

Mars Exploration Rover Mobility Assembly Design, Test and Performance

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Abstract – *In January 2004, NASA landed two mobile robotic spacecraft, or rovers, on opposite sides of the planet Mars. These rovers, named Spirit and Opportunity, were each sent on their own scientific mission of exploration. Their objective was to work as robotic geologists. After more than a year the vehicles are still in excellent health, and returning vast amounts of scientific information on the ancient water processes that helped form Mars. Key to the success of the rovers was the development of their advanced mobility system. In this paper the mobility assembly, the mechanical hardware that determines the vehicles mobility capability, is described. The details of the design, test, and performance of the mobility assembly are shown to exceed the mission requirements. The rovers' ability to traverse the Mars terrain with its combination of rocks, craters, soft soils, and hills was verified, and the system design validated.*

Keywords: Rover, rocker bogie suspension, Mars, mobility, traversability.

1 Introduction

NASA has a limited history with missions to the surface of Mars. The Viking missions of the mid 1970's were followed eventually by the Mars Pathfinder mission in 1996 [1]. NASA's current Mars Program is once again focused on missions to the Martian surface to answer fundamental questions of the extent Mars ever supported a liquid water environment on its surface. To that end, the Mars Exploration Rover project was embarked upon in mid 2000 to land two mobile exploration platforms at different science targets on the red planet. The center-piece of each mission is the rover and its scientific payload.

Spirit and Opportunity are identical vehicles and each carries the same science instrument payload and engineering subsystems [2], [3]. They were designed to meet a set of key requirements that included the ability to traverse over obstacles of at least 25 cm dimensions, sloped terrains of at least 20 degrees tilt, and to travel distances in excess of 1 km over hard high-traction terrains, and soft deformable soils. At the rover wheelbase, each vehicle is approximately 1.4 m long and 1.2 m wide. At the solar panel each rover is 2.25 m wide by 1.5 m long. In their

fully deployed configuration each rover is just over 1.5 m tall and has a ground clearance of about 0.3 m. The rovers are 6-wheel drive, 4-wheel steered vehicles with a rocker bogie suspension system similar in design to their predecessor, Sojourner, the rover sent to Mars on the Mars Pathfinder mission in 1996 [4]. The vehicles center of mass is near the pivot point of the rocker bogie suspension. As a consequence, the vehicles are able to withstand a tilt of 45 degrees in any direction without over-turning. The rocker bogie design allows the traversing of obstacles of at least a wheel diameter (25 cm) in size, though in operation the system is limited to 20 cm. Each wheel has cleats and is independently actuated, providing for climbing in loose soil-like materials and traversing over rocks approximately as high as a wheel diameter. The front and rear wheels are independently steered, allowing the vehicles to turn in-place as well as execute arcing turns. The rovers have a top speed on flat hard ground of 4.6 cm/s, but under autonomous control with hazard avoidance, the vehicles travel much more slowly, averaging less than 1 cm/s. The rovers were designed to drive to many different science targets for investigations by the instrument payload. Also, the rovers were designed to be highly autonomous, such as during traverses receiving only a single command sequence at the beginning of each Mars day, called a 'sol', and returning data by the end of the sol.

The Mars Exploration Rovers represent a great advance in planetary rover technology since their predecessor, the rover 'Sojourner', explored the local vicinity around the Mars Pathfinder lander in 1997 [5]. At 176.5 kg each, Spirit and Opportunity dwarf the 10.5 kg Sojourner. A great increase in size, mass, and power was necessitated by the need to carry extensive science payload, avionics, and telecommunications equipment; as well as to travel distances of up to 1 km from the landing site in rough terrain, and to function on the Mars surface for at least 90 sols. Whereas Sojourner operated in conjunction with the MPF lander, its data and command link to Earth, the MER vehicles left behind their dead landers once they egressed onto the Martian surface. Communicating directly with Earth or through one of two NASA Mars orbiters, Mars Global Surveyor (MGS) and Mars Odyssey, the rovers executed command sequences and performed autonomous mobility and instrument arm placement

operations. This paper covers the requirements and development of the rover as a mobile platform, with detailed descriptions of the mobility assembly, and its connection to higher level rover traverse capability requirements derived from mission science goals. Specifically the limited design heuristics that date back to the Sojourner rover were, extrapolated to the MER vehicles during the design phase of the Project and utilized as the key system requirements. The implementation of the resulting designs in the wheel assemblies and their drives, and in the differential mechanism, and the rocker bogie suspension are discussed in detail. This papers' emphasis is on the deployed vehicle as a mobile platform (i.e., the configuration in which it drives), the hardware development of the mobility assembly, and testing at the assembly level will also be described, and the key results given. In addition, the performance of the flight vehicles on Mars will be contrasted against their test program on Earth.

2 The Mobility Assembly

The MER vehicles were designed with a similar mechanical architecture to Sojourner [7]. The suspension of the rover is a mechanical architecture called a rocker bogie that connects the 6-wheels to the body of the rover. In the body of the rover, an internal differential connects the left and right side rocker bogie assemblies to the rest of the vehicle. All 6 wheels of the rover are independently driven by their own d.c. motor driven actuator, and the front two wheels and rear two wheels are also steered by identical d.c. motor driven actuators as are the wheel drives. In Figure 1 the Spirit rover is shown performing its first drive in the Spacecraft Assembly Facility at JPL. This represented one of the few times that the flight vehicles mobility hardware was put through their paces as part of the full up system. The vast majority of mobility testing was performed utilizing either of the two engineering model vehicles that were also developed and assembled in the same time frame.

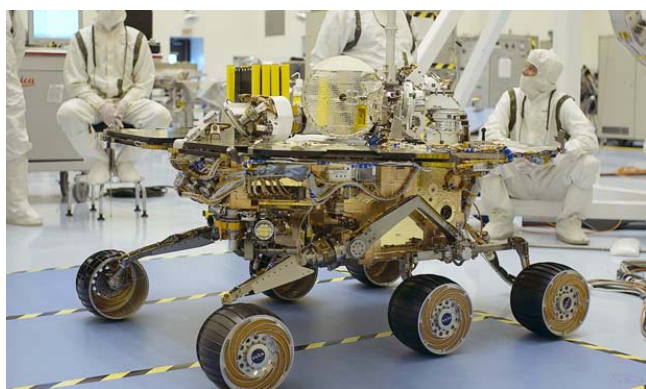


Figure 1. Flight Rover 'Spirit' in the JPL Spacecraft Assembly Facility

2.1 Rocker Bogie Suspension

The primary role of the MER suspension subsystem is to provide the rover with a mobility system that has the kinematic range to permit the rover to safely traverse 25 cm obstacles, such as rocks or ditches, and allow the wheel assemblies to rotate for drive maneuvers. The two types of standard drives commanded for the rover mobility, in addition to straight drives, included "arc-turn" and "turn-in-place". In addition other general traversability requirements were particular to the MER vehicle. Specifically, the suspension was required to give the rover mobility stability on a 45 degree tilt. Also, the suspension had to be designed to absorb the majority of the impact loads the rover would experience during lander egress and surface traverse. In figure 2 the left side of the rocker bogie is shown.

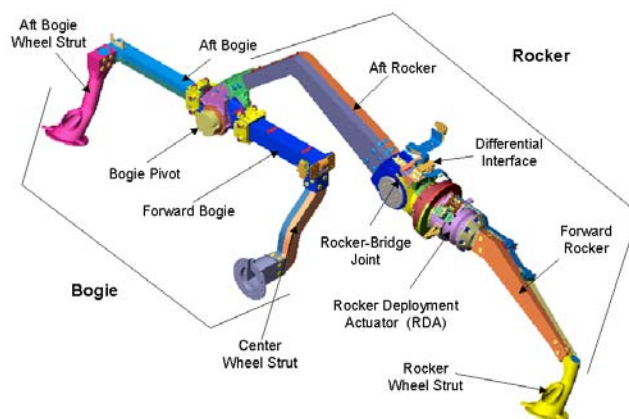


Figure 2. Left-side of Rover Rocker Bogie Assembly

The rocker bogie suspension is a mechanism that, along with a differential, enables the vehicle to passively keep all six wheels in contact with a surface even when driving on severely uneven terrain. There are two key advantages to this feature. The first advantage is that the wheels' pressure on the ground will be equilibrated. This is extremely important in soft terrain where excessive ground pressure can result in the vehicle sinking into the driving surface. The second advantage is that while climbing over hard, uneven terrain, all six wheels will nominally remain in contact with the surface and under load, helping to propel the vehicle over the terrain. The MER rovers take advantage of this configuration by integrating each wheel with a drive actuator, maximizing the vehicle's motive force capability.

Another key feature of the suspension that has not been emphasized in previous space applications is the ability to absorb significant energy from driving loads. In the past, rocker bogie suspensions have been used on rovers where the loads generated during driving have been relatively low due to the small mass and size of the vehicle, as well as its low speed. Therefore, the suspension served

primarily as a set of “rigid” kinematic links between the rover body and the wheels. With the increase in size and mass of the vehicle, the necessity to design for the vehicle’s dynamic response while driving over larger obstacles became mandatory.

The MER rover had the challenge of egressing from a lander poised on airbags and surface features, a maneuver that required the vehicle to drive off of and drop down from a significant height above the surface. Instruments that had been stowed during the landing phase of the mission were deployed during driving and were not designed to withstand large loads in their science-gathering configuration. A compelling design requirement was to therefore create a “soft” suspension to limit the accelerations experienced by the payload during all driving conditions.

However, one of the more challenging design issues to address was how soft to make the suspension. A suspension that was too soft would result in large deflections where the rover body or its science appendages could contact Martian surface features in an uncontrolled manner. Therefore, the suspension had to be designed to give the rover a ride somewhere between a luxury vehicle and a truck. The suspension system stiffness target was one that would produce a translational impact load no greater than 6 G’s and not let the rover body deflect below a 20 cm ground height. The resulting suspension structural members were fabricated from tapered, welded, titanium box beams tuned to meet these requirements. The design of these elements also provided exceptional bending and torsional capability while minimizing the volume and mass impact to the spacecraft.

Titanium alloy was used exclusively for the structural components of the suspension. This material was selected for several reasons. The high strength-to-weight ratio made it attractive for a mission where volume and mass was at a premium. The ability to weld titanium allowed the suspension structural components to be optimized for strength and flexibility. Eight of the ten suspension tube members were welded. The desire to increase the Ti-6AL-4V from the annealed to a solution treated and aged (STA) state was resisted. While the STA process would increase the strength of the titanium from 900 MPa (130 ksi) to 1100 MPa (160 ksi), the weld seams would remain in the annealed condition, creating an obvious and unacceptable weak link that could only be mitigated if the STA process was performed after welded. The possibility that the weld members would distort significantly during the STA process due to their thin walled construction was deemed too risky to accept.

The desire to create a suspension that efficiently absorbs energy leads to structural members that are thin walled tapered box beams. A box beam design is a mass

efficient geometry for components subjected to both bending and torsional loads. The beams are also tapered wherever possible to approximate a constant strength flexural design. Based on these desired design features, the fabrication method selected to create the members was electron beam welding.

2.2 Differential

The rover’s body is attached to the left and right side rocker bogie assemblies through a differential mechanism. The geared differential resides in the main structure of the rover body called the WEB, or Warm Electronics Box. The housings of the differential are the corner fittings of the WEB structure. In figure 3 the differential assembly is shown. The differential is composed of two sets of epicyclic gearing contained in the opposing structural housings. On the left side of the rover the gearing is in a planetary gear configuration, and on the right side of the rover in a star gear configuration. The two gear assemblies have the same ratio of 4:1, but they have opposite hands or rotations. Therefore they act to create the 3 link differential motion with the rover body acting as ground. Therefore, when the left side suspension goes up, the right side suspension goes down. The result is a natural equilibration of loads from the body to all 6 wheels which helps to minimize the maximum or average ground pressure. Minimizing the maximum ground pressure is critical on soft terrain to reducing sinkage.

The two gear assemblies are connected together by a titanium torque tube that reacts the vehicles moment loads induced during traverses. The individual gears and bearing sets inside of the differential assemblies are all made of ultra high strength stainless steels and nickel based super-alloys. Like all other gears and bearings in the mobility assembly, they are lubricated by perfluoropolyether (PFPE) based greases which are sold under the trade name Braycote 602 which are effective down to -70 degree C.

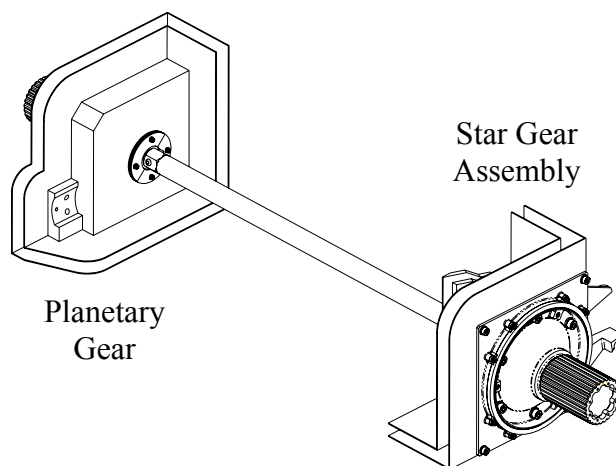


Figure 3. Differential Assembly

2.3 Wheels and Actuators

The mobility assembly has 6 wheels, with all wheels driven independently by their own actuators. The wheels are all machined out of single billets of high strength Aluminum 7075. The spiral pattern in the wheel structures adds a significant amount of compliance to the wheels thus aiding the suspension assembly in absorbing energy and reducing impact loads. The front two wheels and the rear two wheels also have steering actuators of identical design to the wheel actuators. The actuators are powered by modified commercial permanent magnet dc brushed motors. Each motor drives a series of stages of gearing that result in the final torque-speed relationship of the actuator. In figure 4 the wheel and actuator assembly are shown up to their connection to a rocker bogie strut.

The wheel and steering drives both use modified commercial brushed permanent magnet d.c. motors. The motors are produced by Maxon inc., but have been modified with brush materials that work in the near vacuum conditions of the surface of Mars, and also with low temperature PFPE lubricants. The motors are geared down through a two-stage planetary gearbox, which then powers a harmonic drive. The total gear reduction in the actuators is 1500:1. An encoder on each motor is utilized for sensing purposes to both control speed, determine steering angle, and to determine wheel odometry. Under very low load conditions, the wheel drives turn at 3.5 rpm, which results in a nominal vehicle speed at the 25 cm diameter wheels of 4.6 cm/sec. Under maximum loading conditions, the wheel drives will pull 2 amps at 28 Volts D.C. producing about 90 N-m of torque at a wheel speed of 2 rpm, which results in a speed under maximum loading of 2.6 cm/sec. The wheel and steering drives, as well as the rocker bogie passive joints must operate on Mars at temperatures down to -55 degree C.

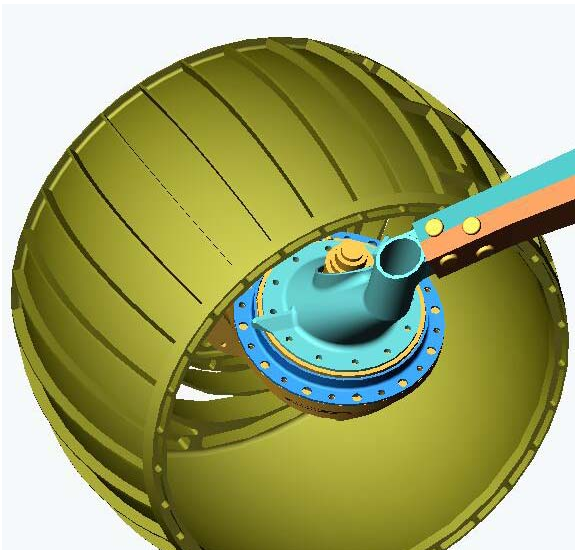


Figure 4. Wheel and Actuator Assembly

3 Tilt Platform Mobility Testing

The system level mobility testing of an engineering model of the rover, called the Dynamic Test Model or DTM, was conducted on a 16 foot square tilt-able table, called the variable terrain tilt platform, or VTTP. The DTM rover was ballasted to within 120% of the flight vehicles' Mars weight, in order to achieve a center-of-gravity accuracy within two centimeters of the flight configuration. The DTM vehicle was driven on the VTTP at slope angles between 0 and 20 degrees, at different orientations to the slope, while simultaneously traversing over obstacles up to 25 cm in height. These values represent the key traverse related mission requirements. The success of individual traverses as well as the currents, speeds, and induced trajectory errors on the overall vehicle were recorded.

In Figure 5 a picture is shown of one DTM test which occurred at JPL in May of 2003. The platform was covered by a driving surface in preparation for test. Two driving surfaces were identified and implemented. First, a high friction mat material was attached directly to the platform. Second, a 6 inch deep layer of dry, loose beach sand was added on top of the high friction mat. The choice of these two driving surface materials was meant to bound the range of possible terrain variability that the rover was expected to experience during the surface mission. The high friction material caused high internal loads but allowed very low slip during drives. In contrast, the dry loose sand gave a soft and cohesionless material with low effective traction, induced general wheel sinkage, and afforded substantial slip.



Figure 5. Dynamic Test Model rover on the variable terrain tilt platform at a 20° slope, driving over 25 cm obstacles

The specific testing undertaken on the platform bounded the rover's potential operational scenarios. Specifically, at each platform tilt level, the rover was placed in a specific combination of initial conditions. The vehicle's orientation to the platform was set relative to the

slope. These orientations included driving upslope, down-slope, cross-slope, and at a 45 degree angle either to an up or down-slope condition. At each of the different slopes, and orientations to the slopes a set of rock-like concrete obstacles were then placed in the rover's path on either or both sides of the vehicle for some of the tests. The obstacles were of variable height from 10 to 25 cm. Completion of the full set of tests resulted in over 200 separate trials and significant amounts of detailed information about the vehicles performance under the set of engineered conditions.

4 Testing Results

The results of the DTM rover tests on the VTTP verified that the rover design met its requirements. On the hard, frictional surface the rover showed exceptional capability to climb over obstacles up to 15 cm in height on all slopes. On slopes between 10 and 15 degrees, the rover was generally able to scale obstacles at the full system requirement of 20 cm without excessive wheel slippage. The results of testing on the soft sand were much more complicated. In figures 6 through 9 are a set of curves that show the rovers slip as a function of slope, and orientation to the slope, while traversing the dry loose sand. Figure 6 shows the compilation of test results for driving down slope. Figure 7 shows the compilation of test results for the rover traversing up slope. Figure 8 shows the compilation of rover slips while the rover performed a 360 degree turn in place maneuver on different slopes. And finally, Figure 9 shows the results for the rover driving cross slope with the result representing the side slip of the vehicle as a percentage of the total drive. In these tests no rock obstacles were used. In general the rover's ability to scale vertical obstacles taller than a wheel radius was sharply diminished for cases either up-slope or diagonally up-slope. In general, the result would be highly increased traction sinkage of the other wheels.

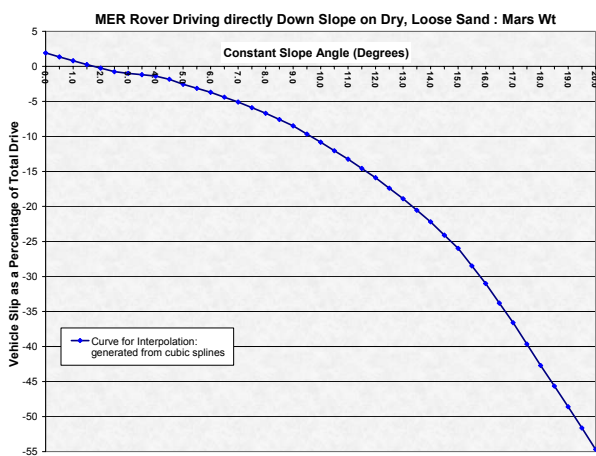


Figure 6. Test results showing the rovers slip on various slopes of dry loose sand while driving down slope

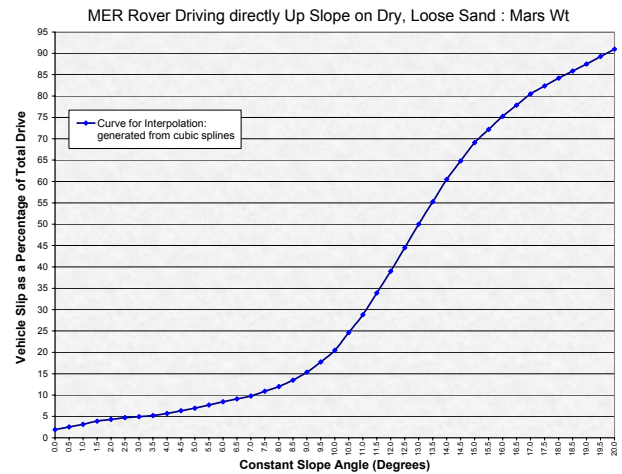


Figure 7. Test results showing the rovers slip on various slopes of dry loose sand while driving up slope

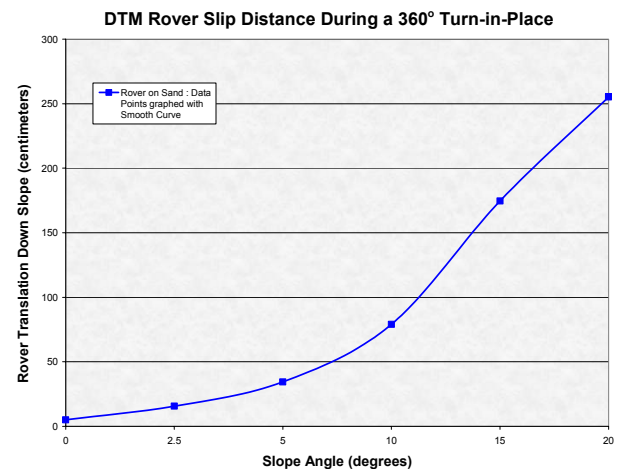


Figure 8. Test results showing the rovers slip on various slopes of dry loose sand while performing a 360 deg turn-in-place maneuver

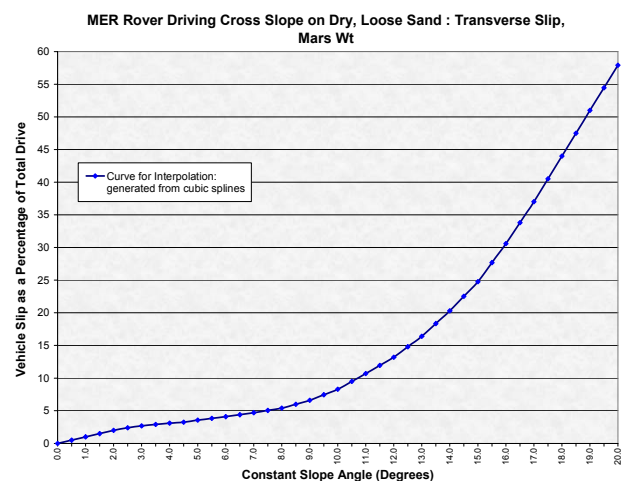


Figure 9. Test results showing the rovers slip on various slopes of dry loose sand while driving cross slope

5 Rover Mobility Performance

Rover mobility testing produced consistent results for identical initial and boundary conditions. Specifically, the trajectory errors induced in the rover's drives was a function of wheel sinkage, rock height, and slope angles and not simply a random effect. Drives over rocks induce vehicle slip and yaw, with the magnitude of those errors directly related to the height and traction available on the rock. Driving in a soft soil on a cross slope induces only small amounts of vehicle yaw, but substantial amounts of side or lateral slip proportional in a non-linear way to the magnitude of the slope. The rover slip as a function of driving up and down slope on the soft soil also showed a highly non-linear response to slope angle, with up to 91% slip found for the 20 degree case of the rover driving up slope. The rover typically sinks down in soft soils, like dry loose sand, between 1 and 2 cm. During a traverse over a 15 cm or taller rocks, the wheel sinkage will increase substantially to as much as 6 to 12 cm. This results in a greater accumulation in wheel odometry estimation error of position due to slip, and also a substantial increase in energy consumed in the drive due to extensive soil work. The rover will tend to yaw when climbing a large rock obstacle by as much as 10 to 20 degrees. There was a distinct transition point in soil performance at about 10 degrees of slope. Below 10 degrees of local slope, the slip performance was nearly linear, and progressed in an intuitive way. Whereas above 10 degrees of slope, the rovers slip performance was highly non-linear, growing very quickly in magnitude due to small changes in absolute slope.

As a result of the testing program we developed a very good understanding of the rover's hard-failure limits or catastrophic scenarios. These hard-failure modes are representative of the vehicle being overturned, the rover becoming stuck in soft terrain, or becoming high-centered on an obstacle. In all cases they would result in an end to the mobile mission of the vehicle. Less severe are the rover's soft-failure scenarios, these are cases where the specific goals of a traverse were not met, such as due to excessive slip or yaw of the vehicle. As a result, the rover does not end its drive at the desired location, and a sol of operations could be lost, but not the whole mission. These results of the testing on the VTP show the extraordinary importance of this type of system validation for all future rover missions. The Earth-based testing results showed an uncanny correspondence to the Opportunity rover's driving performance at Meridiani Planum. This is due to the soil conditions for Opportunity being essentially low in dust accumulations, with the resulting character of the soil being a blocky-to-cloddy slightly cohesive, moderately frictional material, much like our dry loose beach sand. As a result of this serendipity, Opportunity's drive accuracy at Meridiani Planum when planned with our Earth-based results was typically within 10% of the rover's planned destination.

This strategy was used to plan drives into and out of craters, where the consistent slope angles at different depths of the crater resulted in a very accurate prediction of the rover slip during all segments of the drives [7], [8]. The MER vehicles have performed exceptionally well in their Mars missions. Their demonstrated abilities to climb rocks, traverse soft and hard soils, and to negotiate hills and craters has validated the mobility assembly design and construction over a total accumulated traverse, as of this writing, in excess of 10 km; thus proving the great value of the autonomous rover mission concept for NASA.

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