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Mechanical Design and Testing of 3D-Printed Non-Pneumatic Wheels for Human-Powered Vehicles: A NASA HERC Case Study

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Abstract*– This research investigates the design and manufacture of non-pneumatic tires (NPTs) utilizing additive manufacturing (AM) techniques for human-powered vehicles (HPVs) operating in challenging terrains, such as those encountered during competitions like NASA's Human Exploration Rover Challenge (NASA HERC). Traditional pneumatic tires are often susceptible tot punctures and require extensive maintenance, making them less effective in these demanding environments. In contrast, NPTs provide enhanced puncture resistance and significantly lower maintenance needs, yet their design poses complex challenges concerning load-carrying capacity, traction, and durability. This study leverages the advantages of AM to tackle these challenges, allowing for the creation of intricate geometries and internal structures that can be optimized for specific terrains. Additionally, the research emphasizes the use of flexible materials, particularly thermoplastic polyurethane (TPU), and thoroughly evaluates the influence of various AM processes on the mechanical properties and performance of NPTs. Through rigorous experimental and field-specific testing, our goal is to refine NPT designs, ensuring they meet demanding performance criteria while promoting sustainable manufacturing practices, ultimately contributing to advancements in HPV technology.

Keywords*-- 3D printing, FDM technology, additive manufacturing, non-pneumatic wheels, modular design, terrain adaptability.

I. Introduction

A. 3D Printing Technology

3D printing is an innovative technology that has already revolutionized many industries by allowing for the rapid fabrication of complex designs. It promotes innovation by making it possible to explore new design possibilities that were previously unattainable [1].

In the automotive sector, 3D printing is a promising method for producing lightweight components faster and more efficiently. This technology also encourages iterative design, facilitating continuous improvement through testing [2].

By taking advantage of materials such as TPU, which enables the creation of flexible and shock-absorbing components, manufacturers can modify the structural density to achieve the desired properties of each part depending on its specific function [3].

Modularity in 3D printing is essential for optimizing manufacturing and reducing costs. By allowing the creation of interchangeable components, modularity makes it easier to assemble and fit product parts efficiently. This approach also simplifies maintenance and repair by allowing replacement of specific parts without the need to rebuild the entire system.

The ability to flexibly integrate modules contributes to greater efficiency in the manufacturing process and a significant reduction in associated costs [4].

3D printing contributes to sustainable manufacturing by minimizing material waste through an additive approach, which builds objects layer by layer from digital models. This process significantly reduces the amount of waste generated compared to traditional methods, which typically cut or mold materials into final shapes. Additionally, 3D printing allows the use of recyclable and eco-friendly materials, thus supporting more sustainable manufacturing practices [5].

B. Background - NASA HERC

Non-pneumatic wheels are a key solution to meet the challenges in competitions such as NASA HERC, where components capable of operating in extreme conditions are required. These wheels must offer traction and durability without the use of air, using innovative materials and structures that mimic the functions of traditional wheels but without the problems associated with air pressure.

In the NASA HERC competition, terrain analysis is crucial to the development of a rover capable of navigating simulated conditions on Mars and the Moon. The terrain features features such as cross-tilt slopes, rocks, gravel, regolith, cracks, and undulating irregular surfaces that pose significant challenges to the rover's mobility and stability. It offers us advantages for design and performance, giving us greater flexibility and sustainability [6].

II. Methodology

A. Requirements Definition

The project aimed to cover a distance of nearly 1 kilometer in 8 minutes, overcoming various terrains simulating the lunar environment. Each challenge presented different obstacles where the wheels had to withstand loads, maintain traction, and facilitate the Rover vehicle's movement during the competition [6].

After analyzing possible solutions for a vehicle weighing approximately 70 kg unladen (excluding drivers), a custom wheel concept was developed to meet the following criteria:

- Improve vehicle grip: Wheels were designed with a V-pattern, optimizing the vehicle's traction with the ground surface and ensuring better performance on uneven terrains.
- Minimize weight: An optimal design was sought to make the wheels as light and strong as possible, reducing the vehicle's total weight and improving its efficiency.
- Modular design: A modular design was implemented for the wheels, allowing for quick and easy repairs in case of damage, ensuring better performance during the competition.

To achieve these objectives, advanced materials and innovative manufacturing techniques were used. The wheels were made with flexible and durable plastics, specifically elastomers, offering high resistance to abrasion, cracking, and dynamic loads. The tires were produced using the fused deposition modeling (FDM) method, allowing for adjustable infill density and stiffness modification according to the design needs [7].

B. Concept Development

a. Material research

The mechanical properties of the selected materials for additive manufacturing were evaluated based on manufacturer data, focusing on tensile strength and elongation at break. The selection also considers interlayer adhesion, cost, and local availability in Bolivia. The detailed properties of candidate materials are summarized in Table I. Material selection was determined through a weighted decision matrix, where parameters were prioritized according to functional requirements for wheel treads:

TABLE I
PROPERTIES AND DECISION MATRIX OF MATERIALS

Material	Tensile Strength [MPa] (25%)	Elongation at Break [%] (25%)	Cost [USD/kg] (10%)	Availability (20%)	Interlayer Adhesion (20%)	Total
TPU	35 12.2/25	800 25/25	35 6.7/10	Medium 13.3/20	High 20/20	**77.2**
PLA	72 25/25	11.8 0.4/25	16.47 10/10	High 20/20	Medium 10/20	65.4
PETG	52.2 18.1/25	83 2.6/25	36 6.6/10	Medium 13.3/20	High 20/20	60.6
ABS	43 14.9/25	22 0.7/25	30.71 8.1/10	Medium 13.3/20	Low 5/20	42.0
ASA	50 17.4/25	30 0.9/25	40 5.0/10	Low 6.7/20	Medium 10/20	40.0

Scores were calculated by normalizing each parameter to its best-performing value (highest elongation = 100% score), then applying the designated weights. Qualitative metrics (adhesion, availability) were converted to numerical scales proportional to their assigned weights

TPU (Thermoplastic Polyurethane) stands out as the most suitable candidate for the tread. It combines excellent tensile strength (35 MPa) with high flexibility (≥800% elongation at break), which allows it to deform without failure, an important requirement for adapting to irregular terrain and operational strain in space. It also shows high interlayer adhesion and medium availability in Bolivia, making it an optimal balance between performance and accessibility [8].

PETG (Polyethylene Terephthalate Glycol) is a semi-flexible, high-strength material with a tensile strength of 52.2 MPa and an elongation of 83%. Although not as elastic as TPU, its high strength and good interlayer bonding make it viable for rigid, durable parts. However, due to its limited flexibility, it's less ideal for tread applications [9].

PLA (Polylactic Acid) features the highest tensile strength of the group (72 MPa), but with a much lower elongation at break (11.8%). It is rigid and easy to print, making it a strong candidate for solid or structural parts. Its brittleness and limited elasticity invalidates it from tread applications requiring significant deformation under load [10].

ABS (Acrylonitrile Butadiene Styrene) offers a good combination of strength (43 MPa) and moderate flexibility (22% elongation). It has medium availability and interlayer adhesion, which makes it useful for mechanically demanding components, though not ideal for continuous deformation [11].

ASA (Acrylonitrile Styrene Acrylate) is similar to ABS but with enhanced weather resistance. With a tensile strength of 50 MPa and elongation at break of 30%, it provides a good balance between flexibility and mechanical performance. Its low availability in Bolivia, however, reduces its practicality for local manufacturing [12].

b. Modularity

To effectively address the highly variable terrain conditions of NASA's Human Exploration Rover Challenge (HERC), the tire design process began with the decision to implement a modular structure. This modularity allows for easy interchangeability of tread components, enabling customized configurations based on terrain requirements. By segmenting the tire into eight independent pieces, it was possible to experiment with different surface patterns and mechanical behaviors without altering the entire wheel structure. This flexibility provided the opportunity to iterate quickly, test individual components and adjust traction and damping properties as needed.

c. Terrain challenges

The NASA Human Exploration Rover Challenge 2024 course spans nearly 1 kilometer and includes ten obstacles that replicate extraterrestrial terrain conditions. These challenges feature undulating ramps, craters with ejecta, transverse slopes, steep buttes, wide ravines, deep cracks, narrow slalom paths, boulder fields, soft regolith, and loose pea gravel. Each obstacle introduces specific traction and structural demands, such as navigating steep inclines, resisting sinkage in soft materials, and maintaining control over loose or uneven surfaces. The diversity in obstacle surfaces requires tire designs that ensure consistent grip, impact resistance, and weight distribution across the full course [13].

To address these challenges, two tread designs were developed. The first features a V-shaped spike pattern designed to maximize grip on loose and unstable terrain. Its elevated spikes enhance surface contact and traction, improving the rover's control when traversing slopes or shifting gravel. The second tread also uses a "V" design but is flatter and inspired by bike tire patterns. It distributes the rover's weight across a broader area, improving mass distribution and providing cushioning over rough or rigid surfaces. This design reduces impact stress and enhances comfort while preserving control. The modular system allows these treads to be interchanged based on the terrain, enabling optimal adaptation to the course's varied challenges.

C. Design Process

As previously mentioned, the proposed design is intended for the NASA HERC. Throughout the construction process, the design underwent significant changes, resulting in improvements in size, weight, and overall design.

Fig. 1 Wheel design focused on pressure points.

The presented design in Figure 1 is based on a pressure point approach, where it was crucial for the tire's tread to be narrow and follow a traditional tread pattern similar to that of off-road tires. The primary goal of this model was to create a robust, wide, and durable traction system capable of withstanding a variety of challenging terrains. However, while the initial design met these objectives, it also posed significant challenges. The system's excessive size, combined with the substantial amount of materials required for its construction, resulted in an inefficient model. This led to a revision and redesign, focusing on a more efficient and optimized traction system. The new design aimed to maintain the ability to tackle rough terrains but with a lighter, more compact structure that required fewer resources in terms of materials and assembly. This approach not only reduced the system's weight and size but also enhanced its overall performance, improving its adaptability to the demands of the competition.

Fig. 2 Mountain Wheel-Based Model.

The new design was inspired by mountain bike wheels (Figure 2), incorporating key features that enhance both strength and adaptability to challenging terrains. At the heart of the design is a robust structure made of 6061 aluminum, chosen for its excellent balance of lightness and durability. This central structure is surrounded by aluminum circumferences that act as shock absorbers, designed with internal veins to prevent deformation under heavy loads and impacts.

- V-Shaped Design: This pattern was created to maximize traction by providing a surface that effectively grips the terrain. Additionally, the design allows water to be channeled to the sides, improving performance in wet or rainy conditions by preventing hydroplaning.
- Lightning Design: This model is characterized by offering greater friction with the ground, providing exceptional grip, especially on flat terrain. While this design increases resistance during rolling, it benefits from enhanced stability on smooth surfaces, ensuring that the vehicle maintains a steady and controlled path.

These two design options allow the vehicle to adapt to a variety of conditions, combining traction, durability, and responsiveness depending on the terrain and the specific needs of the competition.

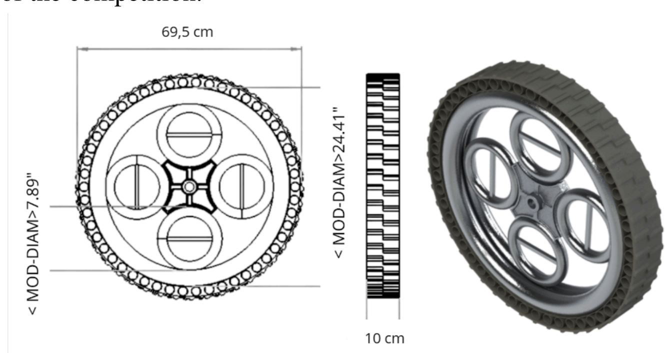


Fig. 3 Robust 4-ring model.

Finally, a hybrid design was chosen that provides effective adaptation to various terrains (Figure 3). This design strikes a balance with an adequate width to ensure stability without being overly bulky. Its lightweight construction allows for good impact absorption. The tread pattern is designed to grip the terrain effectively, minimizing movement during travel and ensuring consistent traction throughout the competition.

Once the design was finalized, it was modeled to meet the following parameters: the wheel is constructed from 6061 aluminum with a tubular structure, featuring a diameter of 64,8[cm] and a width of 10[cm]. The tread design is intended to cover the entire surface, achieving symmetry that helps absorb shocks from the terrain. The arrangement of the aluminum tubes contributes to increased traction, optimizing the vehicle’s performance.

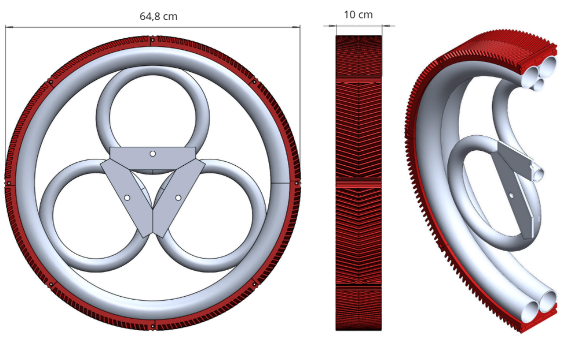
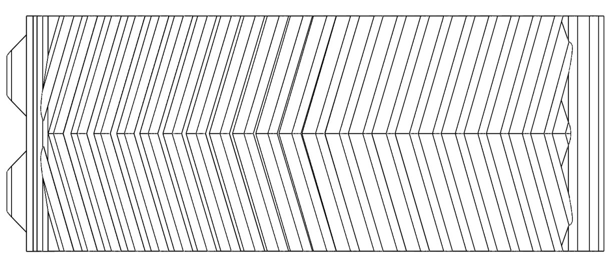


Fig. 4 Final Wheel Mode with 3-ring.

This approach ensures that the wheel is not only durable and capable of withstanding various impacts but also provides reliable performance across different types of terrain, maintaining stability and traction throughout the competition. To ensure that the non-pneumatic wheels, as shown in Figure 4, meet the performance requirements for the NASA HERC event, detailed simulations were conducted to model their behavior under various load and terrain conditions.

D. Manufacturing

Two distinct wheel tread designs were developed, each carefully considering the specific traction and cushioning requirements of the vehicle as shown in Figures 5 and 6



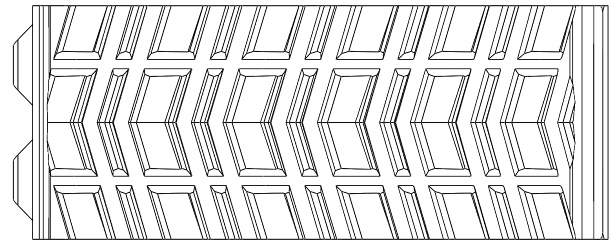


Fig. 5 Top view of the first tread design (top); and second tread design (bottom).

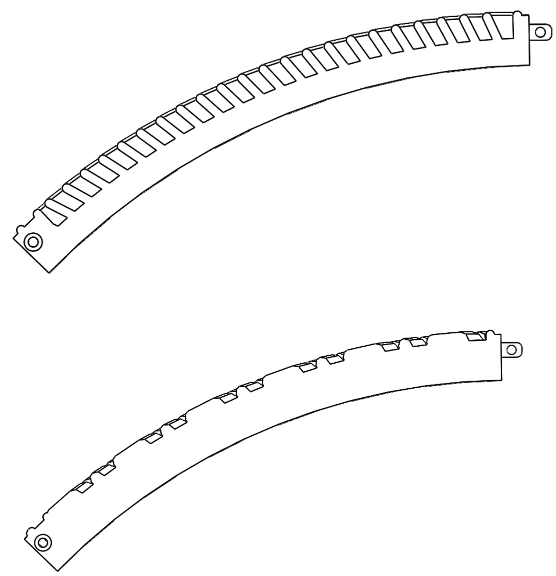


Fig. 6 Side view of the first tread design (top); and second tread design (bottom).

In the upper panel of figure 5 and figure 6, it can be observed the tread aimed to provide traction to the vehicle, having a design that provides more stiffness and provides traction due to its geometry. In the lower panel of figure 5 and figure 6, the tread designed to provide cushioning to the vehicle can be observed, taking advantage of the infill that will be applied during 3D printing, so it will have a cushioning effect on the performance of the vehicle.

Both pieces should be printed in a flexible material such as TPU to properly provide the characteristics expected of each footprint design. Factors such as relatively low layer adhesion when working with TPU, delamination, use of support structures, infill density and tensile strength are parameters that must be taken into account when planning to 3D print parts with TPU.

By decreasing the printing speed, increasing the printing temperature, and raising the infill density, improvements in layer adhesion as well as tensile strength are demonstrated [14].

FDM technology was successfully applied to 3D print non-pneumatic tires based on TPU material, showing that the three-dimensional stiffness obtained is basically 50% of that obtained by simulation [15].

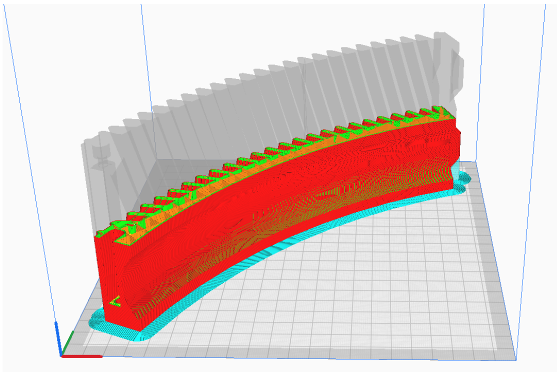


Fig. 7 Model isometric view.

The isometric view in figure 7 also considers the shape and diagonal position relative to the base on which it was printed. The layers were adhered in the same direction as the traction generated when making contact with the surface, which makes it more resistant to tensile and bending stresses. Additionally, this approach helps prevent filament separation in the layer adhesion.

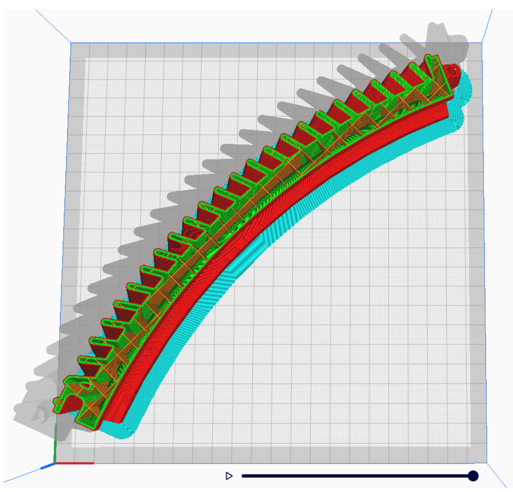


Fig. 8 Model section view.

The cross-sectional view of the model is observed in Figure 8, which shows a square-shaped infill structure. This allowed for a cushioning reaction during its application on the tread.

E. Verification & Validation

a. Stress Analysis

To perform an adequate stress analysis on the wheel, it is essential to consider the following technical specifications (Table II):

TABLE II
WHEEL SPECIFICATIONS

Description	Value
Wheel diameter	0.648 [m]
Wheel width	0.1 [m]
Wheel weight	12 [kg]
Number of wheels	4

In this analysis, the stress on an aluminum wheel of a vehicle with a mass of 70 kg (total mass including drivers: 200 kg) is evaluated. The vehicle has four wheels, and the load is assumed to be evenly distributed among them. We will calculate the contact pressure, Von Mises stress, and the safety factor for the aluminum wheel material based on these assumptions. The vehicle , including its load (drivers) has a total mass of 200 kg.

1. Load Calculation per Wheel

The total load on the vehicle, including the drivers, is 200 kg. This mass results in a gravitational force F_g acting on the system, calculated as:

$$F_g = m_{total} g = 200\,kg\,9.81 m/s^2 = 1962N \quad (1)$$

Since the vehicle has four wheels, the load per wheel is determined by:

$$F_{wheel} = \frac{F_g}{n_{wheels}} = \frac{1962N}{4} = 490.5N \quad (2)$$

This evenly distributed force simplifies the stress analysis by considering a uniform load on each wheel.

2. Pressure Calculation over the Contact Area

The pressure exerted on the wheel is calculated based on the contact area between the wheel and the ground. The wheel has a diameter of 0.648[m] and a contact width of 0.1[m]. Therefore, the contact area is given by:

$$A = d_{wheel} A_{contact} = 0.648\,m\,0.1\,m = 0.0648\,m^2 \quad (3)$$

The pressure P acting on the contact area is then:

$$P = \frac{F_{wheel}}{A} = \frac{490.5\,N}{0.0648\,m^2} = 7567.59\,Pa \quad (4)$$

This pressure provides a measure of the normal stress acting on the surface of the wheel due to the load.

3. Von Mises Stress Calculation

For ductile materials such as aluminum, the von Mises stress criterion is used to predict yielding under a complex state of stress. The von Mises stress σ_v is calculated using the principal stresses σ_1 and σ_2. The equation is:

$$\sigma_v = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \quad (5)$$

In this case, the principal stress σ_1 is equal to the pressure P, and since we assume no lateral stresses, σ_2 is zero:

$$\sigma_1 = P = 7567.59\,Pa,\ \sigma_2 = 0\,Pa \quad (6)$$

Substituting these values into the von Mises equation:

$$\sigma_v = \sqrt{7567.59^2 + 0 - 7567.59 \times 0} = 7567.59\,Pa \quad (7)$$

This value represents the equivalent stress that would cause yielding in the material under the given loading conditions.

4. Safety Factor Calculation

The safety factor is calculated to determine the margin of safety of the design. For aluminum, the yield strength is typically $\sigma_{yield} = 275\,MPa$. The safety factor FS is defined as the ratio of the yield strength to the applied von Mises stress:

$$FS = \frac{\sigma_{yield}}{\sigma_v} = \frac{275\ 10^6\,Pa}{7567.59\,Pa} = 36342.01 \quad (8)$$

This high safety factor indicates that the wheel design is well within the acceptable limits, suggesting a robust design against the applied stresses.

5. Von Mises Stress Simulation

Stress simulations are useful for validating the mechanical strength and durability of components under operational loads. This section presents the von Mises stress analysis of two key components of the rover: the aluminum wheel ring and the TPU tread designs. These analyses aim to identify potential failure points and ensure the designs meet performance and safety requirements under expected and extreme conditions.

a. Aluminum Ring Simulation

The aluminum rings are the structural elements of the rover's wheel, ensuring that it remains stable during rotation and load-bearing activities. Aluminum was chosen for its balance between strength and lightness, essential for maintaining the rover's mobility. This analysis evaluates the ring's behavior under applied stresses to confirm that it can safely withstand dynamic forces encountered during operation.

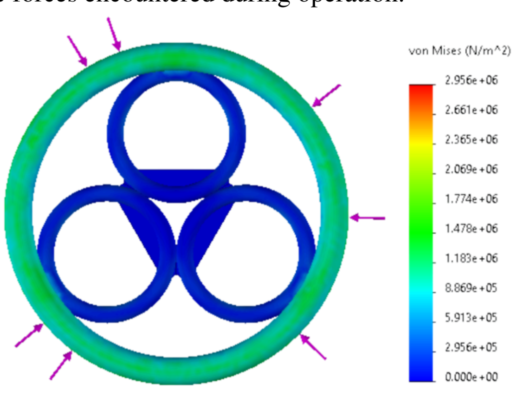


Fig. 9 Von Mises analysis of the wheel's aluminum ring.

The Von Mises stress simulation for the aluminum ring used a uniformly applied force of 200[kg] across the wheel's surface. The goal was to assess the ring's capacity to endure high operational loads and identify any stress concentrations that might pose a risk during rotation. The results confirm that the design is structurally sound under these conditions, ensuring reliable performance even under heavy loads.

b. Tread Simulation

The TPU tread provides traction and shock absorption on uneven terrains. TPU is favored for its flexibility and toughness, but understanding how stress distributes across the tread structure is essential to optimize performance and prevent premature wear. The following analyses focus on two different tread designs to evaluate their strength, durability, and suitability for varied terrain conditions.

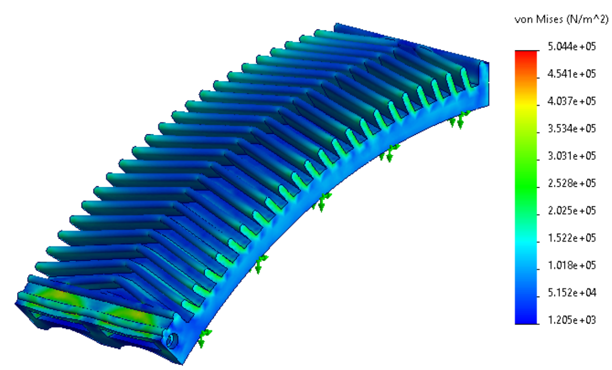


Fig. 10 Von Mises analysis of the first tread design.

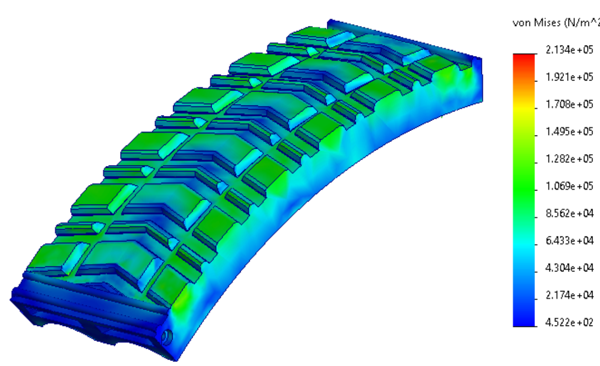


Fig. 11 Von Mises analysis of the second tread design.

The first tread design was tested with a total load of 200[kg] distributed across four wheels. The analysis shows the tread maintains structural integrity at stress levels up to $1.5 \times 10^6\,Pa$. The analysis highlighted areas of concern in the lower regions of the "spikes," where stress levels reached $2.4 \times 10^5\,Pa$, indicating potential vulnerability.

The second tread design, featuring a honeycomb pattern for improved cushioning, was analyzed under a load of 200[kg].

The results indicate that the design can withstand the applied forces but suggest keeping stress below $1.48 \times 10^{5}\ Pa$ to ensure durability. While the honeycomb structure improves shock absorption and provides better weight distribution, it reduces grip and limits surface contact with the ground, potentially affecting performance on challenging terrains.

The "Test Like You Fly" (TLYF) approach, as outlined in the NASA Systems Engineering Handbook [16], emphasizes testing systems under conditions that closely replicate actual operational environments to ensure reliability and uncover latent defects. In alignment with this principle, the validation process for this project was designed to mirror the expected conditions of the NASA Human Exploration Rover Challenge as closely as feasible.

Simulations and structural analyses were conducted using real mission parameters, including the full vehicle and rider mass of 200 kg, evenly distributed across four wheels. Material selection, TPU for the tread and 6061 aluminum for the structural rings, was driven by their proven performance in real-world applications, ensuring mechanical behavior (under load, impact, and deformation) matched expected competition conditions.

While full-scale terrain testing on a lunar-simulated track was not performed (due to constraints), the validation followed NASA's acceptance of analytical rigor when physical testing is impractical. Von Mises stress evaluations, safety factor calculations, and contact pressure analyses were employed to verify structural integrity under both nominal and extreme loading scenarios, consistent with the "Test Like You Fly" (TLYF) philosophy.

This approach, grounded in NASA's systems engineering best practices, provides strong empirical and analytical assurance of the wheel's performance, despite the lack of large-scale physical testing.

III. Results

A. Analysis Results

The performance evaluation of the non-pneumatic wheel system was based on structural simulations, stress analysis, and validation under real-world parameters from NASA's Human Exploration Rover Challenge (HERC). Representative operational conditions were applied, including a total mass of 200 kg evenly distributed across the vehicle's four wheels.

The analysis results showed that each wheel supports a vertical load of approximately 490.5 N and experiences a lateral force of 30.63 N during turning maneuvers. Based on a contact area of 0.0648 m^2, the contact pressure was calculated as 7,567.59 Pa, which also represents the principal stress in the system. The resulting Von Mises stress was 7,567.59 Pa, yielding a safety factor of 36,342, confirming the wheel's robust structural capacity under expected loading conditions.

The use of 6061 aluminum for the structural rings offered an excellent balance between strength and weight, while TPU was selected for the tread due to its flexibility and shock absorption capabilities. Stress simulations on both tread designs—one featuring a V-shaped spike geometry and the other with a honeycomb infill—demonstrated that both maintained structural integrity under load. However, stress concentrations were observed in the thinner spike regions of the first design, with values up to 2.2×10^{5} Pa, suggesting possible points of failure under extreme conditions.

The use of 6061 aluminum for the structural rings provided an optimal balance between weight and strength, while TPU was selected for the treads due to its flexibility and energy absorption properties. Simulations of both tread designs—one with a V-shaped spike geometry and the other with a honeycomb infill pattern—showed that both could withstand the applied load. However, localized stress concentrations were observed. In the spiked tread, critical regions reached up to 2.2×10^{5} Pa, indicating a potential risk of failure under extreme conditions. In contrast, the honeycomb design maintained structural integrity with stresses below 1.28×10^{5} Pa, benefiting from enhanced cushioning at the cost of slightly reduced grip.

Although full-scale physical testing on a simulated lunar track was not performed, the simulation-based evaluation provides strong confidence in the system's performance. These results validate the design's terrain adaptability, structural resilience, and manufacturability using FDM-based additive manufacturing technologies.

TABLE III
RESULTS OF THE FORCES AND STRESSES CALCULATIONS ON THE WHEELS

Parameter	Value
Vertical load per wheel (F_{wheel})	490.5 N
Lateral force (F_{lat})	30.63 N
Contact area	0.0648 m^2
Contact pressure/Normal stress (σ)	7567.59 Pa
Von Mises stress (σ_{vm})	7567.59 Pa
Lateral acceleration (a_{lat})	1.75 m/s^2
Number of wheels	4

B. Manufacturing

a. Mechanical process

The fabrication of the four complete aluminum rings, crafted from 6061 aluminum, involved utilizing tubes of varying dimensions. Following a preprocessing stage that included spiral bending, the rings were successfully formed to their desired shape. Each ring then underwent a thermal deformation process to seamlessly join its ends before being straightened.

Each complete ring comprises two larger tubes and three smaller tubes. The two larger tubes were meticulously assembled to create a single, robust double ring. Within this double ring, the three smaller rings were strategically arranged in a triangular configuration. To further enhance structural integrity, triangular plates were cut and assembled, then securely joined using TIG welding, as depicted in Figure 4.
The total mass of each ring is approximately 4.00 kg ± 0.10 kg. With the addition of a plastic mount for the tire tread, the total mass increased to 6.00 kg ± 0.20 kg.
The dimensions, such as weight, diameter, weld width, and balance, were carefully verified to ensure uniformity and quality in each component.

b. 3D printing parameters

After testing and prototyping during the development of the parts, the data and settings relevant to 3D printing are collected in table IV, optimizing the manufacturing of the 3D printed parts used in the project and their intended purpose. These parameters have been carefully selected to ensure accuracy, strength and quality of the final parts.

TABLE IV
OPTIMIZATION OF PARAMETERS FOR 3D PRINTING

Parameter	Optimized value
Layer height	0.28 mm
First layer height	0.2 mm
Wall thickness	1.2 mm
Number of perimeters	3
Printing speed	40 mm/s
Flow	100%
Extrusion temperature	225 °C
Build plate temperature	60 °C
Build plate adhesion	Brim
Retraction speed	45 mm/s
Retraction distance	5 mm
Top and bottom solid layers	4

IV. DISCUSSION

A. Performance Evaluation

The performance evaluation of the non-pneumatic wheel system was based on structural simulations, stress analysis, and validation under real-world parameters from NASA's Human Exploration Rover Challenge (HERC). Representative operational conditions were applied, including a total mass of 200 kg evenly distributed across the vehicle's four wheels.
The analysis results showed that each wheel supports a vertical load of approximately 490.5 N and experiences a lateral force of 30.63 N during turning maneuvers. Based on a contact area of 0.0648 m^2, the contact pressure was calculated as 7567.59 Pa, which also represents the principal stress in the system. The resulting Von Mises stress was 7567.59 Pa, yielding a safety factor of 36,342, which confirms the wheel's robust structural capacity under the expected load conditions.
In terms of materials, the use of 6061 aluminum for the structural rings offered an excellent balance between lightness and strength, while TPU was selected for the tread due to its flexibility and shock absorption without compromising traction. Stress simulations on the different tread designs revealed that both models—one with a V-shaped spike geometry and another with a honeycomb pattern—maintained structural integrity under load, although stress concentrations were observed in the thinner spike regions of the first design.
Although no physical testing was performed on a simulated lunar track, the results provide strong confidence in system performance, confirming its terrain adaptability, structural resilience, and manufacturing feasibility via FDM-based additive technologies.

B. Design Trade-offs

During the early stages of development, multiple design alternatives were evaluated in order to achieve an optimal balance between functionality, efficiency, and safety. Several ideas were tested and later discarded based on detailed analysis. The main considerations included the following:

a. Tire design

One of the first ideas was the creation of an all-terrain wheel with V-shaped protrusions. This design promised strong grip and traction on uneven surfaces due to the increased friction. However, after testing and simulations, it became clear that it consumed a considerable amount of material, making it inefficient and unsustainable for mass production. For this reason, the design was ruled out despite its mechanical advantages.

b. Number of Printed Parts

Another aspect that was taken into account was the number of components to be printed. Initially, the idea of designing a system with more modular parts seemed beneficial, as it would allow for easy replacement of individual sections in the event of damage or failure. This approach also aimed to increase the availability of spare parts during emergencies. However, the increase in part quantity also led to longer assembly times and higher complexity, which could compromise the robustness of the final product.

c. Joining Mechanisms for Segmented Pieces

Various methods for connecting the cut or modular parts were proposed. Two of the main ideas included:

- The use of metal rods with stoppers, designed to prevent the pieces from detaching during operation.
- The incorporation of retaining rings to hold segments securely in place.

While these methods offered interesting mechanical solutions, they introduced challenges in terms of precision during assembly, added manufacturing steps, and potential safety issues. After reviewing these factors, both proposals were discarded.

d. Material Efficiency and Structural Simplicity

As the design evolved, emphasis was placed on reducing unnecessary material usage without sacrificing strength. Designs that were overly complex, required special fasteners, or had low utility in real-world conditions were gradually eliminated. This refinement process was key to ensuring that the final prototype would be both practical and cost-effective, without compromising performance or safety.

C. Challenges Faced

The design and manufacturing process encountered significant challenges stemming from the mechanical behavior of TPU, the material selected for 3D printing the wheel treads. Key issues included low interlayer adhesion and localized stress concentrations that compromised structural integrity, particularly in the lower spike regions as identified through von Mises simulations. These findings directly impacted critical performance measures including traction capability, stress tolerance, and overall durability, requiring multiple design iterations to resolve. Similar challenges emerged during fabrication of the aluminum rings, which demanded precise thermal bending and TIG welding techniques to achieve the necessary structural stability and geometric consistency.

Faced with these constraints, the project team implemented tailored systems engineering approaches in accordance with NASA's guidelines on adapting methodologies to project-specific conditions. The academic nature of this project, with its inherent limitations in time and resources, justified substituting comprehensive environmental and endurance testing with targeted high-fidelity simulations and focused mechanical evaluations. This tailored approach maintained engineering rigor while operating within practical constraints, as evidenced by the project's ultimate success criterion - the rover's completion of the test course within required parameters without structural or operational failures.

The application of NASA's systems engineering principles provided a structured framework that ensured methodological robustness and credibility, even within an academic setting. While certain traditional validation activities were necessarily abbreviated, the systematic use of analytical modeling and iterative verification preserved the fundamental intent of NASA's engineering standards. This experience demonstrates the adaptability of NASA's systems engineering approach, where properly justified tailoring can maintain technical integrity while accommodating real-world project constraints.

IV. Conclusions and Recommendations

The findings of this research highlight several key points related to the use of 3D printing in the design of non-pneumatic wheels for human-powered vehicles. The versatility of modularity in 3D printing plays a crucial role in the success of this design. By enabling interchangeable and easily replaceable components, the modular approach facilitates quick repairs and adjustments during demanding competitions, improving the adaptability and maintainability of the vehicle. This modularity not only optimizes manufacturing processes, but also reduces costs, as specific parts can be replaced without the need to recreate the entire system. This modularity is a clear advantage of 3D printing wheels applications, making it an ideal manufacturing approach for dynamic and rapidly changing conditions.

Another significant point is the fitting design derived from the intricate possibilities offered by 3D printing. The complexity of the design allows wheels to be precisely tailored to the performance demands of the terrain. For instance, V-band pattern designs were optimized to improve grip and stability, increasing the overall efficiency of the vehicle. The ability to adjust parameters such as infill density and structure through additive manufacturing makes it possible to achieve both strength and flexibility, essential for racing in extreme conditions. Taking advantage of the complexity in 3D design offers the ability to fine-tune performance with a high degree of precision.

Finally, the use of different materials, particularly those that are lightweight but durable, such as TPU, offers substantial advantages in weight optimization. Taking advantage of different materials allows for weight reduction without compromising performance, as these materials are flexible and resistant to mechanical stress. This weight optimization is crucial to improving vehicle efficiency, as a lighter vehicle requires less energy while maintaining its structural integrity. The combination of advanced materials and design complexity enables the creation of a highly efficient, durable, and sustainable wheel system for human-powered vehicles.

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