ADAPTIVE SPOKE DESIGN FOR ENHANCED MOBILITY OF RIMLESS WHEELS ON THE SCOUT ROVER

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ABSTRACT

Planetary exploration missions demand robust locomotion systems to traverse harsh terrain. Unlike traditional rovers, the German Aerospace Center (DLR) SCOUT rover employs rimless wheels specifically designed for extreme environments such as Martian caves, steep slopes, and rocky surfaces. This study presents a redesigned spoke geometry addressing limitations of earlier iterations, which were affected by premature fatigue and suboptimal climbing dynamics. The new design incorporates tapered, three-dimensional spokes forming an elliptical profile, intended to improve energy storage, traction, and self-righting capability, while reducing the effective footprint and protecting rover modules. Additional modifications, including an enlarged interface for the flexible feet, limit excessive bending under high loads, thereby preserving structural integrity and stability. Preliminary experiments, including an end-to-end demonstration in a lava tube, indicate that the adaptive spoke design maintains overall driving performance, while suggesting a potential improvement in spoke durability. A comprehensive test campaign will be required to confirm these findings.

Key words: planetary robotics; exploration; rover; mobile robotics; planetary exploration; rover locomotion.

1. INTRODUCTION

Exploration of extraterrestrial environments continues to advance, yet traversing harsh terrains and cave systems remains a significant challenge. Many existing rovers, such as *Curiosity* and *Perseverance*, are too sensitive to navigate rocky fields due to high value and delicate scientific instruments, potentially missing scientific opportunities or spending excessive time finding alternative routes around obstacles [1, 2].

The SCOUT rover (displayed in Fig. 1) is designed to address these limitations: it can support scouting operations for other robotic systems and actively explore previously inaccessible locations, such as lava tubes [3] or

Figure 1: The SCOUT rover during the demo mission on Lanzarote; photo: Dr. Roy Lichtenheldt

steep crater environments. Cave systems are also considered potential habitats for future human outposts on the Moon and Mars [4, 5], further highlighting the need for robust robotic exploration.

To operate reliably in such challenging environments, the SCOUT rover employs rimless wheels capable of handling diverse surfaces, from hard ground to loose soil and rocky terrain [6]. While rimless wheels are not a new concept – RHex, for example, uses so-called “whegs” for its locomotion system [7] – the SCOUT rover introduces a novel approach. Each wheel features three flexible spokes that can deform and store energy, providing enhanced adaptability and obstacle-crossing capability, as well as a fail-safe mechanism that allows continued operation if a wheel becomes stuck.

The SCOUT rover consists of three modules connected by flexible vertebrae, each segment carrying two rimless wheels. The central module houses the onboard computer, power storage, and communication system, whereas the outer modules accommodate cameras and lighting while leaving space for payload, such as additional sensors. In its current configuration, SCOUT serves as a research platform undergoing continuous testing and design improvements.

This work presents the development and testing of the redesigned rimless wheel spokes for the SCOUT rover, demonstrating improvements in robustness, stability, and terrain adaptability.

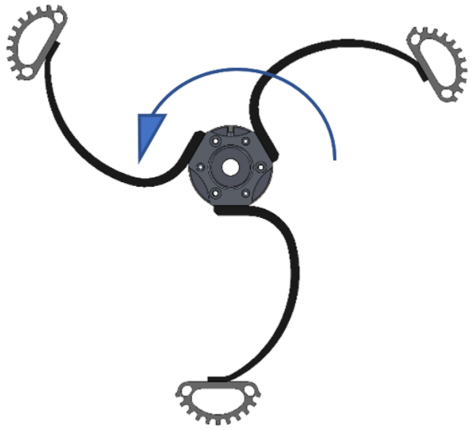


Figure 2: 3D model of the SCOUT wheel with indicated turning direction

2. RIMLESS WHEEL DESIGN

Each wheel of the SCOUT rover comprises a central hub, which interfaces with the motor, three polyoxymethylene (POM) spokes, chosen for ease of manufacture and good resilience, and three flexible feet 3D-printed from thermoplastic polyurethane (TPU) to ensure easy printability, high elastic deformability, and adaptability. While the TPU feet serve as the primary contact points with the ground, the POM spokes may also come into contact depending on their geometry and the terrain's surface properties. In addition, the spokes are carefully balanced to combine flexibility, durability, and controlled breakability. The latter is an intentional fail-safe mechanism, which allows a spoke to fracture if a wheel becomes stuck, ensuring that the rover can continue its mission without compromising overall mobility.

The nominal forward driving direction is with the closed side of the spokes leading, which corresponds to a counter-clockwise rotation for a wheel as shown in Fig. 2. An exception occurs during point turns, when the left and right wheels rotate in opposite directions. While one might intuitively expect that using the spokes as hooks – with the open side leading – would improve traction, experimental results show that orienting the spokes as treads actually provides superior performance in both driving and climbing scenarios.

3. EVOLUTION OF THE SPOKE DESIGN

In earlier iterations of the SCOUT rover, several modifications to the spokes were introduced, primarily to extend their lifetime. While the option of deliberately breaking off a jammed spoke is considered a useful fail-safe to allow the mission to continue, the first design broke off too easily due to an unintended weak point near the hub.

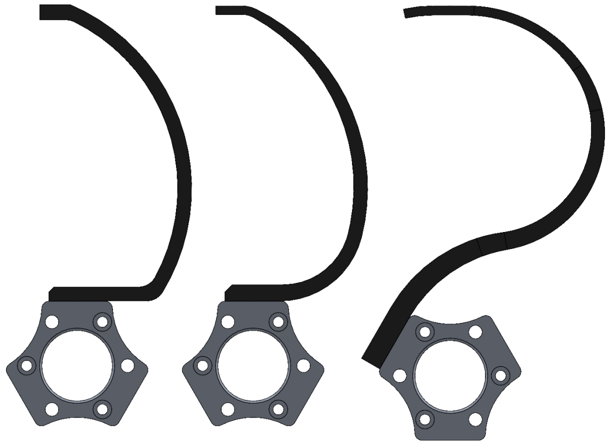


Figure 3: Profile comparison of the earliest (left) to latest (right) spoke design, and its mounting position on the wheel hub

Subsequent iterations also addressed spoke thickness. The initial design featured an almost uniform cross-section, whereas the second version adopted a tapered profile with greater thickness at the hub connection and reduced thickness toward the foot connection. This geometry enhanced the spring-like behavior of the spokes, allowing them to store more energy when deflecting upon ground contact and to release it during roll-off. A secondary benefit was weight reduction while maintaining approximately the same structural strength. This design remained the standard configuration for the SCOUT rover until 2024.

The most recent and most comprehensive redesign of the spokes revealed both challenges and opportunities, leading to modifications in:

- the positioning of the feet relative to the motor axis,
- the geometry of the foot connection surface,
- the 2D spoke shape, and
- the spoke depth.

Fig. 3 presents a side-by-side comparison of the three main spoke design versions: the first design (left) shows the original spoke, the second (center) illustrates the first revision with a tapered profile and stress-reducing curvature, and the third (right) depicts the latest version incorporating the modifications described above. These changes are explained in detail in the following subsections.

3.1. Foot Positioning

When comparing the feet position relative to the motor axis, and using the parallel connection planes of the hub, spoke, and feet as reference, a displacement of 7 mm in

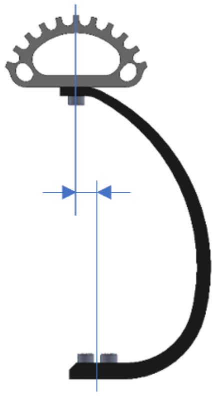


Figure 4: Previous spoke design showing the shift of the foot relative to the motor axis

the opposite direction of travel was observed (see Fig. 4). This displacement slightly altered the effective wheel radius. The unintended offset has been corrected in the new design, which originated from an early development stage. Its correction does not adversely affect the spoke or the driving performance of the wheel and is therefore classified as a minor overall modification.

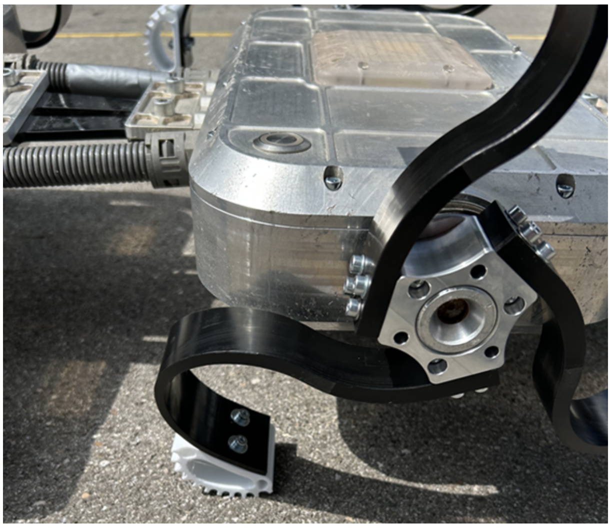
3.2. Foot-Spoke Interface

During many tests it was observed that the flexible feet often bent excessively under high loads, which could negatively affect climbing performance, reduce lifetime, and decrease the predictability of the SCOUT rover in simulations. Being made of TPU and therefore very flexible, overstretching around the bolt and washers occasionally led to the loss of feet. This impaired the driving capability of the corresponding wheel but fortunately had only a minor impact on the overall locomotion of the SCOUT rover due to redundancy. Improvements to the joint components and an extension of the spoke's running surface beyond the screw connection are expected to solve this problem in the new design (see Fig. 5).

3.3. Shape of the 2D Spoke Design

In earlier designs, the spokes bent around 180 °, forming a semi-circular profile that made attaching the spokes to the hub and the feet to the spokes cumbersome (see Fig. 3). The limited accessibility prevented the use of standard power tools, rendering part replacement or screw tightening both tedious and time-consuming. To address these limitations, the 2D spoke profile was redesigned into a question mark–like shape (see Fig. 6), further enhanced by a three-dimensional curvature (see Sec. 3.4). This geometry provides free access to the hub connection and significantly facilitates the attachment of the feet. While earlier changes to the curvatures primarily aimed to reduce stress concentrations, the new geometry was also expected to affect driving behavior. Indeed, the

(a) Foot connection on previous spoke design under load



(b) Foot connection on revised spoke design under load

Figure 5: Comparison of previous and revised foot connections under load

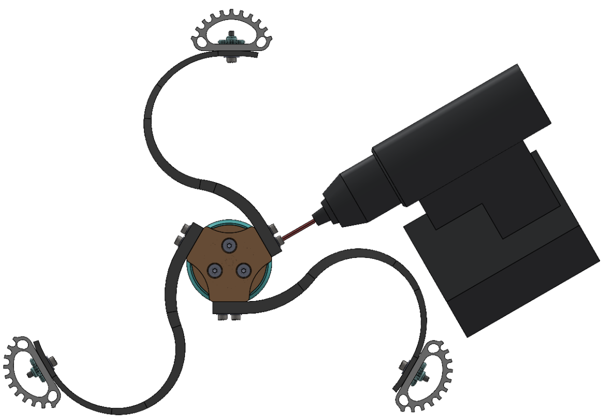


Figure 6: New spoke design with modeled tool showing facilitated assembly

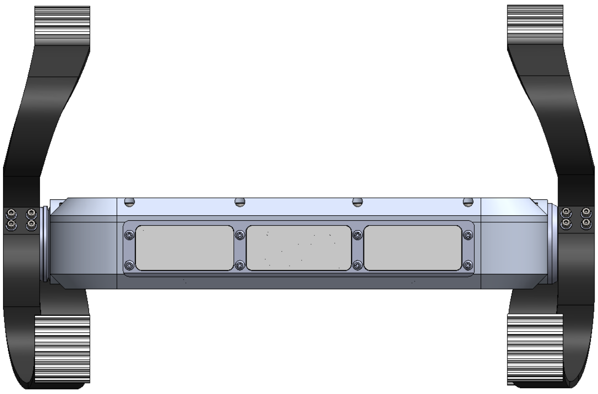


Figure 7: Front view of the SCOUT rover with redesigned 3D spokes

revised design allows greater bending under load, and the outer curvature forms a tread-like surface that engages the ground before the feet, leading to smoother and more continuous rolling, even on flat terrain.

3.4. Spoke Depth and 3D Geometry

Previous designs used simple extruded 2D profiles with drilled holes. To improve self-righting capability and reduce the rover's overall footprint, the spokes were redefined as true three-dimensional structures. When viewed from the front or rear, the wheels now form an elliptical contour rather than a boxed profile (see Fig. 7). The combination of a smaller resting surface when the rover lies on its side and the curved wheel geometry improves its ability to roll back into an upright position, resulting in a more reliable and controllable self-righting maneuver. Such functionality is critical when descending into caves or traversing large steps, where the rover may end up on its side. Controlled flipping onto its top or bottom can also be advantageous, as some payload instruments may only operate in specific orientations.

Additionally, the spoke depth at the hub connection was reduced, while maintaining the original depth at the foot connection. This modification narrowed the rover's overall width by 30 mm – from 50 cm to 47 cm, and down to 42 cm at the narrowest point near the feet – corresponding to a 16 % reduction in footprint. The slimmer profile enables access to a wider range of narrow openings and passageways. To preserve structural strength despite the new geometry, the spoke thickness distribution was adjusted, with a minor weight increase of 9.7 g per spoke (from 65.4 g to 75.1 g).

4. FIRST DEPLOYMENT IN LAVA TUBE ON LANZAROTE

In 2024, the SCOUT rover was tested during an analog site campaign in a lava tube on Lanzarote [8]. This harsh environment represents one of the intended application scenarios of the rover [3]. In this near end-to-end mission, the new spokes were deployed for the first time, and several improvements in behavior were clearly observable, such as increased deformation under load and enhanced durability. The mission included traversing hard and uneven lava tube floors, overcoming constrictions and natural obstacles, as well as descending into the cave system through a skylight serving as the entrance point for the demonstration mission, as they are known to exist on the Moon and Mars [9, 10, 11]. The following describes the observations related to the wheels.

4.1. Deformation

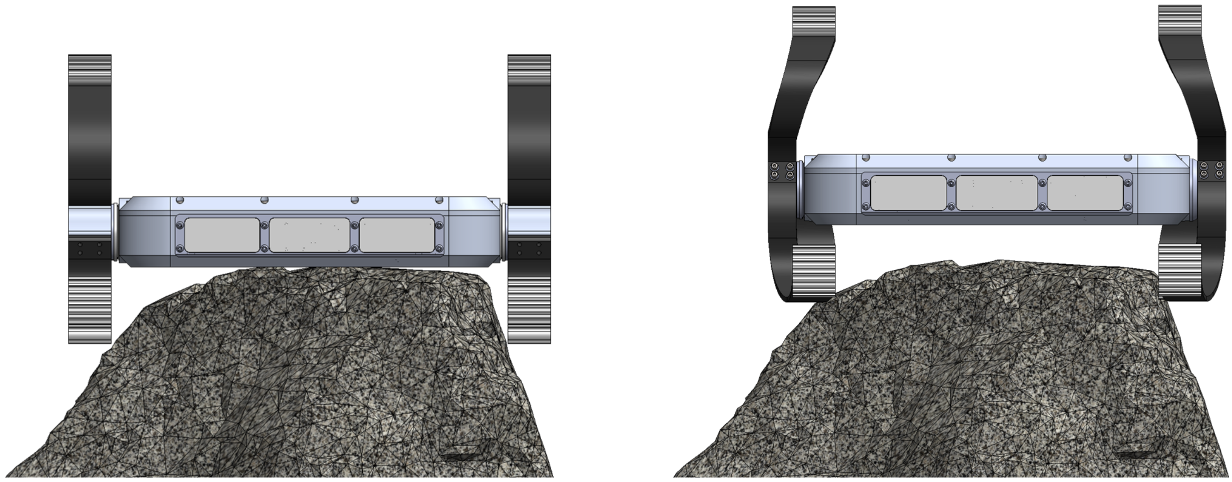
The new spoke design enables greater deformation without failure. This results in smoother driving behavior and improved obstacle traversability, as the spokes adapt more effectively to the surface and thereby stabilize the rover modules. High loads in both driving directions, combined with a software torque limitation of the SCOUT rover motors, so far has prevented the breaking of spokes. Although the rover is designed to intentionally shere off a spoke as a self-recovery mechanism when stuck, such a failure should not occur during nominal driving. Even during point turning on the rough lava tube surface, which repeatedly led to significant spoke deformation, no damage was observed.

During the drop of approximately 6 m into the cave entrance, the spokes absorbed the rapid impact and deflected the associated energy. Compared to the fall into the Cisternazza crater on Mt. Etna during the Arches mission in 2022 [12], no spokes failed this time. A direct comparison, however, is not possible due to the different fall conditions and other parameters.

4.2. Improved Module Protection

The bent spokes reduce the effective contact footprint of the rover by up to 16 %. This geometry can, under certain conditions, provide additional protection to the rover modules, including electronics and payload (see Fig. 8). The extent of this effect depends on several factors, such as wheel orientation, obstacle size and shape, ground profile, and the executed maneuver.

The spoke geometry also mitigated impact effects during the drop into the lava tube entrance, as several modules benefited from partial shielding by the inward-curved spokes upon ground contact. Under load, the spokes can bend further inwards, potentially enhancing this protective effect.



(a) Previous spoke design interacting with a large stone; chassis contact occurring regardless of wheel orientation

(b) Revised spoke design interacting with the same large stone; chassis contact potentially prevented depending on wheel orientation

Figure 8: Comparison of previous and revised spoke designs under the same large-stone obstacle; revised design mitigating chassis contact depending on wheel orientation

4.3. Advanced Shape

Although the previous iteration of the spoke design already featured a more continuous thickness distribution, the geometry was further refined in the new version. The adapted thicknesses combined with smoother and larger curvature radii further reduced stress concentrations. As a side effect, the rimless wheels now use their spokes as tread elements for rolling, instead of relying solely on the feet.

While in the old design contact between spokes and ground occurred only with large rocks or in loose soil after sinking, the new configuration allows contact even on flat surfaces. This larger contact area alters the rolling behavior and may increase abrasion. However, no adverse effects have been observed so far during testing.

5. CONCLUSION

The redesign of the SCOUT rover spokes highlights how incremental yet targeted modifications can yield substantial improvements in performance and reliability. Across three major iterations, the spoke geometry evolved from a uniform and failure-prone structure into a tapered, question mark-shaped, three-dimensional component that combines strength, flexibility, and improved installability. Each design stage not only addressed shortcomings of the previous version but also introduced new functional opportunities.

The latest spoke generation was validated during a near end-to-end demonstration mission in a lava tube on Lanzarote. Here, the new design proved its durability under demanding conditions, including rough volcanic ground, rocky obstacles, and a drop through the skylight entrance. Several benefits became evident:

- Greater deformation capacity without failure, resulting in smoother driving and safer obstacle negotiation, even under point-turning loads.
- Enhanced protection of sensitive rover modules due to the inward-bent spoke geometry, which can partially shield the chassis from impacts.
- A more continuous structural profile with reduced stress concentrations, leading to higher longevity and smoother rolling behavior, with the spokes themselves contributing to ground contact.

In addition to these functional gains, the spoke redesign reduced the SCOUT rover effective footprint by 6 % at the hub and 16 % at the feet, enabling access to narrower passages while slightly increasing overall spoke weight but maintaining structural strength. The design also improves maintainability, as the revised geometry allows easier access to connections at both hub and feet.

Together, these improvements represent a significant step toward a more resilient and versatile locomotion system. The new spoke design enhances the robustness of the rover in harsh environments, expands the range of traversable terrain, and increases operational safety. These results underline the importance of adaptive component design for planetary exploration and provide a solid foundation for upcoming field campaigns and potential mission deployment.

6. OUTLOOK

To directly quantify the improvements introduced by the new spoke design, a dedicated test campaign is planned at the DLR Moon-Mars Test Site in Oberpfaffenhofen [13]. In these trials, the current and previous spoke designs will be systematically compared across a variety of mission-relevant scenarios, with the goal of identifying not only the advantages but also the remaining limitations of the new configuration. The outcome will be critical for deciding whether this iteration of the spoke design will be adopted for the SCOUT rover in upcoming campaigns, or whether further modifications are required.

Complementary to the physical tests, simulations of the SCOUT rover equipped with the new spokes will provide an additional means of validating performance across different terrains and maneuvers. These efforts will also allow a more systematic assessment of critical aspects such as durability, traction efficiency, and climbing ability.

Looking further ahead, the spoke design may continue to evolve through targeted optimization campaigns. Both incremental refinements and more radical changes remain conceivable, depending on the findings of the upcoming evaluations. Possible directions include tailoring geometries to further extend lifetime, enhancing climbing performance on steep slopes, and improving agility during turning maneuvers. In this sense, the current iteration should be regarded not as a final solution, but as an important step in an iterative development process aimed at maximizing the adaptability and resilience of the SCOUT rover in planetary exploration missions.

REFERENCES

[1] A. Rankin, M. Maimone, J. Biesiadecki, N. Patel, D. Levine, and O. Toupet, "Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years," in *2020 IEEE Aerospace Conference*, Big Sky, MT, USA, 2020, pp. 1-19, doi: 10.1109/AERO47225.2020.9172469.

[2] A. Rankin et al., "Perseverance Rapid Traverse Campaign," in *2023 IEEE Aerospace Conference*, Big Sky, MT, USA, 2023, pp. 1-16, doi: 10.1109/AERO55745.2023.10115835.

[3] R. Lichtenheldt, E. Staudinger, S. Adeli, J.-P. de Vera, G. Giudice, and M. Baqué, "A Mission Concept For Lava Tube Exploration On Mars And Moon – The DLR Scout Rover," in *52nd Lunar and Planetary Science Conference (LPSC)*, Mar. 15-19, 2021. [Online]. Available: `https://www.hou.usra.edu/meetings/lpsc2021/pdf/1443.pdf`

[4] F. Horz, "Lava tubes - Potential shelters for habitats," in *Lunar bases and space activities of the 21st century*, Houston, TX, USA, 1985, pp. 405-412.

[5] E. Gibney, "How to build a Moon base," in *Nature*, vol. 562, pp. 474-478, 2018, doi: 10.1038/d41586-018-07107-4.

[6] L. Stubbig, R. Lichtenheldt, F. Becker, and K. Zimmermann, "Model-based development of a compliant locomotion system for a small scout rover," in *59th Ilmenau Scientific Colloquium*, Ilmenau, Germany, Sep. 11-15, 2017.

[7] E. Z. Moore, D. Campbell, F. Grimminger, and M. Buehler, "Reliable Stair Climbing in the Simple Hexapod 'RHex'," in *Proceedings of the 2002 IEEE International Conference on Robotics and Automation (ICRA)*, Washington, DC, USA, May 11-15, 2002, pp. 2222–2227.

[8] R. Lichtenheldt, et al., "Exploration of Martian Caves with the Scout Rover: Robust Design and Advanced Navigation," in *iSAIRAS 2024*, Brisbane, Australia, Nov. 19-21, 2024.

[9] G. E. Cushing, T. N. Titus, J. J. Wynne, and P. R. Christensen, (2007): "THEMIS observes possible cave skylights on Mars," in *Geophysical Research Letters 34 (17)*, 2007, doi: 10.1029/2007GL030709.

[10] L. Carrer, R. Pozzobon, F. Sauro, D. Castelletti, G. W. Patterson, and L. Bruzzone, "Radar evidence of an accessible cave conduit on the Moon below the Mare Tranquillitatis pit," in *Nat Astron 8*, 2024, pp. 1119–1126, doi: 10.1038/s41550-024-02302-y.

[11] X. Qiu and C. Ding "Radar Observation of the Lava Tubes on the Moon and Mars," in *Remote Sensing 15 (11)*, 2023, doi: 10.3390/rs15112850.

[12] A. Pignède, et al., "The DLR Scout Rover during the 2022 Arches Demomission Space on Mount Etna: Operating the Rover outside of its Comfort Zone," in *72. Deutscher Luft- und Raumfahrtkongress 2023 (DLRK)*, Stuttgart, Germany, Sep. 19-21, 2023, doi: 10.25967/610059.

[13] M. Görner et al., "The DLR Moon-Mars Test Site for Robotic Planetary Exploration," in *2024 International Conference on Space Robotics (iSpaRo)*, Luxembourg, Luxembourg, 2024, pp. 245-252, doi: 10.1109/iSpaRo60631.2024.10687411.