Evaluating the Performance of the Novel Spoke Design in the SCOUT rover's Rimless Wheels

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***Abstract*— This study evaluates the performance of a newly designed spoke geometry for the rimless wheels of the SCOUT rover. Developed at the German Aerospace Center (DLR), this lightweight robotic platform is intended for exploration of challenging extraterrestrial terrain, such as lava tubes and steep rocky environments. The redesign introduces continuous thickness, optimized curvatures, and a 3D bend that gives the rover an elliptical wheel profile. This is intended to enhance durability, driving performance, and the rover's ability to upright itself after tipping on its side.**

A comprehensive series of tests was conducted at the DLR Moon-Mars analog testbed and on adjacent asphalt terrain. These included linear driving, point turning, obstacle traversal, as well as controlled flipping and uprighting maneuvers. Tests were run on both hard and loose surfaces, using both automatic and manual control schemes where applicable. Performance was assessed primarily by time-to-completion metrics under consistent test conditions for both old and new spoke designs.

I. INTRODUCTION

Planetary exploration presents numerous challenges and opportunities, especially when it comes to accessing rough and remote terrain, as well as exploring these for the first time. Despite decades of missions, many regions of Moon and Mars remain unexplored. In particular underground environments and steep geological features have so far not been accessed by traditional rovers, such as the NASA rovers Curiosity and Perseverance [1, 2]. The reason for this being their size, weight and sensitive instruments, making them unsuitable for taking risks by driving an unsafe passage.

The SCOUT rover (displayed in Fig. 1), in contrast, is specifically designed to navigate challenging terrain and access areas that are typically avoided, including lava tubes [3–5]. Its compact, lightweight design allows it to complement larger planetary rovers, which carry bigger and heavier instruments, in a cooperative exploration approach. Several test campaigns have been conducted in the recent years, thoroughly testing and evaluating the SCOUT rover's capabilities in a variety of scenarios. To highlight just a few of them: the ARCHES demo displaying a Moon mission [6], the first terrestrial in-cave tests [7], as well as the end-to-end demo mission in a lava tube on Lanzarote [8].

By refining the rover's individual subsystems, its performance is gradually increased. Therefore, this study focuses on the improvement of the spokes, which are part of the rimless wheel assembly [9].

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Fig. 1: The SCOUT rover in action on the DLR Moon-Mars Testbed

The SCOUT rover is not the first system to feature rimless wheels. A prominent example for a robot with so called "whegs" is the RHex robot [10]. However, the wheels used on the SCOUT rover are unique, since they are using three spokes for each wheel, having a flexible design that allows bending and storing energy. Adding to that, the rover system is comprised of three flexibly connected modules, enabling the rover to adapt to a variety of surface conditions. Improving its performance furthermore, the rimless wheel spokes have recently undergone a significant redesign aimed at improving mobility, durability, and self-righting capabilities.

This article presents the design and test of the previous and novel spoke designs. Starting with a brief history and overview of the design changes. Following that, the test setup is described by explaining the test site and the controls. After this explanation, the test results are presented and categorized. Finally, a conclusion of the results and an outlook on future development steps are provided.

II. GENERAL ROVER DESIGN

The SCOUT rover consists of three aluminum modules interconnected by vertebrae made of polyoxymethylene (POM), which is also used for the rimless wheel spokes. Aluminum, widely used for the rover's metal components, was selected for its light weight, availability, and ease of manufacturing, while POM offers high flexibility under load and production efficiency. Each module of the SCOUT rover

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houses motors and motor controllers. The central module additionally contains the onboard computer, battery packs, power conditioning and distribution unit (PCDU), and communication systems. The outer modules are equipped with cameras, matrix LEDs, and a LiDAR, as well as dedicated payload areas for additional sensors and instruments. The rover's current configuration weighs approximately $18\,\mathrm{kg}$, with an expected payload margin of up to $10\,\mathrm{kg}$. The battery provides a lifetime up to $10\,\mathrm{h}$, with potential for optimization. The total length of the rover is approximately $1.20\,\mathrm{m}$.

III. Novel Spoke Design

After several years of iterative development, the spokes of the SCOUT rover's rimless wheels have undergone multiple redesigns, with the latest representing the most significant improvement to date [11] (see Fig. 2). The wheels consist of three main parts, a wheel hub, three spokes, and three flexible feet, which together form the core of the rover's locomotion system. Key modifications introduced in the iteration include a revised geometry featuring more continuous thickness and curvature, as well as the addition of a three-dimensional bend that gives the wheelbase an elliptical profile (see Fig. 3). Additionally, the hub size was reduced, resulting in a narrower overall footprint of the rover by $3\,\mathrm{cm}$. Table I gives a brief overview about the attributes in the different revisions.

TABLE I: Overview of Spoke Evolution Across Revisions in Terms of Attributes

Attribute	Rev 1	Rev 2	Rev 3
Mass	$72.8\,\mathrm{g}$	$65.4\,\mathrm{g}$	$75.1\,\mathrm{g}$
2D Profile	C-shaped	C-shaped	Question mark-shaped
Installability	Bad	Bad	Improved
Foot hub	Short	Short	Extended
3D Profile	No	No	Yes
Width at wheel hub	$44\,\mathrm{mm}$	$44\,\mathrm{mm}$	$29\,\mathrm{mm}$
Continuous curvature	No	Yes	Yes

These design changes aim to improve structural durability, increase the lifespan of the spokes, and enhance overall locomotion performance – especially in scenarios where the rover needs to upright itself after tipping on its side. The introduced three-dimensional bend reduces the area on which the rover can rest when lying sideways. Depending on the terrain, a stable stand might not even be possible, thereby facilitating the uprighting maneuver. To achieve these improvements, a manual optimization process was carried out: different design ideas were created, reviewed, and evaluated using Finite Element Method (FEM) analyses to identify and reduce stress peaks. Fig. 3 provides a direct visual comparison of the old and new spoke configuration, highlighting the updated three-dimensional shape and its impact on the overall design of the SCOUT rover.

IV. Test Setup

Following its first major deployment during a lava tube demonstration mission on Lanzarote, the new spokes of the SCOUT rover's rimless wheels were subjected to a structured test campaign. The objective was to evaluate their performance across various realistic scenarios, always considering the rover's intended use in rough and unpredictable terrain. Tests were conducted both at the Moon-Mars Testbed [12] (see Fig. 4) at the German Aerospace Center (DLR) in Oberpfaffenhofen, as well as on the adjacent asphalt surface.

The test campaign was divided into four main categories: linear driving, point turning, obstacle traversal, and rover flipping. Each configuration and its relevance to the SCOUT rover's operation, including whether the tripod gait was pre-initialized, are described in the corresponding subchapters.

The tripod gait is a wheel phase pattern where three wheels arranged in an alternating, non-opposing configuration move together, while the remaining three are equally offset by $60\,\mathrm{degrees}$ [13].

In some cases, the tripod gait was initialized prior to positioning the rover at the starting line to ensure a defined gait phase offset from the beginning. Without this step, the gait phase would only be established upon the first actuation. As this could influence the results by introducing unintended

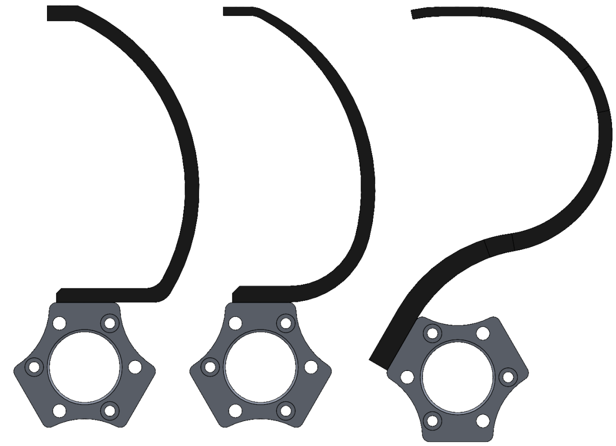


Fig. 2: First design (left), second design (center) and newest design (right) of the spoke, and their mounting positions on the wheel hub

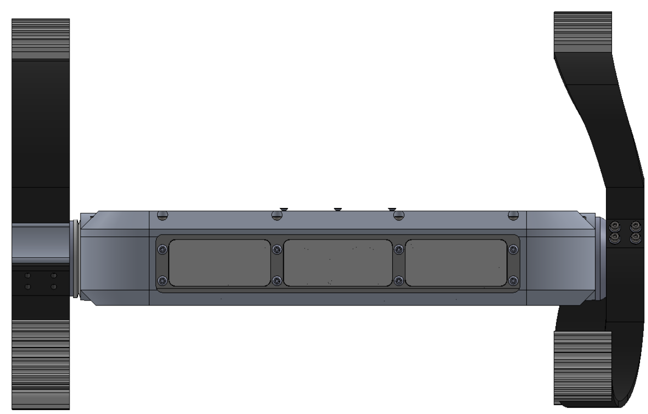


Fig. 3: Old design (left) compared to the newest spoke design (right)

drift, it has to be avoided. All tests were conducted by a trained operator and, unless otherwise specified, manually driven.

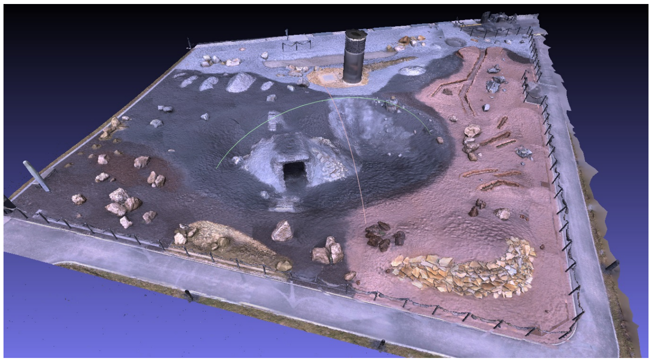


Fig. 4: 3D scan of the Moon-Mars Testbed at DLR Oberpfaffenhofen

A. Linear driving

Driving is the primary mode of locomotion for both traditional and rimless-wheel-based rovers. To ensure reliable performance across varied planetary terrains, extensive surface testing is essential prior to deployment. Due to time and resource constraints, the SCOUT rover's linear driving tests were limited to two surface types: hard asphalt and loose gravel (grain size $2\text{–}8\,\mathrm{mm}$, depth $10\text{–}15\,\mathrm{cm}$), as shown in Fig. 5 (green- and yellow-marked areas). Both areas feature a slight lateral tilt of approximately $1\text{–}2\,\mathrm{degrees}$ relative to the driving direction, causing a slight sideways slope during operation.

Tests were performed at two commanded speeds: $1\,\frac{\mathrm{m}}{\mathrm{s}}$ (nominal drive mode) and $2\,\frac{\mathrm{m}}{\mathrm{s}}$ (fast mode). In both scenarios, the SCOUT rover was operated using predefined scripted commands without manual input. It was initialized in its tripod gait and placed at a designated starting line. Each run ended either upon reaching the 10-meter finish line or when the rover drifted out of the defined test area. For the fast mode, a gradual acceleration was implemented to mitigate vertical oscillations caused by rapid spoke deformation. The time taken to complete each 10-meter run was recorded.

B. Point turning

In addition to forward driving, turning capabilities are essential for the SCOUT rover to reach its target destinations. As with the linear driving tests, point turn maneuvers were conducted on two different surfaces: hard asphalt and loose gravel, as shown in Fig. 5 (green- and yellow–marked areas). Both areas featured a slight lateral tilt of approximately $1\text{–}2\,\mathrm{degrees}$ relative to the driving direction, resulting in a minor sideways slope during operation.

All tests were executed using predefined scripted commands without any manual control. The rover was not initialized in its tripod gait. Each test run was manually stopped after the rover completed a rotation of more than $360\,\mathrm{degrees}$, and the time required for a full revolution was recorded. Lateral drift was not quantified in this test, as it

Fig. 5: Moon-Mars Testbed with marked testing areas: green for hard ground driving tests; yellow for loose soil driving and uprighting tests; red for obstacle traversal tests

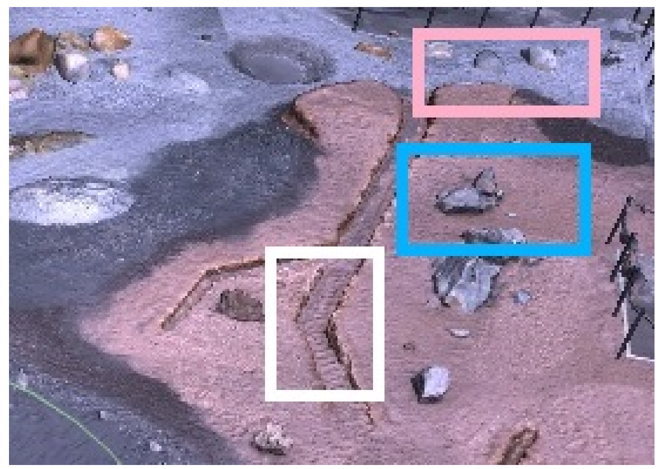


Fig. 6: Moon-Mars Testbed with marks for tested obstacles: pink for climbing and flip initiation; blue for stone traversal; white for trench curve

was presumed to be caused primarily by the consistent tilt of the test surface and was considered outside the primary scope of this evaluation.

C. Obstacle traversal

To operate effectively in rough terrain, the SCOUT rover must be capable of more than just forward driving and turning. Therefore, three representative obstacle types were selected for this test campaign: navigating a curve in a narrow trench, traversing a field of large rocks, and climbing a high vertical step (see red-marked area in Fig. 5; see Fig. 6 for detailed obstacle areas). All obstacle tests were conducted without initializing the rover's tripod gait. Each test was performed under manual control, starting from a predefined position and concluding at a marked finish line. The time required to complete each task was recorded.

The narrow trench test evaluates the presumed improvement in the spokes' ability to navigate tight spaces, driven in the white marked area in Fig. 6. For comparison, the trench width is $54\text{–}60\,\mathrm{cm}$, while the SCOUT rover's footprint measures $50\,\mathrm{cm}$ with the old spokes and $47\,\mathrm{cm}$ with the new spoke configuration. Since the trench has no overhead cover, the rover can also employ adjusted motion strategies beyond ground-level traversal. A finish line was predefined.

The rock traversal test assesses how well the new spokes enable the rover to overcome irregular terrain. The obstacle consists of multiple large rocks, two of which constrain the navigable path and naturally guide the rover's motion (see blue-marked area in Fig. 6). A finish line was predefined.

The step-climbing test represents a particularly demanding scenario. The vertical obstacle is approximately $40–45\,\mathrm{cm}$ high (see Fig. 7 and pink-marked area in Fig. 6), more than twice the radius of the rover's wheels. The SCOUT rover was commanded manually at a limited maximum speed of $0.4\,\frac{\mathrm{m}}{\mathrm{s}}$ to prevent instability or tipping. The test concluded once the front module's foot made contact with the step's upper surface after successfully climbing up.

D. Rover flipping

Designed for extreme environments such as skylights [14], collapsed surface openings that provide access to subsurface lava tubes on the Moon or Mars [4, 5], the SCOUT rover is capable of moving with either its top or bottom side facing upwards. However, certain payloads may require a specific orientation, necessitating a controlled flip maneuver to align the rover accordingly [15]. Furthermore, following a drop or an incomplete flip, the rover must be able to autonomously return to an upright position. This self-righting capability is a core feature supported by the redesigned, curved spoke geometry. Both maneuvers were tested separately, each from a predefined starting point and executed manually.

To evaluate the initiation of a controlled flip maneuver, a step approximately $35–40\,\mathrm{cm}$ in height, roughly twice the wheel radius, was approached from the side (see Fig. 8; test area marked in pink in Fig. 6). The rover was driven laterally into the obstacle from a predefined starting point, and the maneuver was performed without initializing the tripod gait. The test concluded once the rover had tipped onto its side, reaching a vertical orientation. The duration of the maneuver was recorded.

In the second test, the SCOUT rover was placed on its side on a flat gravel surface (yellow area in Fig. 5) and initialized into its tripod gait, being in a stable position. Without any obstacles to push against, the rover had to rely solely on the dynamic momentum generated by its rotating wheels to tip itself upright (see Fig. 9). The activated tripod gait reflects a realistic configuration, as the angled wheel orientation theoretically provides a broader support base for self-righting. After each test run, the gravel surface was manually leveled to ensure consistent conditions. Two sets of control strategies were tested: in the first, a simple forward driving command was issued; in the second, the operator manually reacted to the rover's movements to assist the process and minimize the time needed. The test concluded when the upper wheels made contact with the ground again, and the duration was recorded.

Fig. 7: SCOUT rover with old spokes climbing the high step

V. RESULTS

After explaining how the tests had been set up, this section presents the respective results. Each scenario was executed five times using both sets of wheels, except for the uprighting, which was executed six times. Some runs were excluded from specific tests for various reasons, as noted in the corresponding subchapters. An overview of the criteria, the total number of executed runs, and the excluded runs for all scenarios can be found in Table II. All plots use color pairs for the comparable tests. The dot marks the average time, while the error bars show the range of all measured times.

TABLE II: Overview of Experimental Run Criteria, Total Number of Runs, and Excluded Runs

Run name	**Criteria (time to...)**	**Runs each**	**Excluded (old/new)**
Drive, hard	Reach $10\,\mathrm{m}$ within area	5	1 / 1
Fast, hard	Reach $10\,\mathrm{m}$ within area	5	4 / 3
Turn, hard	Turn 360°	5	0 / 0
Drive, loose	Reach $10\,\mathrm{m}$ within area	5	2 / 1
Fast, loose	Reach $10\,\mathrm{m}$ within area	5	0 / 0
Turn, loose	Turn 360°	5	0 / 0
Trench curve	Reach finish line	5	0 / 0
Rock traversal	Reach finish line	5	0 / 0
Step climb	Be horizontal after climb	5	0 / 0
Flip initiation	Be flipped by 90°	5	1 / 0
Flip completion	Upper wheels touch ground	6	0 / 0

Fig. 8: SCOUT rover with new spokes initializing a flip

Fig. 9: SCOUT rover with new spokes during uprighting

A. Linear driving

The linear driving tests were divided into two: first, the normal speed with a commanded theoretical velocity of $1\,\frac{\text{m}}{\text{s}}$ (without slip and deformation of the spokes); second, the acceleration ramp to a maximum speed of commanded $2\,\frac{\text{m}}{\text{s}}$. The goal was reached after $10\,\text{meters}$, the time was recorded. The results are shown in Fig. 10 and discussed below.

Driving the SCOUT rover on hard ground showed a major performance increase of the new spokes (Blue; Avg. Old: $15.09\,\text{s}$; New: $12.76\,\text{s}$), being $18.3\,\%$ faster. For the loose soil this advantage is reduced but still noticeable (Red; Avg. Old: $13.79\,\text{s}$; New: $13.41\,\text{s}$), being $2.8\,\%$ faster. In the first test, one run for each spoke design was excluded due to drifting out of the driving area. In the second test, one run with the new spokes was excluded after veering off approximately half a meter before the finish line. Two runs with the old spokes were excluded due to drifting out of the driving area. No test runs were repeated, as the remaining results show only minor variation, as well as close runs being on the same pace.

Driving fast on hard ground challenged the SCOUT rover, since it tends to bounce quite heavily. An acceleration ramp was used to limit this behavior. The old spokes failed $80\,\%$ of the runs, finishing only one, while the new one failed $60\,\%$, finishing two (Green; Avg. Old: $13.13\,\text{s}$; New: $11.49\,\text{s}$), being $14.3\,\%$ faster. The runs were not repeated already seeing the improvements in the new design jumping less, and interpreting the drifting itself also as a result. However, driving fast on loose soil also showed the performance increase of the new spokes (Yellow; Avg. Old: $10.67\,\text{s}$; New: $9.64\,\text{s}$), being $10.7\,\%$ faster.

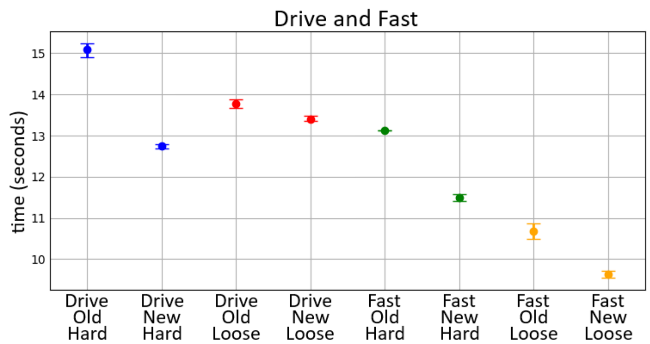


Fig. 10: Results for "Drive" and "Fast" driving tests on hard ground and loose soil

B. Point turning

The point turn tests happened on both tested surfaces, using a fixed commanded turning speed, measuring time to reach $360\,\text{degree}$ revolution. The results are shown in Fig. 11 and discussed below.

Driving on hard ground, the point turn showed the new spokes improved performance (Pink; Avg. Old: $12.49\,\text{s}$; New: $10.96\,\text{s}$), at $14.0\,\%$ faster. However, the test on loose soil showed the old spokes performing better (Blue; Avg. Old: $8.85\,\text{s}$; New: $9.97\,\text{s}$), the new spokes being $11.2\,\%$ slower. Overall, a drift could be seen, always heading towards the same direction. The slight slope of both test areas is assumed to be the cause. Therefore, drifts have not been measured or taken into account.

C. Obstacle traversal

The tests were carried out as described in Sec. IV-C. For the trench curve and rock field, the rover was driven manually at a maximum speed of $1.2\,\frac{\text{m}}{\text{s}}$; for the step climb, a maximum speed of $0.4\,\frac{\text{m}}{\text{s}}$ was used. Completion time was measured from the start line to the finish line, or to first contact with the upper level of the step. The results are shown in Fig. 12 and discussed below.

Following the narrow trench into its curve, the new narrower and more curved design of the spokes proved to perform significantly better (Green; Avg. Old: $6.45\,\text{s}$; New: $4.65\,\text{s}$), being $38.7\,\%$ faster. The old spokes got stuck inside the trench, or the rover slightly climbed out of it even a curve was commanded. This behavior, caused by a design not optimized for this use case, was also reflected in the variation of the recorded times.

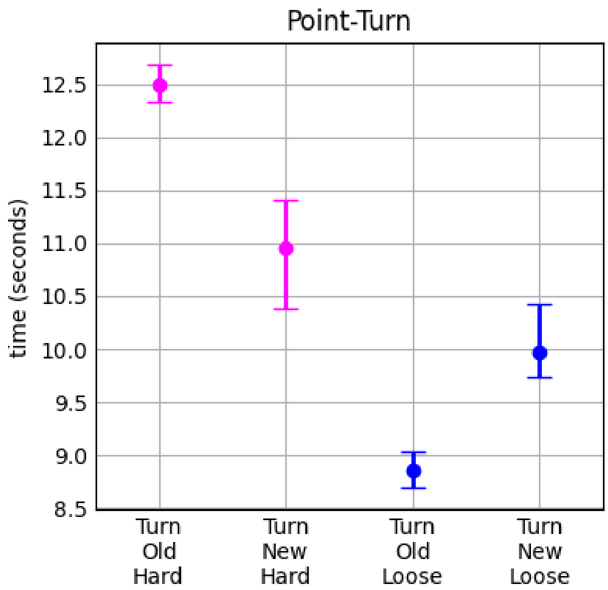


Fig. 11: Results for point turning tests on hard ground and loose soil

Navigating over the stone obstacle, there is almost no difference between the spoke variants (Yellow; Avg. Old: 4.43 s; New: 4.46 s), the new design only being 0.7 % slower. Therefore, the overall stone traversing performance seems to be equal.

Climbing the high step, the new spokes perform slightly better (Pink; Avg. Old: 15.29 s; New: 14.82 s), being 3.2 % faster. Since this manually controlled maneuver could not be performed consistently in every run, it is reasonable to say that the new variant performs equally.

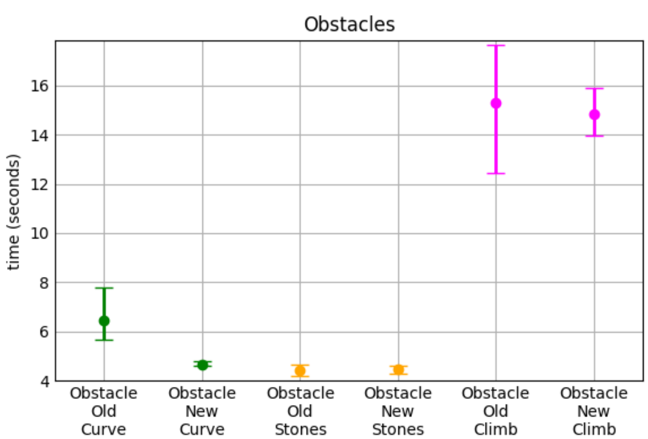


Fig. 12: Results of tests for traversing obstacles

D. Rover flipping

The flipping tests were divided into two categories: first, the flip initiation, putting the rover sideways; second, the completion of the flip, also referred to as "uprighting" the rover. Both tests were driven manually at a maximum speed of $1.2\,\frac{\mathrm{m}}{\mathrm{s}}$. The time to reach a vertical state for the initiation, and the time until more than three wheels touched the ground during uprighting, were measured. The results are shown in Fig. 13 and discussed below.

To initialize the flip, the new spokes' time savings were significant (Blue; Avg. Old: 4.10 s; New: 2.69 s), being 52.4 % faster. The first run with the old spokes has been ignored, due to a driving mistake. The starting orientation of the rover made it possible to drive this maneuver without steering, which all other runs considered.

Uprighting the rover from a sideways position, the new spokes showed a significant performance increase (Red; Avg. Old: 14.09 s; New: 2.55 s), being 452.5 % faster. The huge spread comes from a very slow, but valid run. The manually driven run could only finish the uprighting after 44.6 seconds. The assumption that manual driving is worse than commanding driving forward only could be made. However, additional tests are required and were beyond the scope of this study. Looking at the individual times for the old spokes in this scenario, even after excluding the 44.6 second outlier, both the fastest and the slowest runs were driven manually, disproving this assumption based on current data. Without the slowest time, the old spokes were still at an average of 7.98 seconds, with the new spokes uprighting 212.9 % faster.

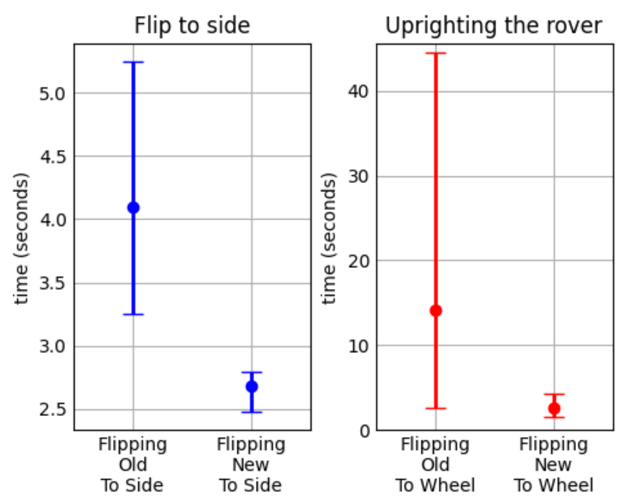


Fig. 13: Results for flip initiation (left) and uprighting (right) tests

VI. CONCLUSION

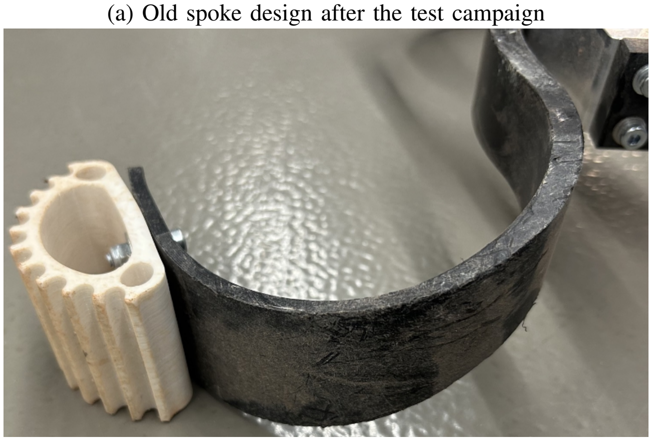
The new design of the SCOUT rover's spokes demonstrated clear advantages throughout a wide range of tests, with almost all showing better performance compared to the old spokes. Only two scenarios favored the old design, one significantly so, and the other with nearly equal outcomes. All results are summarized below.

Besides the scenarios these design changes were primarily intended for – the flipping and uprighting of the SCOUT rover (faster by 52.4 % to 452.5 %) – the tests also show improved performance in almost all other scenarios. Driving on hard ground became faster and more reliable due to softer and more flexible spokes, even in the fast driving tests (faster by $14.0\,\%$ to $18.3\,\%$). Driving on loose soil showed a similar effect (faster by $2.8\,\%$ to $10.7\,\%$), except for the point turn (slower by $11.2\,\%$). In the tight trench curve, the narrower profile reduced driving time (faster by $38.7\,\%$) and contacts with the trench walls. The stone obstacle showed almost equal results, with neither improvement nor deterioration. Climbing the high step showed results favoring the new design, but overall performance is considered equivalent.

In addition, the spokes come into contact with the ground more frequently due to the changed curvatures (see Fig. 2). This causes the so-created tread to wear, more than in earlier designs (see Fig. 14). During prior tests and the usage of the new spokes in general, there has been no case of this causing a spoke to break.

The switch towards the new variant is therefore a tested improvement, worth being implemented for the current state of the SCOUT rover, without adding significant driving impairments to the system.

(a) Old spoke design after the test campaign



(b) New spoke design after the test campaign

Fig. 14: Comparison of old and new spoke designs after the test campaign

VII. Outlook

Certain relevant scenarios for the SCOUT rover may currently be unknown and therefore untested. Once identified, these scenarios should be prioritized for future testing and evaluation. Additionally, exploring improved spoke designs, using the current state as a benchmark in an iterative process, should be pursued. This approach aims to achieve the best possible outcome for the SCOUT rover in fulfilling its planned future missions. This includes modifications to the outer curvature, which acts as a tread, to enhance durability. Lastly, further surface features to improve climbing ability and terrain interaction could also be developed.

Further, there will be more test campaigns in the future, checking for the durability of the crucial elements, as well as failure resistance, when spokes are missing or wheels stopped responding.

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