Proceedings of IDETC/CIE 2005
2005 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Long Beach, California, USA, September 24-28, 2005

DETC2005-85622

DYNAMIC TESTING AND SIMULATION OF THE MARS EXPLORATION ROVER

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ABSTRACT

In January of 2004, NASA landed two mobile robotic spacecraft on the surface of Mars as part of the Mars Exploration Rover (MER) project. Named Spirit and Opportunity, each of these rovers is performing their separate scientific missions of exploration more than a year after landing. The Mars Exploration Rovers represent a great advance in planetary rover technology. Part of that advance is represented by the mobility capabilities of these vehicles. At the 1.5 year mark, the two vehicles have traversed more than 10 km over broad plains, craters, rocks, and hills. In order to assess the mobility characteristics of the rovers in the Mars environment, an engineering model vehicle was tested before the mission launches in a representative environment of slopes, rock obstacles, and soft soil. In addition, to gain better insight into the rovers' capabilities, a dynamic model of the rovers was created in the software package ADAMS. The rover model was then used to simulate many of the test cases, which provided a means for model correction and correlation. The results and lessons learned of the test and dynamic simulation of the MER vehicles is provided in this paper. The results from the test and simulation program allowed Spirit and Opportunity to be used in terrain well outside of the original mission requirements. The resulting increase in terrain access, led to substantial additions to the missions science return.

INTRODUCTION

The Mars Exploration Rover (MER) Project sent two mobile robotic laboratories to the surface of Mars with both missions landing in January of 2004. The first rover to land was named Spirit, and the second rover was named Opportunity. Spirit landed at a location inside of the Gusev Crater, and Opportunity landed in the Meridiani Planum [1], [2].

The MER rovers were designed to be autonomous vehicles for planetary surface exploration. These flight rovers needed to traverse an alien world, a natural environment formed and modified by mostly unknown processes. In order to achieve those goals the project had to set requirements, design a flight system to meet those requirements, and then prove that the final flight system met the requirements. NASA has a limited history with surfaces missions to Mars including the Viking I, II landers and the Mars Pathfinder project. These have given us a broad, yet shallow, understanding of Mars soil and dust characteristics, ground strength, and regional rock and slope distributions [3], [4]. Based upon this understanding and the MER mission goals, the project generated the engineering requirements associated with rover mobility. The rovers were designed and tested to traverse at least 1 km of accumulated distance, climb over 25 cm obstacles, such as rocks or trenches, drive on slopes up to 20 degrees, traverse hard and high traction terrain which can generate high loads, and finally traverse over soft soils only capable of sustaining low ground pressures, under 7 kPa [5]. As of this writing, both flight rovers have met or exceed these requirements on Mars; for instance, having traveled in excess of 5 km each, and traveled on slopes up to 30 degrees [6]. The rovers were supported in their development by two engineering models that were utilized for ground testing and software development. One of those engineering models was called the Dynamic Test Model, or DTM, and its purpose was to be used for the verification and validation, v&v, of the rover subsystems and system. Specifically, the DTM v&v program demonstrated that the rovers could endure the loads, deflections, and frequencies generated by their operations on Mars. Initially the DTM vehicle went through the typical spacecraft development program of vibration testing, to simulate the environments of launch, aero-entry at Mars, and landing on the surface.

Since the mission focus was a mobile science platform, the mobility loads of the rover traversing worse case environments became an important part of the hardware verification and system validation. The nature of mobility loads is relatively new for the space flight community, and novel approaches had

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to be developed to address the issues. NASA's history being only one previous flight rover sent to Mars, the rover 'Sojourner' on the Mars Pathfinder mission [7]. For rover design and structural testing, an understanding of the peak loads and deflections the vehicle would experience traversing the worse case terrains was paramount. At higher levels of vehicle integration, validating that the system does what you meant it to do is central to the flight system development. For activities that lead to qualifying a system for space flight, the cardinal rule is to "test as you fly, fly as you test". In many cases the ability to test a flight system appropriately on Earth is very limited because all of the proper conditions can only be replicated in space. For all these reasons, typically a set of analyses and simulations are created that overlap the boundaries of the limited test conditions that are practical to perform. And it is this combination of testing and simulation that validates the flight system and provides the confidence that it can fulfill its mission. Therefore the MER project embarked on a process of DTM rover testing, dynamic modeling, test simulation, and test-model correlation. In testing, the DTM rover was driven on a set of relevant terrain and slope conditions on an engineered platform. A series of dynamic simulations were created to allow a means of virtual testing of the modeled DTM rover in its terrain environment. In order to ensure the quality of the simulation results, a process of model-to-test correlation was developed that allowed the dynamic models to be further developed by iterative comparison to the test data, and successive refinement of the model parameters. The simulations were then used to explore other terrain regimes that were not tested.

DTM ROVER MOBILITY TESTING

The DTM rover was constructed as a mechanical-only test model in its initial configuration. It contained no electronics, power, or communications equipment, nor any science instruments. The DTM rover was ballasted to a mass of 80 kg to have the same center of gravity as the flight rovers, and as close as possible to their Mars weight. This made the DTM rover a good analogue on Earth for the flight rovers on Mars. The DTM in this configuration was not an autonomous or self-powered vehicle, and was connected by a tether to a power and control station. The rover was driven in a button box mode for operation at only the lowest level of control. Simple commands were utilized exclusively, and the rover was driven in constant traverse configurations, such as straight line, arcing, or turn-in-place drives. This mode of testing was especially beneficial to the mechanical mobility testing of the vehicle, allowing the straightforward assessment of its basic functionality and capabilities. In early testing with this mode of operation, the rover was driven in natural terrain settings over relatively realistic geologic analogs of Martian conditions found naturally on the Earth. It was quickly found that this type of field testing was qualitatively valuable, but it was difficult to achieve specific and detailed quantifiable indicators of the rovers' capability to meet the traverse requirements.

To facilitate the development of a quantifiable test program that could be used to verify specific requirements, a variable terrain tilt platform, or VTTP, was developed for drive testing the rover over combinations of obstacles, slopes, and terrains at a number of different orientation angles. In figure 1 below the DTM rover is shown on the VTTP, tilted to a slope angle of 15 degrees. The rover is shown tethered to the motion controller station; which is comprised of electronics, power supplies, and a computer for controlling the test, as well as taking and storing the telemetry data. The VTTP was constructed out of plywood and wood struts, giving a 5 meter square driving surface area. The driving surface was composed of plywood sheets that were painted with a non-slip or 'grip coat' surface. The grip coat surface resulted in a coulomb or dry friction value with the rover wheels of approximately 0.6 to 0.8 as measured by simple hand tests. That range represents a static friction angle of between 31 and 39 degrees. The VTTP could be rotated about its base and then supported at five different pre-set angles. The angles relative to horizontal were 0, 5, 10, 15, and 20 degrees. Once the MER landed missions were underway it became clear that the rovers would be required to traverse slopes greater than 20 degrees, and the VTTP was augmented for additional testing at 25 and 30 degrees of tilt.

The DTM rover was driven on the VTTP in different configurations for 95 traverse tests. The rover's orientation to the platform varied between directly up the slope of the platform, down the slope of the platform, across the slope to the platform (called cross slope), and at a 45 degree diagonal to either the up or down slope direction. The data taken during these tests included the telemetry from the on-board rover avionics (e.g., motor currents, potentiometer and encoder positions and velocities, etc.), as well as external information gathered on the vehicles true traverse course. The external measurements were made by utilizing a laser ranging system to measure the beginning and ending positions of the vehicle on the VTTP. The laser ranging system used was a commercial unit called a 'Total Station'.

Figure 1: MER DTM rover on the VTTP at JPL

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DYNAMIC MODELING AND SIMULATION

Requirements for mobility dictated the rover could traverse over 25 cm obstacles, such as rocks and trenches. The nature of the loads and deflections exerted on a rover as a function of such traverses was an unknown and ill defined problem. A conservative approach was chosen to envelope the environments the vehicle would see by assuming that the rover would essentially "fall off" of the largest rocks it was designed to amble over onto hard, rigid ground. Because of the impact and transient nature of these mobility requirements on the rover, a time-domain or dynamic model of the rover system was developed to look at critical displacements and loads. Once the DTM rover was assembled it was then used in a "Drop Testing" program to verify both the dynamic simulation results used for the design, as well as to confirm the ability of the rover to withstand those loads and deflections. The software package utilized to develop the dynamic model is called ADAMS, which is an acronym for Automatic Dynamic Analysis of Mechanical Systems, a software package sold by the MSC Corporation. ADAMS is a physics-based modeling environment for simulating the dynamics of mechanical systems.

The ADAMS model originally developed was a high fidelity representation of only the rovers' structure, its mass and stiffness distribution, an approach typical in finite element modeling. The specifics of the drop testing was to lift one or more of the wheels above the ground by the maximum height of an allowed obstacle and then letting the wheel(s) fall. For reference, any obstacle that is too large, tall, or deep for the rover to safely scale is dubbed a 'hazard', and the rovers' autonomous software was designed to actively navigate its course around such hazards. The initial ADAMS structural simulations were correlated closely to the drop test results, allowing the verification that the dynamic simulation results used as design cases where accurate for determining the peak loads, deflections, and energy that had to be absorbed in the rovers' compliant suspension. This verified the vehicles design and its structural integrity under the worse case mobility load events, and it also proved the utility of dynamic simulations of rovers to accurately predict the results of mobility events.

Interaction between the rover wheels and the terrain is modeled using the ADAMS contact force algorithm, which includes visco-elastic sinkage model, static and dynamic friction models. The original ADAMS model did not incorporate the complex mechanism functions, both active and passive, that were inherent to the real system. Therefore a new effort after the initial project v&v took the ADAMS model as previously developed and evolved it to include the additional details involved in the various mechanisms of the rover assembly. These aspects included wheel and steering actuators and passive mechanisms such as hard-stops on the joint pivots. The ADAMS model was developed until all designed-in functionality at the lower mechanism level was included. In figure 2 below a picture is shown of the geometric representation of the DTM rover with all of the icons shown for the various parts, joints, and forces.

The final ADAMS model of the rover included 428 degrees of freedom, associated with 85 individual parts or rigid bodies. The rigid bodies represent the distributed and lumped masses of the vehicle. The rigid bodies are connected to one another in the structure by massless beam elements. In the mechanism parts of the model the rigid bodies are connected by revolute or pin joints. These revolute joints have the mechanism functions associated with them for the actuator torques and drags, bearing friction, and mechanical stops. Six external forces to the rover represented the contact dynamics between the wheels and the ground. These external forces, which represent the wheel interaction with the terrain, are modeled as contact forces. A contact force not only represents the normal force relationship between the two bodies during an impact, but also in the plane perpendicular to the normal force, friction forces are automatically generated as a function of a user-specified coefficients of static and kinetic friction, and as a function of system determined rates of relative slip velocity between the surfaces.

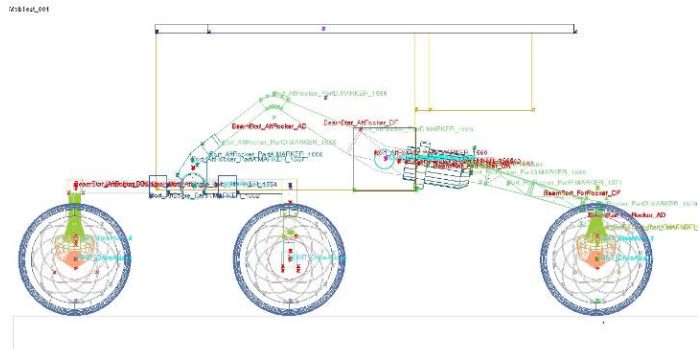

Figure 2: ADAMS model geometry for the MER rover

The torque-speed relationship of the motor gearheads in the wheel drives was included along with the details of the holding brake properties of the magnetic detents. The motor torque-speed relationship as a function of wheel odometry (integrated positions) and wheel orientations were included. Taken together this approach mimics the dead reckoning calculation of using the wheel odometry and the steering actuator potentiometer angles to determine vehicle location. As a benefit of this approach is an ability to control the rover simulation directly in the actuator model functions. At all of the passive joints of the rover suspension such as the differential and the bogie pivots, a friction force was included to represent the drag caused by the seals, and also the high stiffness representative of the hard stops that restricts their ranges of motion.

During the construction of the full rover model, a process of comparison or tuning between limited simulation cases and thought experiments was utilized to check the performance of the vehicle under known end conditions where the characteristic response of the rover was either not in question a

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priori, or had been observed in test. Once the dynamic models were constructed, the act of simulation is to set up the models up for a scenario representing a particular physical test. In each scenario the initial and boundary conditions are fully defined and then "running" the simulation means integrating the equations of motion as a function of time for the full duration specified. The results of the simulation are both graphical, in terms of an animated playback of the system and its responses, as well as quantified in terms of detailed numerical system state descriptions of motions and forces. The simulations of the MER rover took from approximately ½ hour to 6 hours depending on scenario complexity, running on a 2 GHz Sun Microsystems Ultra 60 machine.

TEST-MODEL CORRELATION

Three specific aspects of the model were "tuned" by successive refinement in the model correlation phase of the task. The first was the effective wheel radius, which was calculated to be 129.7 mm under the test conditions. The actual wheel has a non-constant radius due to the periodic placement of cleats around its periphery. The effective wheel radius compares very closely to the maximum wheel radius from cleat to cleat of 131 mm. The second aspect of the model refined by comparison to the tests was the friction model between the wheels and the high-friction mat of the VTTP. The simulation utilized a built-in contact model in the ADAMS software. This model provides the detailed contact dynamics for the interaction of the wheels to the terrain, including a visco-elastic normal component of force and a coulomb or stick-slip friction model for forces in a plane perpendicular to the instantaneous normal force vector. The friction force model is represented by coefficients of static friction, and kinetic friction, and is created as a cubic spline function of the normal force magnitude and the relative sliding velocities of the two contacting bodies in the perpendicular plane. The value determined for the static friction coefficient was 0.78, and for the kinetic friction component was 0.58.

The final aspect of the model to be refined was the nominal internal and external losses of the rover, which can be thought alternately as either the electrical current or power to overcome resistances, or the equivalent output torque during motion. For this discussion it was decided to use power as the metric to measure and analyze. The internal losses of the wheel drives are given by the no-load current required to turn the wheels at the given system voltage as if the vehicle was suspended in mid-air. Those losses are the most substantial and amount to 30.1 Watts of electrical power. The external losses are representative of the rover overcoming what is typically termed rolling resistances at each of the wheels. Under the weight of the rover, the wheels and the ground give an imperfect and non-rigid interfacing surfaces that don't allow perfect rolling motion, therefore small forces are created that cause a resistance to motion even in the case of hard, flat, highly frictional ground. These additional rolling resistances cause 4.5 Watts of power to be expended for the case of driving on a flat and level terrain. This 4.5 Watts can be translated into a required torque value across all wheels of 8.3 N-m. After taking the wheel radius into account an equivalent thrust force needed to overcome the rolling resistance for this case can be calculated at approximately 64 N. This is the nominal thrust force needed to maintain the steady motion on the VTTP.

Mobility test 01 was a series of four drives in the forward and reverse direction on the VTTP with flat and level conditions (no obstacles and zero VTTP slope). These drives were used to calibrate the rover dynamic model by determining the average current drawn by the wheels undergoing steady state motion on the platform with no inclination. The power drawn by the motors was used to overcome the no-load current of the motors, and the rolling resistance of the wheel-terrain interface. The average current drawn in testing per wheel was found to be 0.206 Amps. While the overall boundary conditions were steady, the currents drawn by each of the actuators, as measured at 10 Hz, were found to be extremely noisy as can be seen in figure 3 below. This is due to complex interactions between the brush motor noise, gear torque ripple, minor random changes in friction, and motor controller noise.

Because the wheel drive currents are so individually noisy a relationship to compare the tests to the simulations was needed, and the average total power was decided upon. The average power of a traverse is determined by first calculating the total average current of all of the wheels and then multiplying by the system bus voltage of 28 V_{dc}. In Figure 4 the total current averaged over all the wheels is shown. For all wheels the total average current is found to vary in a moderate range around 1.236 Amps. For comparison, the equivalent graph for the total average power of the simulated version of mobility test_01 is shown Figure 5 from the ADAMS model; where the simulated steady state conditions show a completely smooth and consistent response in comparison to the test telemetry.

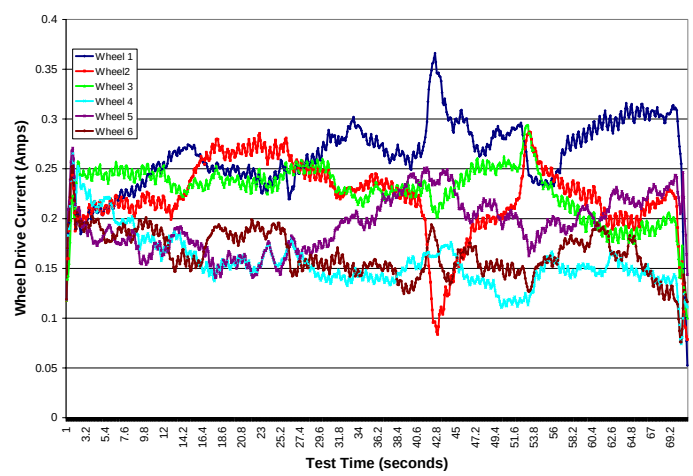

Figure 3: Raw Wheel Drive Currents for MobTest01

While the commanded drive distance was 3 m, the true length of the traverses was found to be 3.111 m due to the

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effect of the true wheel radius, as determined by the Total Station measurements. This value was compared against the wheel encoder readings to calculate the odometry (accumulated distance measurement) under assumed no slip conditions. This calculation gave an effective wheel radius for use in the model of 129.7 mm, which compares closely to the maximum radius of the physical wheels of 131 mm. Another calibration of the ADAMS model was to fine tune the friction properties of the wheel interface to the platform. Tests were performed where the rover drove up the platform and then down the platform, and the results were utilized for friction model calibration. When the rover drove up the platform the wheels slipped in a positive sense causing the vehicle to travel less distance than would be calculated by wheel odometry. When the rover traveled down the slope the vehicle slipped in a negative sense causing the vehicle to travel a greater distance than would be calculated by wheel odometry. For this series of drives on the high friction grip coat material, a static coefficient of friction of 0.78 was determined, and the wheel slippage at the greatest slopes produced measurable total vehicle slippage of approximately 2% of the overall drive distance.

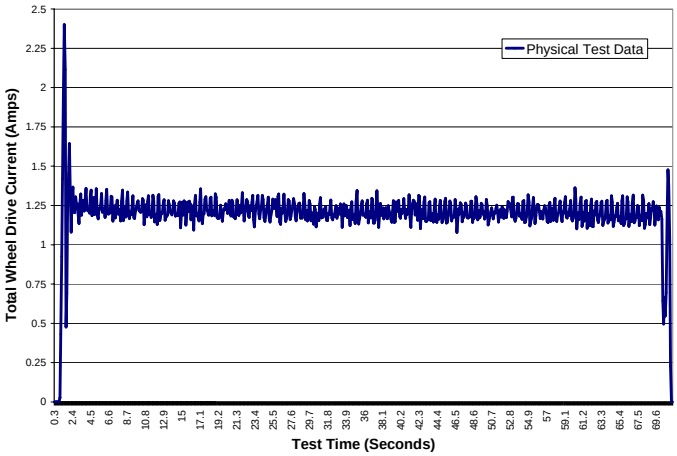

Figure 4: Total Test Current for all Wheel Drives

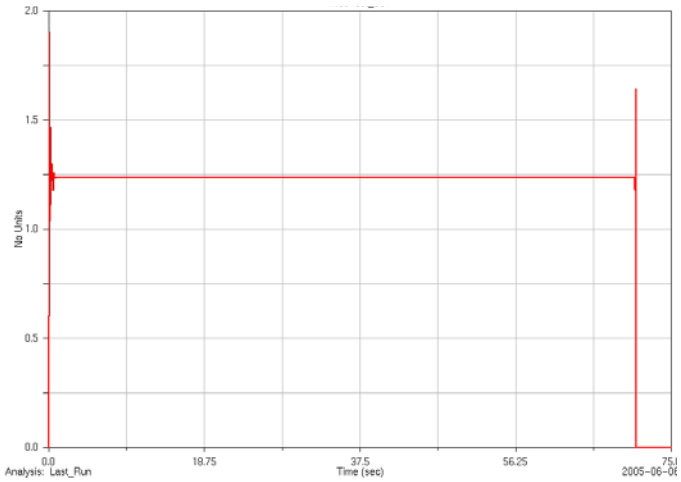

Figure 5: ADAMS simulation of Total Wheel Current

TEST AND SIMULATION RESULTS

The comparisons chosen to investigate between the test data sets and the simulations were the average total power and the total vehicle slip as functions of the drive conditions of VTTP slope angle, and the orientation of the vehicle to the slope. The cases investigated were for slopes of 0, 5, 10, 15, and 20 degrees of platform tilt, and drive orientations to the platform of directly up slope, down slope, cross slope, and 45 degrees to the up slope orientation, and 45 degrees to the down slope orientation. Because time was limited during the MER vehicle system development for testing, only a small set of desired test cases could be performed. The tests cases chosen were those at the limits of the environmental conditions.

The first data set are for the up slope drive test cases. The rover was commanded to traverse a straight path at a constant vehicle speed of 4.5 cm/sec, directly up the incline of the VTTP for 3 meters. The data taken for the test include the full set of on board telemetry; such as wheel positions, velocities, and electrical current, all taken at a data rate 10 Hz. In addition a precise measurement of the rovers' initial and final positions were taken with a laser ranging system called a Total Station. In figures 6 and 7, three physical test cases are shown in blue for 0, 15 and 20 degrees of platform tilt. The first graph shows the average total power consumed in the traverse, and the second graph shows the overall vehicle slip. In comparison, the simulation results are shown in red for all cases.

The thrust force due to weight of the rover on a 20 deg incline is 268 N. The power seen for the test case of driving the rover up slope, and down slope of the VTTP, show additional losses due to inefficiencies in the actuators and changes to the rolling resistance value. The equivalent total thrust force from the power reading of the up slope drive is 293 N, representing a 9.3% higher loss. The equivalent total thrust force benefit to the power reading of the down slope drive is 216 N or 19.4% less benefit than a straight application of the gravity term would predict. These values are within the acceptable range for a simple model of internal losses to be used in the simulations, and give good confidence that the approach taken is sufficiently accurate. The second data set are for the down slope drive test cases. The rover was commanded to traverse a straight path at a constant vehicle speed of 4.5 cm/sec, directly down the incline of the VTTP for 3 meters. In figures 8 and 9, three physical test cases are shown in blue for 0, 15 and 20 degrees of platform tilt. Figure 8 shows the average total power consumed in the traverse, and Figure 9 shows the overall vehicle slip. In comparison, the simulation results are shown in red for all cases.

The third data set are for the cross slope drive test cases. The rover was commanded to traverse a straight path at a constant vehicle speed of 4.5 cm/sec, directly across the incline (nominally with no elevation change) of the VTTP for 3 meters. In figures 10 and 11, three physical test cases are shown in blue for 0, 15 and 20 degrees of platform tilt. Figure 10 shows the average total power consumed in the traverse, and

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Figure 11 shows the overall vehicle slip. In comparison, the simulation results are shown in red for all cases. The fourth data set are for the drive test cases at 45 degrees to the up slope direction. The rover was commanded to traverse a straight path at a constant vehicle speed of 4.5 cm/sec, directly along a diagonal to the platforms incline for 3 meters. In figures 12 and 13, three physical test cases are shown in blue for 0, 10 and 20 degrees of platform tilt. Figure 12 shows the average total power consumed in the traverse, and Figure 13 shows the overall vehicle slip. In comparison, the simulation results are shown in red for all cases. The fifth data set are for the drive test cases at 45 degrees to the down slope direction. The rover was commanded to traverse a straight path at a constant vehicle speed of 4.5 cm/sec, directly along a diagonal to the platforms incline for 3 meters. In figures 14 and 15, three physical test cases are shown in blue for 0, 10 and 20 degrees of platform tilt. Figure 14 shows the average total power consumed in the traverse, and Figure 15 shows the overall vehicle slip. In comparison, the simulation results are shown in red for all cases.

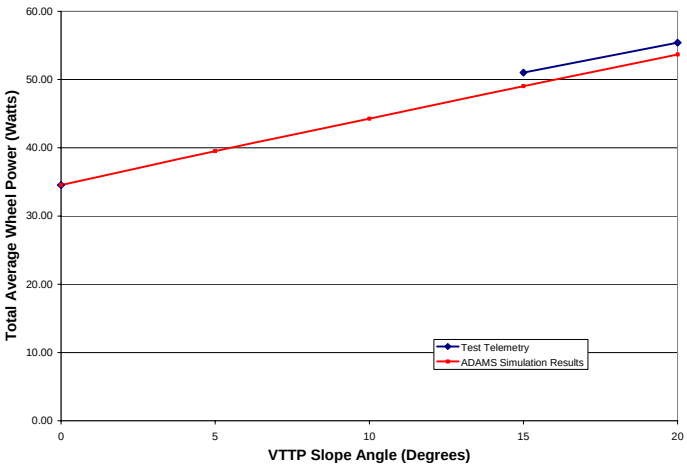

Figure 6: Rover Power while Driving Up Slope

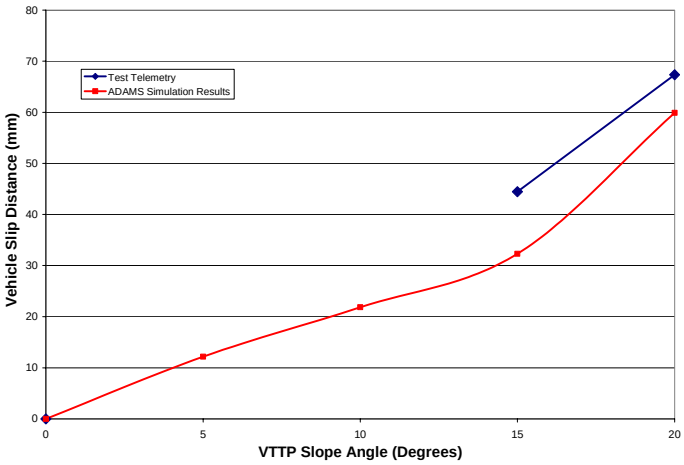

Figure 7: Rover Slip while Driving Up Slope

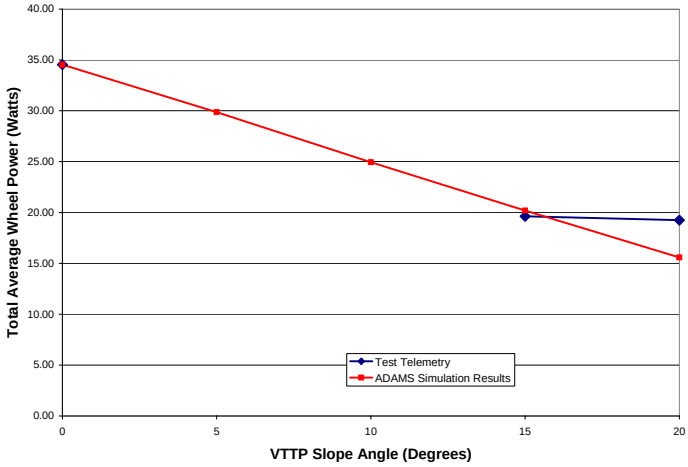

Figure 8: Rover Power while Driving Down Slope

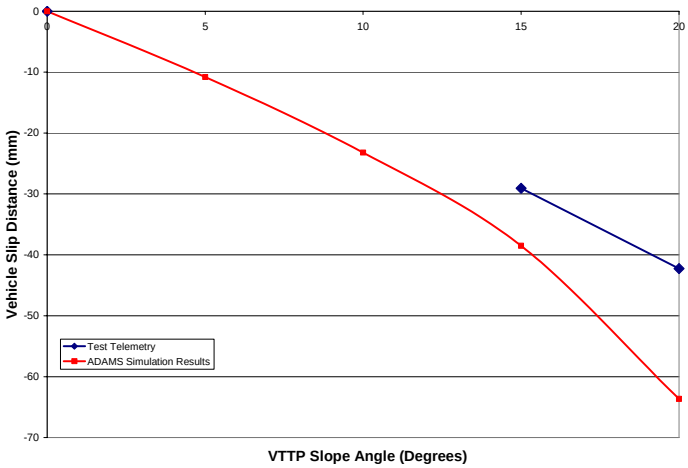

Figure 9: Rover Slip while Driving Down Slope

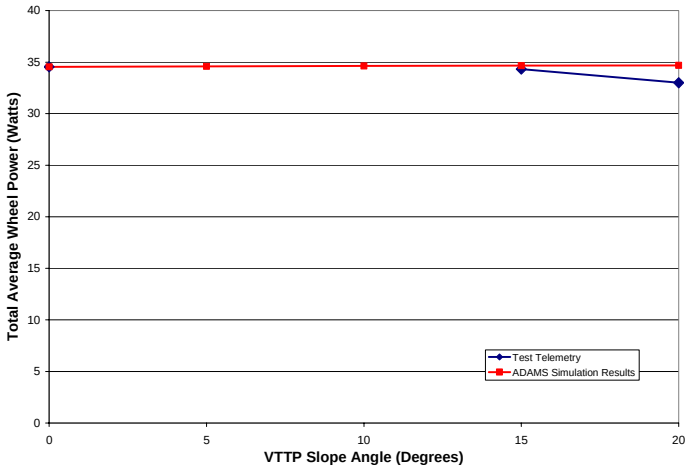

Figure 10: Rover Power while Driving Cross Slope

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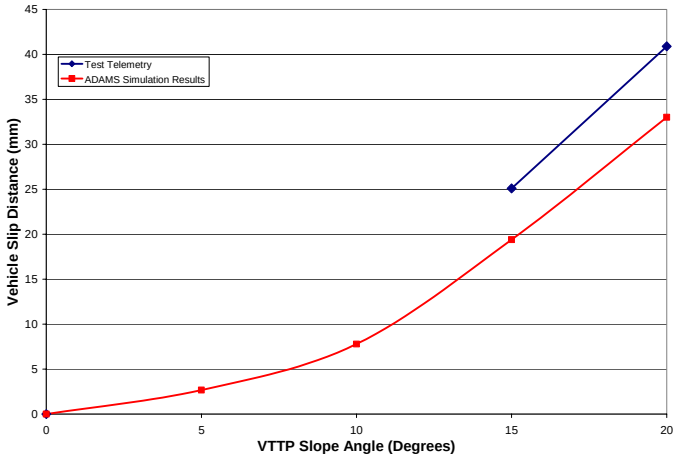

Figure 11: Rover Slip while Driving Cross Slope

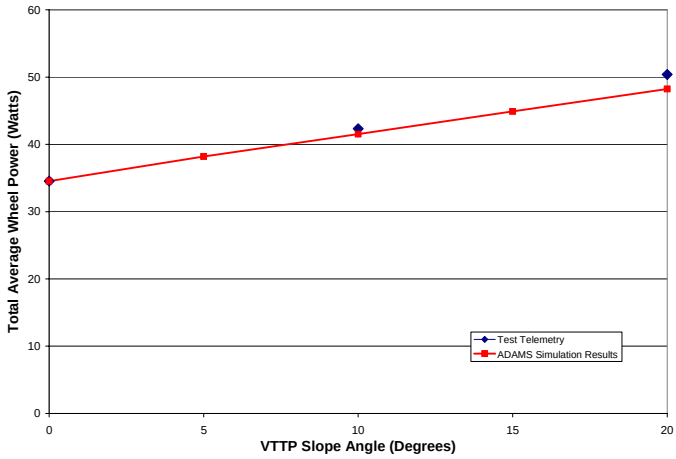

Figure 12: Rover Power Driving at 45° to Up Slope

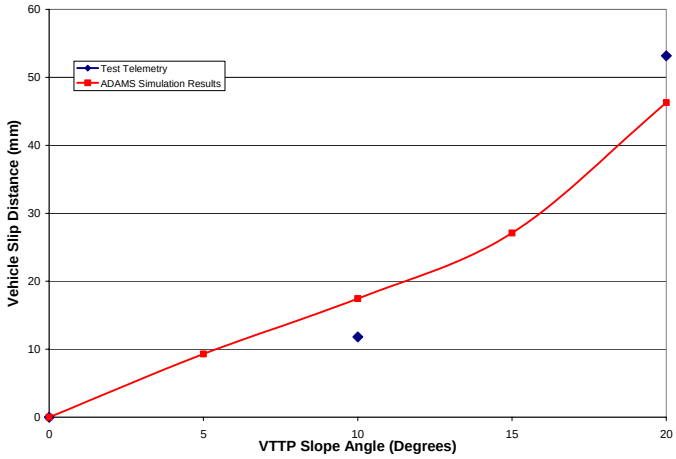

Figure 13: Rover Slip Driving at 45° to Up Slope

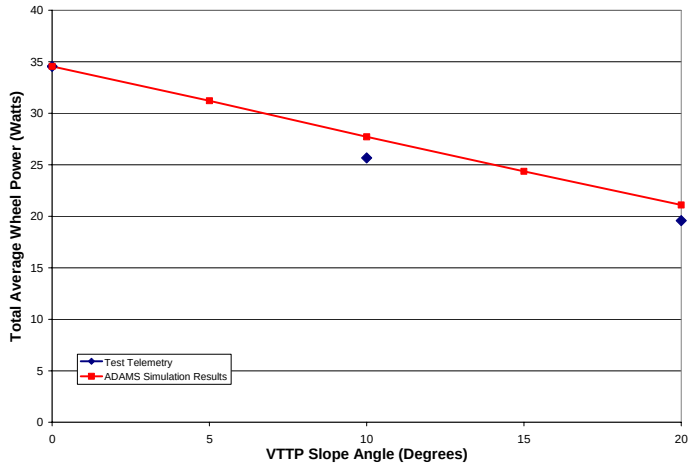

Figure 14: Rover Power Driving at 45° to Down Slope

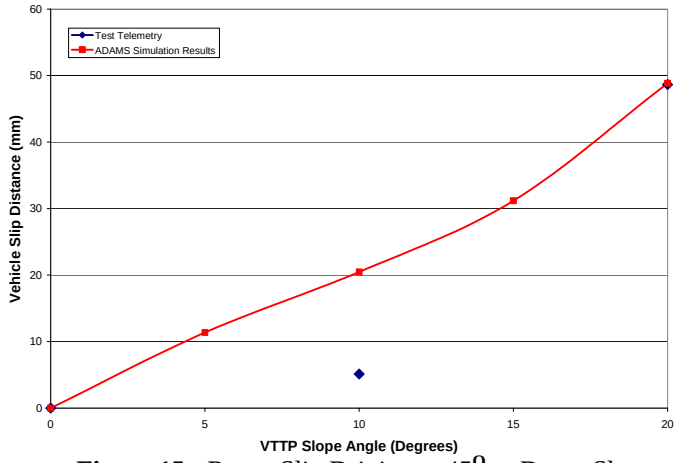

Figure 15: Rover Slip Driving at 45° to Down Slope

CONCLUSIONS

The MER DTM rover was driven on a prepared platform called the VTTP in a series of highly repeatable and quantified engineering tests. Those tests verified capabilities of the rover to meet its design requirements. Each test was created to give as close as possible to a pre-set steady state driving condition. A detailed dynamic model of the rover and the test environment was created in ADAMS. The ADAMS model was used to simulate the specific test cases performed. The results from the test cases were then used to guide the refinement of the ADAMS model and provide a pathway for test-model correlation. Three aspects of the model were modified or "tuned" by successive refinement in the model correlation phase. The first aspect refined was the wheel radius, which was set to null out the effects of cleats, surface compliance and roughness; the second aspect refined was the friction model between the wheels and the high-friction mat of the VTTP; the final aspect of the model refined was the internal and external

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losses of the rover, thus taking into account the no-load power consumed by the wheel mechanisms, and the nominal rolling resistance. Testing showed that the rover met the quantitative design requirements, and qualitatively met the performance as envisioned by the project. It was found that the rover really did not slip much in these particular tests, and since they represented the high friction case, that was expected. However measurable slips did occur and were a key part of the analyses, as was the total average power expended by the wheel drives. The creation of the VTTP and the engineering test program was found to be extremely valuable and a powerful new addition to space flight system v&v programs. The platform testing resulted in crucial data sets of rover performance in well quantified regimes of terrain and tilt to gravity that could not be readily achieved by testing only in off-road conditions on Earth.

Simulation showed that a detailed dynamic model of a rover could be developed and "tuned" to the results of testing of the physical system with a high level of correlation. In terms of total average power, the correlation was found to be better than $\pm$10% between test and simulation. The rover used approximately 34 Watts while driving on flat ground and that number climbed to 54 Watts while driving up a 20 degree slope, and dropped to 19 Watts while driving down a 20 degree slope. The graphs of power showed it to be a mostly linear function of slope, in all drive directions. While the overall vehicle slip during the traverses generally correlated between test and simulation to better than $\pm$20%. Total vehicle slip amounted to a maximum 70 mm out of a drive distance of 3.1 meters. There was a distinct transition point in the plots of slip at a 10 degree platform tilt. Above 10 degrees of slope, slip increased dramatically in a non-linear way for all driving directions, where as below 10 degrees, the slip performance of the rover was fairly linear. The set of engineering tests were designed to be highly repeatable and that was proven in the results of the cases looked at. The rovers' performance in terms of the metrics chosen was highly repeatable within a surprisingly narrow test parameter band, given the often difficult nature of testing or modeling systems with substantial coulomb friction. These results indicate that the set of mobility performance characteristics are not driven excessively by random or stochastic processes; therefore simulation is a viable, while still involved and complex proposition.

The MER rover mobility verification and validation program successfully proved the flight system mechanical design. Many lessons learned were achieved by the MER mobility team. The DTM drive testing successfully demonstrated the capability of the rovers to traverse environments as planned for the mission. The ADAMS dynamic simulation and its correlation to test demonstrated the ability to generate mobility loads and general driving performance data. Given a correlated dynamic system model the user has the ability to perform an infinite number of virtual experiments. In comparison, testing has many associated issues such as budget constraints, hardware and facility access, test duration in the project schedule, and human resources which are difficult to bring together often or for more than the minimum set of the most important and required system demonstrations. Dynamic simulation capabilities and the process used to create them, represent a substantial new tool in the design and development of rovers for planetary surface missions. A test correlated dynamic model can accurately predict system aspects such as internal loads and driving performance. The tools have great utility in the design phase of a mission, investigating system limitations, predicting system resource utilization, and exploring capabilities of the system in environments that are not readily achieved on Earth. In the operations phase of the mission, these tools give a project the ability to estimate and plan safe and resource limited traverses.

ACKNOWLEDGMENTS

The research described in this paper was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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