Design and Fabrication of a Mars Rover Four-Wheel Rocker System

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In the University Rover Challenge (URC), teams from across the globe design and build rovers to compete at tasks that a rover might encounter on Mars, such as long-distance communication, scientific testing, cargo delivery, and equipment servicing. Robonav, a team from the Georgia Institute of Technology, participated in this competition and qualified for the on-site challenge for the first time in 2024. On an interplanetary mission, every pound of weight is critical. Saving mass allows for more complex designs with greater functionality. Therefore, Robonav chose to modify the rover (Wall-II) to switch from a six-wheel rocker-bogey system to a four-wheel rocker system. The transition would allow for many benefits. It would decrease weight and required power by removing two wheels and their attached legs. It would also make the system simpler from a mechanical and electrical perspective. In addition, switching to a four-wheel system would allow Robonav to transfer the differential bar from the top of the rover's chassis to the back, freeing space for the electrical connections in the chassis. To begin this process, research had to be done into the various forces and stresses that would change with the modified wheel system. A literature review of existing designs revealed several equations that could be used to calculate optimal parameters for the design. After a mathematical model was put together, the design was developed in SolidWorks. It was iteratively adjusted to achieve equal or better clearance as the previous design while retaining stability. There was also a strong focus on reusing as many components of the prior design as possible to minimize costs. After the design process, many parts were constructed as low-cost trial alternatives through 3D printing. Once the design was verified, all of the parts were machined out of carbon fiber and metal, and the full system was assembled onto the rover. After completing the assembly, the team was able to test the new system and found that installing legs at 90-degree angles allowed for greater clearance while traversing obstacles. In addition, the decreased weight allowed more of the mass to be allocated to the arm and end effector. In addition, the change in the system improved structural rigidity and increased the differential in slope that could be traversed. Therefore, this study has interesting implications for the designs of rovers for use on Mars. While the more common six-wheel rocker-bogey design is currently favored, for missions of shorter duration, it could be very beneficial to consider a four-wheel design.

I. Introduction

A. Background

As technology and science advance and humanity grows in its capacity to understand the universe, the prospect of off-planet exploration has gone from science fiction to fact. In 1997, Sojourner landed on the surface of Mars, beginning an 83-day mission of scientific discovery [1]. From 2003 to 2010, Spirit and Opportunity made valuable observations about the geology of Mars and found evidence of trace amounts of water. [2]. Today, Curiosity and Perseverance study the geological makeup of Mars and search for the building blocks of life. These rovers can explore a greater area than stationary landers, last longer than flying vehicles such as drones, and are far safer and less expensive than manned missions. With the advancement of publicly available manufacturing tools and off-the-shelf components, it is feasible for amateur teams to build systems similar to Mars rovers. From these scaled-back prototypes, new systems can be trialed and a great deal can be learned about potential avenues for future development in real missions. The

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University Rover Challenge (URC) is an international engineering competition open to collegiate teams. Participants must design and assemble a full-size rover to compete in four mock missions similar to those performed by rovers on Mars. To mimic the level of rigor demanded by a mission to Mars, URC provides competitors with stringent specifications. The rover has strict design constraints, weight chief among them; the system cannot exceed 50 kg when fully assembled.[3] Additional physical constraints are detailed in Table 1. Furthermore, the competition takes place at the Mars Desert Research Station (MRDS) in Utah, where temperatures reach over 100 F and conditions such as dust, wind, and rain are expected.[3] The rover cannot be accompanied by a team as it performs its missions, meaning that complex, failure-prone systems have an unacceptable degree of risk. However, because the tasks that the rover must carry out are so varied, interchanging components such as arms or end effectors is permissible, introducing a degree of modularity that necessarily increases the overall complexity.[3] All of these requirements must be taken into account when designing and manufacturing the rover.

Table 1 Basic requirements from the URC competition.

Constraint	Requirement
Size	Rover must fit completely within a 1.2 x 1.2 x 1.2 m box
Weight	50 kg when deployed, 70 kg for fielded rover parts for all events
Power	No tethered power. Rover must use power and propulsion systems applicable to Mars.

B. Motivation

In essence, the mission forces teams to prioritize simple, lightweight, durable systems that can be easily repaired and supplanted as they seek to complete the four missions. Robonav, a team from the Georgia Institute of Technology, qualified for and competed at the 2024 URC competition with a rover (Wall-I) that drove on a six-wheel rocker-bogie drivetrain, pictured in Figure 1. This system is the same as Sojourner, Spirit, Opportunity, Curiosity, and Perseverance. This system has three main advantages: it evens the pressure that the vehicle exerts on the ground across all the wheels, allows all 6 wheels to maintain contact with the ground on uneven terrain, and provides redundancy in the case of wheel failure[4]. On Mars, an environment with alternating soft dirt and hard, rocky terrain, this setup offers many advantages.

However, it also adds considerably to weight: Wall-I's drivetrain alone had a mass of 11 kg or 33% of the total mass. The additional weight of two wheels and the bogie adds approximately 3.5 kg to the system which could be better used on the arm or reinforcing the structure. It is worth noting that on missions of shorter duration with the ability to service the rover between missions, having redundancy in the form of 2 extra wheels is not worth the extra weight.

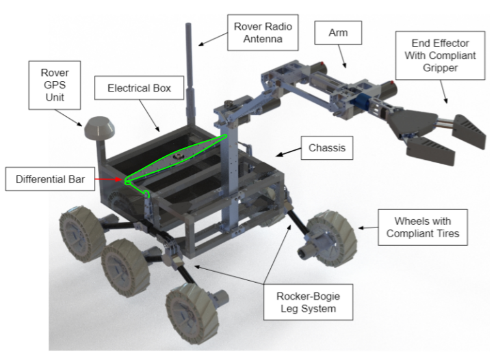

Fig. 1 CAD model of Wall-I.

Systems with rockers necessitate some form of differential bar to average the angle of both sets of wheels and keep the rover body as level as possible. Differential bars connect the two rockers and transfer wheel jerk to the body as rotation, rather than translation, allowing for smoother traversal of uneven terrain [5]. In Figure 1, the differential bar highlighted green, can be seen centrally located on top of the chassis. This design places the pivot point at the center of the body, increasing stability, but also makes it difficult to access the electronics inside the chassis. For a robot that is expected to be serviced frequently with parts interchanged often, this is a critical concern. Furthermore, the six-wheel system was more complex than the four-wheel system would be for obvious reasons. Each additional joint and bearing is a new failure point and vulnerable to sand and grit.

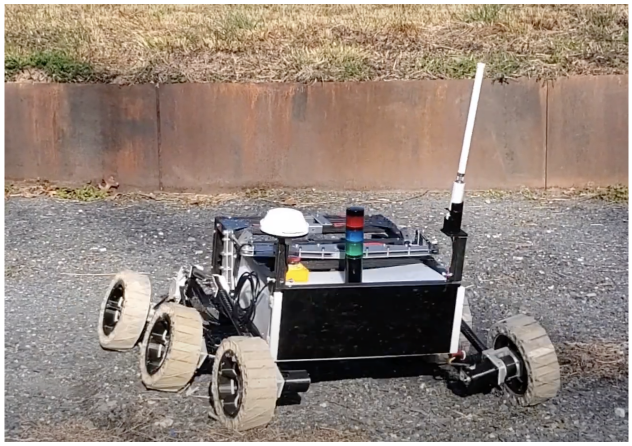

Fig. 2 Demonstration of legs bowing in Wall-I.

Structural integrity was also a serious concern with the original drivetrain system. The drivetrain system was not rigid enough to withstand the weight of the rover, and as it drove, the wheels bowed outwards as pictured in Figure 2. This bowing was a major concern for two reasons. First, it stole traction from the wheels because they were angled, rather than tangent to the surface terrain. Decreased traction led to difficulties with traversing slopes. Second, the bowing placed compressive stress transversely on the carbon fiber tubes that make up the legs from the joints to the wheels. Carbon fiber tubes are significantly less rigid to compressive stress than tensile stress, so a misalignment of the forces such as that caused by bowing puts the legs at risk of kink-band failure [6]. However, reinforcing the six-wheel drivetrain system with more rigid materials such as aluminum would add considerably to the weight of the rover.[7]

The final reason for converting to a four-wheel drive is sheer novelty. To date, there has never been a four-wheeled rover on Mars for the reasons elaborated above. However, as manned missions to Mars become a reality, the ability for rovers to be serviced regularly could make the six-wheel design redundant, provided that the four-wheel design is successful. To validate the design, though, it must be tested. For these reasons, the Robonav team chose to explore a four-wheel rocker design of the drivetrain for the 2025 URC competition.

II. Literature Review

The four-wheel system was motivated by a desire to experiment with a new system, reduce weight, reduce complexity, and increase accessibility to the electronics in the chassis. Due to budget constraints, reusing components from the original design was a priority. These constraints drove the ideation process and influenced which prior designs served as models for Wall-II.

According to Malenkov and Volvov, four-wheel rovers do have the capacity to navigate slopes of similar angles as six-wheel rocker-bogie rovers without affecting the body of the rover[8]. However, this statement was made about a four-wheel rover with independent suspensions on each wheel. This system is considerably more involved than Robonav could create, so while it does validate the potential of a four-wheel rover, its applicability to this design is minimal. Robson and Baumgartner devised a four-wheel parallelogram suspension that was capable of climbing obstacles taller than the wheel diameter by a factor of three.[9]. For context, the Curiosity rover's six-wheel system is only capable of climbing 1.5x the diameter of its wheels. This design was promising, but to reproduce Robson and Baumgartner's suspension system with the rigidity required of Wall-II, Robonav would be forced to build it almost entirely from metal, rather than carbon fiber. As a result, the suspension system would have exceeded the weight limits. Kuncoliencar et al. proposed a four-wheel rover that accounted for lateral slope with a rotary actuator to adjust the height of the left and right sets of wheels relative to each other[10]. Bouton et al. proposed a four-wheel system that actuated each set of wheels with a joint able to bring them closer or farther [11]. Both designs were rejected because of the complexity that an actuator would add, not to mention the difficulty of manufacturing such a system under the limited time before the competition. The four-wheel rhombus-arranged drivetrain proposed by Wen et al. was rejected because of the massive overhaul of the entire rover structure that it would require. [12] This style of drivetrain would not only demand detailed analysis of how stresses on Wall-II would change to determine whether it was at all feasible but also require that the chassis be redesigned to accommodate the new system. Such a redesign would have been costly: new carbon fiber tubes and aluminum joints would need to be purchased and assembled.

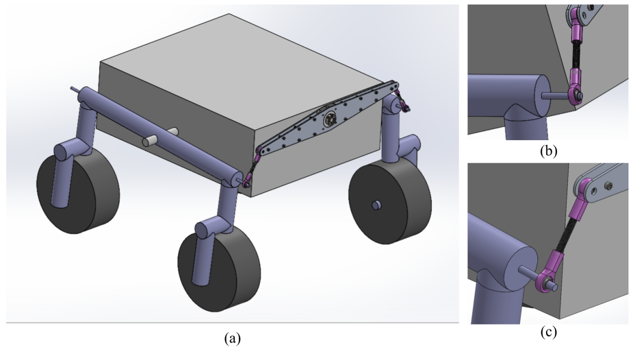

Fig. 3 Initial design of new four wheel rocker suspension system.

III. Design

IV. Ideation and Initial Design

To balance the aim of creating a novel system with feasibility, Robonav chose to keep the differential bar from the 2024 design, but mount it on the back of the rover, rather than the middle. This transition freed the center of the chassis for the electronics and negated the need to design and manufacture an entirely new differential bar. Additionally, its greater distance from the pivot point of each leg gave it more leverage with which to exert torque on the legs. This basic design is depicted in Figure 3 a. Immediately, the most noticeable effect of switching to a four-wheel system was a greater degree of freedom with regard to how the leg sets could be articulated. With just two points of constraint, they were more flexible while remaining built out of rigid bodies.

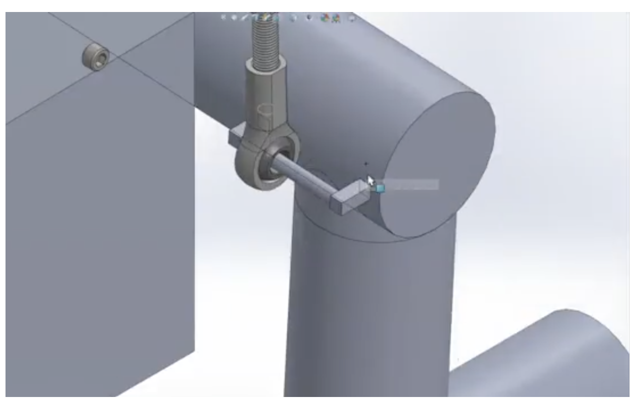

Fig. 4 Updated design of connection to legs.

This simple design evolved to the setup depicted in Figure 4, with a rod clamped between two shaft collars that are each attached to the carbon fiber tube. This system allowed the linkage to rotate in the same plane as the differential bar while still maintaining a connection to each leg.

A. Design Evolution

Due to the geometry involved in moving a differential bar from rotating about a vertical axis (used in Wall-I) to rotating about a horizontal axis, the linkage connecting the differential bar to the legs for Wall-II was no longer rotating about the same axis as the legs. As a result, the linkage translated along the rod at the end of the legs as can be seen in Figure 4 b and c. This arrangement was not structurally sound; it introduced motion and friction for the linkage-leg connection and placed a great deal of stress on the small cross-sectional area connecting the legs to the rod. Even the design in Figure 4 was unable to avoid this issue. This entire arrangement was complicated by the fact that the horizontal bar of each leg was a 2in x 2in carbon fiber (CF) tube. Carbon fiber is frequently used in contexts where strength and weight are the primary concerns, as was true for Wall-II. However, this material does not take well to stresses placed on holes that have been drilled into it, and Rezasefat et al. found that CF samples with such holes experienced more severe damage under stress. [13] Therefore, to prevent significant damage to the drivetrain of Wall-II, it was vital to limit the size and number of holes drilled into the CF tubes. Any reorienting of the linkage would need to connect to the legs without placing significant stress on holes in the CF tubes.

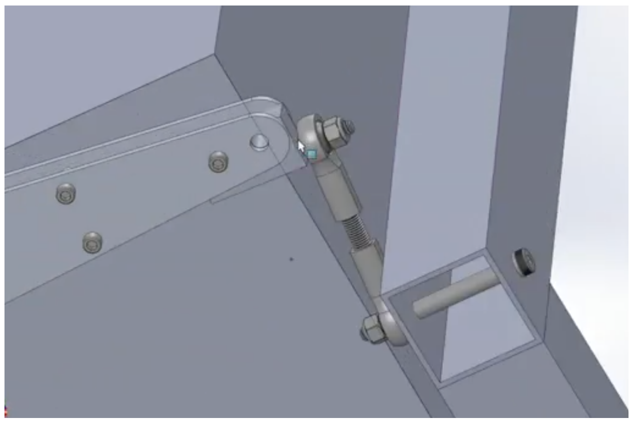

Fig. 5 Alternate design of linkage-leg connection.

Ultimately, it was necessary to allow the linkage to rotate more freely and not be constrained to the same plane as the differential bar. This goal was accomplished by placing a small block between the plates of the differential bar that connected to the linkage as seen in Figure 5. Because this block placed the linkage outside of the differential plates, the linkage rotated generally perpendicular to the differential bar's axis. A bearing inside the connection from rod to joint removed the geometric constraints that had previously forced Robonav to install a rod parallel to the horizontal leg beam and removed the concern of motion and friction entirely.

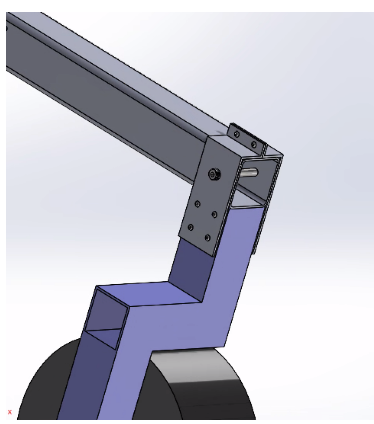

Fig. 6 Clamp design of linkage-leg connection.

The final step was to connect the linkage to the legs in a way that would not place undue stress on CF tubes. Multiple paths were attempted. The first was extending the aluminum shafts that made up the vertical portion of the legs into the CF tube and using them as reinforcement to hold a shoulder screw that the linkage would rotate about. This plan was rejected because the size of the hole required for the shoulder screw was deemed too large for structural stability. The next attempt was to use 1/8 inch aluminum plates, bent around the CF tube and clamped at the top, to reinforce the CF tube-vertical shaft connection and hold the shoulder screw in place. The shoulder screw itself would pass through the clamp and CF tube as shown in Figure 6. Because the clamps required very precise angles to fulfill their purpose and clamp the CF tube, this design was rejected.

B. Final Design

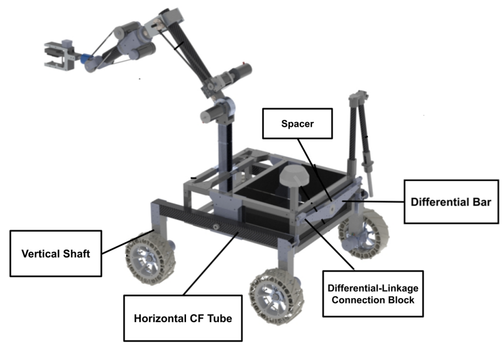

Fig. 7 Full Rover design.

Table 2 Components and how they were made.

Component	Manufacturing Method
Vertical Shaft	Aluminum plates welded together
Spacer	3-D printed parts fitted around a bearing
Horizontal CF Tube	Purchased
Differential Bar	Cut out of aluminum plate on water jet
Differential-Linkage Connection Block	Cut out of aluminum plate on water jet, milled with vertical mill

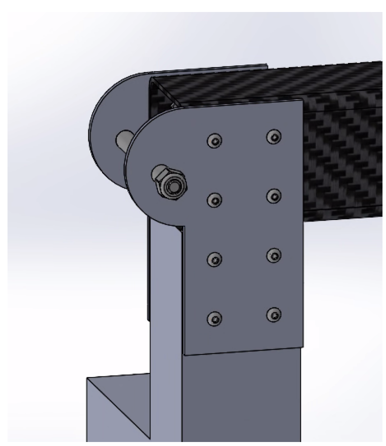

Fig. 8 P-shaped gussets for linkage-leg connection.

The full drivetrain system is pictured in Figure 7, and labels are defined in Table 2. The final CF tube-vertical shaft connection, which is currently in use, is a set of gussets. These 1/8 inch aluminum plates lie on either side of the CF tube and vertical aluminum shaft, attached with bolts. The gussets were manufactured in-house with a water jet. At the back of the rover, the gussets have a P shape as depicted in Figure 8. A shoulder screw sits in the curve and connects to the linkage, placing less direct strain on the CF than there would be if the shoulder screw went through the carbon fiber.

The shoulder screw provides a smooth surface about which the linkage rotates and connects each set of legs to the differential bar. Regarding the differential bar, it was redesigned to accommodate the updated horizontal distance of the CF tubes when Robonav's expected funding increased midway through the design process, and reusing parts was less of a priority. The differential bar width was increased by 1.2 in.

In order to maintain the same clearance from the bottom of the chassis to the ground as Wall-I, the vertical shafts for Wall-II were sized at a height of 12 in length. Because these forces applied to the vertical shaft put the shaft entirely in compression and CF is weakest in compression, the vertical shafts were made from aluminum rather than carbon fiber to prevent the legs from bowing. The horizontal bars were kept as carbon fiber because the stresses placed on them were only partially compression stresses, specifically along the top of the tube. Robonav deemed this would be acceptable, especially given the weight reduction due to using CF rather than metal. These tubes were sized at 30 inches long to keep approximately the same size wheelbase as Wall-I.

A detailed discussion of the manufacturing process of the drivetrain is outside the scope of this paper but is summarized in Table 2 for completeness.

V. Results and Discussion

After the rover was fully manufactured, Robonav began testing. Testing was conducted on the campus of the Georgia Institute of Technology primarily in parks and over rocks. The testing environment differed from the MRDS in a few major ways. It had grass and organic matter such as trees and pine needles, which softened the terrain and could have provided more traction than would be available at the competition. The test itself was conducted on a clear day at about 60 F, significantly cooler than expected temperatures and weather in the MRDS. Given these factors, Wall-II may not perform as well at the URC competition as in testing. However, many of the primary metrics affected by the transition from six to four wheels are geometric, and therefore not affected by the quality of the terrain. For example, maximum obstacle height, or the highest obstacle climbable by the rover while maintaining nominal contact with the ground on all four wheels, is only influenced by the geometry of the rover. To validate other aspects, such as the wheel design, Robonav drove Wall-II over sand and pebbles that did not have rocky enough terrain to test the suspension system.

It was immediately apparent that the four-wheel system was significantly more structurally stable than the original six-wheel design. There was no bowing whatsoever, even under maximum stress. This is largely creditable to the aluminum joints and shafts, which perform better under compression than Wall-I's original carbon fiber.

Fig. 9 Rover climbing a rock 16 in tall.

One of the main concerns of transitioning to a four-wheel system was maximum obstacle height. Mathematically, six-wheel rocker-bogie systems are capable of traversing obstacles that are taller than the diameter of the wheels by a factor of 1.5 [14]. Wall-I had wheels of diameter 9.8 inches, so the maximum obstacle height was 14.7 inches. Empirically, Robonav determined that Wall-II achieved a maximum vertical leg height differential of 16 inches, meaning that, given sufficient wheel torque, Wall-II was able to traverse taller obstacles than Wall-I despite having wheels of the same diameter. This capability is demonstrated in Figure 9, where the rover has one wheel 16 inches higher than any other while maintaining contact with the surface for all four wheels. It should be acknowledged that this obstacle was not a 16-inch vertical face; it began about 3 inches tall and sloped upwards to 16 inches. In the case that Wall-II encountered a 16-inch staircase in the Utah desert, the rover would likely be unable to climb it due to the torque required.

VI. Conclusion

At the close of the 2024-25 design cycle for Wall-II, Robonav had designed and manufactured a new, fully functional drivetrain system. Through the process, design decisions were driven by weight, cost, durability, simplicity, and repairability. Several iterations of a four-wheel rocker with a back differential were attempted, and eventually, the final design was completed and tested in February of 2025. The new system was lighter by [X] pounds. The cost was marginally less than Wall-I. The rover was also more durable: it no longer bowed at the leg joints. Simplicity was improved with the removal of two wheels, two motors, and six joints. The repairability was increased by transferring the differential to the back and out of the way of the electrical components. The new drivetrain was also capable of traversing the same obstacles as Wall-I, so it was considered successful by all metrics of interest. This evaluation will be tested at the URC competition in May 2025.

As compared to the six-wheel system, a four-wheel system does have more risk involved: in the case of a single-wheel failure, the four-wheel system would be barely operable. For this reason, six-wheel systems such as Curiosity's or Spirit's are more practical for situations where there is no capability for repair. However, as manned missions to Mars become a reality, four-wheel rovers could be more practical due to the more optimized weight, durability, and simplicity since having a human available would make repair possible. Another point of note is that rocker-bogie systems generally have higher overturning angles than four-wheel systems with passive suspension, such as Wall-II. Curiosity, for example, has an overturning angle of 45 degrees. [14]. Wall-I was validated as working at angles of 30 degrees longitudinally and approximately the same laterally. Further testing is necessary to determine the exact overturning angle.

A. Future Work

As Wall-II matures, Robonav intends to focus on refining the current drivetrain system, rather than attempting another full redesign. As it stands, the differential bar is mounted via an aluminum rod in the CF tubes that make up the chassis. This joint is not reinforced with any other material and therefore is a concern for long-term durability. Finding some lightweight method of minimizing the strain on the chassis CF tube is a key goal for the future drivetrain team. Additionally, the P-shaped gussets can be redesigned to fasten on the inner side of the CF tube, rather than on the outside. This change would mean that when the shoulder screw connecting the legs to the linkage is tightened, it does not force the gussets to compress the CF tube between them, placing less stress on the CF tube. Additionally, in May of 2025, Wall-II will participate in the URC competition, gaining valuable data about how its new suspension system performs under mission conditions. Robonav is curious to determine whether the rocks in the MRDS will provide enough traction for Wall-II to perform as it did during testing.

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