wheel's width, and thus its contact area with the terrain, led to higher vehicle velocities than when the wheel was narrower. Higher vehicle velocities at the same rotational

speed means there is a decrease in the slip ratio of the vehicle as well. Overall, this graph shows that increasing wheel width decreases the slippage of a vehicle on granular terrain.

### **Preliminary Test:**

The purpose of this preliminary test is to verify that a flexible wheel performs better than a rigid wheel

on granular terrain. This is done by making a low-fidelity prototype of the inflatable flexible wheel, as shown in Figure 3, that would be used in the autonomous extrication mechanism and compare its slippage and sinkage on a sand test bed to a rigid wheel of similar dimensions. Note that although the original idea was to use air pressure to alter the geometry of the wheel (based on research by

Almusa et al., 2020), it was later realized that inflatable wheels aren't efficient for exploration of Mars.

This is due to Mars' lack of atmosphere, resulting in a lower external pressure on the wheel, likely causing it to burst. A wire mesh for the surface of the wheel is being used in the final design instead.

Contact force can be varied by changing the mesh stiffness, and width can be changed with the use of linear actuators.

**Justification and Feasibility.** Despite the design change, results from this test still show that a flexible wheel performs better than a rigid wheel on sandy terrain, even though the final design will be different. In this test we looked at the slippage and sinkage of both the rigid wheel and the flexible wheel, helping us know if the design idea aligns with specific aim #2. This also ties into specific aim #3

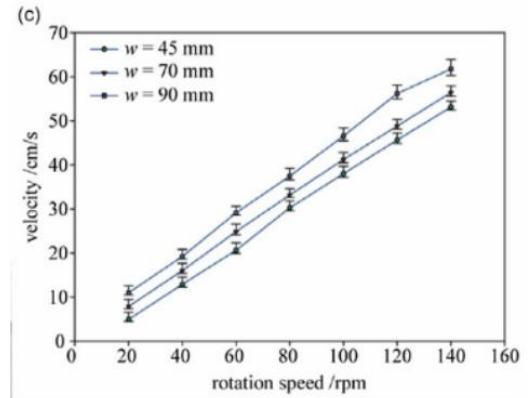


Figure 2: *Velocity analysis of origami robot from Hu et al. (2024).* The graph shows how the rotational speed and velocity of origami wheel changes at different wheel widths.



Figure 3: *Inflatable wheel.* The image shows the prototype flexible wheel I used during my preliminary experiment.

because reducing slippage and sinkage of the rover will extend the vehicle's lifespan. Specific aim #1 will be addressed in the final experiment when the extrication mechanism is automated.

### Summary of Preliminary Data.

During the preliminary sand box test, a Vernier Go Motion sensor was used to generate position vs time graphs of a robot with the flexible and rigid wheel. Then the slope was calculated to get the average vehicle velocity.

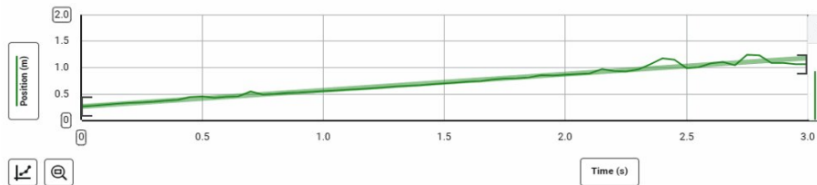


Figure 4: *Inflatable wheel position vs. time.* The graph shows the position over time during one of the three tests with the flexible wheel.

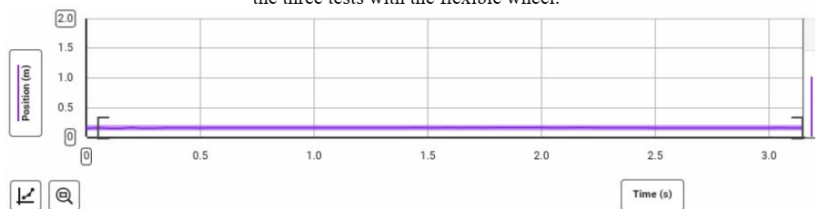


Figure 5: *Rigid wheel position vs. time.* The graph shows the position over time during one of the three tests with the rigid wheel.

The rover with the inflatable wheel was tested 3 times, generating 3 different position vs time graphs. Fig 4. is an example of one of these graphs. These gave the average vehicle velocity of 0.275m/s and the wheel's rotational velocity of 0.528 m/s. The inflatable wheels had a slippage of 48%, but there were no incidents of sinkage in any of the 3 tests.

The rover with the rigid wheel was also tested 3 times on the same testbed. Fig 5. is an example of one of the 3 position vs time graphs generated during these tests. The wheel itself had a rotational velocity of 0.31 m/s; however, it didn't move forward when placed on the test bed, which means it has a 100% slippage. Furthermore, the wheel also sunk 11mm into the sand during one of the tests.

This test shows that a flexible wheel experiences less sinkage and slippage than a rigid wheel.

**Expected Outcomes.** The outcomes of this test will be used as evidence of a flexible wheel's superior mobility on granular terrain than compared to the traditional rigid wheels.

**Potential Pitfalls and Alternative Strategies.** While the outcome of the preliminary test correlates with past research, the difference in the test may have been exaggerated due to different amounts of current supplied to the motors driving the wheels. For future tests, this discrepancy will be mitigated with the addition of resistors in the circuit when needed.

### Section III: Resources/Equipment

**Table 1.**

The table lists the materials required to complete the project, the cost of each material and a justification for why it's needed

Material Name	Cost	Justification
20 kg MGS-1 Martian Sand Simulant	\$38.25/kg	For testing prototype in realistic Martian conditions
2 TT Dual DC 3-6V Motors	\$9.88	For spinning the wheels in order to drive the vehicle
Vernier Go Motion Sensor	\$129	To calculate vehicle velocity with and without extrication mechanism, which will be used to calculate slip %
Arduino UNO R4 Wi-Fi	\$15	Microcontroller to take input from velocity sensor and control motor and linear actuator accordingly
GY521 MPU6050 3 Axis Accelerometer Module	\$9.99	So that rover can detect when its stuck
Basic Electrical Components Kit	\$9.99	To supply power to the Arduino and motors
5-9 V Power Supply	\$0.5 - \$1	Power source for electrical components
DC HOUSE Mini Electric Linear Actuator	\$22.39/each	To change the wheel's width and stiffness
Stainless Steel Spring Wire	\$40 - \$42	To create the flexible, variable geometry wheel.

### Section V: Ethical Considerations

During the development of this project, several ethical issues were considered. As planetary exploration is publicly funded, improving the rover's reliability must genuinely reduce the risk associated with such missions while gathering as much scientific data as possible to justify the public's investment.

That being said, the extrication mechanism also shouldn't damage critical hardware on the rover in any way, as it would directly impact its reliability. Since the current extrication mechanism design focuses only on the creation of variable geometry wheels, the chance of damage to scientific equipment is unlikely. Since the mechanism will be automated, fail-safes will be included in the program to allow for human oversight before the mechanism makes any irreversible decisions. Another concern was the disturbance or contamination of the extraterrestrial terrain, but this is unlikely because the extrication mechanism will be similar to the locomotion method of current Martian rovers, aside from the fact that it can adjust its geometry according to the terrain. These considerations shaped how the system was designed, tested, and evaluated.

**Section VI: Timeline**

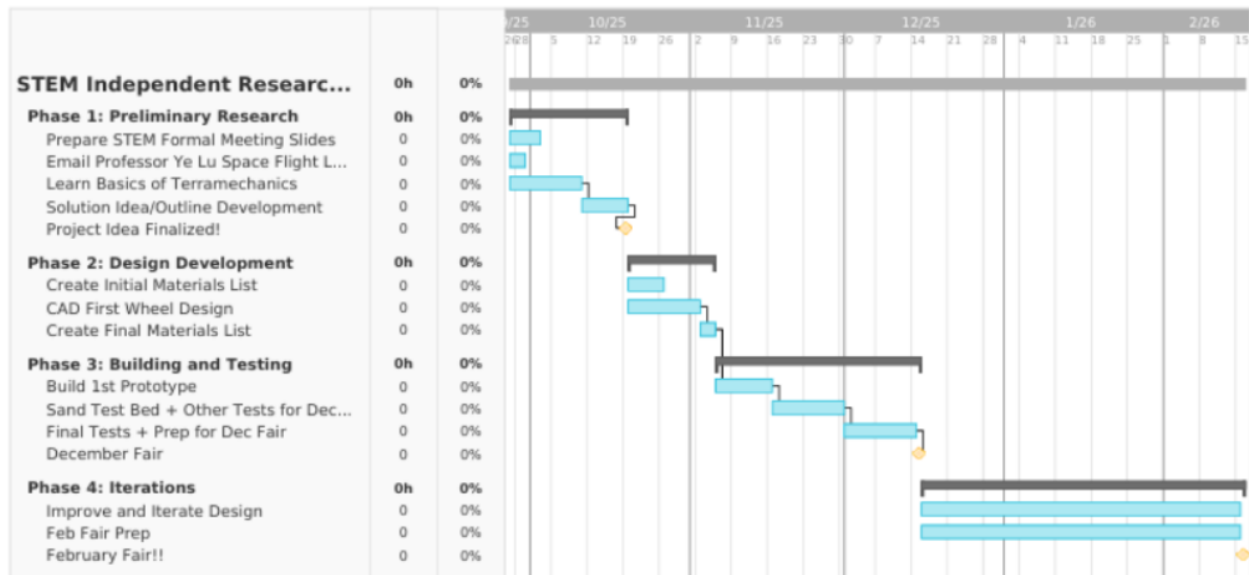


Figure 6: Project timeline. This image shows the anticipated timeline for this project, made using Project Gantt.

**Section VII: Appendix**

The grant this proposal is intended for is called the Engineering Design and Systems Engineering program by the U.S. National Science Foundation. The aim of this program is to promote research that focuses on the design of engineering artifacts and systems. They encourage proposals that incorporate

the use of multiple disciplines, focus on the theory of their design, and show evidence that the design has been improved through an iterative process, as seen in this project.

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