Design, Fabrication, and Testing of Composite Wheels for Lunar Mobility

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Abstract

Wheels made with composite materials have many advantages for lunar rover exploration. Composite materials are lightweight for energy efficiency and yet have high strength for navigating rough lunar terrain. Composites also do not outgas like traditional rubber tires and can be very resistant to abrasion. For these reasons, Kevlar and carbon fiber composites are chosen to create two wheels for a lunar rover. The design, fabrication, and testing of these composite wheels are discussed in detail. Methods used throughout the entire design process are explored in detail and final testing and fabrication procedures are presented. Suggestions for future work on the subject are also put forward. The final wheels were proven successful under all loading tests while weighing less than their mass allocation of 3 kg making them ready for field testing and lunar missions.

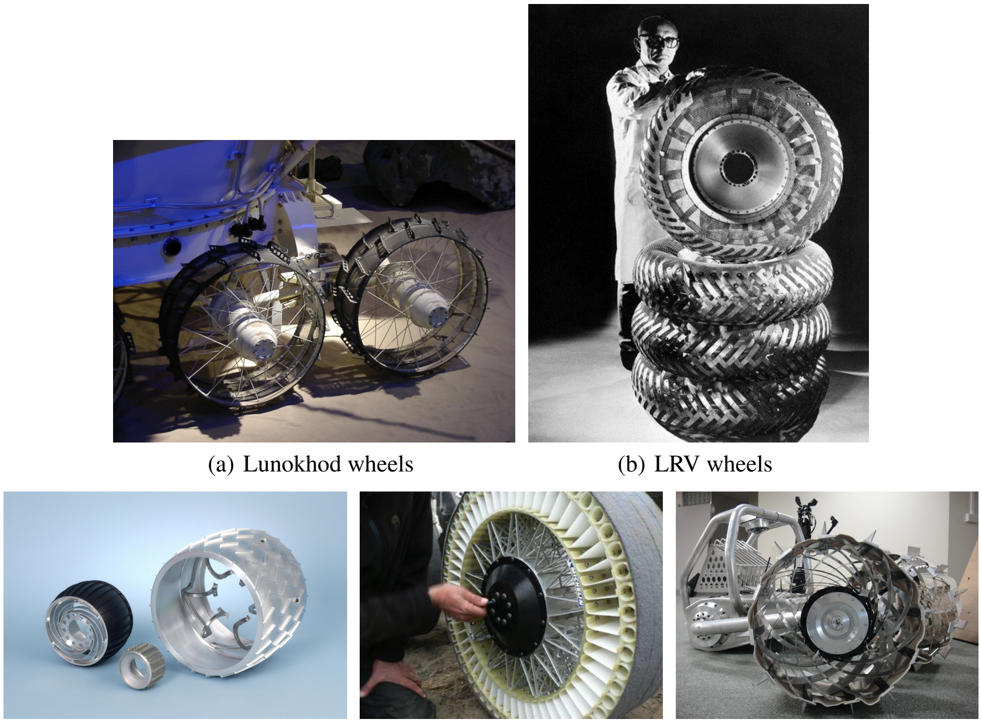
1 Introduction

Wheeled locomotion is fundamental to the exploration of lunar environments. Successful wheels must withstand the various extreme conditions of the lunar environment and perform well under all loading scenarios while minimizing mass. Vehicle dynamics also play a role in the types of forces the wheels will encounter. Space exploration wheels must endure forces to drive, turn and surmount obstacles while robustly achieving great locomotion and traction characteristics.

This paper describes the process and results from the design and fabrication of two lunar wheels made for the Polaris lunar rover. The final products were successful in that they withstood all worst-case loading scenarios while remaining below the specified mass budget. If proven successful in further testing, this wheel design will be used in Astrobotics mission to win the Google Lunar X-Prize and find water at the lunar pole.

2 Research of Previous Work

A large range of different designs concepts have been utilized before for various space missions. Russias Lunokhod rover used bicycle spoke-like wheels that had straight grousers for traction (Figure 1(a)). The NASA Lunar Roving Vehicle (LRV) wheels used an aluminum mesh making the wheels very flexible for good surface contact (Figure 1(b)).



(a) Lunokhod wheels (b) LRV wheels

(c) Mars Rover wheels (d) Michelin Tweel (e) Tri Star IV wheel

Figure 1: Previous lunar wheel designs

The Mars Rover wheels are all quite different. The Mars Exploration Rover (MER) has an inner spiral and straight lines for grousers (Figure 1(c)). The Sojourner wheels are hub-like with spikes for traction. The Mars Science Laboratory wheels used curved spokes and jagged grouser pattern. All of these wheels are machined from aluminum and do not utilize composite materials.

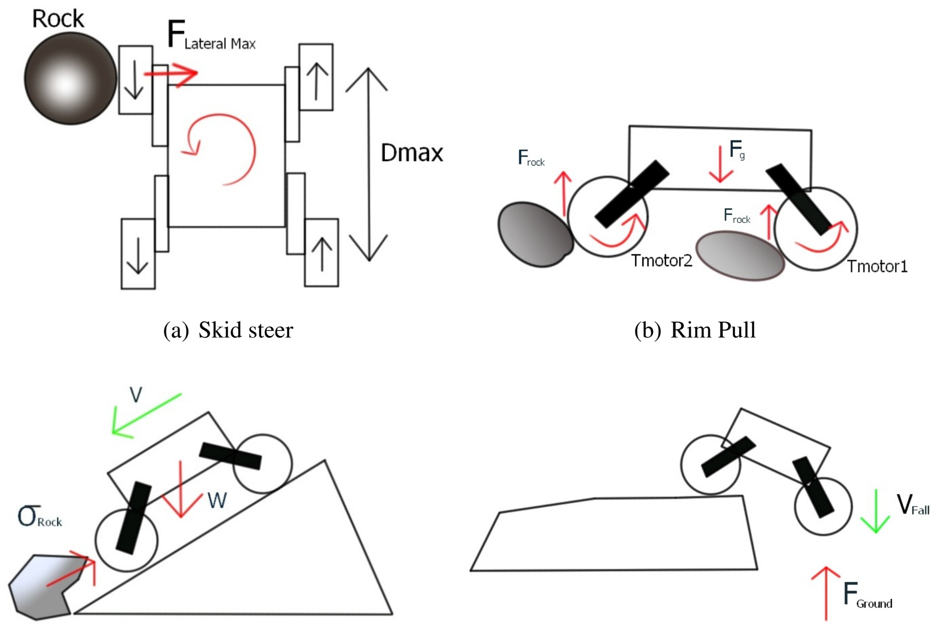
Newer wheels have also been investigated. The Michelin tweel is a wheel made of fabric in tension (Figure 1(d)); this utilizes the strength of the fabric and keeps the wheel very flexible, allowing for superior traction. Tri Star IV wheels use a double-spiraled core, with flexible spokes providing a large contact patch with the ground. These wheels also use flat plates for grousers (Figure 1(e)).

3 Design Specifications

Our design specifications for each wheel were the following: A wheel diameter of 24 inches, a wheel width of 6 inches, and a maximum mass of 3 kg per wheel.

In addition to these basic requirements, grouser geometry was based on previous research conducted in the Gates Highbay at Carnegie Mellon University. This research has shown that straight grousers with a 2:1 grouser spacing to grouser height ratio have been proven to be most effective for increased traction.

Carbon fiber was chosen for the majority of the composite structures due to its very high strength to weight ratio. Kevlar was chosen for the outer layers of parts which contacted the ground to provide durability against abrasive wear. Wet layup was chosen based on the success of wet layup in the bucket wheel project last semester. This particular composite-epoxy mixture has been proven to withstand the wear of regolith in the testing rig, allowing for its use in this high wear application. The strength of the composite materials are tested later.



(a) Skid steer (b) Rim Pull

(c) Dynamic Spoke Load (d) Point Load

Figure 2: Worst Case Loading Conditions

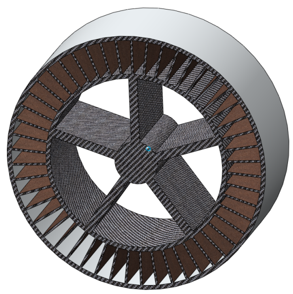
3.1 Loading Conditions

Accurate design and concept requires knowledge of the loads the wheel will be subjected to. These calculations were done in static conditions and dynamic factors were then added. Four specific worst-case scenarios are developed. First, the rover uses skid steering; meaning the side loads when turning could be significant. For a worst-case scenario, we modeled the rover as having one wheel stuck on the rock and the drive motors trying to pivot the entire robot around this point. The resultant side was found to be 256 lbf (Figure 2(a)). In the second load case, each wheel is rolling over a rock at the same time. This can be modeled as the rover climbing a vertical wall and is the worst-case scenario for rim pull. The resultant load was calculated to be 165 lbf for each wheel (Figure 2(b)). The third loading condition looks at the rover falling from a height onto the rim of the wheel and was calculated to be a 413 lbf load on the spokes (Figure 2(c)). The last worst-case loading condition is that of a point load on the rim of the wheel. A contact area the size of a dime was used, mimicking a sharp corner of a rock. The calculated pressure for this load case was determined to be 1058 psi (Figure 2(d)).

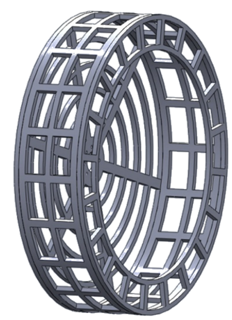
3.2 Design and Concept

Before deciding on a final design to fabricate, many potential wheel design concepts were created. Some of these designs were derived from previous work on lunar wheels while others were entirely original. These concepts (Figure 3) were then complied into a weighted matrix to evaluate the best wheel for space applications (Table 1). In this way, the each wheel was evaluated based on how well it fulfilled specific design criterion such as strength, mass, durability, and traction performance.

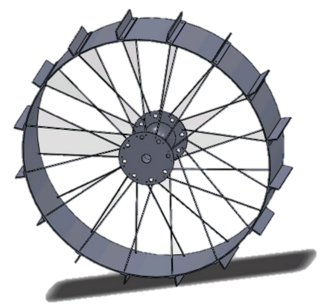
Based on this matrix it was determined that a curved 6-spoke composite design (Figure 4) with composite grousers was the best design to move forward with because it scored well in most categories and was decided to be the most likely design to meet the 3kg mass requirement. This design consists of three major components which are fabricated individually and then assembled together in the last step. The three parts are the spokes, a grouser support rim, and many composite grousers which are adhered around the support rim providing a tough and high-traction surface. The number of grousers was determined to be 36 based on the 2:1 grouser spacing to grouser height ratio determined previously.



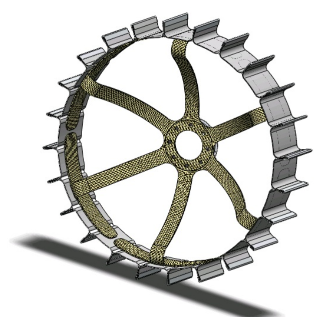
(a) Leather and composite Tweel



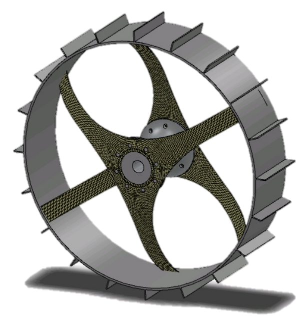
(b) Aluminum frame wheel



(c) Bicycle spoke wheel

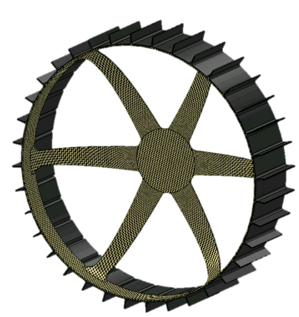


(d) Flanged composite wheel

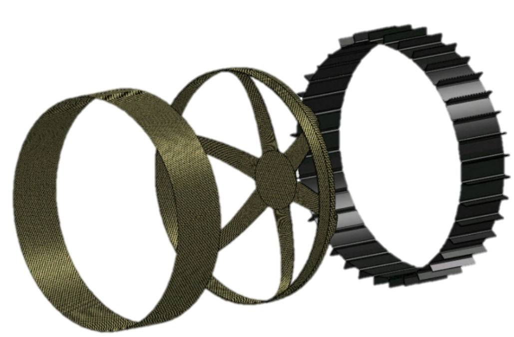


(e) Double sided composite wheel

Figure 3: Abandoned concepts



(a) Whole view

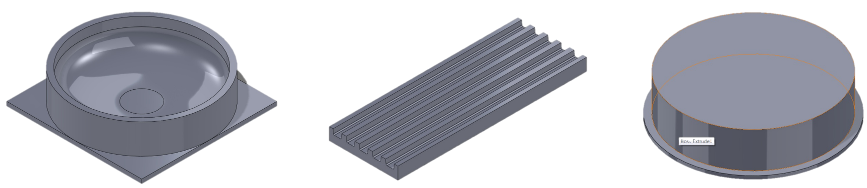


(b) Exploded view

Figure 4: Six-spoke wheel design

Table 1: *Design Comparison in Weighted Matrix*

CRITERIA	WEIGHT	Spiral	1-Curved Composite	2-Curved Composite	Tweel	Spring Spokes	Straight Spokes	Mesh
Mechanical Reliability	5	3	4	4	2	2	5	2
Strength	4	3	3	4	2	2	5	2
Weight	5	3	5	3	2	4	5	4
Ride Smoothness	2	4	3	3	5	2	2	5
Obstacle Performance	3	3	3	3	4	3	3	3
Stability	3	3	3	2	4	2	3	3
Wear Resistance	3	3	3	4	2	2	4	2
Ground Compatibility	4	3	2	2	5	4	1	5
Feasibility	4	2	5	4	1	2	4	2
WEIGHTED TOTAL		97	**118**	**108**	92	87	**124**	100



(a) Spoke Mold (b) Grouser Mold (c) Rim Support Mold

Figure 5: Molds designs for composite parts

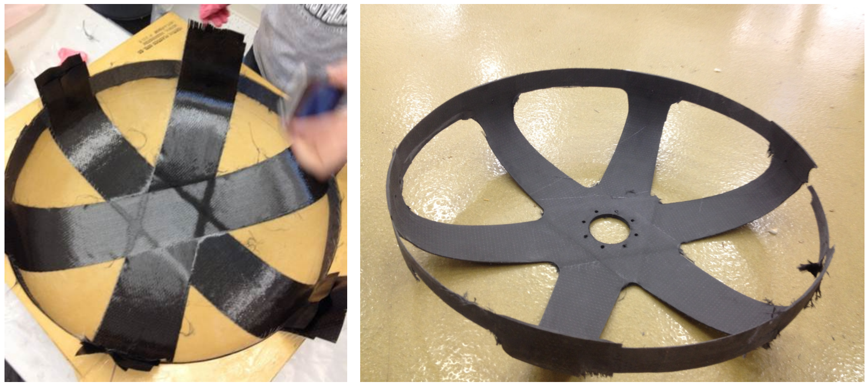
4 Fabrication

Because the wheel design was made entirely of composites, molds had to be designed and fabricated for every part. Three molds were designed in CAD: One for the spokes, one to make the 36 grousers needed, and one for a rim for the grousers to attach to (Figure 5). These CAD models were then used to machine the mold out of high-density foam using a CNC robot arm. These foam blocks were then sanded and sealed with epoxy multiple times in order to prevent the wet composite from adhering to the mold. The final sanded surfaces were then cleaned and sealed. Finally, three coats of mold release were applied to the finished surfaces in order to ensure easy separation of the part from the mold.

Once the molds were completed, the parts could then be fabricated by laying up composite layers one by one on the molds. The final product consisted of three separate layups: the Spokes, the Grousers, and the Tread Support. These three layup procedure are described in detail below.

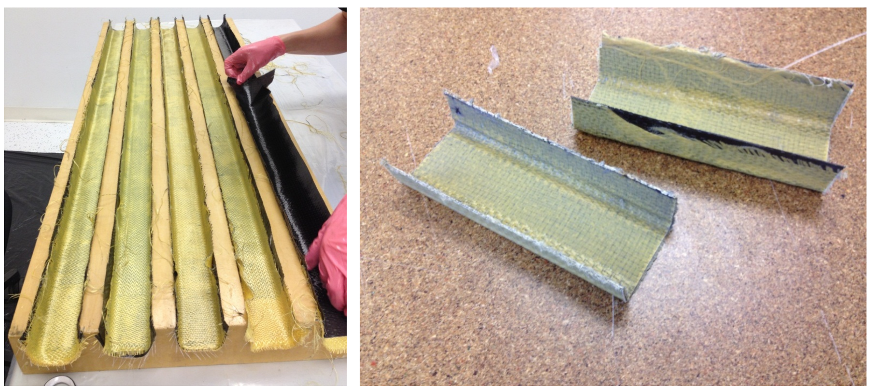
4.1 Spokes

For the spokes, 10 layers of carbon strips were used for each spoke. The strips were laid down one by one across the diameter of the wheel so that each strip would make up one spoke. This caused the center hub of the wheel to be 30 layers thick for high strength which is necessary to resist the torque loading from the drive motors. Three layers of carbon were also laid up around the entire circumference of the wheel to provide a good adhesion surface for the grouser support. After curing in the oven, the spokes were trimmed into the correct shape from the CAD model using the robot arm CNC machine (Figure 6).



(a) Spokes during layup (b) Spokes after curing and trimming

Figure 6: Photos of spokes



(a) Grousers during layup (b) Grousers after curing and trimming

Figure 7: Photos of grousers

4.2 Grousers

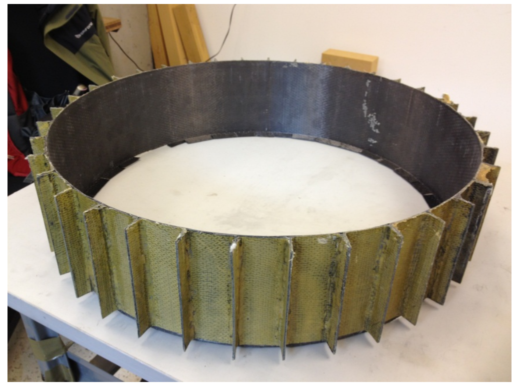
The grousers were laid up in five long channels. Each channel had two layers of carbon to give the parts strength and one layer of Kevlar on either side for abrasion resistance. A toughening resin was added to the epoxy mixture to give the parts further abrasion resistance. Once the mold was cured in the oven, the five channels of grousers were cut into 36 six-inch long grouser pieces using a wet saw and then were trimmed again to the proper grouser height of 0.5 inches (Figure 7). Finally, the grousers were sanded thoroughly to provide rough surfaces for proper adhesion to the Tread Support.

4.3 Tread Support

To support the grousers along the rim of the wheel, a Rim Support composite piece had to be fabricated. This mold was made into a disk with the same diameter of the wheel. Four layers of carbon were then wrapped around the circumference of the wheel. Then the 36 grousers were stuck around the entire outer surface of the rim with small pieces of carbon used to fill the void between the grousers. This setup was then cured in the oven to create a finished outer rim (Figure 8). This rim was then adhered to the spoke mold to create the finished product wheel (Figure 9).

The final wheel had a mass of 2.166kg (Appendix A) and met design specifications of 24 inches diameter and 6 inches width.

(a) Tread support during layup



(b) Tread Support after curing and trimming

Figure 8: Photos of tread support

Figure 9: Finished wheel

5 Testing

Four tests have been conducted to replicate Skid Steer, Rim Pull, Point Loads, and Spoke Load. A testing rig was developed for this purpose consisting of two 1.5 inch cast iron pipes with flanges at the end to simulate the wheel hub. The wheel is then bolted onto the flange and the appropriate loads can be replicated (Figure 10).

Skid steer testing was conducted by placing the wheel on its side and looping a rope around one part of the rim. Then weight was applied by loading the rope with 250 lbs of weight (Figure 11(a)). The wheel deformed under the load, but did not break.

The rim pull test was done using a wooden board; force was applied on the board which transferred to the grousers (Figure 11(b)). The weight of the worst-case scenario was used, and the grousers did not break or separate from the rim.

The point load test was done by placing the wheel on the head of a bolt (Figure 11(c)) and applying a downward force on the testing rig. The wheel did not crack or yield from the test.

Testing spoke load required a large amount of force to be applied to the wheel while in driving configuration. This test was conducted by having two large men load the wheel by standing on either end of the testing rig (Figure 11(d)). While the wheel can hold the load of the rover falling from a small height, the adhesion between the rim and the spokes was not done well and they separated at points. The Tests showed that the wheel withstood all loading conditions with no permanent deformation or damage.

Figure 10: General setup for testing

(a) Test setup for skid steer loading

(b) Test setup for rim pull

(c) Screw to apply point load

(d) Test setup for spoke loading

Figure 11: Specific setup for each loading case

6 Future Work

Possible future work for this project may include the addition of metal tips to the grousers for improved wear resistance as well as further optimization for weight and flexibility of the wheels for improved traction performance. Moreover, the attachment between grousers, rim and spoke can also be improved. Instead of gluing the three parts together after they are manufactured separately, a new layup method could be developed so that weak connection points could be avoided. Fabrication of two more wheels should also be fabricated so that the rover can be properly outfitted. Finally, thorough field testing should be performed to determine the performance, robustness, and longevity of the wheels.

7 Conclusion

Two functional composite wheels have been developed for a lunar robot. These wheels are 2.166 kg, which is within the mass requirement of 3 kg per wheel and have met all size specifications. The wheels have also successfully passed testing under worst-case loading conditions. The wheels will be thoroughly tested with the rover on Earth before the lunar mission. Furthermore, because the wheel design is original, these wheels validate the concept for completely composite wheels with composite grousers. If proven successful in test missions, these wheels will be remanufactured with only slight modifications and used for lunar pole exploration and excavation.

8 Acknowledgements

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Appendices

A Actual mass of final wheel

B Team and the wheel