



The Mobility System Wheel Design for NASA's Mars Science Laboratory Mission

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1. Abstract / Introduction

NASA's Mars Exploration Program is planning to launch its next robotic explorer to the surface of Mars in September of 2009. This explorer, the Mars Science Laboratory (MSL), is the largest terrain vehicle ever sent to another planet. The size of the rover is largely governed by the amount of scientific payload on board – almost 200 lbm. Due to this large size, the mobility system is also required to be extremely capable in order to move this platform across the Martian surface. One of the key elements in making a capable mobile platform is the wheel design.

In the case of the MSL mission, the mobility system is not only the traverse mechanism on the surface of Mars, but also the landing gear for the rover at touchdown, illustrated in Figure 1. As such, the wheels are designed for both a surface traverse life and also as the first contact element and energy absorber in the landing gear design. This paper discusses the differences in wheel design for landing versus traverse. It also covers the requirements on the wheel design and the system architecture of the MSL wheel chosen to meet those requirements. The paper concludes with test data on as built capability and expected performance on the MSL rover once it lands safely on Mars.

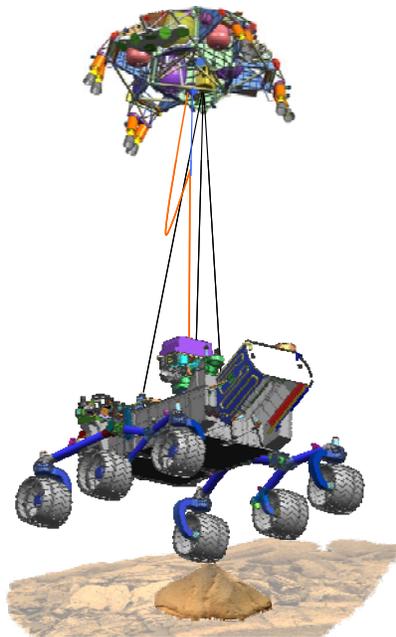
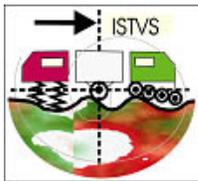


Figure 1: MSL Rover Wheels as Landing Gear



2. Mission Overview / Landing Site

The Mars Science Laboratory mission is part of a continued exploration of the Martian surface called NASA's Mars Exploration Program. MSL is the "big sister" of twin robotic explorers Spirit and Opportunity, both of which have been exploring the surface of Mars since early 2004.

While Spirit and Opportunity search for evidence of water, MSL will look for signs that Mars once had, or still has, an environment that could support microbial life. This environmental ability to support life is what scientists call "habitability." MSL carries on board an organic chemistry laboratory with instruments that can examine the composition of soil samples using various methods to answer basic questions about the habitability of planet Mars.

With this desire to further understand Mars comes the need to visit new places on the planet's surface. At the time this paper was written, the final landing site for MSL was not yet chosen.

Figure 2 shows in yellow where the past missions of the Mars Exploration Program have landed on Mars. In white are the proposed landing sites for the MSL mission.

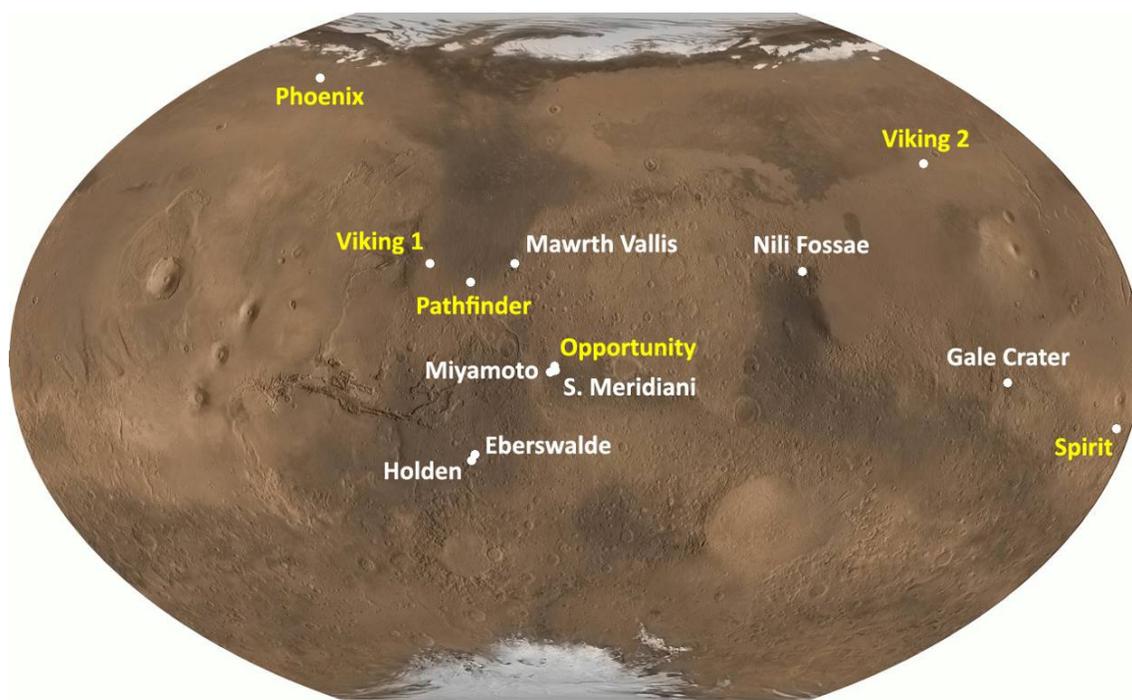
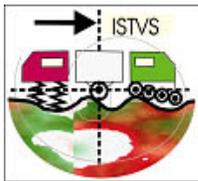


Figure 2: Landing on Mars - the past, present, and future (1)

Each of the proposed landing sites for the MSL mission contains a host of scientific questions that could be answered and a host of engineering challenges for the robotic explorer to overcome. Some of the landing sites are very cold, which poses difficulties for the operation of mechanisms like the drive and steer actuators. Some of the landing sites have a lot of rocks, which makes the mobility system of the rover have to work a lot harder to navigate than it



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would in smoother terrain. Some of the sites contain a landing site that is far from the location of scientific interest. This means that once the vehicle lands safely on Mars, it would have to drive a long distance in order to reach the science target as quickly as possible.

MSL uses an innovative landing technology which includes landing the vehicle directly on the wheels. This means that the wheel for the MSL robotic terrain vehicle must not only be designed to traverse through any of the proposed landing sites, but also to land safely on any of the proposed landing terrains.

3. Wheel Design Requirements and Considerations

When designing a wheel the first parameters to look at are the size and weight of the wheel. Weight is rather an easy requirement, as it is always desired to make the lightest structure possible while meeting the strength requirements. Wheel size requirements get to be a bit more complicated.

To a first order, the diameter of the wheel determines the size of the obstacle that the vehicle will be capable of traversing. A general rule of thumb is that a vehicle with a rocker-bogie suspension system can climb an obstacle that is 1.5 times the diameter of the wheel. The MSL vehicle is required to climb a 0.5-meter high obstacle. If this were the only parameter to determine the wheel size, then the MSL wheels would be approximately 0.33 meters in diameter.

In transit to Mars, the MSL rover is nested inside a protective aeroshell in order to keep the rover from being exposed to the harsh environments that the spacecraft will see on the journey from Earth to the surface of Mars. To fit inside the aeroshell, the wheels must be sized appropriately to give safe clearances to all of the surrounding hardware. As such, the wheels cannot be too big, or the vehicle would not fit. Volumetric constraints like this one are often just as important in sizing the wheels as all of the technical parameters.

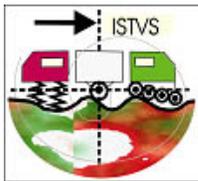
Another consideration for the size of the wheel is ground pressure. Ground pressure is a term that describes how well the vehicle will “float” in terrain versus sink in. One can imagine that a very thin wheel like a bicycle tire would sink in sand a lot more than a very wide tractor tire. It is this concept that determines how wide the tire should be.

Ground pressure for the MSL vehicle is calculated as follows:

$$GP = \text{weight of the rover on Mars} / (\text{tire_width} * \text{tire_radius} * \text{number of tires})$$

The desired ground pressure for MSL would be less than or equal that of the MER vehicles. Ground pressure is not an absolute parameter, but rather one which describes in relative terms how difficult it will be for a vehicle to drive in soft soil conditions.

Once the size of the wheel is determined, then work on all of the details like grouser design, stress analysis, and load mitigation methods can begin.



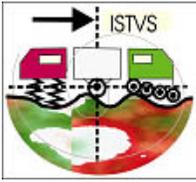
During landing and traverse events, the wheels are the first contact with the Martian terrain. As such, they are designed to act as a spring, or load mitigator, in order to minimize the loads that are transferred up to the rest of the rover body. The wheels are also the only springs that minimize loads to the drive actuators. The wheels must be compliant enough to ensure that those delicate items survive, while still strong enough to not catastrophically fail during a landing event.

The MSL wheel grousers, or tread, are as much structural as they are traction features. In this case, the grouser is a chevron pattern that provides traction in the drive direction of the tire as well as the transverse direction. Shown in Figure 3 are the wheel designs for all three of the Mars Program rovers. The smallest wheel is from the 1997 mission *Pathfinder* which carried the rover *Sojourner Truth*. The next largest wheel is that of the current robotic explorers on Mars, *Spirit* and *Opportunity*. The largest wheel is an early concept for MSL. The grousers for each wheel are very different. Considerations for grouser designs include weight, structural integrity, what the wheels will drive over, and the traction required. As with everything else, the final grouser design is a compromise to balance all of the design considerations appropriately.



Figure 3: A Family of Wheels (2)

Spirit and *Opportunity* have an asymmetry in their grouser design. This asymmetry was used as a tie down point between the rover and lander. Once safely on the surface of Mars, the tie down points were let go and the rovers were free to traverse the Martian terrain. During traverse operations, the rover drivers began to notice that this asymmetry in the grouser design was useful in determining how much the rovers were slipping. The rover drivers could do this by imaging the tracks that the rovers left in the dirt (Figure 4); the distance between the asymmetric tread features was then measured in the image and compared to what it would



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be if the rover was not slipping at all. This difference indicates the amount of slip the rover is seeing. This odometry method via images of the rover tracks is called *visual odometry*.



Figure 4: Opportunity Image of Tracks (3)

For MSL, there was no need for a tie down point through the wheels. However, the asymmetric tread feature was found to be so useful that it was also done for the MSL wheels. Unlike previous rovers, the MSL asymmetric tread feature has no purpose other than to be easily viewable from the cameras onboard the rover. When designing such a feature, tire structure and weight must always be considered. The final design of the tread feature was the smallest, lightest-weight feature that could be viewed from the MSL cameras and still be able to take the loads from the landing and traverse events. Figure 5 shows images of the MSL tire tracks in a Mars analog media taken from cameras similar to those used for MSL.

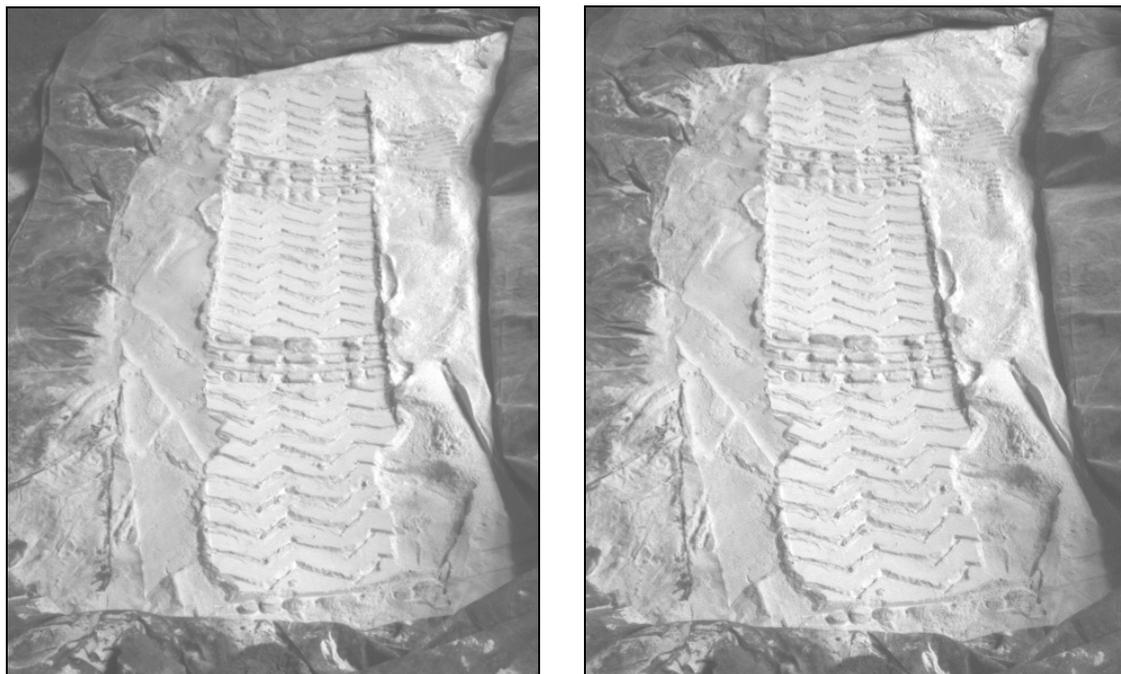
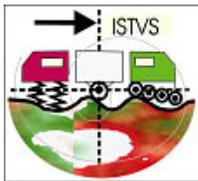


Figure 5: MSL Tread as Seen from Left and Right Rover Cameras

Another concern for all wheeled vehicles is debris management. Rocks, soil, and other debris can get into the tire. Considerations must be made on how to prevent debris ingestion, or on how to make a design robust enough that debris cannot wedge inside the tire in such a way that the wheel can no longer rotate.

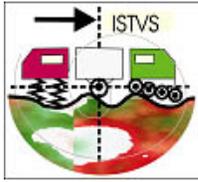
4. Wheel Design Overview

While there are a number of functional requirements that are addressed in the system design of the MSL Wheel Assembly, it is the priority given to some performance requirements, and the consequential compromise of others, that drives the ultimate architecture of this hardware. As discussed, this Wheel Assembly is the first hardware element to contact during delivery of the vehicle to the Martian surface and as such must not only survive a significant impact event but also mitigate that impact to upstream components prior to meeting any of its traverse capability requirements.

The key, often mutually conflicting, design efforts for the MSL Wheel Assembly focused on making the wheel 1) as lightweight as possible, 2) as compliant as possible, 3) capable of withstanding the touchdown event, and 4) as tractive as possible over Martian terrain.

4.1 Hardware Architecture Overview

Traditionally, terrestrial wheel systems that require intrinsic compliance, and even the Apollo Lunar Roving Vehicle (4), employ a flexible tire and rigid hub connection to a drive source. The MSL wheel, however, deviates from this approach because of requirements unique to this mobility system. Cruise vehicle clearances dictate a maximum volumetric constraint while



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ground pressure requirements dictate a minimum surface area requirement. In addition to those two constraints, there is a wheel diameter limitation due to a minimum surface thrust requirement at a given torque threshold. The result of these packaging and performance constraints is a wheel with a width to diameter ratio much larger than that of many terrestrial and lunar designs.

A large width to diameter ratio alone would not preclude the MSL wheel from using a flexible tire as its primary source of compliance; however, because the tire could see significant point loads during the touchdown event, because any traction features on the tire would have to support very high torque transmission to the surface and because of pre-existing interface constraints to the drive source, it quickly became apparent that using a tire with this aspect ratio as the primary load attenuator would require much more mass than was available.

Mass considerations, therefore, drove the primary compliance of the wheel assembly to be built into a series of flexible spokes, or flexures, bridging between the tire and the drive source. The tire, then, provided a ground pressure bearing surface, torque transmission to the surface, and secondary structure support for the wheel flexures. Figure 6 shows the wheel flexures and tire at the assembly level.



Figure 6: Flight Design: MSL Wheel Assembly



4.2 Structural Design

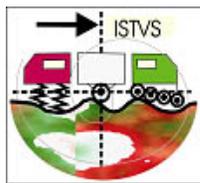
As the both the primary load path and load attenuators in the wheel assembly during the touchdown event, the flexures must be able to react a wide variety of loads. Terrain conditions, vehicle velocity vectors, tire impact locations, etc. can all combine into an array of possible touchdown scenarios that, together, require the wheel assembly as a system to be compliant and to react load in all six degrees of freedom (DOF).

While a number of different flexure options were explored, only the final design solution demonstrated a couple key characteristics. The tire structure is supported by six discrete flexures, each with bolted interfaces at the tire and the drive source. Making the flexures discrete from the aluminum tire enabled the use of another material, titanium 6Al-4V STA, that is better suited for high strength, light weight flexure applications. Additionally, an overall geometry was chosen to give each flexure a reasonably comparable compliance in each DOF. The decision to move forward with a fully-machined flexure, as opposed to a formed spring wire or other construction, allowed for a flexure with a continuously variable cross-section. This ability to vary cross-sectional properties all along the path length of the flexure meant that not only was the design 6-DOF compliant, but that each degree of freedom, each spring stiffness, of the wheel assembly was independently tunable.

The final flexure design, shown in Figure 7, was tailored to mitigate particular loads into the wheel drive actuator during critical landing scenarios.



Figure 7: Flight Design: MSL Wheel Flexure



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In addition to providing a bearing surface for traverse through soft regolith material and providing traction for traverse over rocky terrain, the tire structure plays an important part in allowing the wheel flexures to act together as a system.

The tire is a monolithic machined aluminum structure consisting of a thin bearing skin for generating ground pressure, circumferential stiffening rings at either rim and at the flexure mounting plane, and transverse grouser tread features for traction. Because of the large surface area requirement on the tire, skin thickness became a significant source of mass, and therefore opportunity for mass savings, for the entire vehicle. At a fraction of a millimeter, the skin thickness of the MSL tire is the minimum that was determined feasible to fabricate with conventional machining technology. The structural ring at the flexure mounting plane was sized to aid in distributing point loads between multiple flexures, and all three stiffening rings provide a restoring hoop stress during global deformation of the tire. The tread features, because they run continuously from one rim to the other, contribute to the structural integrity of the tire by bridging the stiffening rings and leaving the thin skin responsible primarily for transferring shear.

The final structural feature of the tire is a slightly crowned profile as opposed to a purely cylindrical one. While a cylindrical tire provides better ground pressure for a given torque-limited diameter, the crowned tire was found analytically to be a stronger structure during the touchdown event and empirically to decrease the chance of catching a trailing tire edge when landing in rocky terrain. Crowned and cylindrical tires that met ground pressure and diameter restrictions were found to have comparable masses.

4.3 Tread Design

Again, due to mass constraints and touchdown performance priorities, the tire tread features are designed to function as secondary structure as much as they are a source of traction on the Martian surface. As a result, the tractive capability of any single wheel is downplayed, somewhat, in favor of taking advantage of the rocker-bogie suspension system to keep as many wheels as possible on the ground, each contributing to overall forward progress. In this way, the tractive performance in regolith media of non-climbing wheels becomes as important for getting over a rock obstacle as the tractive performance of the climbing wheel(s).

Because the ground-tread interaction is quasi-static at only a few centimeters per second, the benefit of cleat height diminishes rapidly only a short distance from the tire surface. In fact, early tread size versus percent slip testing showed that the majority of performance improvement occurred between bare, featureless tires and tires with surface features on order of the particle size of the regolith being traversed. Sandwiched between a minimum bearing surface diameter and a torque-limited maximum envelope diameter, the height of the MSL tread features is only approximately 3% of the overall tire radius.

Within the mass and geometry constraints imposed on the tread, features were still included to improve traverse performance. The tread features are built in a chevron pattern to provide some stability during cross-slope traverses as well as provide locations for localized sharp edges. The tread features were also spaced enough apart to take advantage of the shear angle



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of highly cohesive Martian regolith but still close enough to be likely to “cog” with macroscopic features on rock faces. Sharp edges at the point of each chevron feature, and along each rim, have also been found to generate enough contact stress to cause localized failure in a variety of volcanic rocks and provide enough positive traction for the high-torque drive actuators to pull the vehicle over obstacles in otherwise soft regolith media.

Although sharp, localized tread features are a distinct benefit for climbing obstacles, they necessarily create high, localized loads during an impact event that can yield or even puncture the thin tire skin supporting them. Given the reluctance to increase tire skin thickness and the guarantee of only one touchdown event throughout the wheel life, local, non-detrimental plastic yielding was deemed acceptable. Indeed, any tire with the aspect ratio necessary to meet MSL torque and ground pressure requirements that could survive a worst-case contrived touchdown event and remain completely elastic would be extremely mass-inefficient. Possible energy absorption and/or mechanical fusing due to tire yielding was conservatively ignored when generating the touchdown design loads.

The decision to allow plastic deformation during the dynamic touchdown drove the requirements for complimentary analysis and test programs to predict and verify functionality of the MSL Wheel Assembly.

4.4 Analysis Approach

Design loads for the MSL Wheel Assembly were generated with a dynamic touchdown simulation using wheels with an estimated multi-DOF stiffness matrix (5). Design requirements on the wheel, therefore, included not only flight limit loads but also a target stiffness matrix. Initial concept work, e.g. general flexure shape, was done with solid element linear modeling and used to seed additional rounds of dynamic simulations with stiffness matrices and generate refined design loads. However, as the number of contrived landing scenarios increased and specific, desired wheel characteristics were defined, detailed analysis of the wheel in critical touchdown scenarios required moving beyond linear modeling.

Given the pre-defined loads and stiffness requirements, deflections of both the tire structure and the flexures were necessarily large. With the combination of these large deflections and local, non-detrimental yielding of the tire, the need for both geometric and material non-linear analysis quickly became apparent. Detailed design of the tire and flexures became an iterative modeling process, using over 25,000 beam, solid, and plate elements, shown in Figure 8, looking primarily at strain and material rupture as the design criteria.

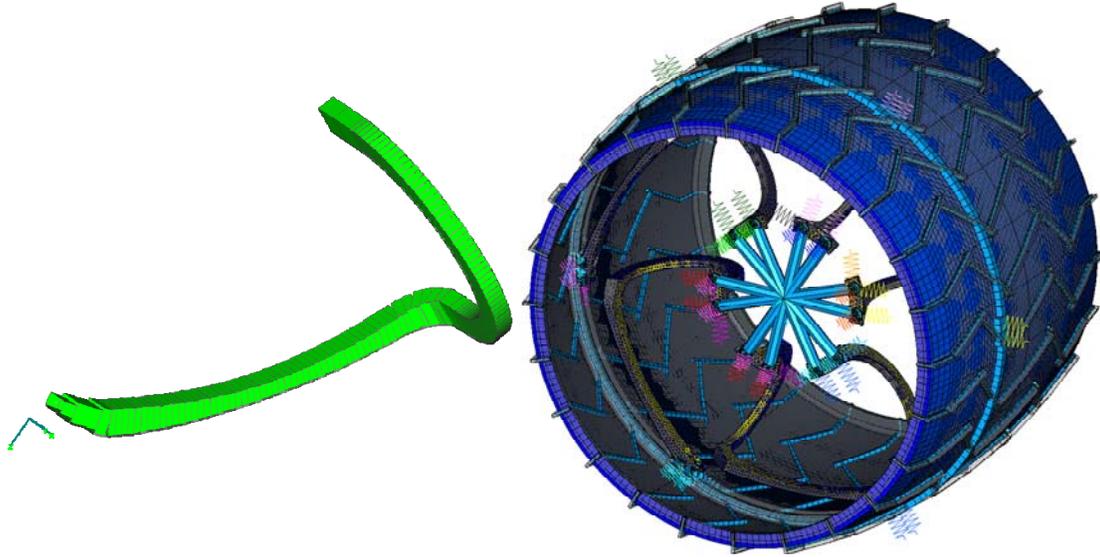
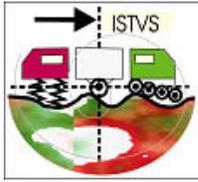


Figure 8: Wheel Assembly FEA Model

Guidelines for determining an acceptable level of yielding were taken from prototype test requirements in NASA-STD-5001 where detrimental yielding is defined as adversely affecting fit, form, function or integrity of the structure and failure is defined as the inability of a structure to sustain specified loads or function as designed. In other words, a successful wheel design would be one that could, after acting as landing gear in a worst-case touchdown event, continue to turn, climb and otherwise simply function as a wheel.

System-level touchdown requirements led to a wheel assembly design and analysis approach that provided an appropriate platform for hardware development and a comprehensive hardware test campaign for model correlation and touchdown and traverse performance evaluation.

5. Wheels as Science Instruments

MSL, like Phoenix, Spirit and Opportunity, carries a microscopic imager on board in order to study the Martian surface up close. On MSL this instrument is called the Mars Hand Lens Imager (MAHLI). MAHLI is capable of imaging features as small as 12.5 micrometers in size (6). This is smaller than a human hair. However, there are still features in the Martian soil that are smaller than this. Mars scientists found evidence of this while using an instrument called the Mössbauer Spectrometer on both Spirit and Opportunity (7), (8) and again while using the robotic arm scoop on Phoenix (9).

When using the spectrometer, the rover places it in the Martian dirt. Once lifted, microscopic images are taken. In some cases, as shown in Figure 9, the Mössbauer left an imprint in the dirt. While the resolution of the microscopic imager cannot show dirt particles down to the size of those surrounding this imprint, scientists can infer a lot about the size and makeup of the soil just based on how crisp the edges of the imprint are seen in the image.

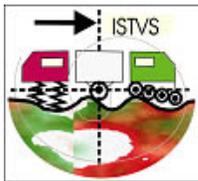


Figure 9: Imprint of the Mössbauer Spectrometer Contact Plate (10)

Since the wheels are in constant contact with the Martian terrain, it seemed a natural choice to include features in them that might be useful to the science community. In a partnership with soil scientists from JPL and Cornell, the wheel design was modified to accommodate features that would help scientists get more information about the soils MSL will drive on. A picture of this feature is shown in Figure 10.

This sharp edged feature will work much like the contact plate of the Mössbauer contact plate. The feature is located on the outside edge of the tire in each of the six wheels. This feature, coupled with images from MAHLI, will provide scientists with information to help understand the size and makeup of the soil being driven on.

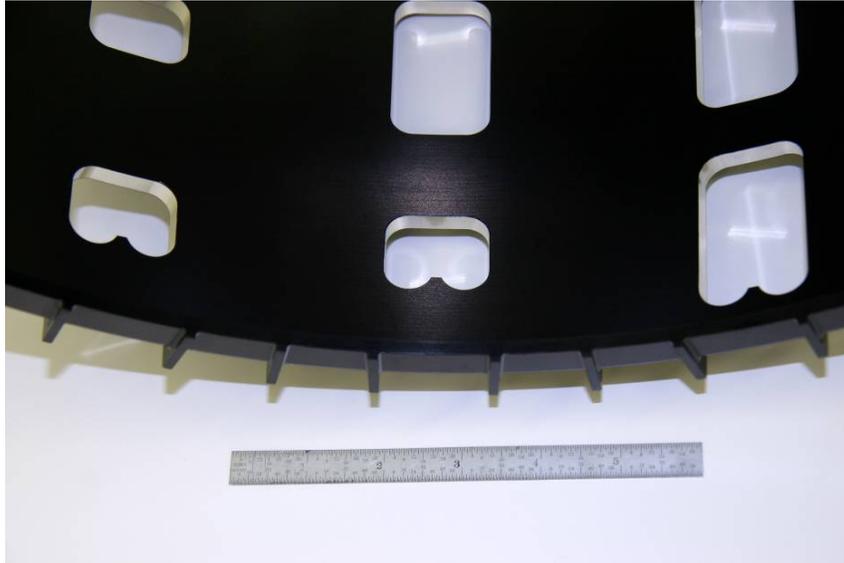


Figure 10: Soil Property Investigation Features in Wheel Tread

6. Wheel Testing and Results

Evaluation of the final MSL wheel design was done through a series of system and component level tests of traverse performance, static load capability and dynamic impact survivability.

6.1 Traverse Testing

An existing 3/8-mass MSL rover prototype, including a full-scale mobility system, allowed empirical performance evaluation of flight-like wheels over a wide variety of terrain conditions. The prototype mobility system exhibited excellent performance over dunes and slopes, climbed rocks larger than requirements called for, and showed itself debris-tolerant to burying wheels during trenching activities. Representative test terrains are shown in Figure 11.

Concurrent with traverse testing, the prototype rover underwent a series of full-scale touchdown tests. More than fifty simulated touchdown events at scaled velocities and with representative impact targets stressed the wheels through many worst-case landing scenarios. As expected, these impact events resulted in local tire deformation and numerous ruptures of the tire skin. Traverse testing continued after touchdown testing with no decrease in wheel performance or further material failure in the tire.

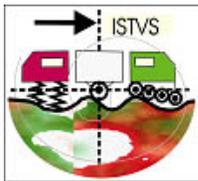


Figure 11: Traverse Testing of Full-Scale Mobility System

In addition to ongoing operation of the prototype rover and monitoring the condition of its wheels, a single wheel test track, shown in Figure 12, was built specifically to address tire wear over the tens of kilometers lifetime traverse requirement for this vehicle. A tire with multiple candidate surface coatings was run for a margined lifetime at 10% – 20% slip over Martian regolith and rock analogs. At the end of testing, a hard anodic coating of the aluminum tire was deemed an adequate, low mass addition to the baseline design.



Figure 12: Tire Surface Wear Life Test Setup

6.2 Static Testing

Static testing of the MSL wheel started with single flexures for simplified model correlation, stiffness characterization, and failure predictions. The test data in Figure 13 show excellent correlation to material and geometric non-linear model predicts. Just as importantly, flexures taken far beyond deflections possible at the system level exhibited graceful, non-catastrophic failure modes.

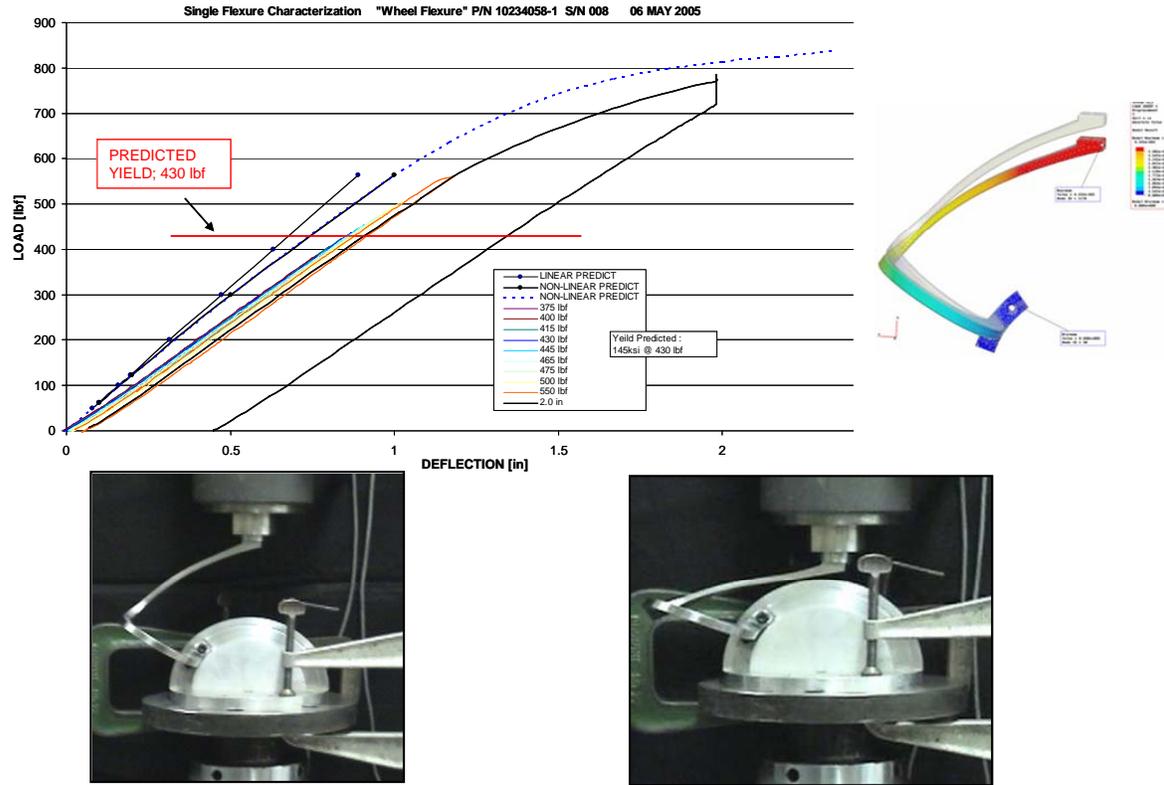


Figure 13: Single Flexure Stiffness and Strength Characterization

Final static qualification of a flight-fidelity wheel assembly was done per NASA-STD-5001 prototype testing requirements to 1.4X flight limit loads. Static testing consisted of applying a point load at a tire rim that resulted in combined loads representative of worst-case touchdown conditions. The static test setup, model predict contour plot, and statically loaded wheel assembly are shown in Figure 14.

Although load-deflection data matched predicts well, static testing was particularly important for evaluating the wheel assembly under extreme deflections where model predicts became unreliable, e.g. after re-contact occurred between the flexures and tire. Post-test inspection of the test article after loading past the 1.4X requirement showed significant local tire deformation as well as some permanent ovalization of the assembly, but not enough to cause interference with other hardware on the vehicle or hinder any traverse operations.

Because the flexure mounting plane and accompanying stiffening ring are offset from the center of the tire, another critical load case not easily modeled but well-suited to controlled dynamic testing was a rock impact on the least-supported expanse of tire skin. Figures 16a-c on the following page show before, during, and after video frames of a mid-skin rock impact from a drop height of 15 inches. The video shows that in the case where significant load does not reach the flexures, the tire itself does still exhibit significant energy absorption and elastic resiliency.

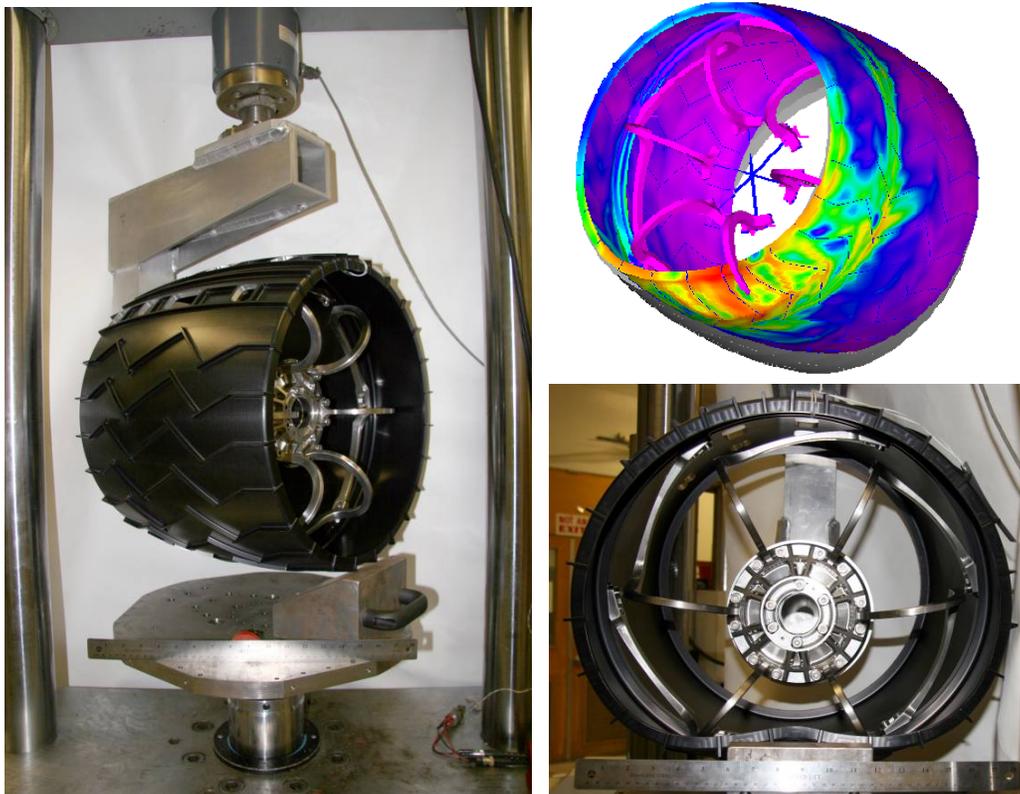
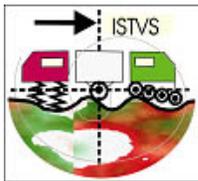


Figure 14: Static Testing of a Flight-Fidelity Wheel Assembly

6.3 Dynamic Testing

Unlike the full-scale rover touchdown test program, single wheel dynamic testing was able to target specific impact locations on the wheel and use much higher frame rate video to observe hardware behavior during touchdown.

A wheel assembly, and roughly 50 lbs of mass analogous to local drive and steer hardware on the vehicle, was mounted on a pair of vertical linear bearing rails and dropped from increasing heights onto rigid steel plates, hemispherical steel “rocks” and real basaltic rocks.

Figure 15 shows two video frames of an 18 inch drop onto a steel plate, just prior to and during first impact. High speed video clearly shows load distribution throughout the assembly as compression in some flexures and tension in others and multiple oscillations of the tire stiffening rings from circular to oval and back. Test articles for this drop case would typically rebound 50% - 60% of the original drop height.

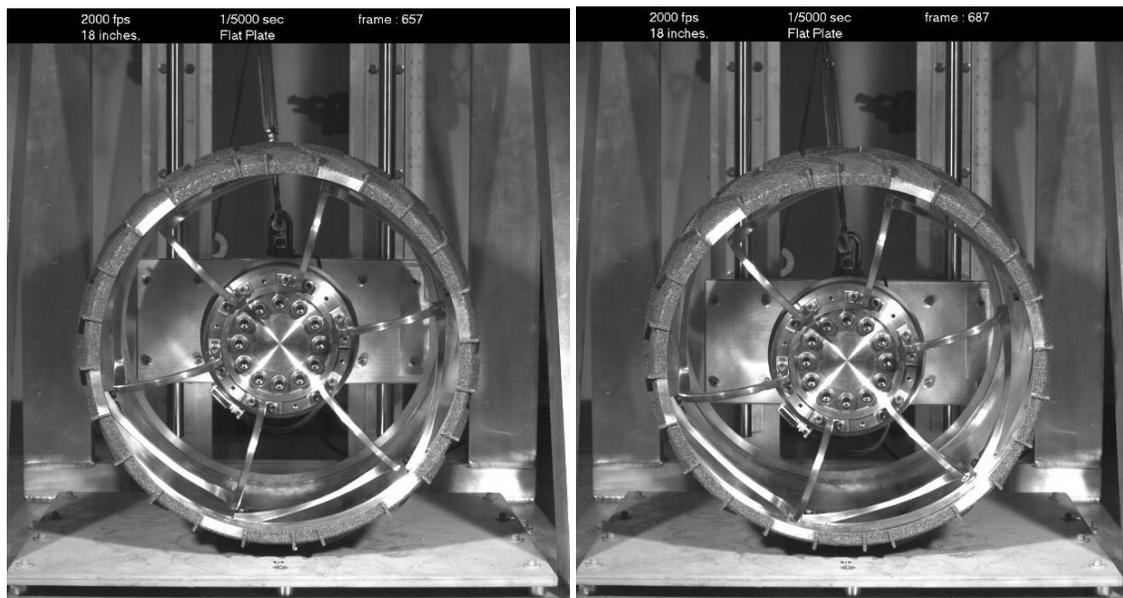
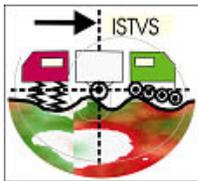


Figure 15: Ovalization of the Wheel Assembly During Dynamic Testing

Analysis and testing have shown that the baseline MSL Wheel Assembly design results in a lightweight wheel that can function as landing gear and as a landing load attenuator and still retain enough structural integrity to support Martian terrain traverse operations for the remainder of the mission.

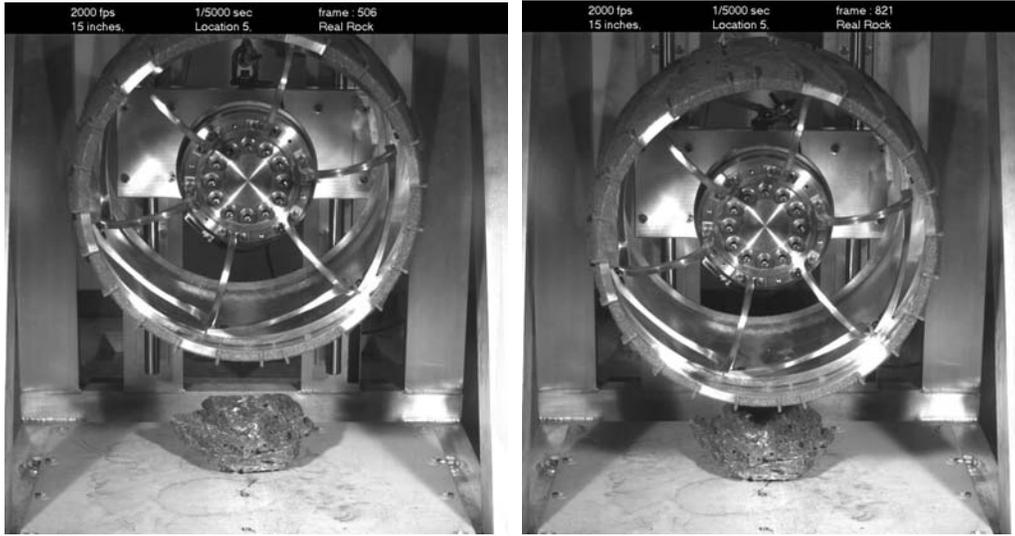
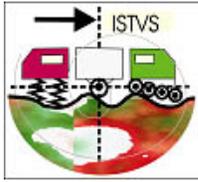
7. Conclusions

To date, all of NASA's extraterrestrial terrain vehicle systems have been wheeled rovers. The Mars Science Laboratory has taken the use of rover wheels even further by using them not only as running gear but also as landing gear. The MSL wheel assemblies have been optimized to meet requirements for both traversing and landing on the surface of Mars.

While traverse requirements dictate the size, shape, and traction elements of the wheel, the landing event drives its structural architecture. The MSL wheel balances these often conflicting requirements into a light weight, energy absorbing system that can mitigate landing loads to upstream rover components as well as support mobility operations over a variety of Martian terrains.

The spoked wheel design, in particular, allows for flexibility in tuning the wheel assembly stiffness in all six degrees of freedom to attenuate particular loads to specific components like actuators and payload science instruments. The wheel design discussed would scale well to other sizes of terrain vehicles as well as all types of loading events.

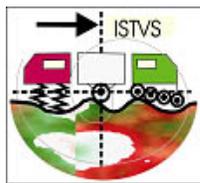
Wheels are shown to be viable first contact elements for landing a platform directly on a planetary surface and should continue to be considered for future mobile landing systems.



Figures 16a & b: Pre- and Post-Impact at Tire Mid-Skin



Figure 16c: Tire Deformation During Mid-Skin Impact



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- (1): Web Address when accessed:
http://marsprogram.jpl.nasa.gov/msl/spotlight/images/20080918a/MSL_sites_globe2.jpg
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