

Dynamic Simulation Tool Development for Planetary Rovers

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Abstract: A dynamic computer simulator was developed to study planetary rover mobility. The simulator was validated for step-obstacle negotiation by comparing simulation results with a quasi-static analysis of a rocker-bogie suspension. In addition, sample rover wheels were constructed and experiments were carried out on a single-wheel testbed to help validate the simulator. It is concluded that to fully validate such a complex simulation tool requires experimental data from a full-size rover chassis.

Keywords: computer simulation, planetary rovers, wheel-soil interaction, experimental validation

1. Introduction

In this paper, the present authors describe a Rover Chassis, Analysis and Simulation Tool (RCAST) to study mobility and support rover chassis design and optimization. RCAST simulates both the rover multibody dynamics and corresponding wheel-soil interactions (Bauer *et al.*, 2005a). Developed in Mathwork's Matlab/Simulink environment, RCAST uses a commercially-available wheel-soil interaction computer model called the AESCO Soft Soil Tire Model (AS²TM) to predict planetary rover locomotion (AESCO, 2003). Step-obstacle negotiation simulations are compared with a quasi-static analysis to validate RCAST. Experimental data from a single-wheel testbed are then used to help validate RCAST simulation results (Bauer *et al.*, 2005b).

2. Rover Model Development

An example six-wheeled rover suspension configuration implemented in RCAST is shown in Figure 1. This design is based on a chassis concept described in a Science & Technology Rover Company Ltd. (RCL) report for the European Space Agency (ESA) Aurora Programme ExoMars Mission (Kucherenko, 2003) which has seven passive degrees of freedom (DOF) associated with each of the three suspension linkages. Additional DOF are associated with the wheels and wheel supports as follows:

- four steering DOF (on the front and rear wheels)
- six wheel-walking DOF
- six wheel-rotational DOF about the wheel axles

RCAST simulations are controlled using a graphical user interface where the user can, for example, select different soil types and terrain cases such as step obstacle negotiation.

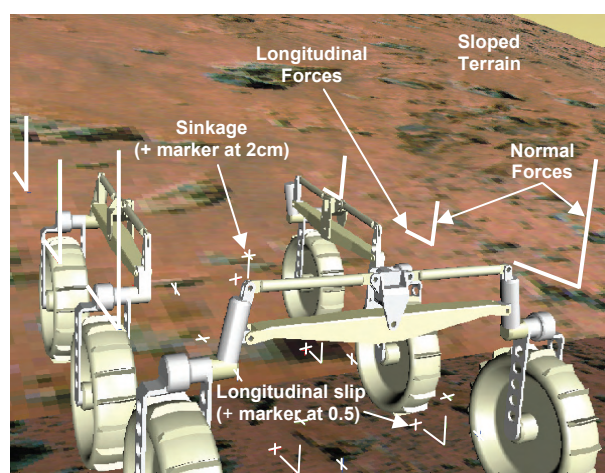


Fig. 1. Sample RCAST Suspension Configuration

3. Applications of RCAST

The ability to negotiate a rigid step obstacle can be used as a performance metric to compare different rover chassis designs. RCAST simulates the contact dynamics between the rigid wheels and the step obstacle by applying a penalty force to each wheel as it interacts with the step. The penalty force depends on both the position and velocity of each wheel in contact with the obstacle and this force determines the magnitude of the normal force N on each wheel.

To validate this step-obstacle implementation, RCAST simulation results were compared with the results from a quasi-static analysis of a rocker bogie suspension system (see Figure 2).

The geometric/mass parameters employed in the quasi-static analysis of the generalized rocker bogie were chosen to match the equivalent RCAST parameters in order to facilitate comparisons.

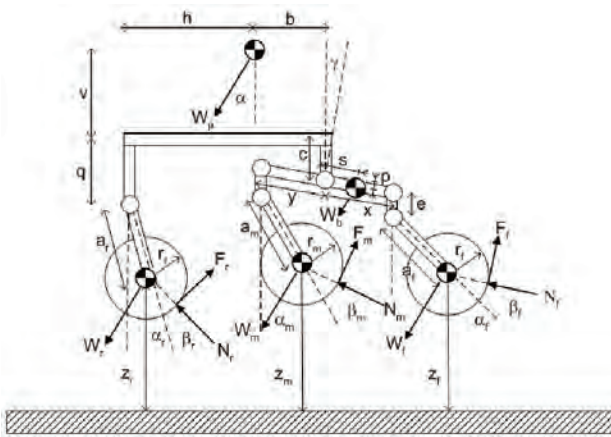


Fig. 2. Generalized rocker-bogey configuration

In general, the quasi-static analysis consists of the following steps:

1. User provides heights of each wheel above a nominal ground plane: z_r , z_m , and z_f , for the rear, middle, and front wheels, respectively.
2. User provides contact angle each wheel makes with the terrain: α_r , α_m , and α_f , for the rear, middle, and front wheels, respectively.
3. Solve for the bogey pivot angle γ which is a function of the geometry alone.
4. Assume the tractive forces on the wheels obey the linear Coulomb relation: $F_r = \mu N_r$, $F_m = \mu N_m$, $F_f = \mu N_f$, for the rear, middle, and front wheel respectively. The F forces are tractive, the N forces are normal, and μ is the coefficient of friction.
5. Solve for the value of μ that allows the tractive forces to exactly balance the gravitational forces on the robot. Each of the forces due to gravity are simply weights of the form $W = mg$ (one for each of the five masses shown in Figure 2).

Step 3 above involves solving a nonlinear equation (numerically). This fully determines the geometry of the situation. Once the geometry is known, Step 5 involves solving a simple linear system of equations (unless we replace the linear Coulomb relation with something more sophisticated).

To compare with RCAST, we considered the quasi-static case of the rover incrementally descending backwards off a step of height, $d = 0.3$ m, as shown in Figure 3. The front and middle wheels have constant height and contact angles. Given the height of the bottom of the rear wheel above the ground, denoted z , we can proceed to determine β_r and γ , as described above.

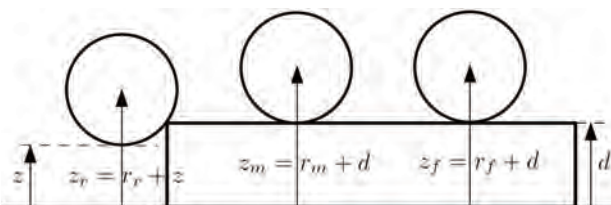


Figure 3. Scenario used to compare RCAST with Rocker Bogey Analysis

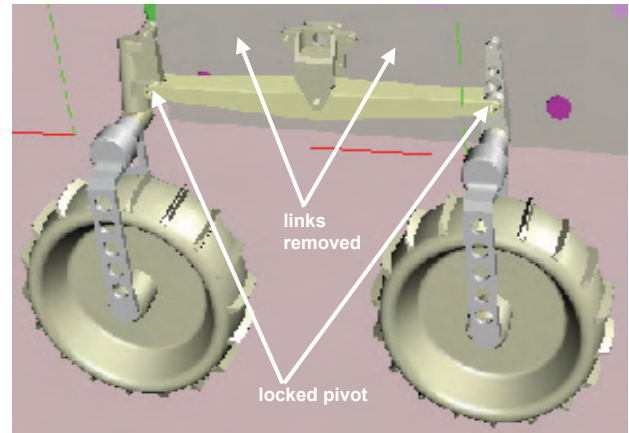


Fig. 4. Approximated Rocker Bogey Suspension

We may then solve for the value of μ that keeps the rover in this configuration. Thus, we have a one-to-one mapping from z to μ . It is this mapping that will be compared to RCAST (and is plotted in Figure 5.).

To compare step-obstacle negotiation results from RCAST with the previous quasi-static analysis, the six-wheeled suspension design shown in Figure 1, was modified to approximate a rocker bogey by removing links and welding/locking the pivots as shown in Figure 4.

Obtaining “static” results with RCAST was challenging given the dynamic nature of the simulation tool. For the case where the rover starts with all six wheels on top of the step obstacle and then begins to slowly back down the step, static results were obtained by specifying a series of desired heights for the rear wheels. Having the rover back down the step obstacle proved to be a useful validation scenario as it avoided the wheel-soil interactions which were difficult to compare due to the large number of associated parameters.

A PID controller was then applied to the position error between the actual and desired rear wheel heights, and a coefficient of friction μ between the obstacle and the wheels was controlled to keep the rover in static equilibrium. This calculated coefficient of friction was used to determine the friction forces F on each of the wheels from the Coulomb relationship:

$$F = \mu N \quad (6)$$

where N is the wheel normal force. The rear wheel target height was then sequentially dropped and, at each new setpoint, the PID controller was allowed time to establish a new value of μ for static equilibrium.

The resulting friction coefficients were plotted as a function of the rear wheel height as the rover incrementally backed down a 0.3m step obstacle. Figure 5 shows a sample of the results from RCAST with the rocker bogey quasi-static analysis results superimposed. Evidently there is excellent agreement between the results. The small difference observed can be attributed to the fact that the quasi-static rocker bogey analysis applied a parallel constraint to the wheel supports. No such constraint was applied in the RCAST suspension shown in Figure 4.

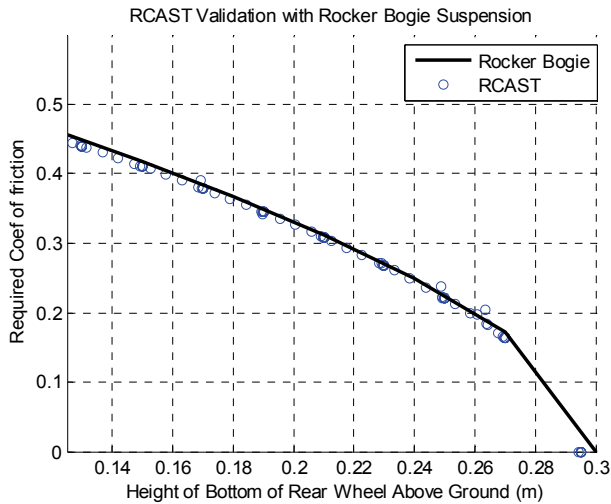


Fig. 5. RCAST and Rocker Bogie Analysis Comparison

To further validate RCAST, experiments were performed on the Massachusetts Institute of Technology (MIT) Field and Space Robotics Laboratory's Wheel-Terrain Characterization Testbed. This testbed consists of a wheel carriage which is equipped with potentiometers and which can translate both horizontally and vertically. A torque sensor and motor are attached to the wheel and a force/torque transducer is located on the wheel carriage above the wheel. Controlling the translational velocity of the wheel carriage and the angular velocity of the wheel enables one to control the slip ratio.

4. Single-Wheel Experiments

The following rigid wheels were tested:

- semi-spherical wheel with 18 straight grousers
- smooth cylindrical wheels
- cylindrical wheel with 9 straight grousers
- cylindrical wheel with 18 straight grousers
- cylindrical wheel with 18 angled grousers

All wheels tested had a radius of 9.80 cm, a width of 5.08 cm and a grouser height of 0.6 cm (except for the "smooth" cylindrical wheel). Figure 6 summarizes the different wheel treads used. As shown in Figure 6, the wheels with grousers were designed so that the number of grousers or lugs on the wheel could be easily changed to 0, 9 or 18 by attaching different grouser/non-grouser plates to the surface of the wheel.

For each tire tread, experiments were carried out for a series of slip ratios. For each slip ratio, at least three trials were performed to provide an indication of the repeatability of the experiments. The trials for each experiment were merged into a single dataset and the last two seconds of each merged dataset were averaged to obtain the steady-state mean values. These data were calculated for each of the five tire treads and a sample of the experimental results is plotted in Figure 7 as a function of slip ratio.

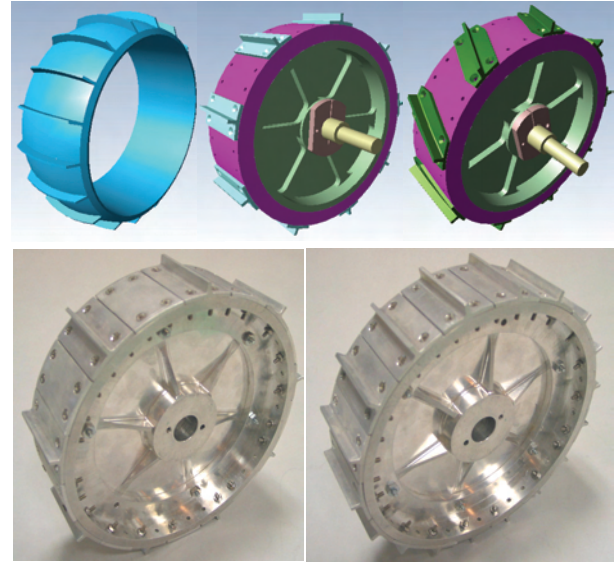


Figure 6. Wheel designs with options for 0, 9 or 18 grouser plates attached

Figure 7 shows that, compared with a smooth rigid wheel with no grousers, the addition of nine grousers to the wheel increased the drawbar pull F_y by about a factor of five. Figure 7 also shows that doubling the number of grousers increases the drawbar pull F_y by approximately 30%. The negative values of the measured sensor forces F_y in Figure 7 are consistent with the sensor coordinate frame of reference. It is interesting to note that there does not appear to be a significant difference in the drawbar pull among the three different 18-grouser tire treads for the slip ratios and dry sandy soil tested.

5. Comparison of Simulation and Experimental Results

In order to compare the above experimental results with the AS²M soft-soil tire model in RCAST, the soil parameters associated with this model were manually tuned.

After this tuning process, it was observed that the sinkage relationship is accurately modeled. In the case of drawbar pull the simulation results generally lie within the calculated 95% confidence intervals.

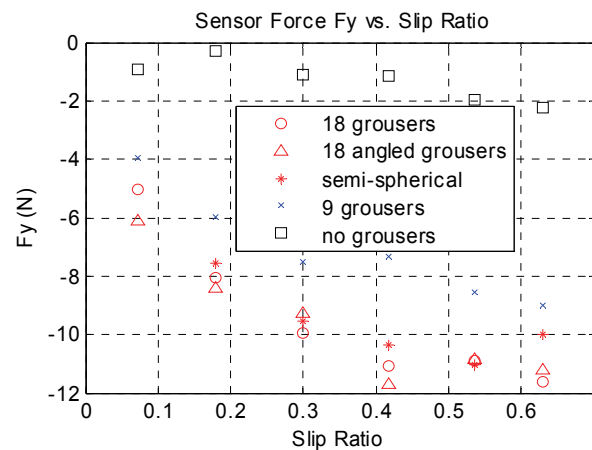


Fig. 7. Measured Drawbar Pull vs. Slip Ratio

6. Conclusions

In conclusion, a rover chassis and analysis computer simulation called RCAST successfully couples a rigid multibody dynamics engine with the AS²TM wheel-soil interaction module to enable locomotion performance to be studied for various rover designs. RCAST simulation results have been successfully compared with a rocker bogie analysis to help validate the implementation of step-obstacle negotiation.

In addition, single-wheel experiments were carried out for five different tire treads and the results were compared with the AS²TM wheel-soil interaction model used in RCAST. Experiments showed that, for the dry sandy soil and wheels used in this research, when compared with a smooth rigid wheel with no grousers the addition of nine grousers to the wheel increased the drawbar pull F_y by a factor of five. Furthermore, the wheels with 18 grousers had approximately 30% improvement in drawbar pull over the wheel with nine grousers with relatively little effect on sinkage. While the quasi-static analyses and single-wheel testing described in this paper provide partial validation of RCAST, to more fully validate the simulator with all six wheels and have confidence in the predictions, experimental data from a full rover chassis will be required. Construction of such an experimental testbed is ongoing work (see Figure 8.).

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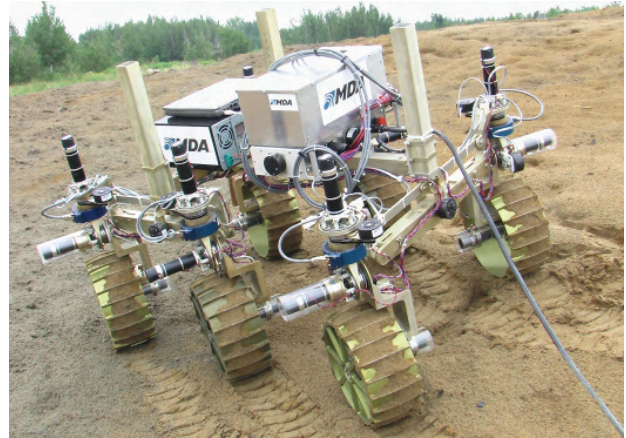


Fig. 8. Full scale rover used for ongoing validation.

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