Rimmed Wheel Performance on the Mars Science Laboratory Scarecrow Rover

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Abstract—**The Mars Science Laboratory (MSL) Curiosity rover experienced increasing wheel damage beginning in October 2013. While the wheels were designed to operate with considerable damage, the rate at which damage was occurring was unexpected and raised concerns regarding wheel life expectancy. As of Sol 2555 (10-14-19), there are two broken grousers on the left middle wheel, and one broken grouser on the right middle wheel. One possible scenario, albeit remote, is that enough grousers break on a wheel such that unconstrained portions of the wheel could contact the cable running from the rover motor controller assembly to the wheel's drive actuator. If the cable to a drive actuator is damaged, that wheel may no longer respond to commands. To make progress towards a navigation goal position, that wheel would need to be dragged. To mitigate the risk of damaging a cable running to a wheels drive actuator, the unconstrained portion of a wheel could be strategically shed by performing driving maneuvers on an immovable rock. What would remain after wheel shedding is a rimmed wheel (the outer 1/3 of the wheel). We studied the feasibility of remotely commanding the rover to perform the shed maneuver on one of its front wheels. To inform whether or not to shed the wheels, we tested the performance of driving on one or more rimmed wheels in flight. This led to a two-month test campaign in the Jet Propulsion Laboratory (JPL) Mars Yard using the Scarecrow testbed rover. Driving and steering performance was characterized on a variety of terrain types and slopes in a worst-case rimmed wheeled configuration. Test results indicate that if wheel shedding could be successfully executed in flight, Curiosity could continue to drive indefinitely on rimmed wheels.**

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1. Introduction

On August 6, 2012, the Mars Science Laboratory (MSL) Curiosity rover landed on Mars and began the surface phase of its mission. On Sol 490, Mars Hand Lens Imager (MAHLI) images revealed an unexpectedly high rate of damage to the rover wheels. Because the rover was only 4.6 kilometers into its prime mission, the MSL project launched an anomaly Tiger Team to investigate the causes of wheel wear. In parallel to the investigation, the MSL project began efforts to reduce further wheel damage by altering the way the rover drives over rocks. Along with careful terrain classification and drive planning, periodic trending of the wheel state, and extensive characterization of the mechanisms of wheel failure per terrain type [1], the MSL project also began the development of a terrain-adaptive wheel-speed software patch, which estimates wheel contact angles and commands wheel angular rates that theoretically would result in no wheel slip. The software patch was approved for nominal use in flight on Sol 1678 (04/25/17). Since its installation, 99.48% of Curiosity's odometry has been achieved with the software patch enabled. [2][3]

As part of the investigation, wheel lifetime tests were performed in the Jet Propulsion Laboratory (JPL) Mars Yard on several rocky terrain types of known rock density using a three-wheel rocker-bogie rig with a MSL wheel in the front, middle, and rear wheel positions. The Tiger Team investigation found that wheel damage initially occurs when a pointed, embedded rock contacts a wheel in between two adjacent grousers during driving or steering, creating a puncture or crack in the wheel skin, which is made of aluminum and has a thickness of 0.75 mm. Over time, additional contact with rocks cause punctures to grow into cracks, and cracks propagate across a skin section.

Each wheel contains a stiffening ring around the interior of the wheel, located two-thirds of the wheel width from the inside edge of the wheel. A drive actuator is attached to a wheel's stiffening ring via spindles. The stiffening ring also provides support to the 19 cleat-like features (called grousers) in between the inner and outer edge of each wheel. Figures 1 and 2 identify the sections and features of an MSL wheel. The current damage on each wheel is assessed after approximately 500 meters of driving by acquiring MAHLI images of the left front (LF), left middle (LM), left rear (LR), and right front (RF) wheels, and MastCam images of the right middle (RM) and right rear (RR) wheels in five 1.257 radian wheel-

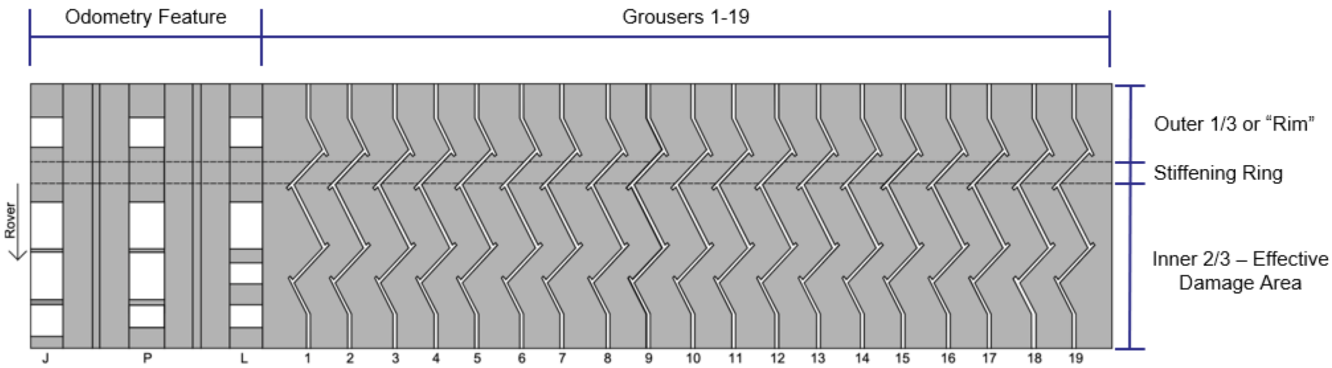

Figure 1. Unrolled MSL Flight Wheel.

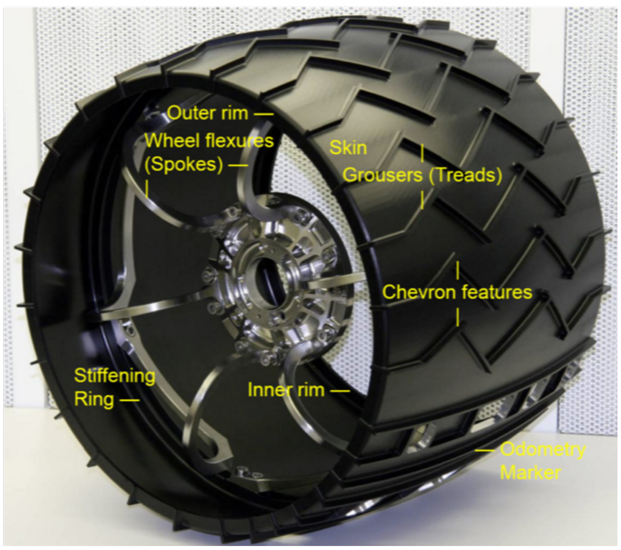

Figure 2. Features of an MSL Flight Wheel.

revolution increments.

The MSL Wheel Wear team analyzes the downlinked wheel images to identify grouser cracks and breaks and to measure the crack lengths in the wheel skin. A grouser is considered at risk of breaking once the average cumulative crack length of the adjacent skin sections exceeds 70% of the 2/3 section width. Only the component of a crack parallel to the width of the wheel is added to the cumulative length. Cracks in the outer 1/3 of the wheel do not contribute to grouser breaks and are not included in the cumulative damage calculation. Where cracks overlap, the overlap portion is measured and accounted for only once. When a grouser breaks, it almost always occurs at the stiffening ring. Three broken grousers on a single wheel signifies 60% of the wheels life has been consumed per Mars Yard test data. A Wheel Wear Strategic Plan was written on October 31, 2016, which predicted that there would be three grouser breaks on a single Curiosity wheel by the 16 kilometer odometry mark [4]. The first two grouser breaks of the mission were discovered during assessment of the Sol 1641 wheel images, at exactly the 16 kilometer odometer mark. Both of those grouser breaks were on the LM wheel. As of Sol 2633 (1/1/20), only one additional grouser break has been identified; it was identified on the RM wheel on Sol 2407 (05/14/19) at the 20.7 kilometer odometry mark. As of Sol 2633 (1/1/20) the rover has been driven 21.875 km.

The Wheel Wear Strategic Plan also predicted that by the end of the 2020 calendar year, all 19 grousers on one of Curiosity's wheels would be broken. Updated predictions as of December 2019 place the 19 broken grouser milestone past 2024 using the most conservative estimates. When nearly all of the grousers on a wheel are broken, one of the risks to the mission is the unconstrained portions of the wheel could contact the electrical cable running from the rover motor controller assembly (MCA) to that wheels drive actuator. If the cable to a drive actuator is damaged, that wheel may no longer respond to commands. To make progress towards a navigation goal position, that wheel would need to be dragged, increasing rover slip and decreasing the rover drive distance per sol.

To mitigate the risk of damaging an electrical cable running to a wheels drive actuator, the unconstrained portion of a wheel could be strategically shed on Mars by performing driving maneuvers on a rock that appears to be immovable in downlinked images. Shedding removes the inner 2/3 section of the wheel's grousers and skin, leaving an intact outer 1/3 rimmed wheel and intact odometry feature. During the first two months of 2018, the MSL project conducted experiments in the JPL Mars Yard using the Scarecrow testbed rover to characterize steering and driving performance on one or more rimmed wheels and to understand the feasibility of remotely commanding the rover to perform the shed maneuver on one of its front wheels. In this paper, we describe the results of the test campaign.

2. Rimmed Wheel Performance Testing

The primary goal of the Rimmed Wheel test campaign was to identify significant differences or degradation in MSL mobility system performance when driving on rimmed wheels. Performance was assessed relative to a baseline performance on 6 full wheels. The results informed the feasibility and operational impact of continuing the MSL mission on rimmed wheels. The following mobility scenarios were identified as test cases for the campaign:

- Driving on sloped terrain, on a variety of terrain types.
- Driving on Sand.
- Rover stability and slip risk during simulated Robotic Arm activities.
- Steering a rimmed wheel.

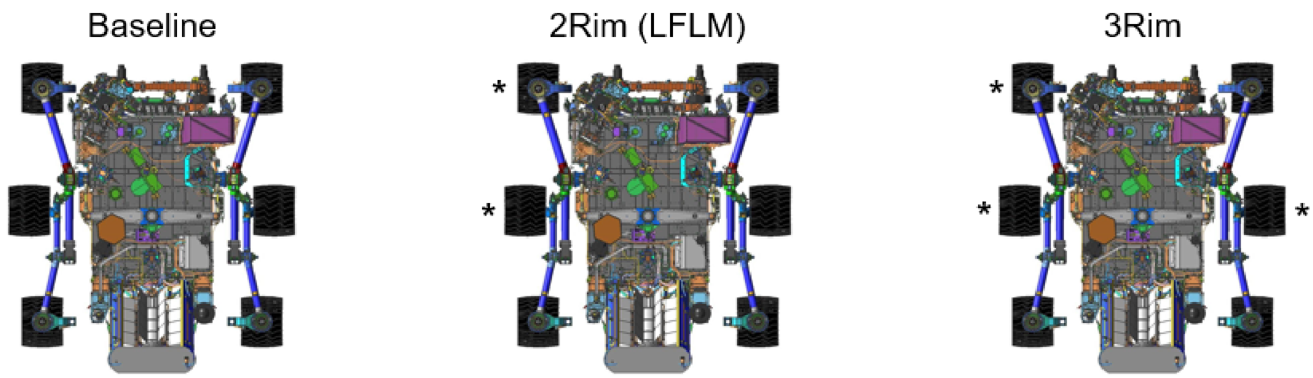

Figure 3. **Rimmed Wheel Testing Configurations (* Denotes a Rimmed Wheel).**

Figure 4. **JPL Mars Yard North Slope Terrain.**

Each test case utilized different or multiple rimmed wheel configurations on the Scarecrow rover to compare performance between configurations or to test a worst case scenario. The different configurations, shown in Figure 3, were informed by the current state of damage to the MSL flight wheels, which is greatest for Left Front (LF), Left Middle (LM), and Right Middle (RM). Damage models indicate that only these 3 wheels could feasibly reach a state of damage great enough to consider a shed maneuver due to excess damage threatening wheel cabling. The Baseline configuration was the Scarecrow Rover instrumented with 6 flight wheels, all in low damage or undamaged states.

Performance on Slopes

Methods—Operating the rover with rimmed wheels presents several concerns for mobility performance. A rimmed wheel has a reduced footprint, with less surface area and grouser area contacting the surface to provide traction. To characterize this impact, the Scarecrow rover was tested in the JPL Mars Yard north slope, performing straight drives on two terrain types including gravel (representative of cohesive martian soil or gravel) and flagstone (representative of martian bedrock). Test trials were done on the 18 degree slopes available to us (Figure 4), which provide a challenging degree of steepness that is within the range of tilts that the flight vehicle can and has traversed. Trials included straight 10m drives up and down each slope while maintaining a consistent starting position and heading. Slope testing was done for all three rimmed wheel configurations: Baseline, 2Rim, and 3Rim.

Results—A number of metrics were explored for slope testing. Datasets were compared to determine the impact, if any, driving with rimmed wheels had on Scarecrow's performance, with the Baseline data representing nominal performance on 6 full wheels. The data analyzed included:

- Slip percentage over the 10m drive step.
- Change in heading (delta-yaw) over the 10m drive step.
- Change in average drive motor current for each wheel.

Rover Slip—Rover Slip % is a measurement of the amount of distance traversed by the rover versus the distance commanded. In this case the commanded distance was 10m, the furthest single straight drive step allowed on MSL. Slip results for uphill driving are shown in Figures 5 and 6.

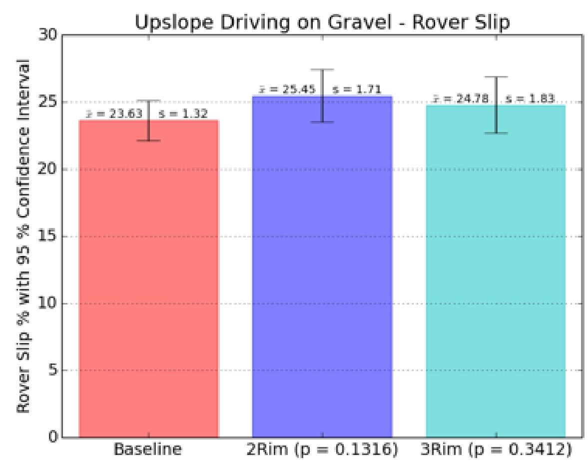

Figure 5. **Average Rover Slip % on Gravel.**

As expected, greater slip was observed traveling uphill, and on the more cohesive gravel slope. For all test configurations, the only statistically significant increase in slip was seen for the 3Rim configuration driving uphill on stone, with an average slip increase of 2.95%. In context, mobility software fault protection does not respond to slip at percentages lower than 40% under nominal settings.

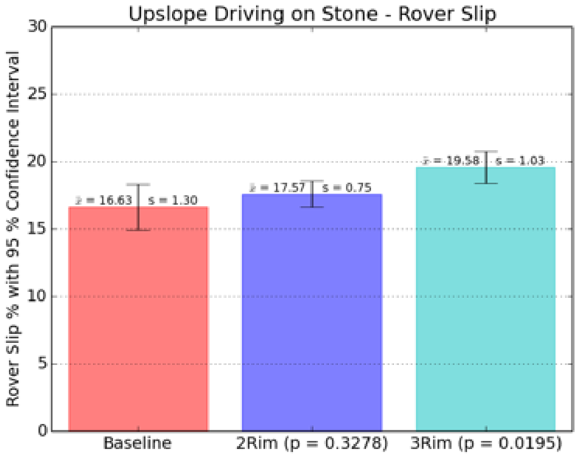

Figure 6. Average Rover Slip % on Stone.

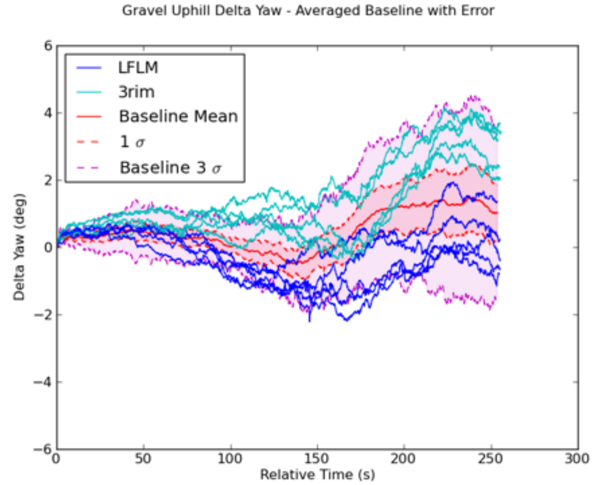

Figure 8. Rover Delta Yaw on Gravel.

Delta Heading—While driving, terrain and wheel slip can induce changes in the rover's heading (yaw). These can cause the rover to deviate from a predefined path of the drive planned by MSL operators over the course of a drive step. Significant deviations can result in the rover driving over obstacles or terrain features that should otherwise be avoided. If a great enough heading error accumulates in a drive, system fault protection will halt a drive autonomously. Figures 8 and 9 show the results for the slope tests. Rover sign conventions are shown in Figure 7.

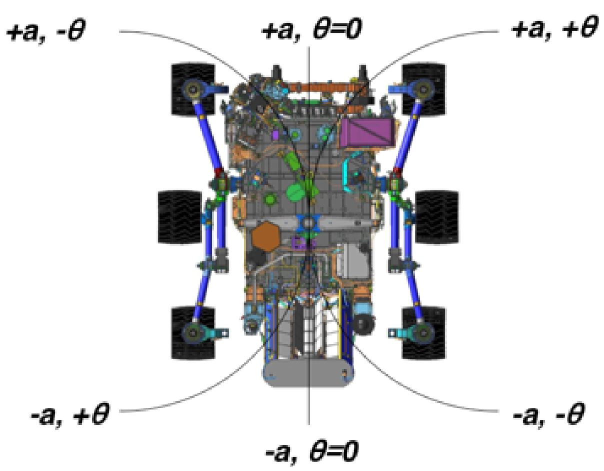

Figure 7. Scarecrow & Curiosity Rover Sign Conventions.

All trials showed the same approximate shape, as induced by the Mar Yard north slope. On looser, gravel terrain, the 2Rim configuration trended towards a negative delta yaw (towards the side with 2 rimmed wheels) relative to the baseline over the course of the 10m drive up the slope. This suggests that the overall reduced traction of the rover on the side with the rimmed wheels results in a tendency to drift off course in that direction over time. This trend is more pronounced and consistent on gravel than stone, due to the more uniform and cohesive terrain. All gravel trails in the 3rim configuration ended with a delta yaw outside the positive 1-sigma bound from the baseline drives.

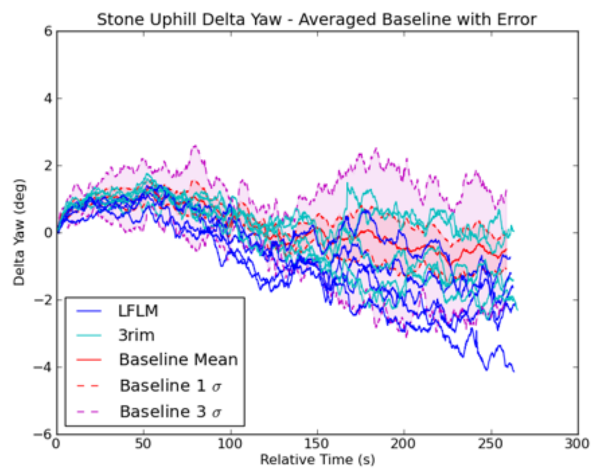

Figure 9. Rover Delta Yaw on Stone.

For both terrain types, the 3Rim trials showed a positive delta yaw relative to the baseline trials. This is believed to be an effect of lateral slip on the north slope, which does induce some roll on the Scarecrow Rover. The additional rimmed wheel in the 3Rim case further reduced traction of the rover, allowing it to slip more laterally and incur a greater effect on heading. This test campaign did not have a section dedicated to testing lateral slip effects on rimmed wheels, which is now a consideration for future work.

In practical terms, the change in delta yaw is not significant and is unlikely to impact MSL mobility. Autonomous protection typically sets heading errors after > 30 degree error accumulates between the current heading and navigation target.

Drive Motor Currents—Average motor current was calculated for each individual drive motor and compared between terrains and configurations. It was found that for all 6 drive motors, in all test cases, differences in average current were < 0.1 A and were not biased in any direction. Statistical significance of the results varied for all wheels. In practice any change in motor current of this approximate magnitude would have no impact on motor performance or lifetime and would not impact MSL operations or motor fault protection.

Performance in Sand

Driving in sand is a high risk activity for Mars rovers due to the high amounts of induced slip and the ability for wheels to sink and potentially get stuck in sand. The Baseline, 2Rim, and 3Rim configurations of wheels were tested using Scarecrow in the Mars Yard sand boxes shown in Figure 10. While testing in the flat sand box, the test team prepared sand dunes of 25cm to drive the full and rimmed wheels over. The sand slope was used to again perform forward and backward straight drives for the various wheel configurations.

Qualitatively, driving on the sand slope mirrored the results from the gravel and stone slopes in that there was more slip and delta yaw in the negative direction when driving on rimmed wheels than on full wheels. Wheel sinkage was shown to increase by 1-2 cm on rimmed wheels vs full wheels. There is no flight metric to compare sinkage against, as the Curiosity rover has no way to measure wheel sinkage.

Quantitative results for sand driving excluded here as there are concerns with the consistency of the test results in this terrain. We observed significant variability in all test metrics between individual trials of all configurations. Slip testing on sand performed earlier in the MSL mission and for the Mars 2020 rover has demonstrated that the soil preparation required for consistent, repeatable sand trials is intensive. Performance and consistency is highly dependent on temperature and moisture content. Required preparation was out of scope for this test campaign.

Stability and Slip Risk

Utilizing the Scarecrow rover to simulate the traction conditions of the Curiosity flight rover, we developed a suite of activities to characterize the amount of slip on rimmed wheels. We developed a worst case scenario in terms of rimmed wheel configuration based on our current wheel damage metrics. It was determined that the most likely worst case rimmed wheel configuration would consist of three rimmed wheels on the LF, LM, and RM wheels (3Rim).

Earlier in the MSL mission, a test campaign was executed to characterize rover stability while performing arm activities. This initial test campaign utilized the full rover wheels and provided the baseline data to which our test results were compared. The main conclusions of the initial test campaign were as follows:

- At slopes greater than 20 degrees, upslope wheels are sufficiently unloaded to allow wheel/rock slip.
- At slopes less than 20 degrees, slip requires local/global terrain motion.
- Full arm activities are allowed on sloped terrain less than 20 degrees after operator assessment of wheel parking locations for stability.

Our goal with this portion of rimmed wheel testing was to determine if slip behavior during arm activities changed significantly enough with rimmed wheels to require a revision to existing flight rules governing the safety of robotic arm activities.

Methods—The Scarecrow rover does not have a robotic arm or tool set to accurately simulate arm activities that occur on Mars. In order to best simulate arm activities on Earth, we developed a surrogate robotic arm made from 8020 aluminum. Using this surrogate arm, we devised several activities that are representative of a drill campaign, which is the most stressing case for wheel traction as it includes a range of dynamics activities including:

- Arm Unstow and Stow.
- Arm Preload against the ground.
- Vibration from sample ingestion.
- Drill percussion.

Three trials of the above arm activities were performed at each cardinal direction heading on two different slopes, 18 degrees and 30 degrees. The heading changes allowed for different gravitational loading of the rimmed wheels. A slope of 30 degrees is the maximum grade traversable by the rover.

Arm Unstow and Stow—Simulating the unstowing of the robotic arm required shifting in the center of mass for the Scarecrow rover. This type of weight shift could potentially cause wheel slip. Simulating this required the movement of a 40 Kg weight from the rover's center of mass out to 1.5 meters in front of the center of mass. The weight shift was done by hand by test engineers.

Arm Preload—Despite the name, arm preload requires lifting the end of the surrogate arm to unload some weight. This simulates the robotic arm pressing the drill into the ground which shifts some of the rover load from the wheels. For our simulation, we utilized a fish scale to exert an upward 300 N force 1.5 meters in front of the rover's center of mass. This type of dynamic weight shift could potentially cause wheel slip.

Vibration—Another function of the robotic arm is to vibrate to clean the turret's tool set or to shift ingested rock sample around a series of sieves before ingestion into the rover's body mounted instruments. This vibration occurs at the end of the robotic arm and induces a shaking force that translates down the arm into the rover chassis at its shoulder connection point. Some small amount of the vibrational load propagates down to the wheels, potentially causing slip. In order to simulate this function on the Scarecrow rover, we attached a 1.1G, 60Hz vibration motor to the top deck, off to one side, simulating the shoulder connection. We turned on the vibration motor for 30 seconds after unstowing the surrogate arm.

Drill Percussion—In order to sample a rock on Mars, MSL is equipped with a percussive drill. This dynamic percussion, while in contact with the Martian surface, can cause vibrations in the ground beneath the wheels. Rather than the rover itself moving, inducing slip, this test was of the ground moving/shifting causing the rover to slip. We simulated this drill percussion using a handheld hammer drill. At first, we simply pushed the drill into the ground/rocks of the Mars Yard. However, the drill was too effective and resulted in a few broken rocks and holes in the ground. In order to be more consistent with our testing, we utilized a block of aluminum resting on the ground as the target for the hammer drill. We ran the drill for 10 seconds each time.

Results—Onboard the Scarecrow is a 3 axis Inertial Measurement Unit (IMU). This provides quantitative data to assess a change in attitude along any of the rover axes. Along with this data set, we set up cameras around the rover and near the rimmed wheels to qualitatively watch for slip. Figure 11 is representative example of the quantitative results for a given attitude.

Figure 10. **Mars Yard Sand Box (Left). Scarecrow on Mar Yard Sand Slope (Right).**

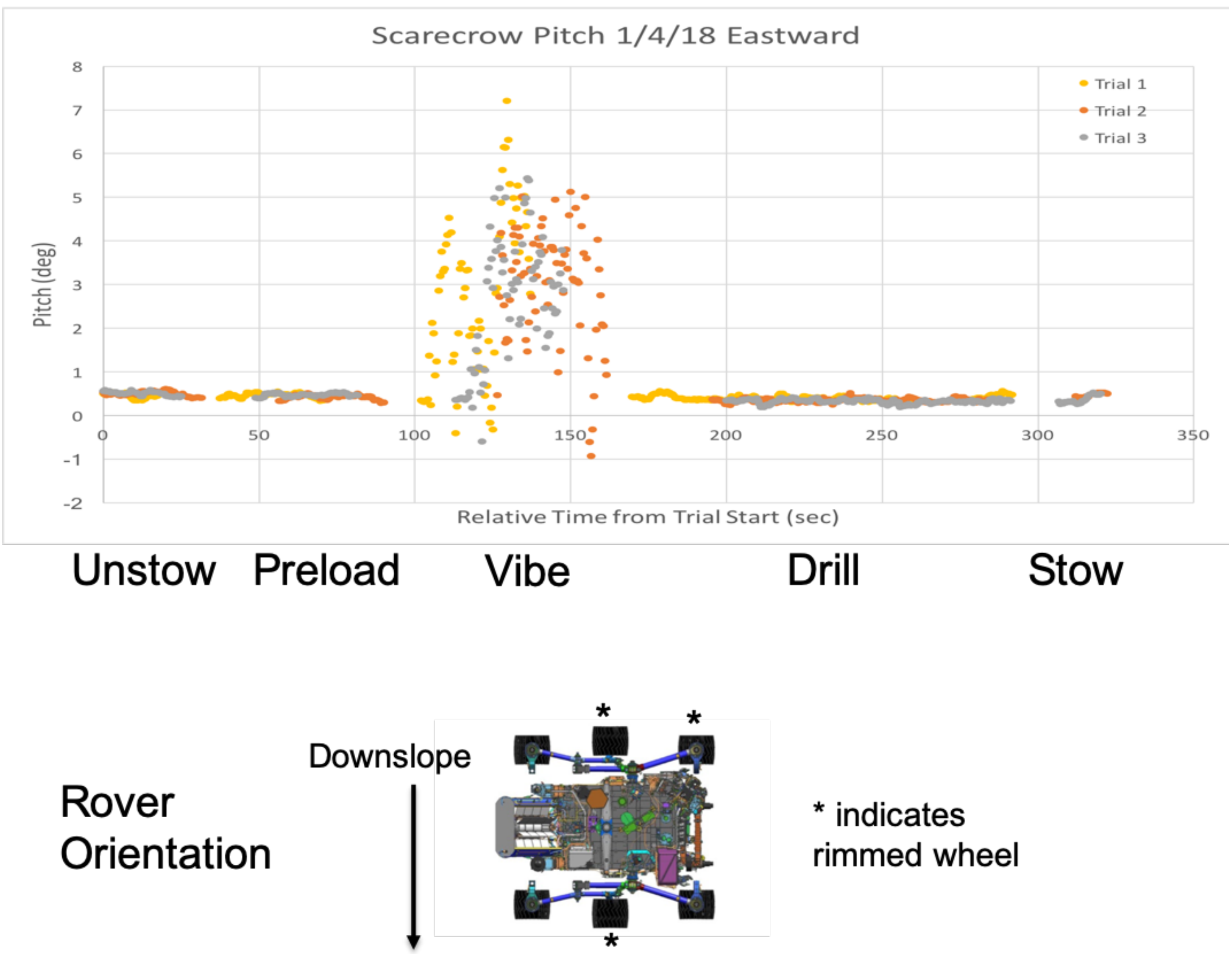

Figure 11. **18 degree slope IMU data.**

All of the plots of IMU data, for each axis, at each orientation, look very similar to Figure 11. There are two main features to point out here:

1) The attitude does not change during all activities except for vibe.
2) The noisy attitude measurements during the vibe section of the test were not actual changes in rover attitude. Rather, the IMU was shook inside the body of the rover instead of the entire rover moving. This claim is supported by video evidence showing no major change in wheel positioning or rover attitude.

Our qualitative results were best viewed as GIFs. We made GIFs showing the wheels and their contact with the ground both before and after each portion of simulated arm motion. Largely uneventful, the GIFs revealed the rimmed wheels surprising stability. Most of the time no motion occurred at all. Occasionally, some settling occurred where the wheel sunk further into the loose soil. Out of all the trials we performed, only once did a wheel actually slip. This occurred on the 30 degree slope during the vibration portion of the test.

Steering Performance

Another sub-optimal mobility condition is created when a steering wheel is rimmed; the nominal ground contact point of the wheel is no longer on the steer axis (Figure 12).

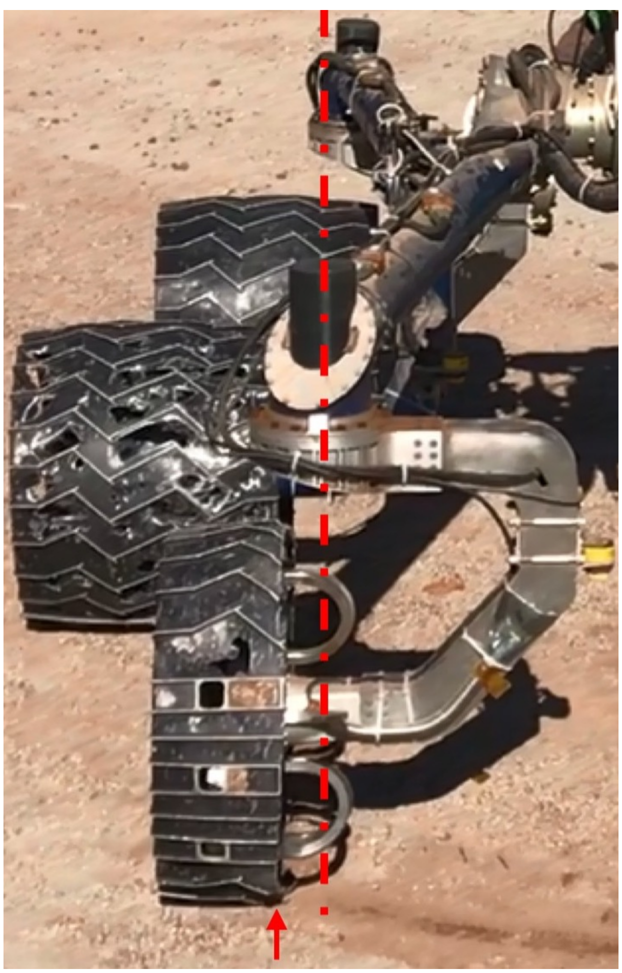

Figure 12. Steer Axis (Dotted Line) vs. Ground Contact Point.

This condition is concerning for two main reasons. First, the increased moment arm increases the torque required to steer the wheel. Second, the contact point sweeping an arc relative to the steer axis (15) will either force and displace the rocker-bogie section of the suspension or displace the terrain underneath the rimmed wheel.

Methods

In order to test the effects of steering with a rimmed wheel (in our case, the right front wheel), the following steering events were commanded multiple times with both intact and rimmed wheels on flagstone and gravel. The 3rim configuration was not used during steer testing, only the RF and RM wheels were rimmed and instrumented with force-torque sensors.

1) Starting with the wheel turned to 0 degrees (straight forward), the right front wheel was commanded to -90 degrees (inward).
2) The right front wheel was commanded to +90 degrees for a full sweep across the steering range-of-motion.
3) The right front wheel was commanded to 0 degrees to return it to its starting position.

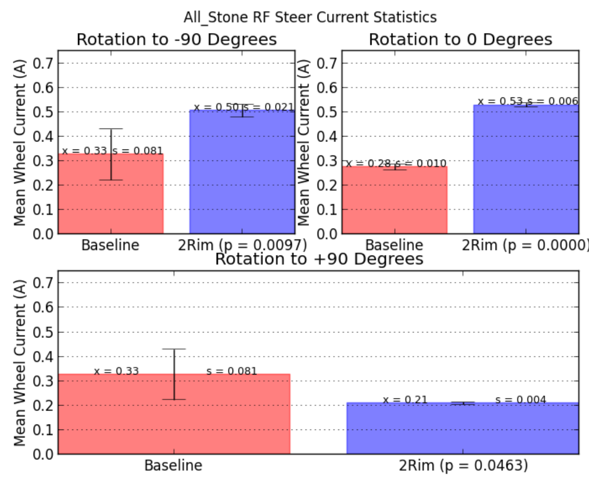

Figure 13. Average RF Steer Current on Flagstone.

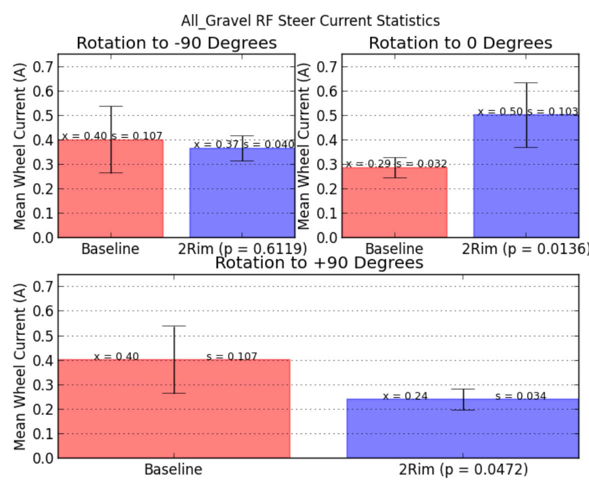

Figure 14. Average RF Steer Current on Gravel.

Results

Current data was collected to assess the risk of causing a steering motor stall. The data (Figures 13 and 14) shows that the current draw for the rimmed wheels (in blue) and the intact wheels (in red) are distinguishable but not different enough to cause significant concern about stalling the steer actuators in flight. Current magnitude differences observed on all terrain were on the order of one to two tenths of an Amp. Steer current differences were more pronounced for the negative direction (+z is down) steering motions where the exposed stiffening ring on a rimmed wheel is exposed to the terrain. The approximate 0.2 A increase would still be insufficient to induce stalls on a more frequent basis.

Qualitatively, the lateral shift in the nominal ground contact point introduces the risk of getting a rimmed wheel caught on a rock or other terrain feature that a full wheel would otherwise rest on top of. In flight, this would require additional attention by MSL's rover planners when steering rimmed wheels.

Figure 15. Contact Point of a Rimmed Wheel Due to Steer Axis Offset.

3. WHEEL SHED DEVELOPMENT

Overview

The primary threat of accumulated damage to Curiosity's wheels is the risk posed to electrical cabling running along the wheel struts between the motors and motor controller assembly (MCA). Once all 19 grousers on a wheel have broken, the inner 2/3 section of the wheel excluding the odometry feature becomes unconstrained and is capable of contacting exposed cabling. Figure 16 shows a Curiosity wheel with 19 broken grousers, a state colloquially referred to as a Heavily Damaged wheel.

The threat to actuator cabling posed by a heavily damaged wheel led to the consideration of methods to strategically remove the unconstrained section of a wheel on Mars in a Shed Maneuver.

Pros of Wheel Shedding:

- Natural deformation of a damaged wheel poses a greater risk to mobility actuator cabling than controlled wheel shedding.

Figure 16. MSL Flight Wheel with 19 Broken Grousers.

- Continuing to drive on a heavily damaged wheel can ultimately result in the odometry feature grousers breaking, resulting in a trapped inner 2/3 wheel section. A trapped section not only risks cable damage but could function as a physical obstruction to driving the rover.
- Rimmed Wheel Performance Testing demonstrated there is no significant degradation to mobility system performance vs. full wheels.
- Rimmed wheels have an indefinite lifetime.

Cons of Wheel Shedding:

- Developmental cost of finalizing, refining, and demonstrating repeat-ability of wheel shed techniques.
- Impacts to mission science return depending on the availability of wheel shed compatible rocks.
- Operational timeline and resource cost of performing a wheel shed in flight.

Methods

The goal of a Shed Maneuver is the removal of the 19 grouser section of the inner 2/3 of a wheel using only in-situ terrain and mobility actuators. The end result is a rimmed wheel with an intact odometry feature. The removal is achieved by inducing two fractures in the inner ring of the damaged wheel, on either side of the odometry feature. These breaks, along with the 19 broken grousers, fully detach the damaged portion of the wheel from the rover. Figures 17 and 18 illustrate the state of a wheel before, during, and after executing a shed.

Rock Characteristics—Shedding a wheel requires a stationary rock to achieve leverage on the damaged section of a wheel. A shed rock must be 10-15 cm in height and be embedded in the ground. Terrain features matching these requirements have been identified during Curiosity's surface mission but are typically relegated to certain geologic units. If a wheel begins approaching a heavily damaged state, the requirements of a shed rock could impact the mission's strategic route. Additionally, preferred characteristics on a wheel shed rock include 1-2 steep faces to make positioning a wheel for shedding easier. A feature or protrusion on the top of a rock is also preferable as a location to hook the inner ring of a wheel onto.

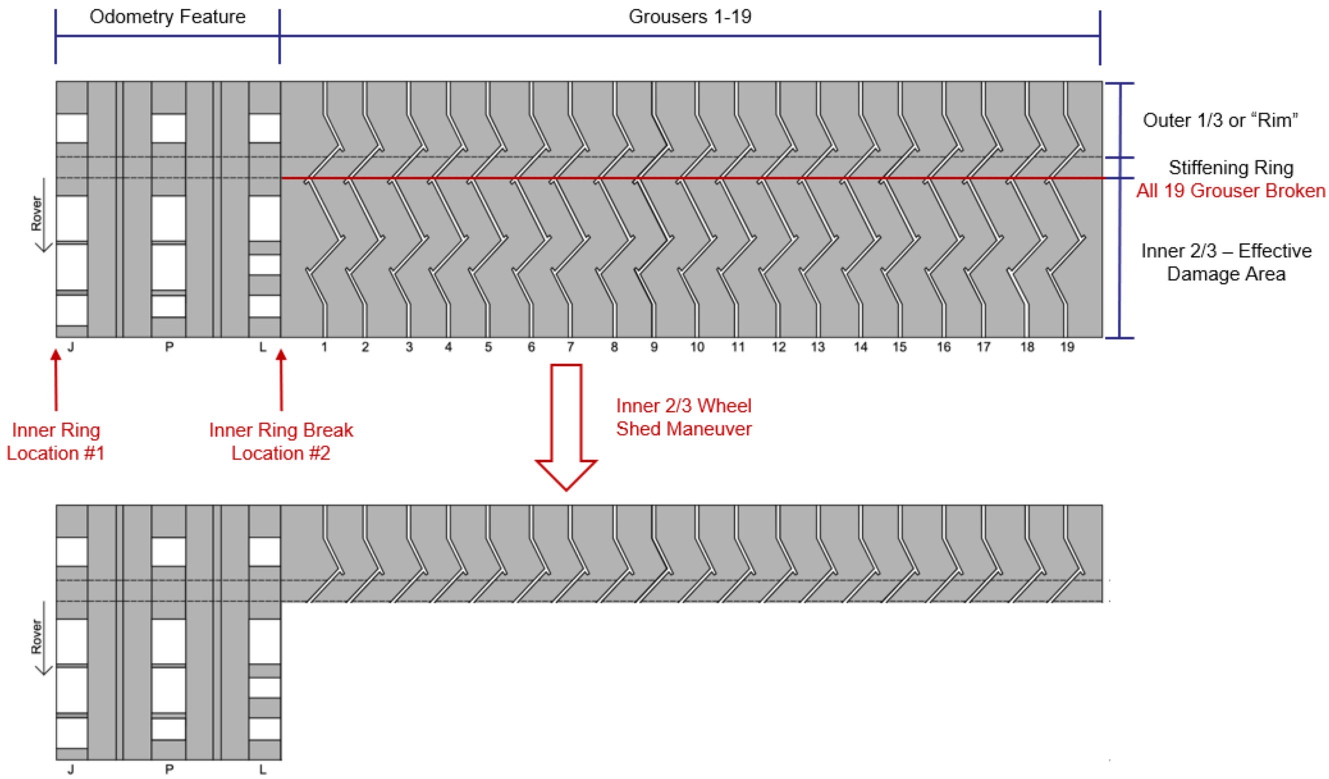

Figure 17. Wheel Shed Maneuver - Unrolled Diagram.

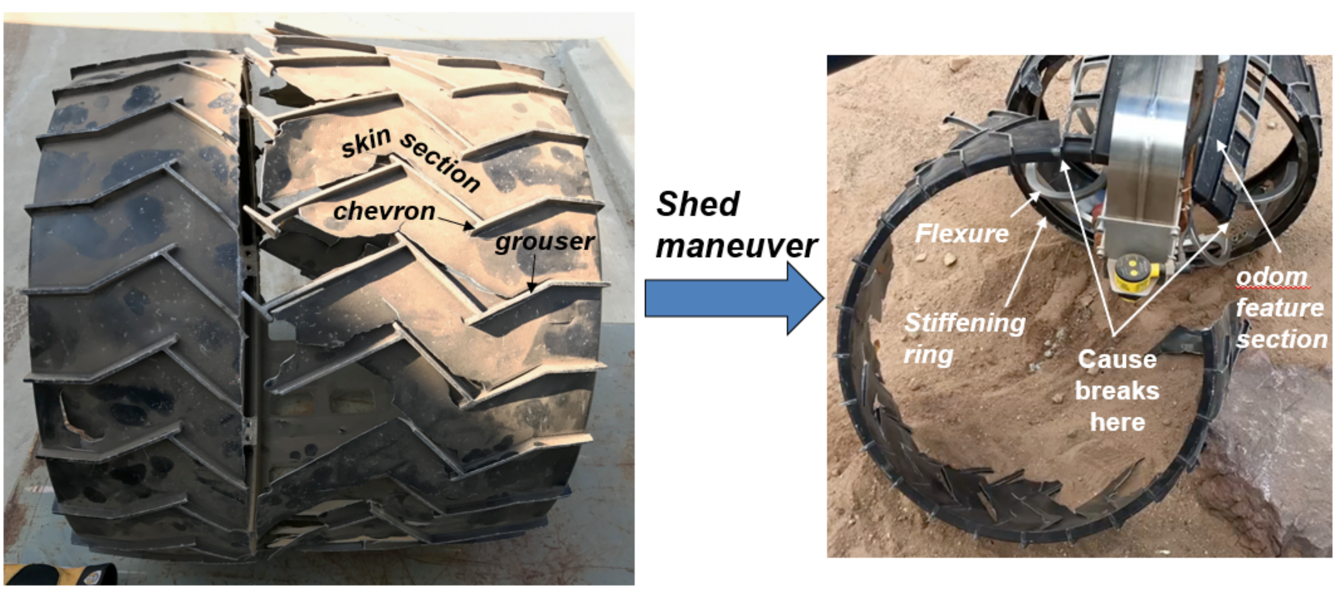

Figure 18. Wheel Shed Maneuver Process.

Figure 19. **LF after being driven onto the shed rock.**

Figure 20. **Rotated LF Prior to Break 1. Break Location 1 Circled.**

Figure 21. **Rotated LF After Break 1.**

Figure 22. **Unconstrained LF portion pinned to the rock.**

Removing the inner 2/3 of a middle wheel had been previously demonstrated by the wheel wear team during damage testing. The goal of this campaign was to adapt and demonstrate the strategy used on LM for use on a front wheel, in this case LF. Additionally, the LF shed was tested using a pseudo-sequenced approach with the engineers deciding on discrete sets of commands to send. This roughly simulates the wheel shed process in flight, which would require sets of commands to be built and sent in between ground-in-the-loop planning cycles informed by images from the rover cameras.

Execution

Break 1 - The Twist and Shout Maneuver—After identifying a shed rock, the rover is positioned such that the stiffening ring runs parallel to the steepest face of the rock. The shed wheel LF is positioned so that the rotation of LF as the rover is driven forward will result in the inner ring of the wheel being in contact with the rock along the range of grousers 2-5 (Figure 19). The center axis of the wheel should be above the peak or protrusion of the rock as pictured.

With LF in place on the rock, LF is rotated -90 degrees (The Twist). The other 5 wheels are then simultaneously driven backwards in incremental steps. With the inner ring caught on the rock, the inner ring bends and ultimately breaks in Location 1 (The Shout). Figure 20 shows LF while the rover is driving backwards, just prior to the inner ring breaking. Break location 1 is circled. Figure 21 shows LF following the completion of the Twist & Shout with the first inner ring break achieved.

Break 2 - The Pigeon Toe Maneuver—Following the first break, LF is straightened and the rover is backed up to take LF off the rock. LF is rotated such that, when pushed forward, the now unattached inner 2/3 section will be pressed up against the shed rock (Figure 22).

Unlike a middle wheel which has no steer actuator, LF isn't constrained to one direction of motion. The test team found through experimentation that turning LF inwards, in this case +30 degrees (Pigeon Toed), helped reduce lateral slip induced by the other wheels pushing LF against the rock. Additionally, the angle of LF helped push the unconstrained wheel portion inward towards the body of the rover and away from sensitive cabling.

Achieving the second break required toggling between two motions. The first is a backwards rotation of LF, slowing unwinding the broken wheel section while keeping the loose

**Figure 23. Unconstrained LF During the Pigeon-Toe Maneuver.
Break Location 2 Circled.**

Figure 24. Overhead View of LF During the Pigeon-Toe Maneuver.

Figure 25. Overview View of LF After Shedding

edge away from wheel cabling. The second is driving all 5 other wheels forward to maintain the pressure of the rock on the broken wheel section. Alternating between these motions increases the stress on the inner ring at break location 2. Figure 23 shows LF during this process, with the break location circled.

Eventually, the stress required to break the inner ring at break location 2 is achieved, and the inner 2/3 section separates completely. The rover can then continue on a newly rimmed wheel. Figures 24 and 25 show an overhead view of LF before and after the second break occurs.

4. CONCLUSIONS

Using the Scarecrow testbed Rover, testing was conducted to assess mobility performance of the rover when driving on rimmed wheels compared to a set of six full wheels. High risk mobility scenarios including driving on slopes, driving through sand, steering rimmed wheels, and performing dynamic activities when stationary were considered. It was determined that driving and operating on rimmed wheels does not significantly degrade performance and would not require any significant changes to operational methods to use rimmed wheels on the Curiosity Rover.

Using the gravel and flagstone slopes in JPL's Mars Yard, multiple configurations of rimmed wheels were tested to assess the impact of rimmed wheels on rover slip, delta yaw, and wheel current. All wheel configurations and terrain types demonstrated minimal impact to the rover's ability to drive on slopes. Sand results proved highly variable without dedicated sand and soil preparation. Stability analysis on rimmed wheels found almost no difference in performance on rimmed wheels. The reduction in wheel contact area resulted in no change in behavior during simulated arm and drill activities. Existing operational rules and procedures in place for operating Curiosity's robotic arm would require no modification in flight following the shedding of a damaged wheel. Steering rimmed wheels introduces negligible changes in wheel current. Rimmed wheels are not more likely to experience stalls than full wheels, but the interaction with terrain does change due to the shift in steer axis.

Informed by the low impact of driving on rimmed wheels, a method of shedding the damaged portions of a front wheel was developed and demonstrated on an LF wheel. The shed method requires only the utilization of an embedded rock, the mobility system actuators, and on board rover cameras for imaging. Shedding is therefore feasible to perform in flight, although the operational impact is significant. Ground in the loop cycle tracking during shed testing suggests the process would take 1-2 months per wheel to perform in flight.

Future Work

Additional testing on rimmed wheels has been considered for the following scenarios:

- Stability testing on more challenging terrain scenarios.
- Sand testing with controlled sand conditions.
- Lateral slip driving across slopes
- Steering a rimmed wheel using other motor control modes available on the rover.
- Suspension stress buildup from straightening rimmed wheels at the end of drives

Likewise, additional development work for wheel shedding is required for a shed to be performed on the flight vehicle. The behavior and removal of the unconstrained odometry feature has not been considered and would require the development and testing of methods to perform in flight or in a test environment.

As of the publication of this paper, the MSL Wheel Wear team is not pursuing additional testing for rimmed wheels or wheel shedding pending significant changes to wheel damage rates. Current damage rates and a decreasing effective driving rate of Curiosity suggest that no wheel will reach a state of heavy damage during the predicted lifetime of the wheel.

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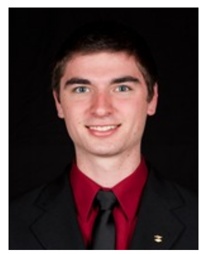

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