Characterization of the ROAMS Simulation Environment

for Testing Rover Mobility on Sloped Terrain

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Abstract

As the duration of rover missions increases (the Mars Exploration Rovers are each currently beyond 1370 sols on the Martian surface), a wider variety of terrain types (slopes, soil types, etc) will usually be accessed. It is extremely important that a simulation environment used for flight systems has the necessary fidelity to model rover mobility on sloped, uneven terrain such as that encountered in actual missions. The main objective of the ROAMS (Rover Analysis, Modeling and Simulation) study was to characterize the dynamics components of the ROAMS simulation environment for mobility algorithm development and testing for the MSL (Mars Science Laboratory) rover currently planned for a 2009 launch. This paper compares the results of a series of tests run on a variety of soil types and on level/sloped terrain with the FIDO (Field Integrated Design and Operations) rover on a tilt table to the ROAMS simulation of the same experimental setup.

1. Introduction

There has been significant growth in the number of space exploration missions devoted to planetary surface exploration using mobile rover vehicles. The Mars Science Laboratory (MSL) due to be launched in 2009 by the Jet Propulsion Lab (JPL) represents the next generation of such surface exploration missions. Highlights of the MSL mission include the extended mission life (over 18 months) and the desire to increase the rover's onboard capabilities in order to reduce the amount of ground intervention needed for the exploration activity. There is a strong need to develop validated modeling and simulation capability for the surface system to allow missions to carry out detailed surface system trade studies, develop and test new rover technologies, support the development of onboard flight software architectures, develop mission operations concepts etc.

The ROAMS (Rover Analysis, Modeling, and Simulation) physics-based simulator [1, 2, 3] is being developed to support the design, development and test of such planetary surface rovers (Mars Exploration Rover shown in Figure 1). One of the goals of ROAMS is to support the early development, testing and maturation of new rover technologies for eventual transfer for mission use. ROAMS (overview shown in Figure 2) includes models for various subsystems and components of the robotic vehicle including its mechanical subsystem, an electrical subsystem, internal and external sensors, onboard resources, on-board control software, the terrain environment and the terrain/vehicle interactions. The ROAMS simulator can be used for stand-alone simulation, closed-loop simulations with onboard software or for operator-in-the-loop simulations.
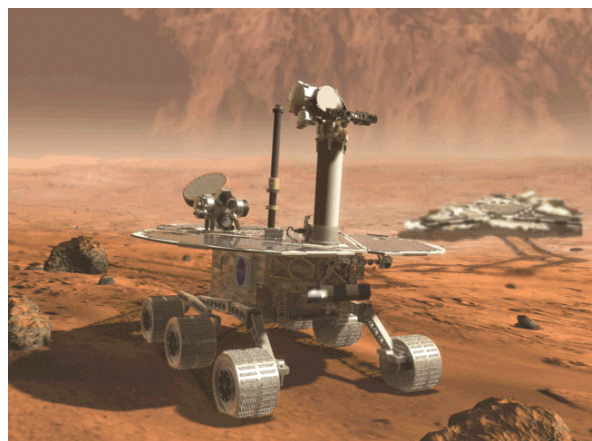

Figure 1. Artist concept of MER (Mars Exploration Rover). The MER *Spirit* and *Opportunity* have been active on the surface of Mars for 1390 and 1370 sols (Martian days) respectively.
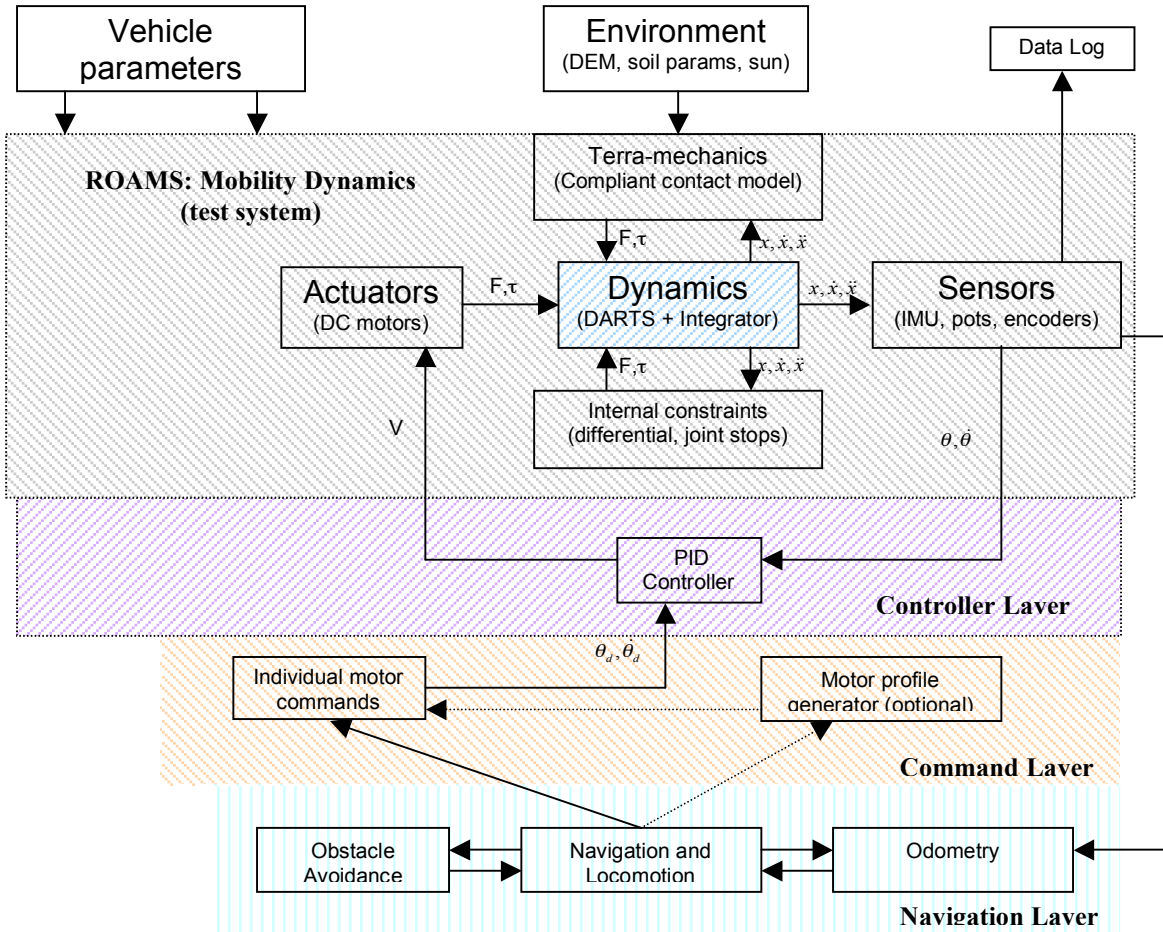
Figure 2. Overview of ROAMS software. The mobility system includes the vehicle dynamics, sensor, actuator and environmental models (further details are found in the text).

The planetary rover vehicle modeled in ROAMS is the rocker/bogie class of 6-wheeled rovers used for planetary surface exploration. There are several variations on the basic design in terms of the location of the differential, the number of steerable wheels and the various mechanical dimensions of the rover. While the underlying DARTS multi-body engine supports very general multi-body topologies, ROAMS specializes this to rocker/bogie vehicles by using parameterized templates. The templates provide entries for the basic kinematics and inertia properties of the rover, its arm (if any), inertial sensors, number of steerable wheels etc. The templates simplify the definition and addition of new rover vehicle models. For existing rocker/bogie platforms, the templates are filled in with numeric values specific to the rover.

The next section gives a brief overview of the underlying models for ROAMS. This is followed by a description of the parameter tuning procedure used for the characterization study.

2. ROAMS overview

2.1. Dynamics algorithms and integration

In order to simulate the rover dynamics, ROAMS uses DARTS (Dynamics And Real-Time Simulation). DARTS provides an efficient dynamics formulation for multi-body, articulated systems. The rover kinematic joint locations, mass, and inertia properties are input parameters to DARTS. Given the forces and torques (F,t) acting on the rover, DARTS computes the accelerations of each articulated body. These accelerations are then integrated forward in time to propagate the rover state ($x, \dot{x}, \ddot{x}$). ROAMS typically uses a variable step, stiff integrator called CVODE. CVODE was developed at Lawrence Livermore National Labs as part of SUNDIALS (Suite of Nonlinear and Differential Algebraic equation Solvers)

and is based on previous Fortran integrators VODE and VODPK.

2.2. Generic model interface (Dshell)

The Dshell (DARTS shell) package provides a generic interface between the underlying physics in DARTS and a variety of models. ROAMS implements several models in the Dshell environment including internal constraint models, actuator/sensor device models, controller models, and a compliance model of the wheel-soil contact.

2.3. Internal constraint models

The rocker differential employed by most rovers forms an internal closed-chain articulation and constrains the right and left rocker arms to deflect an equal amount in opposite directions. ROAMS uses a Dshell-based, compliant constraint model for the rocker differential. This constraint model applies an internal restoring force using a stiff spring to prevent violation of the equal and opposite rocker constraint. ROAMS uses a linear compliance model for the differential joint:

$$\tau_R = k_R e + c_R \dot{e},$$

where τ_R is the differential rocker constraint torque, k_R is the spring constant, c_R is the damping constant, e is the sum of the left and right side rocker angles and $\dot{e}$ is the time derivative of e.

ROAMS employs a similar technique to handle joint limits on rocker/bogie arms. A compliant opposing torque is applied when a joint proceeds past a joint stop. In order to prevent significant violations of either joint stop or the rocker differential constraint, the compliance constraints employ a very stiff spring model. ROAMS uses a non-linear (Hunt-Crossley) spring model for the joint stop system.

2.4. Actuator models

ROAMS uses individual DC motor models to provide actuation force for each steering, wheel and arm joint on the rover. Parameters for the motor model are the motor armature constant, stall torque, resistance and mechanical damping. Input to the model is the motor voltage. The DC motor models apply torques to the rover dynamics as show in Figure 2. Motor current dynamics are assumed instantaneous; the motor inductance is assumed equal to zero. Algorithmically, the motor model first computes the current draw using Kirchoff's law (assuming inductance is zero):

$$Ri = V_{in} - K_t\dot{\theta} \Rightarrow i = \frac{1}{R}\left(V_{in} - K_t\dot{\theta}\right),$$

where K_t is the armature constant (in SI units), $\dot{\theta}$ is the rotational velocity of the shaft, V_{in} is the input voltage, and i is the motor current draw. Based on the current draw, we can compute the motor torque as:

$$\tau = K_t i - b\dot{\theta},$$

where b is the mechanical damping constant and t is the motor torque.

2.5. Sensor models

ROAMS uses encoder and potentiometer models that provide joint angle and rate information for the rover wheel, steering, arm and rocker/bogie joints. Normally, these models output truth data from the simulation. Parameters also allow overriding the positive angle direction of any encoder/potentiometer. The current encoder and potentiometer models do not include any noise.

ROAMS provides a "truth" IMU model that outputs truth (zero noise, zero bias) values for linear and angular rates and accelerations. While ROAMS also includes more accurate IMU models, the truth-based model will be used for validation tests.

2.6. Environmental models

In addition to vehicle modeling, ROAMS also models the rover environment. As a surface vehicle, the rover interacts with the environment primarily through the terrain. A Digital Elevation Map (DEM) represents the terrain (including rocks) in ROAMS. ROAMS parameterizes soil mechanics properties using density, internal friction angle and soil cohesion. The user may explicitly set these parameters or select parameter sets that match certain soil types (clay, loose sand, mixed, etc.).

2.7. Wheel-soil contact model

The primary goal of the wheel-soil contact model is to compute the forces and torques exerted by the soil on the rover vehicle. Given these forces, DARTS can compute the resulting accelerations for the rover using the multi-body dynamics model. For a 6-wheel rover, there are 36 unknowns: 3 forces and 3 torques for each of six wheels. However, a static force/moment balance for the rover-terrain system yields only 6 equations. Constraint equations written about each bogie and about the rocker differential yield an additional 3 equations. The problem is therefore statically

indeterminate (9 equations in 36 unknowns) and there is a large solution space of contact forces/torques that satisfies the equations.

ROAMS makes some assumptions to reduce the number of unknowns. First, ROAMS assumes single point contact for each wheel. This assumption eliminates half of the unknown variables since torque can not be exerted at a point contact. We are still left with 3 unknown forces at each wheel contact point. To solve for these forces, ROAMS uses two separate and independent compliance systems at each wheel contact to compute the unknown forces. One compliance system is used to compute the normal force and the second system is a two degree of freedom system used to compute the tangent force. The spring and damping coefficients for these compliance systems are parameters of the compliant contact model. The compliance model uses Terzaghi's terra-mechanics equations to compute the maximum available traction force at each contact and to estimate the wheel sinkage into the terrain.

3. ROAMS parameter tuning

One of the key questions that must be addressed for acceptance of ROAMS for mission development and operational testing is how well does it represent reality. There are several aspects to this question. The first is whether the simulation captures the basic physics involved adequately. Assuming the first question is satisfied, the next question is whether the parameters involved in the simulation are tuned in such a way that the behavior of the simulation matches that of a specific real vehicle. Failure in the tuning is a clear indication that the basic models are inadequate. The goal in this activity was to tune the ROAMS simulation to the FIDO (Field Integrated Design and Operations) rover and show that both of these issues had been addressed. The FIDO rover is a six wheeled technology prototype with a rocker-bogie suspension system at JPL that was used for MER field trials throughout the period from 1999 to 2002 to develop operational strategies for mobility and science operations [4].

3.1. Identifying key ROAMS parameters

During development of the ROAMS simulation, significant work has gone into developing quality models of all aspects of rover kinematics and dynamics. In particular, special attention has been paid to modeling the interaction of the rover wheels with the terrain [5]. Based on the resulting models and other consideration, there is a set of parameters that most significantly affect the ability of ROAMS simulation to match the behavior of the FIDO experimental runs. These parameters are:

1. friction angle (radians)
2. soil cohesion (kPa)
3. rolling resistance (unitless)
4. Max standard deviation (for tire-soil slip model)
5. Slope standard deviation (for tire-soil slip model)

The first three parameters are typical ground trafficability parameters. The last two parameters are internal parameters in the wheel-soil interaction model relating to the stochastic nature of slip. Based on previous experience, nominal values of these parameters that worked well in simulations were known.

3.2. Tuning to a subset of experimental runs

In order to tune these parameters, a simulation of the FIDO rover with the ability to execute multiple simulation runs with a sweep of the set of parameters was developed. These runs are referred to as "Monte-Carlo" runs, even though the selection of which parameters to use in each case was selected from a list of parameters instead of being chosen randomly, as in a true Monte-Carlo simulation. The fidelity of each simulation run was evaluated by constructing a score based on differences from the final position and heading in the simulation versus the experimental runs.

A subset of the FIDO experimental runs were used and parametric sweeps runs for each test case were set up. Based on which simulations runs best matched the data from the actual runs, the simulation parameters were tuned to give the best overall match.

The tuning was performed in two phases: a coarse phase and a refinement phase. In the first phase, a wider selection of values was used for each parameter about a nominal value guess. Based on comparing the parametric sweeps with the test cases, a new nominal value was selected that was approximately tuned to the FIDO performance. A second phase of tuning was then performed where a smaller range of variation of each parameter with respect to the new nominal values selected in the coarse tuning phase was considered.

Figure 3. Underlying surface of MER tilt table with concrete paving stones glued to a plywood surface. The surface is then covered in sand to produce a mixed terrain.

A wide range of parameters worked on runs for flat terrain, but a much smaller set produced good results on slopes. Fortunately, tuning for slopes produced good results on the flat. In general, it was more difficult to match the behavior of the real FIDO rover on steeper slopes (greater that approximately 15 degrees).

4. Experimental Studies

The characterization of the ROAMS simulation technology with the FIDO rover was conducted from August 31, 2004 to September 23, 2004 using the MER tilt table adjacent to the JPL MarsYard. The tilt table has a mosaic of paving stones glued to a plywood

surface and covered with a layer of fine sand (shown in Figure 3). The ROAMS parameter settings were obtained by using a subset of the test data to tune the ROAMS model for FIDO that then served as the baseline for simulation performance evaluation. Tests were run on the tilt table set at 0, 5, 10, and 20 degrees. The actual tilt table angles used for the tests measured with a Leica TotalStation were 0.085, 5.743, 10.758, and 20.764 degrees, but these will be referred to as 0, 5, 10, and 20 degrees throughout this section. A total of 400 tests were run to determine ROAMS simulation performance for accuracy during straight-line and arc drives, and turns-in-place at the 4 tilt table angles.

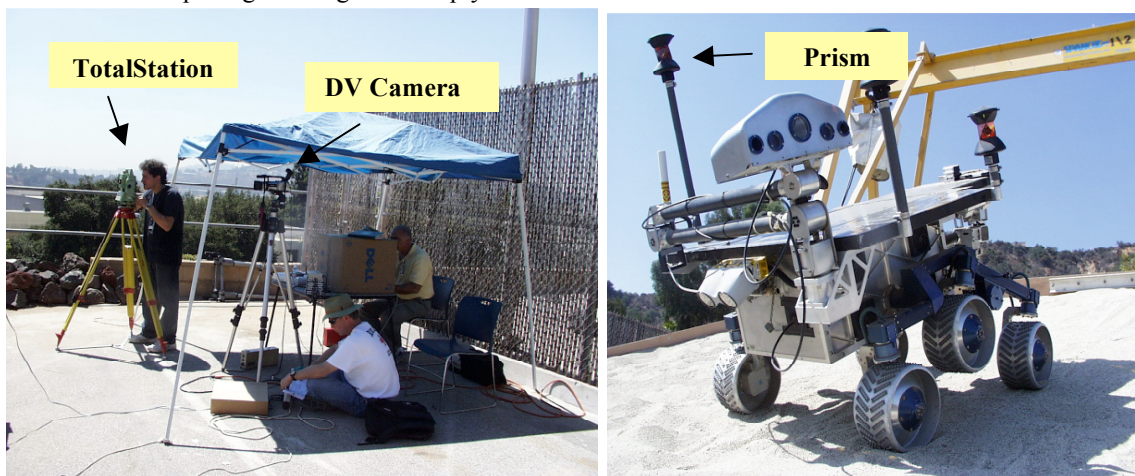All results were compared to ground truth data that was collected by a Leica TCRA1103+ TotalStation

Figure 4. ROAMS test setup. Leica TotalStation is in background and FIDO rover with four prism reflectors is shown on MER tilt table.
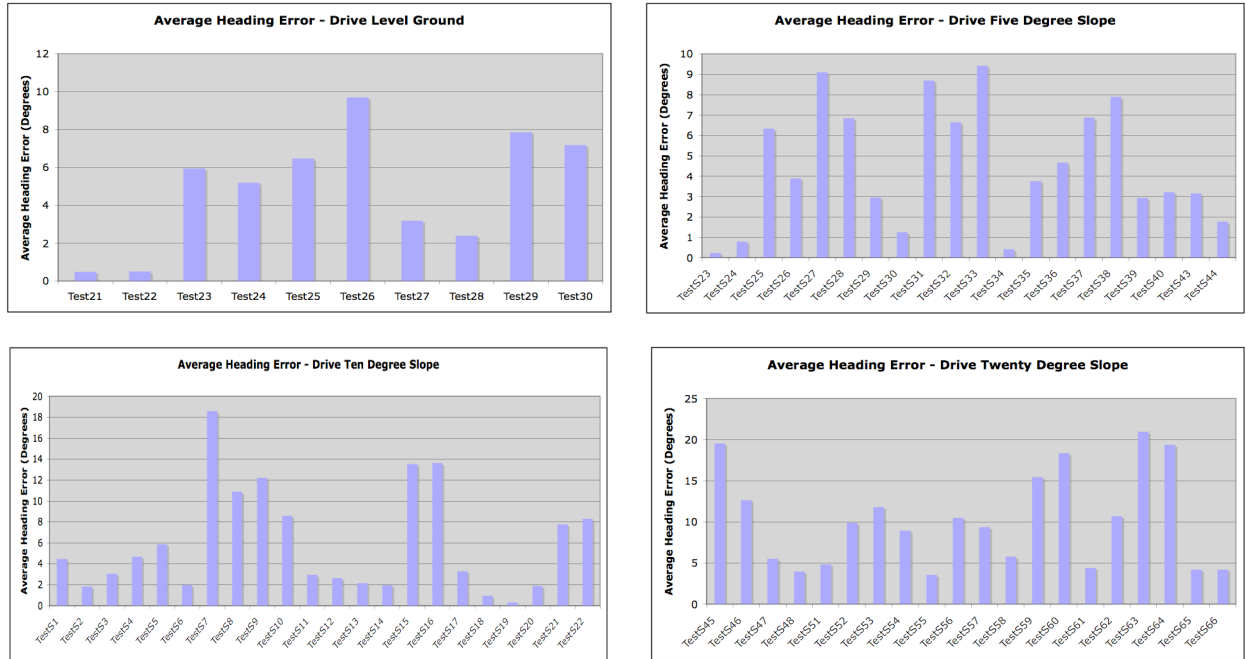
Figure 5. Summary plots for heading errors for the drive runs (defined as the absolute difference between the ground truth and the ROAMS output) for MER tilt table set at 0, 5, 10, and 20 degrees. Note the difference in vertical scales (0 and 5 are more or less equivalent, and 10 and 20 are more or less equivalent).

(rated accuracy of 2mm at 10m range). All of the test runs were also taped on Mini-DV video for possible future analysis of the full behavior of the rover. The test setup is shown in Figure 4, where the FIDO rover has four prism reflectors (one on each corner of the rover) that are used for range and rover attitude determination each time before and after the tests. This setup gives both position and heading information. All tests were run using the current version of the FIDO control code. Logfiles were produced by the FIDO control software at a rate of 50Hz and were used for ROAMS parameter setting and characterization runs.

4.1. Drive runs

The drive tests are numbered Test21 through Test30 for a level tilt table, and TestS1 through TestS66 for the tilt table settings of 5, 10, and 20 degrees. Each one of the tests was run five times for the level table and three times for the tilted table settings (5, 10, and 20 degrees). The drive tests included straight line, shallow arcs, and tight arcs of length 2 meters. These drives were done with up-slope, down-slope, and cross-slope directions and the rover traveling forward and backward. The largest errors are seen in the tight arcs due to interaction of the wheels with the underlying mixed sand and concrete paving stones. The average

heading error (in degrees) defined as the difference between the ground truth and the ROAMS outputs for each tilt table setting (0, 5, 10, and 20 degrees) for all of the drive runs is shown in Figure 5. Also of particular importance for evaluation of the fidelity of
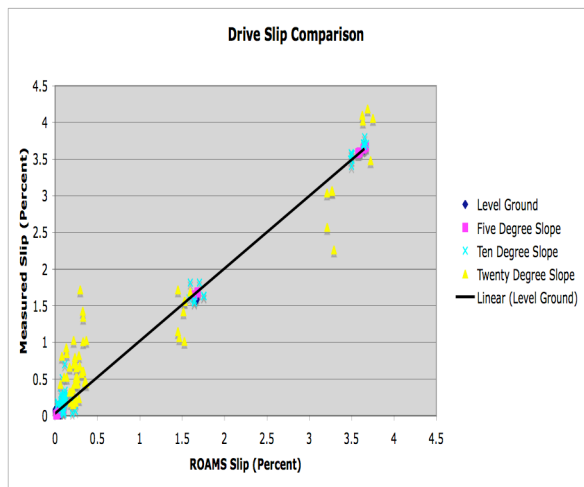

Figure 6. Plot of measured slip versus ROAMS simulation slip for all MER tilt table angles (0, 5, 10, and 20 degrees). Note the wider variance in the slip measurements for the 20 degree slope.

ROAMS is the slip estimate while driving on slopes. A scatter plot of the measured slip versus ROAMS slip (in percent) based on the commanded final position for each drive run is shown in Figure 6. The variance in slip estimates grows with MER tilt table angle, especially in the lower slip range for the 20-degree setting, where ROAMS consistently underestimates the slip. An example of a ROAMS output plot for one of the drive runs is shown in Figure 7, where the dotted outline is the measured final position and the solid outline is the ROAMS final position for the rover.

4.2. Turn-in-place runs

The Turn-in-Place Tests are numbered TestT13 through TestT18 for a level tilt table, and TestTS1 through TestTS54 for the tilt table settings of 5, 10, and 20 degrees. Each one of the tests was run five times for the level table and three times for the tilted table settings (5, 10, and 20 degrees). The turn-in-place runs were done with right and left turns of anywhere from 5 to 245 degrees in upslope, down-slope, and cross-slope directions and the rover traveling forward and backward. The average heading error (in degrees) defined as the difference between the ground truth and the ROAMS outputs for each tilt table setting (0, 5, 10,
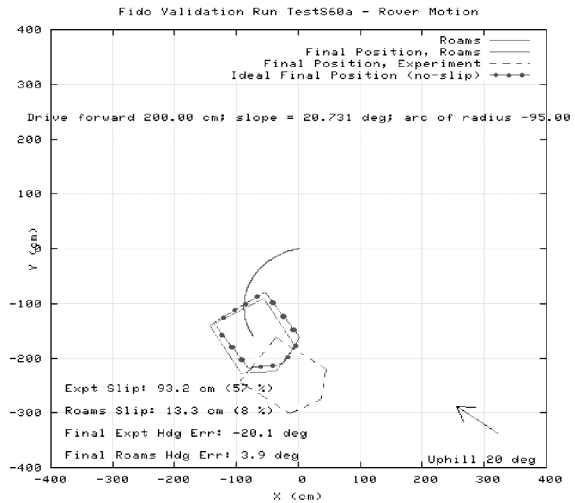

Figure 7. ROAMS output for a down-slope tight left arc drive on a 20 degree slope. Actual final position is shown with a dotted line, ideal final position with no slip is shown with a circle broken line, and ROAMS final position is shown with a solid line. The uphill direction is shown with the arrow. There was extensive down-slope slip.
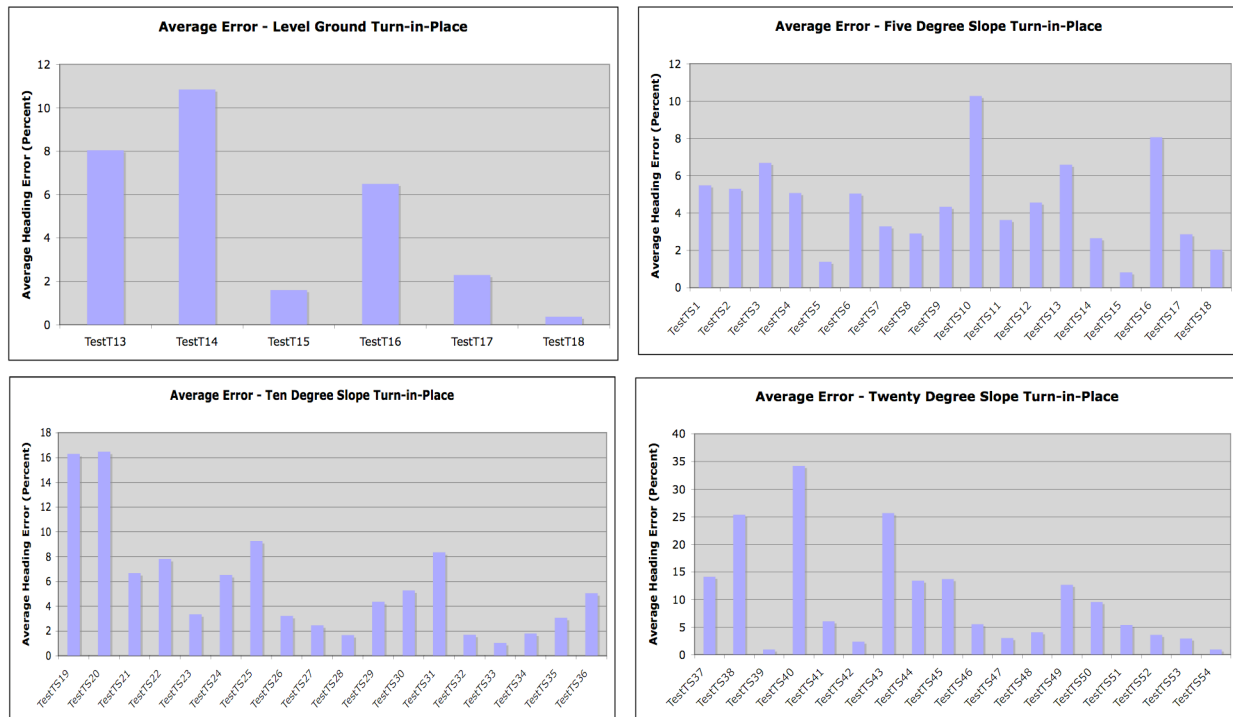

Figure 8. Summary plots for heading error for the turn-in-place runs (defined as the absolute difference between the ground truth and the ROAMS output) for the MER tilt table settings of 0, 5, 10, and 20 degrees. Note the relative doubling of the heading error scale on the 20-degree plot.

and 20 degrees) for all of the turn-in-place runs is shown in Figure 8. Of particular note is the doubling of the range of average heading errors when the MER tilt table was set to 20 degrees.

5. Summary

The overall results indicate that in terms of prediction error, ROAMS simulated the field collected experimental data for MER tilt table slopes up to and including ten degrees. There is a large amount of variability in the field collected experimental data for the twenty degree slope setting on the MER tilt table that can not be captured by ROAMS. Generally, one out of three test runs would be outside the nominal behavior of the rover. The factors that contribute to this behavior are the excessive slip at this slope angle, interactions with the underlying paving stones, and bogie interactions with the terrain. The summary graphs indicate that the average error in heading for the turn-in-place runs were usually less than ten percent for slopes less than twenty degrees. In seven of the eighteen Tests run at a twenty degree slope setting, the average errors were greater than ten percent and as high as thirty-four percent for one of the Tests. The summary graphs indicate that the average error in heading for the drive runs were usually less than six degrees for slopes less than twenty degrees. In twelve of the twenty runs at a twenty degree slope setting, the average errors were greater than six degrees and as high as twenty-one degrees for one of the runs.

In terms of localization in the X and Y coordinate frame, the majority of the error was in the X direction (aligned with the forward direction of the rover). The majority of the errors were less than ten centimeters in the X and Y directions for slopes less than ten degrees, growing to twenty centimeters in the X and Y directions for slopes of ten degrees, and increasing to forty centimeters in the X and Y directions for slopes of twenty degrees. These errors are all measured for two meter traverses.

6. Current Directions

A probabilistic component will be added to the ROAMS simulation model in order to handle the off-nominal behavior of rovers on slopes steeper than ten degrees (MER has driven on slopes greater than twenty-five degrees and the Opportunity rover is currently on a twenty-eight degree slope below the lip of Victoria Crater). Further research will investigate the use of more sophisticated soil contact models using finite element algorithms that relax the current single point contact assumption.

7. Acknowledgments

8. References

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