Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years

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Abstract— NASA's Mars Science Laboratory (MSL) mission landed the Curiosity rover on Mars on August 6, 2012. As of August 6, 2019 (sol 2488), Curiosity has driven 21,318.5 meters over a variety of terrain types and slopes, employing multiple drive modes with varying amounts of onboard autonomy. Curiosity's drive distances each sol have ranged from its shortest drive of 2.6 centimeters to its longest drive of 142.5 meters, with an average drive distance of 28.9 meters. Real-time human intervention during Curiosity drives on Mars is not possible due to the latency in uplinking commands and downlinking telemetry, so the operations team relies on the rover's flight software to prevent an unsafe state during driving. Over the first seven years of the mission, Curiosity has attempted 738 drives. While 622 drives have completed successfully, 116 drives were prevented or stopped early by the rover's fault protection software. The primary risks to mobility success have been wheel wear, wheel entrapment, progressive wheel sinkage (which can lead to rover embedding), and terrain interactions or hardware or cabling failures that result in an inability to command one or more steer or drive actuators. In this paper, we describe mobility trends over the first 21.3km of the mission, operational aspects of the mobility fault protection, and risk mitigation strategies that will support continued mobility success for the remainder of the mission.

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1. Introduction

On August 6, 2012, the NASA Mars Science Laboratory (MSL) Curiosity rover landed on Mars and began the surface phase of its mission. Seventeen Martian solar days (sols) later, Curiosity executed its first drive of 7.005 meters. Curiosity's design lifetime was to survive at least one Mars year (approximately 23 Earth months), and its drive capability was to achieve at least 20km. August 6, 2019 (sol 2488) marked

the seven-year anniversary of the landing of the Curiosity rover on Mars. Curiosity has driven 21,318.5 meters over those years, exceeding the 20km design goal. Thus far, Curiosity has achieved 47.2% of the total odometry achieved by the solar-powered Mars Exploration Rover (MER) Opportunity, which holds the record for off-Earth wheeled vehicle odometry at 45.16km, achieved over its 14.375 years of operation between January 25, 2004 and June 12, 2018. MSL's mobility-related mission peaks are shown in Table 1.

The goal of the MSL mission is to explore and quantitatively assess the habitability and environmental history of the Gale crater field site, which includes the landing ellipse and the adjacent lower portion of Mount Sharp [1]. Figure 1 shows the route that Curiosity has driven since it arrived at Bradbury Landing. As illustrated in Figure 2, much of the driving to the lower layers of Mount Sharp has been uphill. As of sol 2488, 60.75% of the Curiosity's driving has been uphill, resulting in a total increase in elevation of 418.4 meters.

Curiosity has driven over a variety of terrain types and slopes, employing multiple drive modes with varying amounts of onboard autonomy including Visual Odometry, Hazard Detection, Hazard Avoidance, and Visual Target Tracking. During this period, 738 drives planned by the MSL Operations Team were successfully uplinked to Curiosity; 622 of those drives successfully completed with the rover reaching its goal position. Of the 116 drives that did not run to completion, 53 were terminated early due to system fault protection unrelated to mobility, and 63 were terminated early by 16 types of mobility fault protection. Despite 15.7% of its attempted drives terminating early, Curiosity has achieved 91.7% of its attempted odometry.

In this paper, we describe Curiosity's mobility system, visual odometry performance, commandable drive modes, aspects of mobility fault protection, drive and steer actuator health, wheel health, and other risk mitigations that will support continued mobility success for the remainder of the mission.

2. Mobility System

Curiosity's mobility system consists of the wheels, drive and steer actuators and encoders, suspension, inertial measurement unit (IMU), and the flight software related to mobility and navigation of the rover. Similar to the Mars Exploration Rovers (MER), Curiosity is a six-wheeled rover with a rocker-bogie suspension. The six wheels are identical. They are constructed of aluminum (for its light weight), and have a width of 40 cm and a diameter of 50 cm. The six wheels are named left front (LF), left middle (LM), left rear (LR), right front (RF), right middle (RM), and right rear (RR). There are ten identical wheel and steer actuators (WSA) on
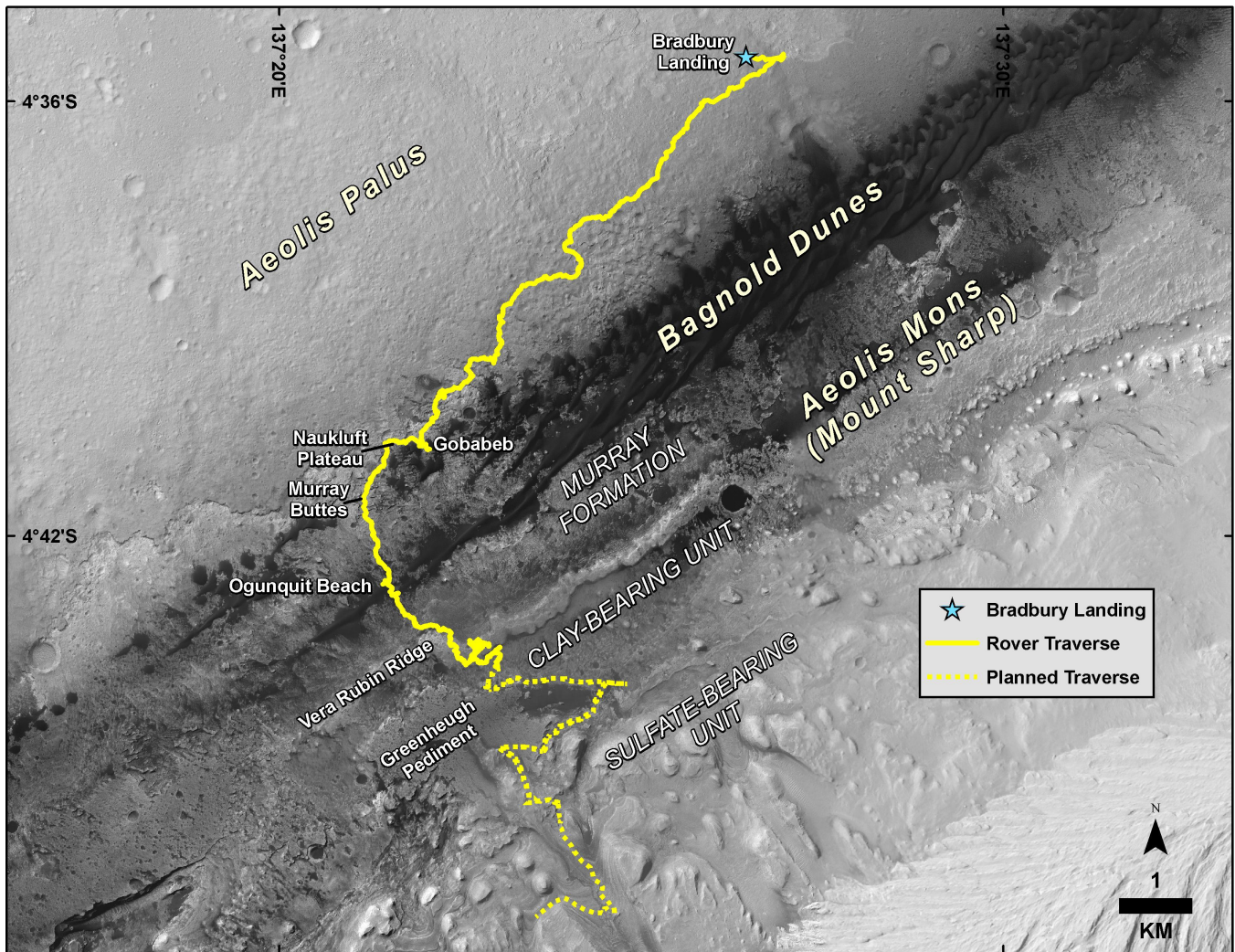
Figure 1. This map shows the route driven by NASA's Curiosity Mars rover, from its August 2012 landing through August 2019, and the planned path through additional geological layers of lower *Mount Sharp*. The blue star near top center marks "Bradbury Landing," the site where Curiosity arrived on Mars on Aug. 5, 2012, PDT (Aug. 6, EDT and Universal Time). Curiosity landed on Aeolis Palus, the plains surrounding Aeolis Mons (Mount Sharp) in Gale Crater. The base image for the map is from the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter. Image Credit: NASA/JPL-Caltech/Univ. of Arizona.

the Curiosity rover. Six of the WSAs are mounted in the hub of each of wheel, and enable driving by rotating each wheel independently about its horizontal axis. Four of the WSAs are mounted above the front and rear wheels and enable steering by rotating each wheel independently about its vertical axis. The middle wheels are not steerable.

Each WSA contains a brushless, direct current (DC) motor with 1024:1, 4-stage, planetary gear reduction, a brake, and an encoder. Each WSA can handle 10A of current and can generate 1000 Nm of torque. In practice, the drive and steer currents are much lower than 10A. Software current limits for each actuator are specified by setting parameters. The current limit for the drive and steer actuators has been set to 5.25A and 4.5A, respectively.

Curiosity has ten WSAs, but the motor controller assembly (MCA) only has eight motor controller driver (MCD) boards. Therefore, all of the WSAs cannot be simultaneously commanded. Due to this limitation, a steer-then-drive architecture is used. Curiosity executes drive steps primarily using two drive primitives; an arc and a turn-in-place maneuver. Arcs are specified with an arc length and the desired change in heading, or delta heading. Straight arcs are specified with a delta heading of zero. Arc commands are executed open-loop, terminating when each wheel's predicted number of rotations have been commanded. Turns-in-place can be specified with an arc length of zero, but in practice are typically commanded using specialized closed-loop turn commands that only terminate when the desired heading has actually been achieved, as determined by the IMU. In addition to these basic commands, the rover also accepts a high-level command to drive to a nearby waypoint. The surface navigation flight software autonomously selects an arc or turn to execute as the next step toward the waypoint goal. During steps requiring steering, the steering actuator brakes are released, the front and rear wheels are steered to appropriate steer angles, the steering actuator brakes are engaged, and the drive step is executed.

There is no motorized actuation in the rocker-bogie suspension system. Changes in the suspension occur passively in
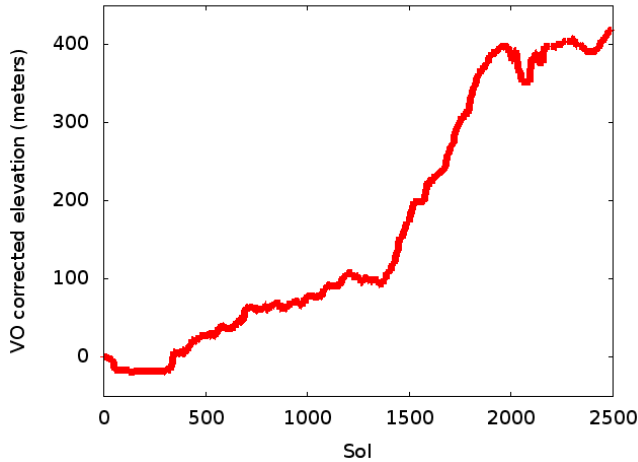
Figure 2. Curiosity change in elevation during the first seven years of the mission.

Table 1. Curiosity mobility-related mission peaks during the first seven years

	Sol	Value
Max rover pitch	2476	25.22 degrees
Max rover roll	2047	20.69 degrees
Max rover tilt	2477	25.34 degrees
Longest drive on RCE-B	665	142.498 meters
Longest drive on RCE-A	2221	59.428 meters
Max number of VO failures in one sol	2434	11
Max rover slip	2087	98.7%
Max wheel slip	2087	98.7%
Max differential angle	1371	9.40 degrees
Max bogie angle	1473	-21.30 degrees
Max non-startup drive current	1587	4.422A (RR)
Max non-startup steer current	1616	3.439A (RR)
Max drive current	1587	4.422A (RR)
Max steer current	494	3.594A (LF)

Table 2. Visual Odometry statistics during the first seven years of the mission

Activity	Count
Drive sols using VO	692
VO attempts while driving	20,682
VO convergences while driving	20,588
VO failures reported	94
VO failures caused by FSW	66
Average VO attempts per drive sol	29.86
Number of drives stopped by VO failures	5

Table 3. Visual Odometry Failures by category

Failure Type	Count
VO failed to converge	66
Step truncation reimaging failure	12
Sequencing failure	10
Strategy failure	3
IMU parameter failure	3
Total	**94**

a drive plan for a given sol, they often specify terrain features like drive goals and hazard locations in map coordinates (expressed in a local "Site frame"). So it's important for the rover to know where it is within that frame, to stay safe and know when it has reached its desired goal location. Curiosity uses its IMU to sense attitude changes, and Visual Odometry (VO) flight software to measure changes in position.

Curiosity's VO capability built on the success of the MER Visual Odometry Algorithm [2], updating the algorithm and improving its performance [3]. The technique works by comparing pairs of stereo images taken in the 45-degree FOV navigation cameras (NavCams) [4] before and after a relatively short drive step, typically one meter apart. Terrain features are discovered and tracked autonomously, and the resulting motion vectors are processed yielding a 6-DOF pose update. So long as enough features are found and multiple internal sanity checks all pass, the position part of the update is incorporated back into vehicle's current position estimate. Although VO computes both attitude and position updates, the IMU attitude solution has performed well during the first seven years, so only VO position updates have been configured for use.

Measuring Slip

Another benefit of VO is that it is the only system on the rover that can provide positional slip estimates. We compute two slip fraction estimates onboard, rover slip and wheel slip.

Wheel Slip Fraction is the sum of the linear distances of all VO-corrected wheel positions from what their idealized/no-slip positions would be, divided by the summed wheel path-lengths driven since the prior VO initialization/update. This definition is valid for all basic motions including turns in place.

Rover Slip Fraction is the Euclidean distance between the initial (idealized/no-slip) and VO-corrected positions of the Rover origin (located at the rover's turning center between its middle wheels), divided by the idealized/no-slip pathlength the Rover origin has taken since the prior VO initializa-

response to the wheels' interaction with terrain. The primary benefit of the rocker-bogie suspension system is its ability to keep the tilt angle of the rover body low when wheels encounter tall terrain features, reducing the risk of rover tip-over. The rocker arm rotates about the differential pivot, and the bogie arm rotates about the bogie pivot. Resolvers measure the bogie and differential angles at 64Hz. A differential angle increases when the corresponding front wheel is climbing, and decreases when it is descending. A bogie angle increases when the corresponding middle wheel is climbing and/or the rear wheel is descending. A differential bar across the top of the rover body connects to the left and right rocker arms through short links, constraining the left and right differential angles to have the same magnitude but be oppositely signed.

3. VISUAL ODOMETRY

Maintaining an accurate pose estimate yields many operational benefits for mobility. When human operators create

tion/update. Note that this is undefined (and therefore not computed) during turns in place.

Table 4. Overall Mission Slip Statistics (max slip from sol 2087)

Category	Percentage
Average of max rover slip per sol	16.69%
Average rover slip	6.24%
Average wheel slip	8.44%
Max rover slip	98.70%
Max wheel slip	98.70%
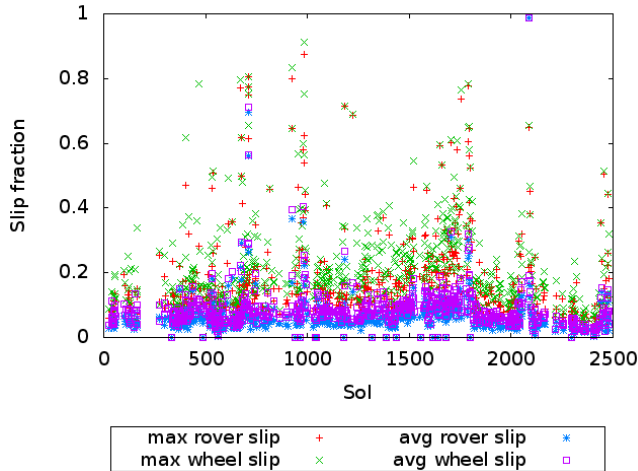
Figure 3. Rover and wheel slip fraction.

For example, a wheel slip fraction of 0.0 means there was no slip; VO confirmed the rover was at its no-slip position. On the other hand, if the rover commanded a straight arc but VO determined it did not move at all, the wheel slip fraction would be 1.0.

To avoid spurious faults due to high relative slip on very short drives, slip fractions are only generated onboard when the path length between VO updates exceeds a minimum threshold, nominally 0.35 meters. Our fault responses can be configured to use either slip measurement, but we have only used Wheel Slip because it is well-defined for all motions.

Excessive slip is one of the many possible mobility faults that can terminate a drive early. Rover Planners (i.e., those members of the operations team responsible for creating mobility, arm and turret command sequences) determine the maximum allowable slip each sol, expressed in two sets of limits. The VO slip "Fast" limit is a slip fraction threshold which, if exceeded, will cause the rover to stop immediately. The VO slip "Slow" limit is a slip fraction and a persistence number; if the "Slow" limit is exceeded for the persistence number of contiguous updates, then a fault will be raised.

Overall slip statistics are given in Table 4, and a plot of the slip fractions measured over the entire mission in Figure 3.

Fault Categorization

Rover Planners decide where to point the VO cameras during each drive step, to maximize the likelihood of VO being able to converge on a solution. So it is important to provide feedback to the planning team whenever VO fails to converge
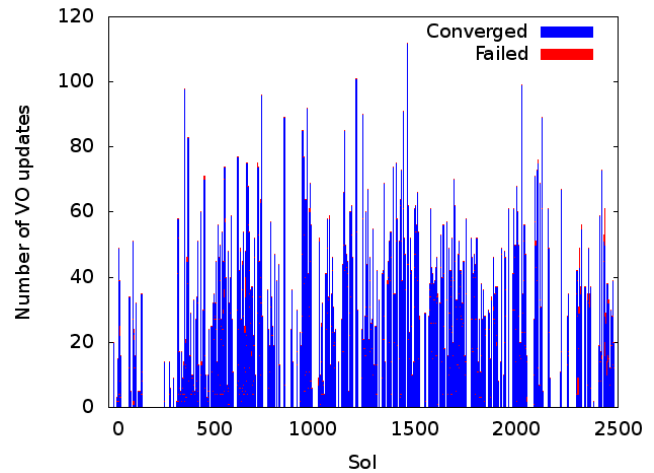

Figure 4. As of sol 2488, VO has been performed 20,682 times during mobility activities with only 94 failures.

on a motion estimate, since that knowledge can help improve results for the future drives.

During mobility operations on Mars thus far, MSL VO has successfully converged to a solution 20,588 times out of 20,682 attempts, yielding a remarkable success rate of 99.55%. See Figure 4 for a per-sol breakdown and Table 2 for additional overall statistics. These numbers do not include VO use during non-mobility activities. The different categories of VO failures that have occurred are summarized in Table 3 and Figure 5. The five categories from that table are:

VO failed to converge The majority of failures (66) were due to the algorithm failing to detect enough self-consistent features to be confident in its estimate and thus failing to converge on a solution; that often happens when the cameras are pointed at all-sandy terrain with few obvious unique features, for instance.

Step truncation reimaging failure When driving to a goal location, the rover may autonomously command a turn so sharp that there would be little or no overlap between VO image pairs. Although the FSW was designed to recognize that possibility and automatically truncate any large steps to enable VO to keep working, a bug in the FSW prevented VO reimaging from occurring in those cases. A fix has been developed and is being considered for uplink.

Sequencing failure Rover Planners sometimes realize during plan construction that their command sequences may result in VO failing to converge, but decide to send them anyway (e.g., on the last leg of a drive if precise localization is not required). Or they may send commands outside the normal recommended bounds (e.g., driving a longer distance between image pairs).

Strategy failure Sometimes a fault unrelated to VO causes a mobility command sequence to stop executing. In that off-nominal case, VO can sometimes accidentally try to match images with completely different pointing configurations, resulting in a failure to converge. But since the original plan did follow the best practices, we categorize these as Strategic failures rather than sequence failures.

IMU parameter failure On sols 122, 123, and 124, one of the built-in sanity checks triggered, forcing one VO estimate to be rejected each sol. The check was that the VO attitude estimate should match the IMU-generated one within one
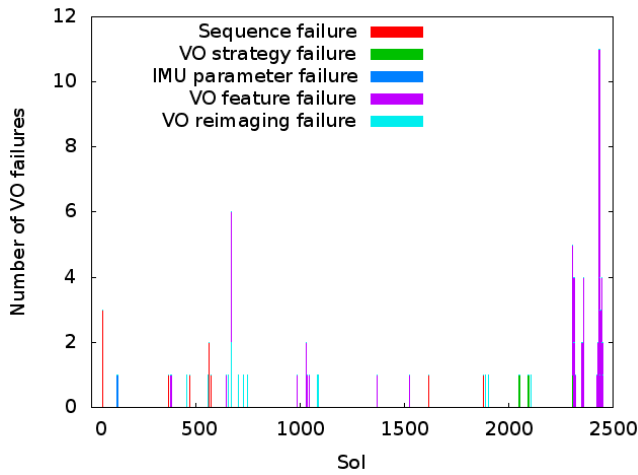
Figure 5. Number of VO failures per sol for each type of VO failure.
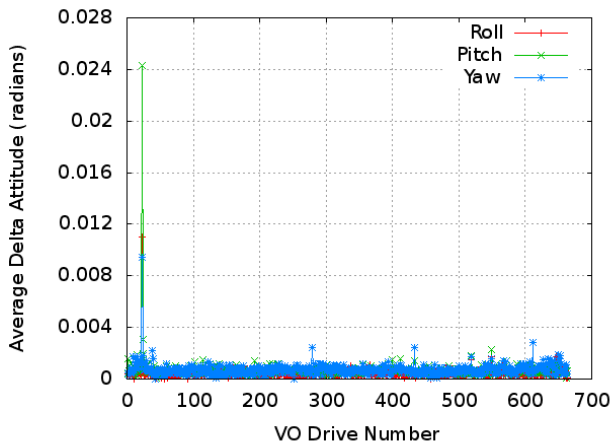

Figure 6. The average difference between SAPP and VO rover attitude angles for each drive where VO was performed.

degree in roll, pitch, and yaw, and each time, the pitch estimate differed by more than one degree (-1.391, -1.072, -2.195 degrees, respectively). Subsequent investigation led to the conclusion that the VO update was actually correct, but there was a bug in the IMU parameter settings (subsequently fixed) that inadvertently dropped attitude updates under high acceleration. Figure 6 shows that there has been little disagreement since those events.

4. DRIVE MODES

Curiosity can be commanded to drive with varying amounts of autonomy and attention. At the highest level, there are three Autonomous Imaging capabilities, four path-selection modes, and two drive motor control strategies.

Autonomous Imaging

Visual Odometry (VO) The process of acquiring VO images, transferring them to the CPU, downsampling them, generating a motion estimate and writing data products takes 47 seconds on average, so human operators choose between four operational VO modes depending on the needs of a particular plan.

Off No VO images are taken, no slip measurements are done.
VO Full VO processing occurs at every step, nominally 1 meter apart.
Slip Check During most of the drive no VO images are taken. But every 20 meters, a pair of stereo images is collected around a [40cm] step. That results in a slip estimate that has the potential to stop the drive if pre-established thresholds are exceeded.
VO Auto In this mode, VO switches autonomously between Slip Check and Full modes, depending on local terrain conditions. There are four criteria than can cause the rover to transition to Full VO imaging: rover tilt, average motor current, angular rate during turn-in-place, and slip amount.

Hazard Detection generates a 3D model of the nearby terrain by processing multiple stereo pairs of images. The 3D information is merged into a multi-layer 2D World Map of nearby local terrain using the GESTALT algorithm [5], and that map is consulted during Guarded and Avoid-all-hazards path selection modes. The World Map models nearby terrain at $40x40cm^2$ resolution by default.

Visual Target Tracking The rover can be commanded to autonomously re-center on a target as it drives. [6] describes the initial demonstration of this capability on the Mars Exploration Rovers.

These onboard autonomous imaging capabilities can be used simultaneously or individually, but in practice they are typically used independently.

Path Selection

In waypoint-style driving, where the goal is specified as a point in the current Site Frame, four different path selection strategies are available.

Directed Drive directly toward the goal.
Guarded Drive directly toward the goal, but consult the World Map to find hazards as you go. If any cell along the path would cause the rover to enter a Keepout Zone or get too close to a geometric hazard, the drive will terminate before planning the step that would drive onto that cell. This mode is often used in conjunction with collecting imagery and building up the World Map.
Avoid Keepout Zones (AvoidKOZ) Autonomously avoid any manually-specified Keepout Zones, but do not consider geometric hazards by consulting the World Map.
Avoid all hazards (AutoNav) Autonomously select a path to steer around any nearby Geometric Hazards and Keepout Zones. Used in conjunction with collecting imagery and building up the World Map.

Both the AvoidKOZ and AutoNav strategies use the D* algorithm to choose a globally optimal path [7], [8].

Drive Strategies

Curiosity implements arc-based driving using traditional double Ackermann steering control, pointing each corner wheel independently along a tangent to the turning circle for that wheel's radius.

Two options exist for controlling each wheel's speed:

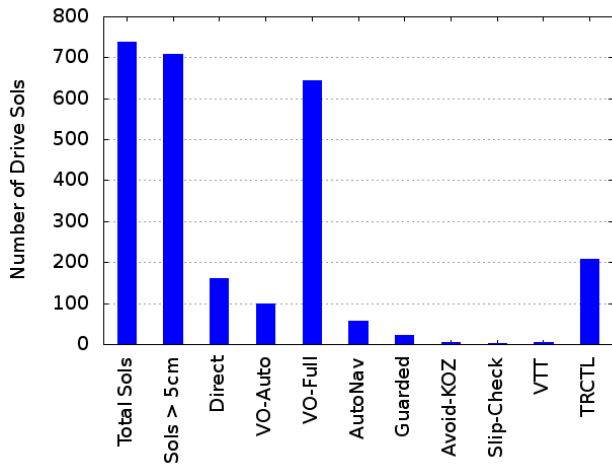**Constant Speed** When driving in its default mode, the FSW

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Figure 7. Number of sols using each drive mode.

Figure 9. Curiosity cumulative commanded odometry by drive mode.

commands each wheel to rotate using a constant angular rate. The maximum rate is 0.168 radians/s, which translates into a maximum linear wheel speed of 4.2 cm/s. Wheels with the greatest turning radius are commanded at this highest speed, with other wheels' rates set in proportion, so that all wheels will end the drive segment at the same predicted time.
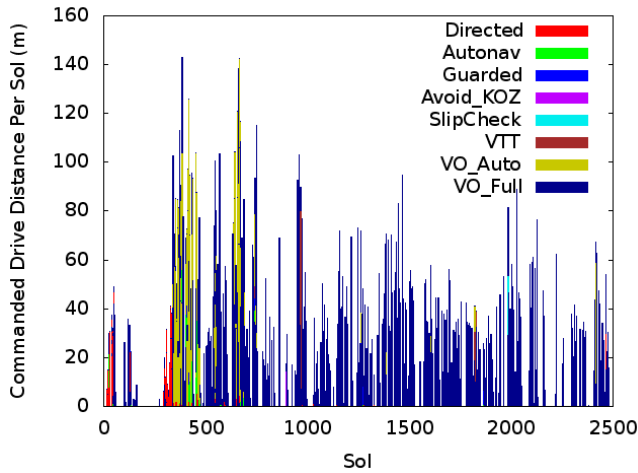

Figure 8. Curiosity odometry per sol by drive mode.

Terrain-adaptive wheel speed control (TRCTL) Since sol 1678, we have primarily used a new terrain-adaptive wheel speed control algorithm called TRCTL [9]. The algorithm combines realtime suspension angle measurements with a kinematic model to generate a real-time estimate of which wheels might be climbing local terrain. In this mode, at least one wheel is commanded at the maximum wheel angular rate, but the other rates vary at 8Hz in response to estimated local terrain shape.

Use of the various drive modes has changed as the mission has progressed. Figure 7 shows the number of drive sols that employed each drive mode, and Figures 8 and 9 show the overall mission odometry categorized by drive mode.

Referring to Figure 9, the rover drove relatively little during the first year, mainly because we had the good fortune to land in an area rich with targets of interest to the science team
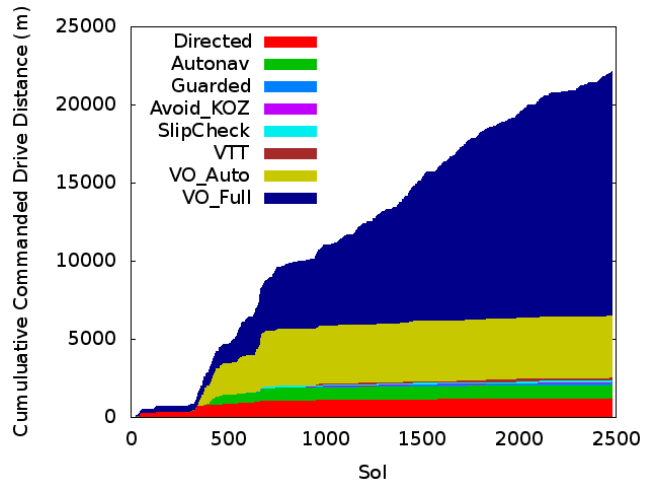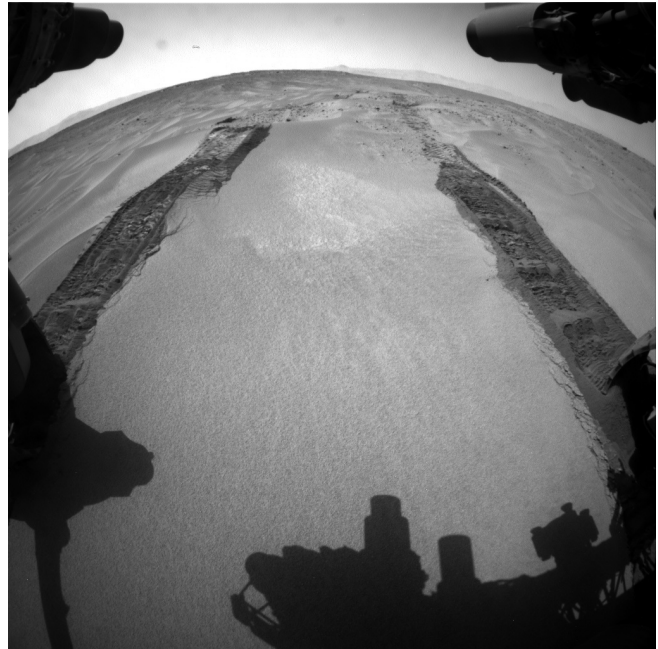

Figure 10. Front hazcam view of the sol 672 partial embedding event where VO Auto stopped the drive early.

("Yellowknife Bay"). It did not take long to reach them, so we mainly exercised directed driving with occasional VO for the first 200 sols. After the first year we started driving as fast and far as possible, making use of VO-Auto for slip safety and AutoNav to enable the rover to extend human-planned drives safely into terrain unseen by human eyes. See the increasing slope in Figure 9 and the distance-per-sol records in Figure 8. Discovery of wheel skin damage around sol 490 and our first partial embedding event on sol 672 (see Figure 10) each led to downturns in drive rate during the subsequent weeks. Those events and the discovery around sol 710 (in "Hidden Valley") that the rover's performance in polygonally-rippled sand was insufficient to make good progress led us to favor somewhat slower VO-Full drives ever since, since that mode can react most quickly to any unexpected slip events.

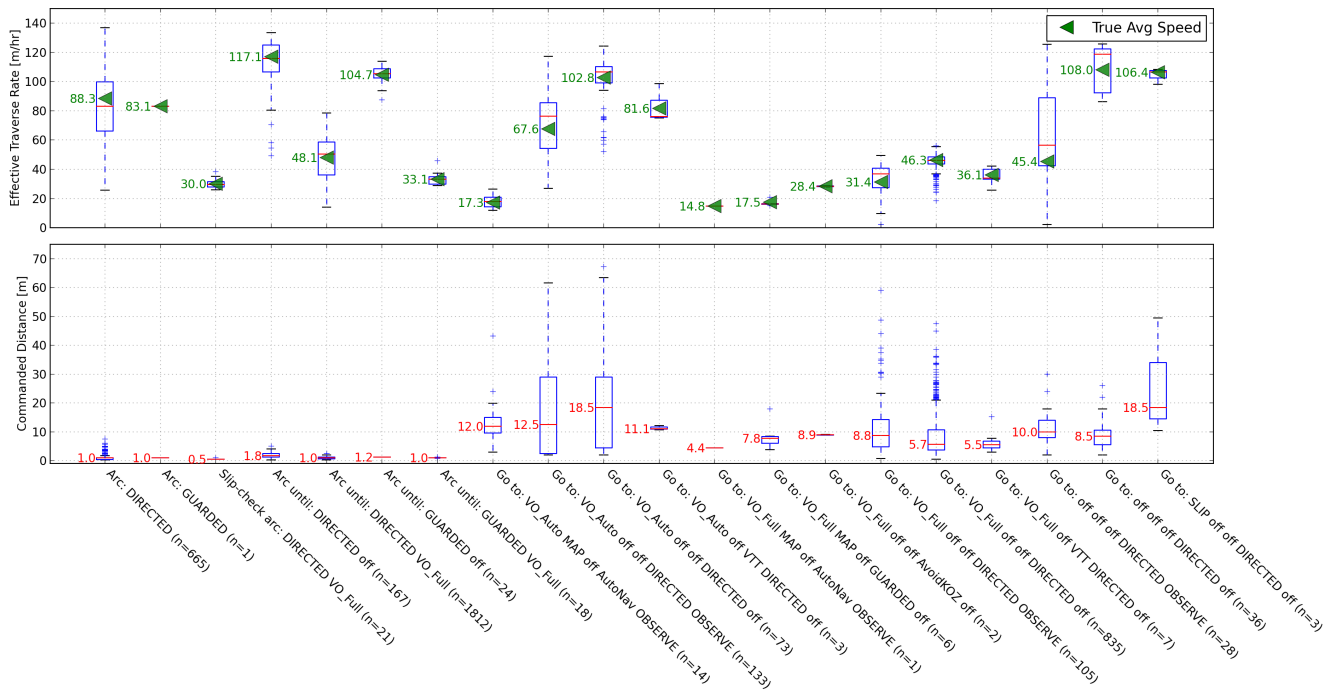Figure 11 and Figure 12 show the overall drive speed with

Figure 11. Effective Drive Rates without TRCTL. Boxplot showing interquartile range (blue) and median (red) for traverse rate and duration of each drive command by mode. Rather than reporting the "mean of the achieved speeds," which is not a meaningful quantity, we instead indicate the true average speed (quotient of total drive distance and total drive duration) for each mode with a green triangle and numeric label. The order of the arguments for "Go to" are VO mode, whether or not to update the Hazard Detection map, whether or not to perform Visual Target Tracking, path selection mode, and whether or not to run an observation sequence to acquire mid-drive images.
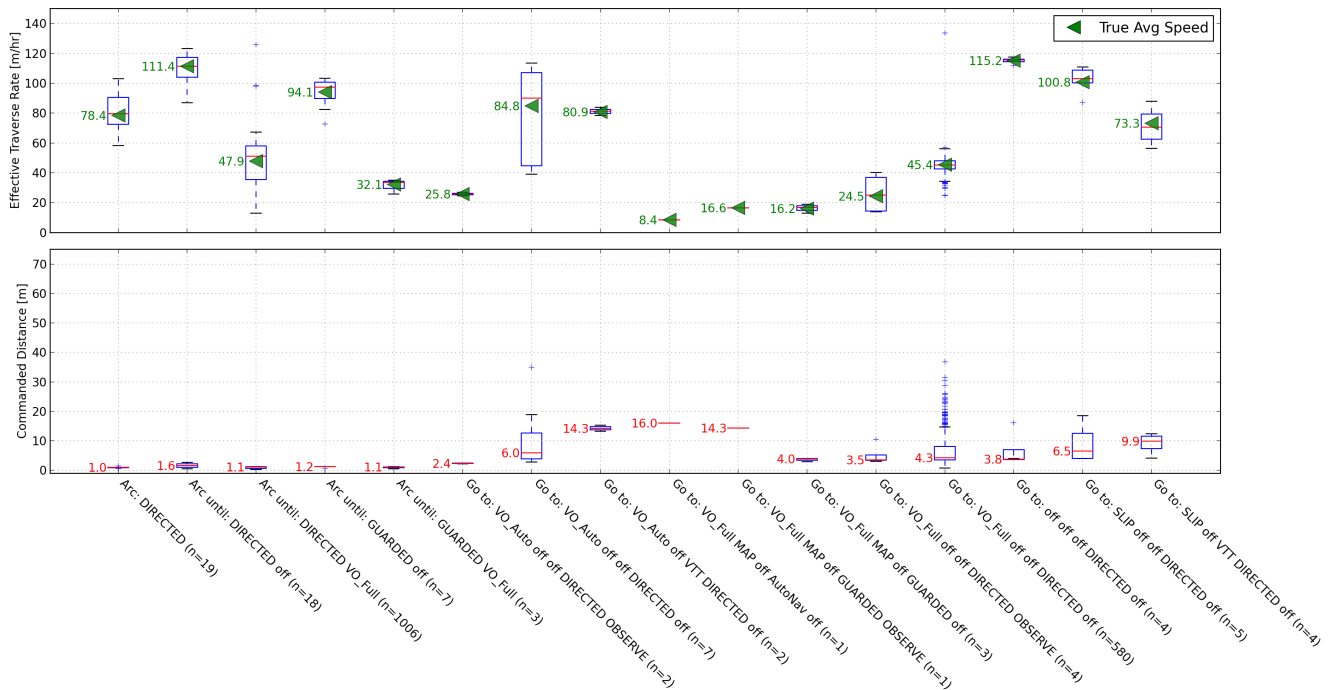

Figure 12. Effective Drive Rates with TRCTL enabled.

TRCTL disabled and enabled, respectively. Recall that since TRCTL entails only one wheel guaranteed to be traveling at the max wheel speed, one might expect longer drive times

for achieving the same drive distance. Indeed, this can be seen in the empirical effective traverse rates with TRCTL enabled and can be viewed as a performance tradeoff in favor
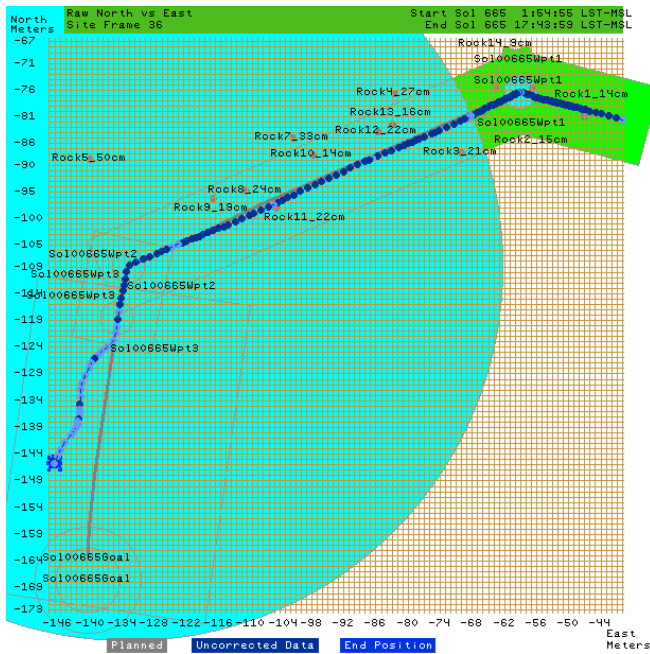
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Figure 13. Map of the longest single-sol drive (sol 665, 142.5 meters). The drive started in the upper right and ended on the way to the goal at the bottom left. The grey path was the simulated path, the circles indicate the route actually taken. Dark blue circles indicate drive steps without VO, light blue circles indicate steps with VO and/or Hazard Detection images, grey circles indicate terrain features individually labelled by Rover Planners. Grey boundaries indicate keep-in zones and and waypoints (including commanded tolerances). The final 25 meters of the drive were in AutoNav mode, and the drive terminated successfully when the time of day limit was reached.

of preserving wheel health.

5. OVERALL DRIVE DATA

At the end of every drive, performance statistics are reported to the operations team. The best such odometry statistic, and the one closest to ground truth we have available, is the ideal path length scaled according to VO corrections, as it incorporates the ideal vehicle kinematics as well as any deviations from it as observed in VO updates. There have been 738 attempted drives as of sol 2488, resulting in a cumulative odometry of 21,318.545 meters. Curiosity's drive distances each sol have ranged from its shortest drive of 2.6 centimeters (sol 1555) to its longest drive of 142.5 meters (sol 665, see Figure 13). The average odometry per attempted drive is 28.887 meters, and the average drive frequency is once every 3.37 sols. Figures 8 and 9 show the achieved odometry for each drive sol, color-coded by drive mode.

At the start of the mission, Rover Compute Element A (RCE-A) was the prime computer and RCE-B was the backup computer. Due to an anomaly related to a failing region of RCE-A NAND flash memory, the operations team commanded a swap to RCE-B on sol 201. After the data product partition on RCE-B failed to mount on sol 2173, the operations team switched back to RCE-A on sol 2188 until after the RCE-B data product partition was reformatted on sol 2342. The cumulative odometry performed on RCE-A and RCE-B are
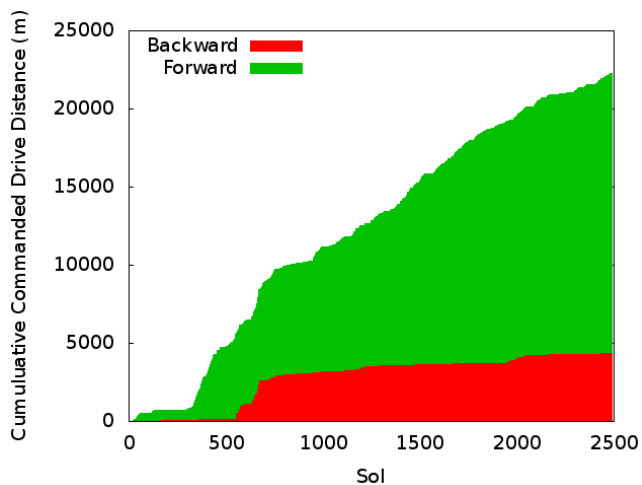

Figure 14. Curiosity cumulative commanded odometry by drive direction.

1,158.793 meters (5.63%) and 20,159.565 meters (94.37%), respectively, with RCE-A mobility occurring between sols 15-166 and sols 2250-2338.

Rover driving can be performed in the forward direction, in the backward direction, or by turning in place. Turning in place is commonly used on benign terrain 1) after the rover reaches a waypoint, to align itself with the next waypoint, or 2) after the rover has reached the drive goal position, to turn to a heading optimal for transmitting telemetry to a Mars orbiter or Earth. Turning in place does not use TRCTL, regardless of whether it is disabled or enabled in software parameters. Steering on harsh terrain can cause more wheel damage than driving on harsh terrain. Since turning in place requires steering the outer four wheels, turning in place is limited to mostly benign terrain.

Although backwards driving has been shown to reduce the forces on the middle and front wheels, forward driving is much more common than backward driving for two primary reasons related to the desire to limit turning in place. First, transitioning between a forward drive and a backward drive in the most efficient manner typically requires turning in place. Secondly, a turn-in-place is typically needed at the end of a backward drive to perform post-drive imaging in the direction of the next drive. Post-drive imaging is performed to update the ground-based terrain mesh used to plan the next drive. A turn-in-place is typically needed after a backward drive because the rover body occludes nearby terrain when imaging backwards with the engineering cameras on the mast. Figure 14 shows the cumulative commanded forward and backward odometry up through sol 2488. The cumulative commanded forward and backward odometry are 17,805.671 meters (80.1%) and 4,435.860 meters (19.9%), respectively. During sols 546-671, backwards driving usage increased due to concerns about excessive wheel wear. Wheel wear test results from the JPL Mars Yard indicated that the wheel damage rate is lower for backward driving than forward driving.

Positive wheel angular rates for a left and right wheel corresponds to forward driving, negative wheel angular rates for a left and right wheel corresponds to backward driving, and left and right wheel angular rates with a different sign corresponds to turning in place. Angular rate data for the LF

and RR wheels were analyzed up through sol 2488. The number of executed forward, backward, and turn-in-place moves are 4,835,049, 1,224,897, and 594,170, respectively. The percentage of the moves that were forward, backward, and turn-in-place are 72.7%, 18.4%, and 8.9% respectively. The average rover pitch during forward, backward, and turn-in-place moves has been 3.5, 2.3, and 2.9 degrees, respectively.

6. FAULT PROTECTION

Drives can stop earlier than expected for a variety of reasons. The rover's flight software monitors dozens of states and thresholds, any of which might lead to the raising of a mobility fault. There are two kinds of faults: a *Goal Error* alone simply means that a command was unable to reach its desired goal state but the rover is still safe, while a *Motion Error* means some safety threshold was exceeded and therefore the operations team must assess the circumstances and correct it. Once either fault has been raised, future mobility commands will recognize that status and gracefully fail without even attempting to move the rover. In this section, we review drives that failed to accomplish all their planned motions, and explain the circumstances that led to their early termination.

Planned drives that were not attempted

Curiosity drives were planned by the MSL operations team on 754 sols. However, drives planned for 16 of the sols were not even attempted by Curiosity for these reasons:

Safe mode For example, the drive planned for sol 1391 was not attempted because an anomaly occurred on sol 1389 that caused Curiosity to go into safe mode (stop executing the plan, reboot and stay safe).

Deep space network (DSN) transmission issue For example, the drive planned for sol 1070 was not attempted because there was a complex-wide power outage at the Madrid DSN site that prevented transmission of the plans for sols 1068-1070.

Planned drive withdrawn before uplink For example, the planned drive for sol 933 was withdrawn after a downlink revealed some of the sol 931 robotic arm activities failed due to a missing file.

Figure 15 shows the temporal distribution of the 16 planned drives that were not attempted by Curiosity. The cumulative predicted odometry for those 16 planned drives was 377.9 meters. On subsequent sols, 11 of the unattempted drives were replanned with no or little change, and 5 were replanned with significant change to the route or distance.

Planned drives that were attempted

Of the 738 drives that were attempted, 622 (84.3%) successfully completed with the rover reaching its goal position, while 116 drives (15.7%) did not run to completion. Despite 116 drive faults occurring, 91.7% of the predicted cumulative odometry over the 738 attempted drives was achieved. Of the 116 drive failures, 29 of them were expected and 87 were unexpected. Table 5 lists the 24 reasons why the 116 drive failures occurred, and includes the number of expected and unexpected drive faults for each reason. A drive fault is categorized as expected if a Rover Planner predicted in their daily plan summary that a drive might end early for a specific reason, and it did.

Twenty-six of the 29 expected drive faults were due to exceeding the time-of-day (TOD) limit, a specific time when

a drive sequence must stop (if it is still running) so there is time to run the other activities included in the plan. An example of this is stopping the drive at a specified time to be able to acquire post-drive imaging (for planning the next drive) prior to transmitting data to a Mars orbiter at a scheduled time. Autonomous hazard-avoiding drives are another common case, since they rely on the TOD limit to end the drive so that the rover can drive as far as possible in the allotted time. The other cases of expected drive faults include one occurrence each of exceeding the slip limit (sol 983), exceeding the tilt limit (sol 151), and entering a keep out zone (sol 163).

Referencing Table 5, of the 24 reasons why drives faulted, 16 are due to mobility events. The other 8 non-mobility reasons why drives faulted are 1) exceeding the TOD limit, 2) the robotic arm was not stowed, 3) a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) short was detected, 4) a MastCam foci mechanism was not closed, 5) the Sample Analysis at Mars (SAM) instrument was not safe for driving, 6) the Chemistry and Mineralogy (CHMN) instrument was in use, 7) a Remote Sensing Mast (RSM) error occurred, and 8) the limits on the difference between a VO and rover IMU attitude angle was exceeded.

Responses to non-mobility faults vary, and can change over the lifetime of the mission. Exceeding the TOD limit and exceeding the limit on the difference between a VO and IMU attitude angle both stop a drive that is in progress. However, the other 6 non-mobility drive faults will prevent a drive from ever starting. The response to a fault can also be changed by updating a parameter. For example, there have been 5 occurrences of a MMRTG short preventing a drive from starting, the last occurring on sol 1305. On sol 1309, the operations team changed a short response parameter to "ignore" for all steer and drive actuators, so that subsequent occurrences of the MMRTG short no longer prevented a drive. Figure 16 illustrates the temporal distribution of all the drive faults.

Planned drives that failed due to mobility fault protection

Real-time human intervention during drives on Mars is not possible due to the latency in uplinking commands and downlinking telemetry. Therefore, the flight software was designed to safeguard the rover during all activities, including driving. During a drive, mobility fault protection evaluates rover state at 8Hz. If any state relevant to driving is outside of set limits, a drive fault will occur, stopping the drive. Of the 116 drive faults that have occurred, 63 have been due to mobility fault protection. Table 6 lists the 16 reasons why the 63 drive failures occurred due to mobility fault protection, and Figure 17 illustrates their temporal distribution.

The operations team has the discretion to alter mobility fault protection limits to match the expectations for the drive. For example, if the drive simulation over a 3D terrain mesh shows a suspension angle will exceed its default conservative setting, Rover Planners will increase the suspension angle limit to be slightly above the maximum simulated suspension angle. Many such limits are nominally set somewhat conservatively, and only increased when the terrain calls for it.

Suspension fault protection

Curiosity suspension angles up through sol 2488 are shown in Figure 18. The max bogie and differential angles experienced by Curiosity are 25.2 and 9.4 degrees, respectively. The nominal flight bogie and differential angle limits are 17 and
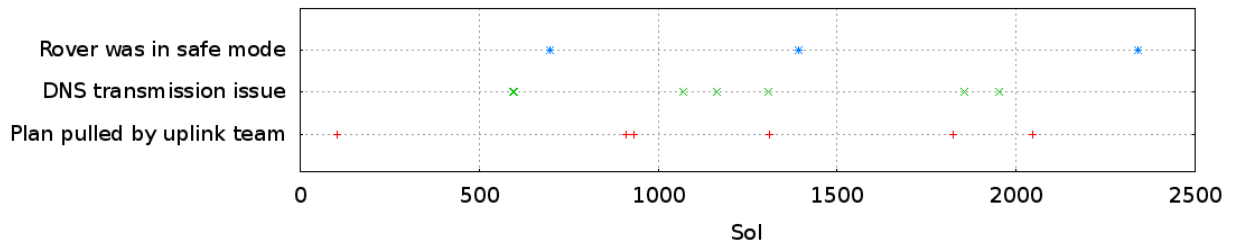
Figure 15. Sixteen drives were planned but not attempted by the rover.

Table 5. All reasons for Curiosity drive failures experienced on Mars. Non-mobility reasons are in italics.

	Expected Faults	Unexpected Faults	Total Faults
Time Of Day limit exceeded	26		26
Robotic arm was not stowed		14	14
Suspension limit exceeded		13	13
Slip limit exceeded	1	10	11
Unsafe AutoNav path evaluation		7	7
Steer actuator stall		6	6
MMRTG short		5	5
Too many VO failures		5	5
Rover yaw limit exceeded		4	4
Rover tilt limit exceeded	1	2	3
Keep-out zone entered or keep-in zone exited	1	1	2
Rover did not reach goal point within time limit		2	2
Rover pitch limit exceeded		2	2
VO deltas out of bounds		2	2
SAM not safe for driving		2	2
Drive actuator stall		2	2
MastCam focus mechanism not stowed		2	2
Previous drive failure		2	2
Rover too close to obstacle after blind drive onto map		1	1
Limit cycle		1	1
RSM error		1	1
Relative turn-in-place exceeded time limit		1	1
CHMN is in use		1	1
TRCTL drive step exceeded time limit		1	1
Total	29	87	116

7 degrees, respectively. Exceeding a suspension limit has caused thirteen drive faults.

Since the suspension system is passive, it is possible for a middle or rear wheel to lift off the terrain for a prolonged amount of time, if sufficient tension has built up in the suspension. For example, on sol 313, the LM wheel popped a wheelie during the final drive command to straighten the front and rear wheels. During that command, the left bogie angle increased 11.9 degrees, lifting the LM wheel off the terrain. On sol 317, the LM wheel was driven while still in a wheelie and the no load current was determined to be approximately 0.16 A.

TRCTL includes a wheelie suppression algorithm that watches for consistently growing bogie suspension angles above a threshold with a corresponding wheel that requires little current to turn. If this is detected, the speed of the other wheel on the bogie is adjusted to correct the condition and maintain six wheels in contact with the terrain. By default,

the TRCTL wheelie suppression algorithm is enabled when TRCTL is enabled [9].

Pitch and roll fault protection

Curiosity pitch and roll angles up through sol 2488 are shown in Figure 19. Rover pitch and roll are measured in a local level frame where x is forward, y is to the right, and z is down. Therefore, positive pitch corresponds to the forward side of the rover moving upward and positive roll corresponds to the left side of the rover body moving upward. The max absolute values of pitch and roll angles experienced by Curiosity are 25.22 and 20.69 degrees, respectively. Rover pitch and roll fault protection are disabled by default, but can be enabled on a drive-by-drive basis. The nominal flight pitch and roll limits are +/-15 degrees. Pitch fault protection has been enabled on seven sols (817, 1035, 1037, 1049, 1051, 1262, and 1371). Roll fault protection has been enabled on two sols (1260 and 1311). Exceeding the rover pitch min or max limit has caused two drive faults.
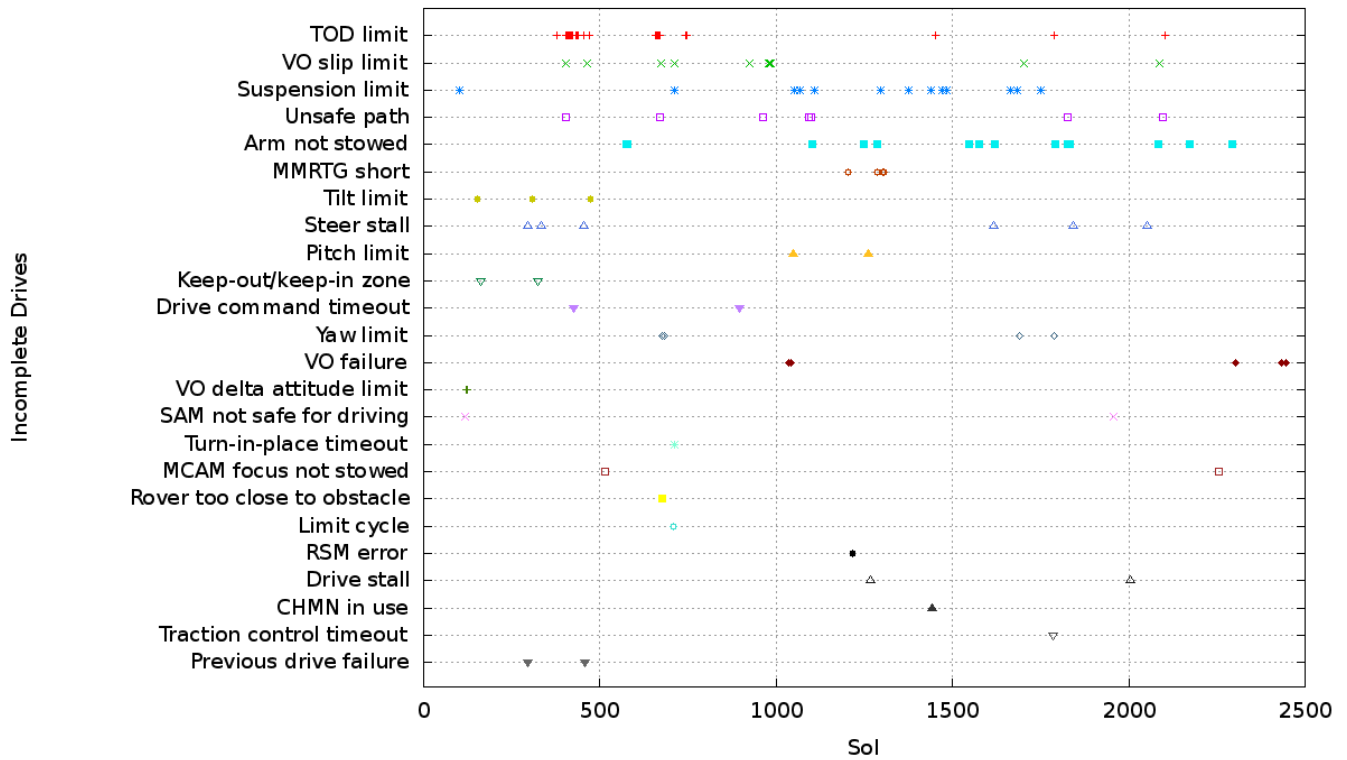
10

Figure 16. Twenty-four types of fault protection caused incomplete drives during the first seven years of the mission.

Table 6. Mobility reasons for Curiosity drive failures experienced on Mars

	Expected Faults	Unexpected Faults	Total Faults
Suspension limit exceeded		13	13
Slip limit exceeded	1	10	11
Unsafe AutoNav path evaluation		7	7
Steer actuator stall		6	6
Too many VO failures		5	5
Rover yaw limit exceeded		4	4
Rover tilt limit exceeded	1	2	3
Rover did not reach goal point within time limit		2	2
Rover pitch limit exceeded		2	2
Rover entered a keep-out zone or exited the keep-in zone	1	1	2
Drive actuator stall		2	2
Previous drive failure		2	2
Rover too close to obstacle after blind drive onto map		1	1
Limit cycle		1	1
Relative turn-in-place exceeded time limit		1	1
TRCTL drive step exceeded time limit		1	1
Total	3	60	63

Tilt fault protection

The rover tilt, which is the angle between the rover body z axis and the gravity vector, can be computed from the rover pitch and roll angles, or from the rover attitude quaternion. Curiosity tilt angles up through sol 2488 are shown in Figure 20. The max tilt angle experienced by Curiosity is 25.34 degrees. Tilt fault protection is enabled by default, and the nominal flight tilt limit is 30 degrees. However, the tilt limit is typically lowered for each drive, based on the max predicted tilt experienced in the simulation of the planned drive. Exceeding the tilt limit has caused seven drive faults.

Wheel slip fault protection

Wheel slip is dependent on terrain tilt and wheel/terrain interaction. Wheel-slip fault protection is enabled by default, with limits of 60% for a single occurrence and 40% for two consecutive occurrences. The operations team has the discretion to change the slip fault protection parameters appropriate
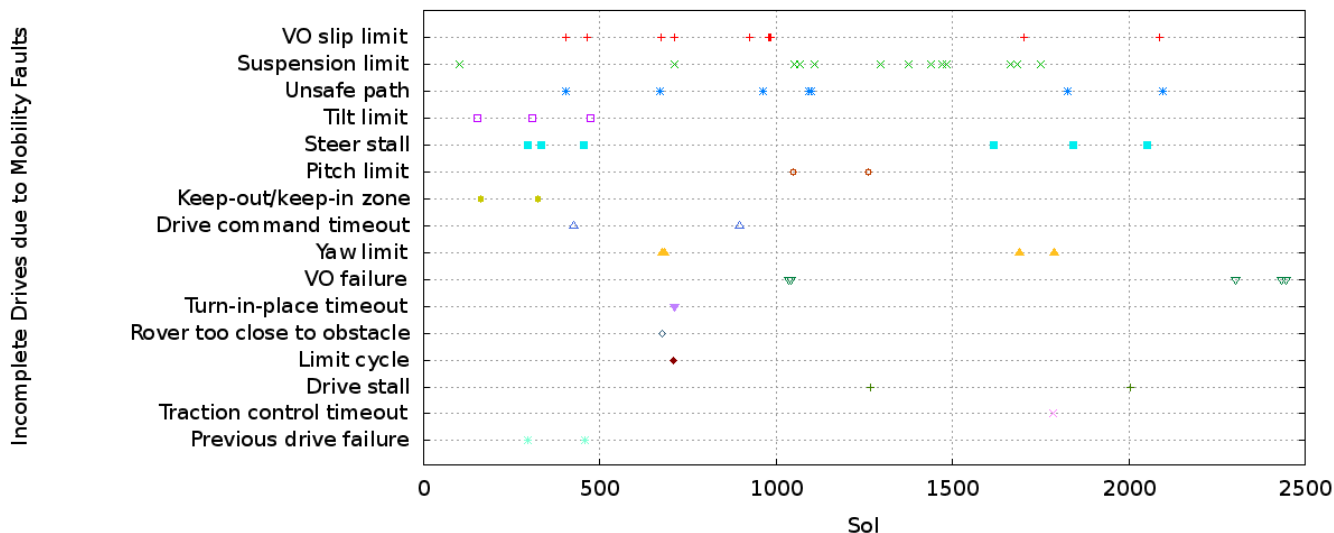
11

Figure 17. Sixteen types of mobility fault protection caused incomplete drives during the first seven years of the mission.
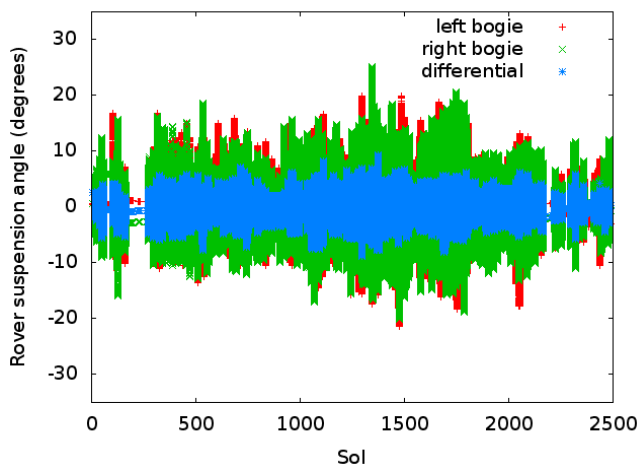

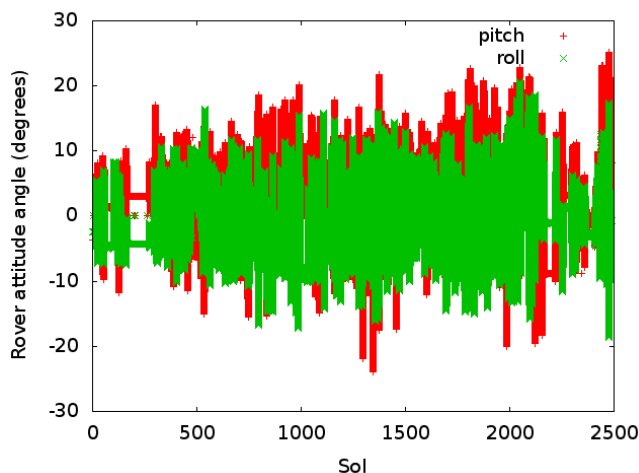**Figure 18**. Curiosity suspension angles during the first seven years of the mission.

Figure 19. Curiosity pitch and roll angles during the first seven years of the mission.

for the terrain and drive objectives. Figure 21 contains sol 2086 and 2087 NavCam images of the terrain where the maximum Curiosity wheel slip occurred, and Figure 22 shows a visualization of the drive path incorporating VO corrections. The sol 2086 drive faulted due to excessive wheel slip of 64.8%. Factors in the high wheel slip were a flat steep rock under the RR wheel, a ridge in front of the RF wheel, and an uphill rover tilt of 18.1 degrees. The operations team increased the single occurrence slip limit to 90% for the drive on the next sol, but that drive faulted with excessive wheel slip of 98.7%. Exceeding the wheel slip limit has caused 11 drive faults.

Unsafe path

During autonomous hazard-avoiding drives, the terrain is analyzed at each drive step and a safe step that brings the rover closer to its goal is selected. But if the path evaluations of all available steps fail to meet the safety threshold, an unsafe path fault is declared and the drive is stopped. During a guarded

drive, only the most goal-directed forward or backward step is considered and evaluated for safety. A common use case of guarded drives is when the desired path would need to cross a small patch of unknown data in the terrain mesh, and the operations team prefers to restrict the rover from autonomously discovering a new path (e.g., due to wheel wear concerns). The team will position the rover a few meters short of the unknown region, then let the rover evaluate the terrain; as long as it is determined by the rover to be safe, the drive will continue. An unsafe path has caused 7 drive faults.

Yaw fault protection

Rover slip can cause significant changes in the rover heading, particularly if the slip mostly occurs on the wheels on one side of the rover. Setting upper and lower limits on the expected yaw for each leg of a drive enables such slip to be detected quickly by the onboard attitude estimator, stopping the drive as soon as the limit is exceeded. Figure 23 illustrates terrain where wheel slip caused a 30 degree change from the desired
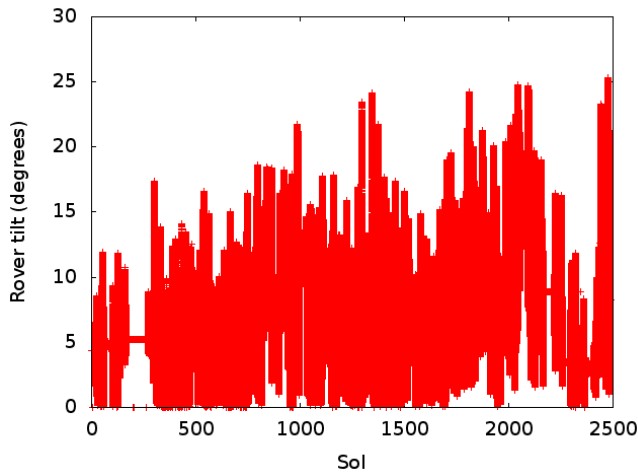
Figure 20. Curiosity tilt during the first seven years of the mission.

rover heading. Exceeding the yaw limit has caused 4 drive faults.

Actuator stalls

On seven occasions, Curiosity has experienced a stall condition of either a steering motor or wheel motor. This occurs when the motor stops turning prior to reaching its commanded position, normally after the motor controller has reached its current or voltage limit, and remains as such for a short amount of time. Like all mobility faults, this will stop further driving until a command is sent to re-enable mobility. Wheel interactions with rigid terrains can cause this condition, as well as possibly a motor under-producing required torque due to inaccurate current control or incorrect motor commutation, should there have been motor backdriving when its relative encoder was previously not monitored. This has occurred on sols 295 (RF steer), 333 (LR steer), 455 (RF steer), 1267 (RR drive), 1843 (RR steer), 2003 (RM drive), and 2051 (RR steer).

A related fault condition is "slow overcurrent," where a motor is consistently drawing more current than usual for a longer period of time and may be overheating or adversely interacting with soft terrain. This would still be below the instantaneous current limit for the motor, which may be needed and is not a problem for a short amount of time. This condition has only occurred once on sol 1616, when the RR steering current exceeded the current limit of 2.5 A for 2 seconds, resulting in a RR steering stall.

Keep-out and keep-in zones

Rover Planners use 2D Keep-out and Keep-in zones to indicate known hazards (including non-geometric hazards like sandy terrain) and specify corridors of safety. The onboard mobility software guarantees that the rover will never choose to enter any area declared off-limits by the combination of Keep-in and Keep-out zones; any such attempt will raise a goal error and cause that command to fail without commanding that motion. When used in combination with Visual Odometry for precise positioning, they enable the rover to stay out of dangerous areas even in the presence of unexpected slip. Zones can be specified as circles, oriented rectangles or triangles. Attempting to violate a keep-in boundary
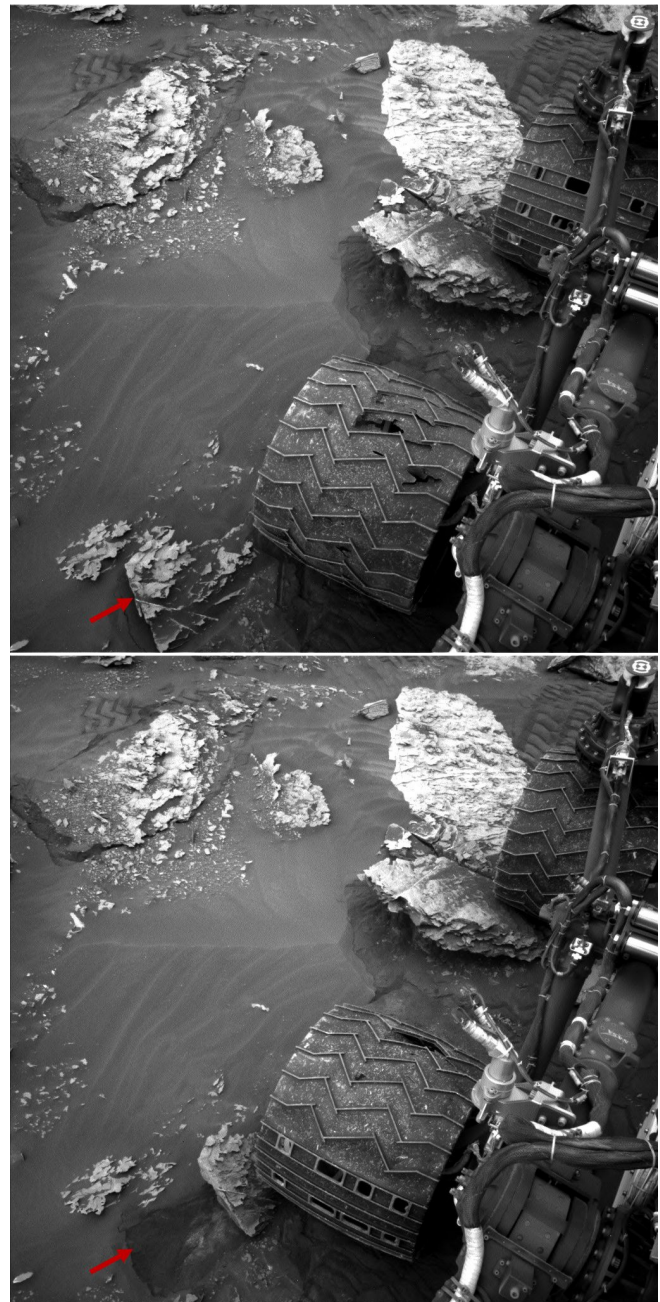

Figure 21. NavCam images of the RM and RR wheels on sols 2086 (top) and 2087 (bottom). The sol 2087 forward drive faulted when 98.7% wheel slip occurred, exceeding the 90% limit set for this drive. No forward progress was made. Note that a rock was dragged backward by the RM wheel.

has caused 2 drive faults (sols 163 and 324) due to rover slip.

Command timeout

A duration limit can be set on individual mobility commands. If the command execution exceeds the duration limit, the drive is stopped with a motion error. Duration limits can prevent a turn-in-place from executing indefinitely while the wheels are slipping and embedding. As illustrated in Figure 24, exceeding the duration limit for a turn-in-place command has caused 1 drive fault (sol 711). Other duration limits that have caused drive faults are exceeding the duration limit
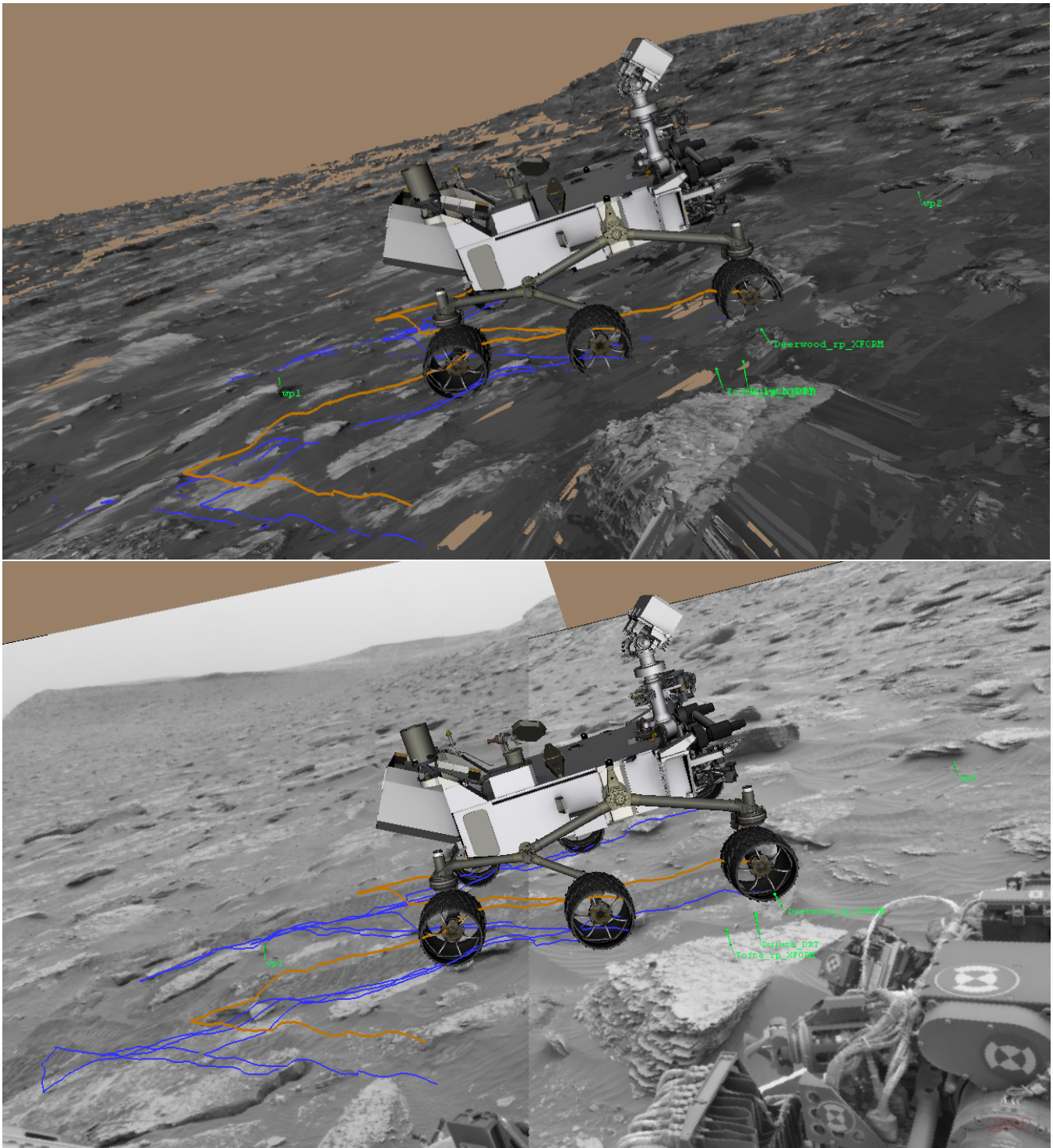
13

Figure 22. Visualizing the Sol 2086 drive, which failed due to high wheel slip. The upper image shows the actual rover path projected into the "planning mesh," a visualization of the terrain used by Rover Planners to create drive command sequences. Orange lines track the wheel centers, blue lines track the lowest point on the wheel (i.e., ground contact). The lower image shows the same data projected into NavCam images taken on sol 2089, after the drive completed. Actual drive tracks are visible in the lower image. Images rendered by the rover planning tool RSVP.

during execution of 1) an arc with TRCTL enabled (sol 1786), and 2) a go to waypoint motion (sols 426 and 896).

VO failure to converge

The operations team can choose to set a maximum number of allowable VO failures to converge. Setting such a limit is a helpful way to bound the amount of position uncertainty that must be evaluated for any given sol's drive plan (by limiting the number of steps that can accumulate unknown
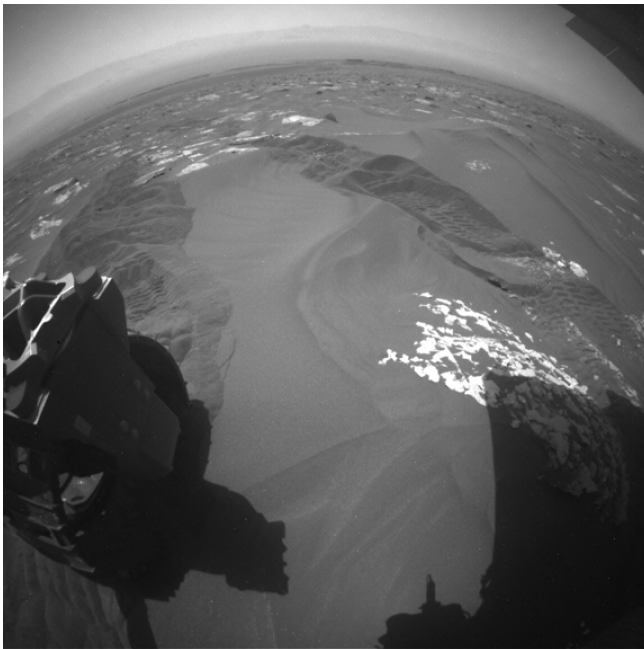
Figure 23. Rear HazCam image acquired after the sol 1789 drive. The RR wheel is visible in the image. High slip in sand caused Curiosity to exceed a 149.265 +/- 30 degree yaw limit, faulting the drive.

Figure 24. Sol 711 NavCam image of the RM and RR wheel after a turn-in-place command timed out. According to IMU data, the turn slip was 40.4%.

and uncorrected slip). Although VO works very well in general, it depends on there being enough features detected in the nearby terrain to enable their motion to be tracked. If any of its internal sanity checks fails or the terrain lacks sufficient features, it can fail to converge, e.g., as in Figure 25. The largest number of failures that have occurred on a single sol is 11 (sol 2434). The 11th VO failure caused a goal error to be declared and the drive to stop due to the VO failure limit

of 10 having been exceeded. VO failures have caused 5 drive faults.
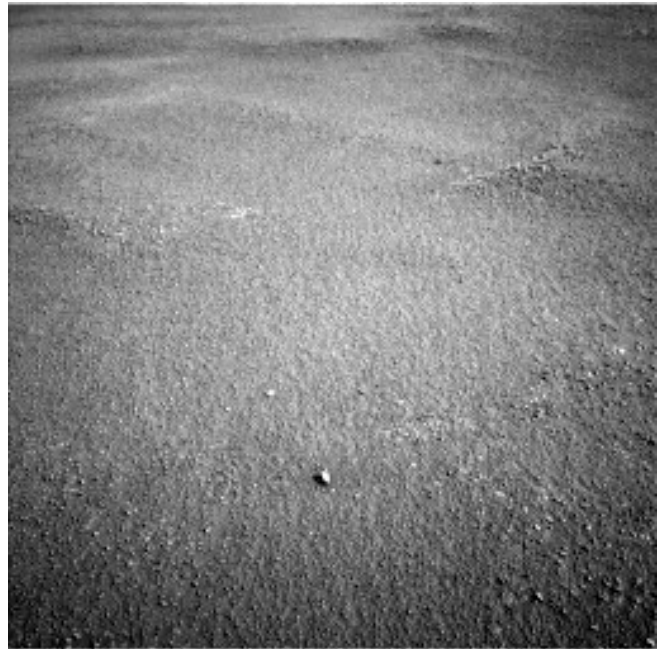

Figure 25. NavCam VO image from sol 2434 of terrain with a lack of autonomously detectable and trackable features. The max number of VO failures in a single drive (11) occurred here. The max wheel slip measured during the drive was 13.5%.
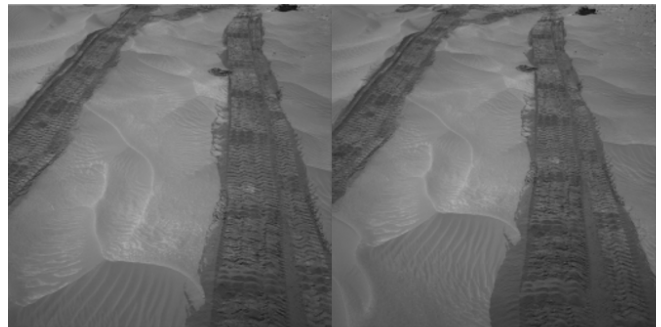

Figure 26. NavCam VO images of wheel tracks from sol 709. The commanded drive distance between the left and right image was 2 meters. Because Curiosity was not making enough progress towards the navigation goal, a limit-cycle drive fault was declared. During the final step of the drive, the wheel slip was 77.5%, below the 90% single occurrence limit set for this leg of the drive.

Rover too close to an obstacle

During Guarded and AutoNav drives, the rover uses its on-board World Map to determine whether it is safe to drive. The map is primed by collecting images of terrain known to be safe, then driving some 2.5 meters onto it (so that it can know the 3D shape of the terrain under the wheels). On only one drive (sol 677) the rover was driven up to the edge of a ridge, where it immediately saw significant steps in the nearby terrain. It was unable to find a safe path forward, so it faulted out with a goal error immediately.
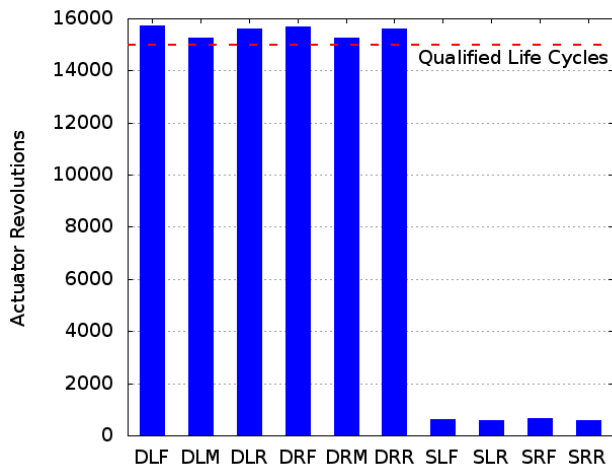
15

Figure 27. Drive and steer actuator revolutions as of sol 2488. DLF=drive left front, DLM=drive left middle, DLR=drive left rear, DRF=drive right front, DRM=drive right middle, DRR=drive right rear, SLF=steer left front, SLR=steer left rear, SRF=steer right front, SRR=steer right rear.

Limit Cycle

A Limit Cycle fault is raised whenever the rover commands a relatively large amount of motion (e.g., 4.5 meters), yet only achieves a much smaller amount of progress in Euclidean distance (e.g., 2 meters). Originally developed as a way to stop the rover from driving back-and-forth again and again during autonomous hazard-avoiding drives, it had been left enabled during the very slippery drive through the polygonal ripple sands of Hidden Valley on sol 709 (see Figure 26). On that drive the rover encountered very high slip (45% growing to 77.5% over seven steps), resulting in very slow progress, and that triggered the only instance of the Limit Cycle fault thus far. Although this demonstrates it can function as a slip detector, we have since relied on the Fast and Slow Slip filters instead.

Previous Drive Failure

When multiple drives are planned without ground in-the-loop in between the drives, if the first drive ends with a fault, the additional planned drives are precluded. Multiple drives without ground in-the-loop between them can be planned on a single sol or over multiple sols (e.g., over a non-planning weekend or holiday). There have been two occurrences of this type of drive failure. The sol 296 and 456 drives were precluded because the drives on the previous sols ended early with a RF steer stall.

7. Actuator Health

The qualified life cycles for the wheel and steer actuators (i.e., revolutions for 1x life) is 15,000 revolutions. During MSL pre-launch testing at JPL, a WSA was tested to 2x life, disassembled and inspected, and no failure was observed. Figure 27 shows the total number of actuator revolutions for each actuator.

The six drive actuators are independently controlled. As shown in Figure 27, the maximum number of Curiosity drive actuator revolutions has ranged from 15,253.0 to 15,716.4 revolutions, slightly above 1x life. Note that the middle drive actuators have experienced slightly fewer revolutions than the front and rear drive actuators. Because the middle wheels are closer to the instantaneous center of rotation than the front and rear wheels, they revolve less during turns-in-place and non-straight arcs.

The four steer actuators are also independently controlled and have a hard limit of +/-95 degrees and a software limit of +/-85 degrees, both of which are measured as angles from the rover's longitudinal axis. Steering is performed much less frequently than driving. As shown in Figure 27, the number of Curiosity steering actuator revolutions has ranged from 596.7 to 643.8 revolutions, approximately 3.8% of their 1x life. The number of revolutions for the rear steering actuators are slightly less than the front steering actuators. Since the rear wheels are closer to the middle wheels than the front wheels, they steer to a slightly smaller angle than the front wheels during a turn-in-place.

As of sol 2488, we have experienced 2 drive actuator stalls (sols 1267 and 2003) and 6 steer actuator stalls (sols 295, 333, 455, 1616, 1843, and 2051). The most recent three steer stalls have occurred on the RR steer actuator, likely a coincidence since there have been no further stalls for 437 sols. The maximum drive and steer actuator currents have been 4.422 and 3.594 amps, respectively, well below the 10 amp max current rating for the WSA. The low number of steer actuator revolutions leads to high confidence in their continued usage for years to come. Given, a WSA was tested to 2x life without any failure, there is also confidence in the continued usage of the drive actuators for years to come.

8. Wheel Health

On sol 490, the MSL team discovered a mission threatening amount of damage to the rover wheels. As the rover had only driven 4.6km of its 20km design goal, it led to an investigation to understand and reduce the rate of damage in order to increase the longevity of the mission. Initial damage was found to be related to the drive control mode of the six wheel drive actuators and the kinematics of the rocker-bogie suspension. Wheels leading a suspension pivot were forced onto sharp, immobile surfaces by the other wheels as they maintained their commanded angular velocities [10].

A new algorithm, known as TRCTL, adapts each wheel's speed to fit the terrain topography in real-time, by leveraging the rover's measured attitude rates and rocker/bogie suspension angles and rates. When one wheel is going over a rock, the remaining wheels reduce their speed in order to not push or pull the rock-climbing wheel into the rock, reducing the forces on the wheel. TRCTL was approved for nominal use in flight on sol 1678 (April 24, 2017). Since sol 1678, 99.48% of the total odometry has had TRCTL enabled, and 93.75% of drive sols have had TRCTL enabled for at least a portion of the drive.

The image of the LM wheel in Figure 28 shows the damage done to the wheel since sol 490 including a broken grouser. The new algorithm has empirically demonstrated reduction of wheel damage rates as predicted, at the cost of increasing drive duration by 10% on average and roughly doubling the drive motor history data volume.

Testing conducted in the Mars Yard facility (located at the Jet

Table 7. Terrain-adaptive Speed Control Efficiency Table

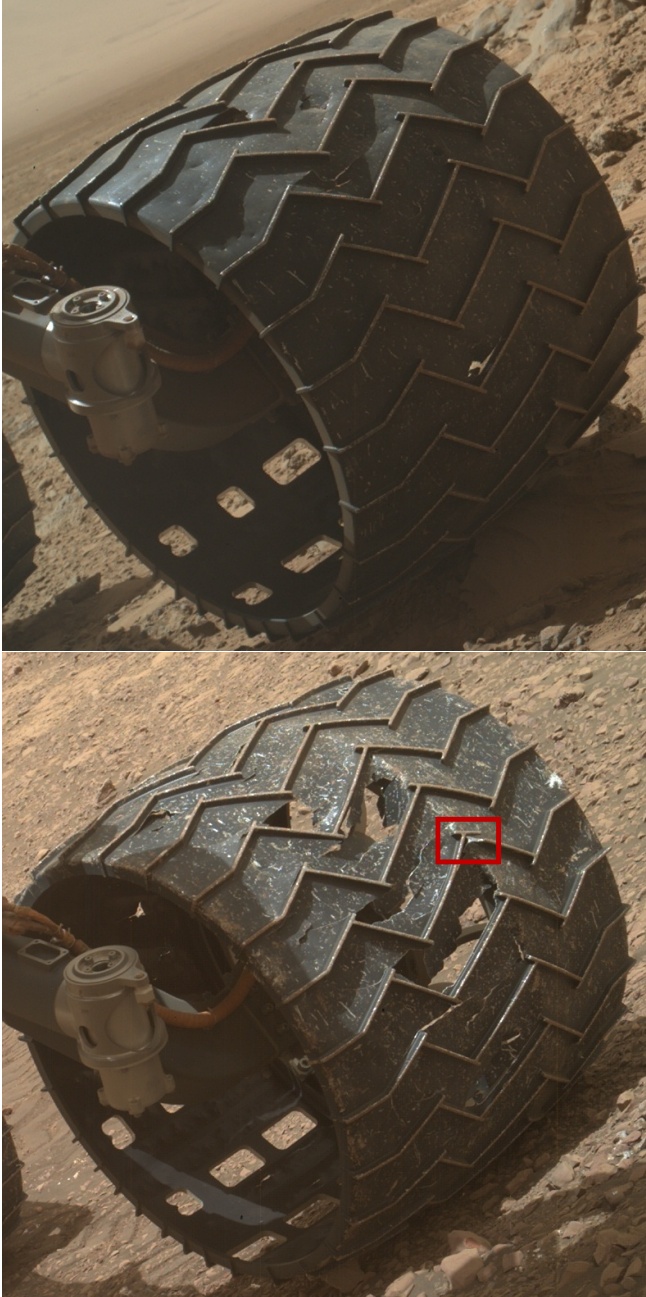|	Pre-TRCTL (sol 0000-1677)	Post-TRCTL (sol 1678-2488)
Mobility sols with some odometry	502	4 (TRCTL disabled) 199 (TRCTL enabled) 9 (both)
Odometry (meters)	16,323.9	26.0 (TRCTL disabled) 4968.5 (TRCTL enabled)
Grouser breaks	2	1
TRCTL drive faults	-	1

Figure 28. Images of the LM Wheel from sol 490 (top) and sol 2030 (bottom). A grouser is visibly broken in the image from sol 2030. Image Credit: NASA / JPL-Caltech / MSSS.

Figure 29. Number of grouser breaks on each wheel, measured since the first grouser break. Thus far, only the left middle and right middle wheels have grouser breaks. GB = good blue terrain, i.e., relatively benign terrain.

Propulsion Laboratory) without TRCTL software predicted a rate of grouser breaks that could result in unconstrained portions of the wheel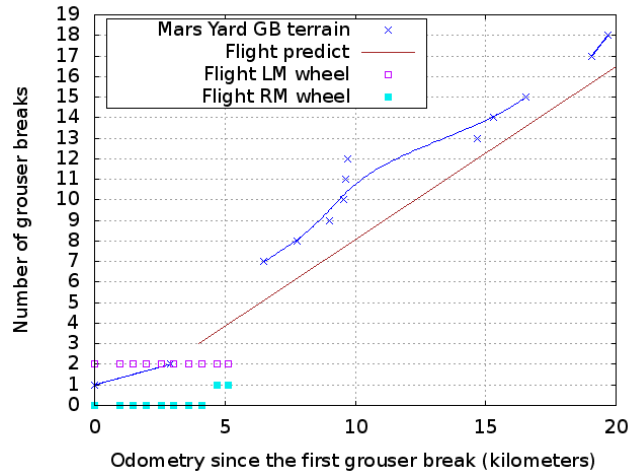 contacting the electrical cable to its drive actuator some 20 km after the first break occurred, shown in Figure 29. Based on that model, after accumulating 5 km beyond the first grouser break, 4 grouser breaks were expected on a single wheel. However, as of sol 2488 and 5 km since the first grouser break on Mars, the number of breaks on the LM wheel is only 2 and on the RM wheel only 1. Both of the grouser breaks on the LM wheel occurred prior to nominal use of TRCTL on Curiosity. Additional testing has shown that Curiosity could continue to drive indefinitely on the portion of a wheel that remains when all the grousers on a wheel breaks, if the unconstrained portion of the wheel can be safely shed [11].

23.31% of Curiosity's odometry thus far was achieved while TRCTL was enabled. Table 7 summarizes the TRCTL results over that period.

9. SUMMARY

In this paper, we reviewed the performance of the Curiosity rover's Mobility subsystem and the challenges of operating it during the first seven years of its surface mission in Gale Crater. We reviewed the mobility software modes and operational uses, described the current state of the mobility subsystem hardware, and gave detailed breakdowns of several example classes of mobility activity failures, including descriptions of their fault protection modes. Despite the rover's fault protection flight software stopping 116 drives short of their goal position, 91.7% of the planned odometry for the attempted drives was achieved. This 8.3% reduction in odometry has been an acceptable cost given the benefits in safety provided by the rover fault protection FSW.

On average, Curiosity drives 96 meters less per year than Opportunity did. Near-term MSL science objectives and safety considerations dictate how frequently and how far Curiosity drives. Curiosity's mobility actuators are in good health at well below their expected lifetime, and TRCTL has demonstrated a reduction of wheel damage rates. However, Mars remains a harsh operational environment. The MSL Mobility subsystem team will continue to monitor Curiosity's progress and develop ground support tools, anomaly diagnostics, recovery strategies, and flight software improvements as we continue to explore as-yet-unseen terrains while summiting the slopes of Mount Sharp.

ACKNOWLEDGMENTS

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BIOGRAPHY

Arturo Rankin received his Ph.D. in Mechanical Engineering at the University of Florida in 1997. He is currently a Robotic Systems Engineer in the Robot Operations group at the Jet Propulsion Laboratory, and the M2020 Robot Operations deputy lead. Prior to that, he was the MSL Mobility/Mechanisms team lead and the MSL Flight Software team lead.

Mark Maimone is a Robotic Systems Engineer in the Robotic Mobility group at the Jet Propulsion Laboratory. Mark designed and implemented the GESTALT self-driving surface navigation Flight Software for MER and MSL missions; during MSL operations served as Deputy Lead Rover Planner, Lead Mobility Rover Planner and Flight Software Lead; developed downlink automation tools for MER and MSL; and is now a member of the Mars 2020 Rover FSW development team. He holds a Ph.D. in Computer Science from Carnegie Mellon University.

Jeffrey Biesiadecki is the Principal Investigator of the MSL Terrain-adaptive wheel speed control effort. He has been a software engineer at NASA's Jet Propulsion Laboratory since 1993, after completing his Master's degree in Computer Science at the University of Illinois, Urbana-Champaign. He designed and implemented the core motor control and non-autonomous mobility flight software for the Mars Exploration Rovers (MER) and MSL, and was a rover driver for MER and MSL, responsible for command sequences that tell the rover where to drive and how to operate its robotic arm on the surface of Mars. He is presently leading the development of the Mars 2020 rover Sampling and Caching Subsystem flight software.

Nikunj Patel is a Tactical Downlink Lead for MSL, which follows the responsibilities of a flight director on the mission. He achieved his Bachelors of Science in Aerospace Engineering from University of Central Florida (UCF) and is currently working towards a Masters degree in the same field. He has lead two cubesatellite develop machines through AIAA and UCF. In addition to that, Nikunj designed the first Ground Support Biobarrier (GSB) that would be utilized by NASA's Planetary Protection (PP) team to meet stringent bioburden requirements for future life detection missions to other terrestrial bodies.

Dan Levine is a robotics technologist in the Perception Systems group at the Jet Propulsion Laboratory. He is generally interested in applications of computational statistical methods to challenging problems in robotic perception, inference, and control. He is currently a software developer for the Mars 2020 rover Sampling and Caching Subsystem. He holds a Ph.D., S.M., and S.B. from MIT's Department of Aeronautics and Astronautics.

Olivier Toupet received his M.S. degree in Aeronautics and Astronautics from MIT in 2006. He is currently the supervisor of the Robotic Aerial Mobility Group at the Jet Propulsion Laboratory, which develops innovative technologies for UAVs with a focus on guidance, navigation, and control. His current research also includes the development of novel robotic technologies for Mars rovers, such as the path planner for the M2020 rover mentioned in this paper, and the traction control algorithm for the Curiosity rover, which optimizes the speed of the wheels in real-time to minimize slip and wheel wear.