ANALYSIS AND SIMULATION OF A ROCKER-BOGIE EXPLORATION ROVER

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Abstract

Rovers will continue to play an important role in planetary exploration. Plans include the use of the rocker-bogie rover configuration. Here, models of the mechanics of this configuration are presented. Methods for solving the inverse kinematics of the system and quasi-static force analysis are described. Also described is a simulation based on the models of the rover's performance. Experimental results confirm the validity of the models.

1. Introduction

NASA recently started an ambitious exploration program of Mars [1]. Pathfinder is the first rover explorer in this program [2],[3]. Future rovers will need to travel several kilometers over periods of months and manipulate rock and soil samples. They will also need to be somewhat autonomous. Rocker-bogie based rovers are likely candidates for these missions (see Figure 1). The physics of these rovers is quite complex.

To design and control these, analytical models of how the rover interacts with its environment are essential [4]. Models are also needed for rover action planning [5]. Simple mobility analysis of rocker-bogie vehicles have been developed and used for design evaluation [6],[7]. In the available published works, the rocker-bogie configuration is modeled as a planar system.

Improving the performances of a simpler four wheel rover has also been explored [8]. In this work, actuator redundancy and the position of the center of mass of a vehicle (the Gophor) is exploited to improve traction. The method relies on real-time measurements of wheel/ground contact forces, which are difficult to measure in practice. Traction can also be improved by monitoring the skiding of the rover wheels on the ground [9]. However, detailed models of the full 3-D mechanics of rocker-bogie rovers have not been developed. Further models including the manipulator's influence are also required to effectively planning and controlling the actions of these rovers. For example it is important for a planner to be able to predict if a rover can successfully negotiate a given terrain obstacles, such as a ditch, without being trapped.

This paper describes a physical model of a rocker-bogie rover, the Lightweight Survivable Rover (LSR-1). An efficient method of solving its inverse kinematics and its quasi-static force analysis is outlined. The methods include the effects of the rover's manipulator, actuator saturation and tire-slip considerations. A graphical interface that enhances the understanding of the physics of the model is also described.

2. The LSR-1 Design

Along with the Sojourner rover, the LSR-1 is representative of a class of NASA prototype planetary rovers based on a rocker-bogie mobility configuration [10]. The LSR-1 vehicle has 20 cm diameter wheels and is approximately 100 cm in length, 70 cm wide, and 45 cm high. It is equiped with a three degrees of freedom manipulator, whose payload is not negligible in the rover mass ditribution. Six independently driven wheels are mounted on an articulated frame, see Figure 1. The frame has two rocker arms connected to a main body. Each rocker has a rear wheel connected to one end and a secondary rocker, called a bogie, connected to the other. At each end of the bogie is a drive wheel and the bogie is connected to the rocker with a free pivoting joint. The rockers are connected to the main body with a differential so that the pitch angle of the body is the average of the pitch angles of the rockers. A more detailed description of the design is given in [10].

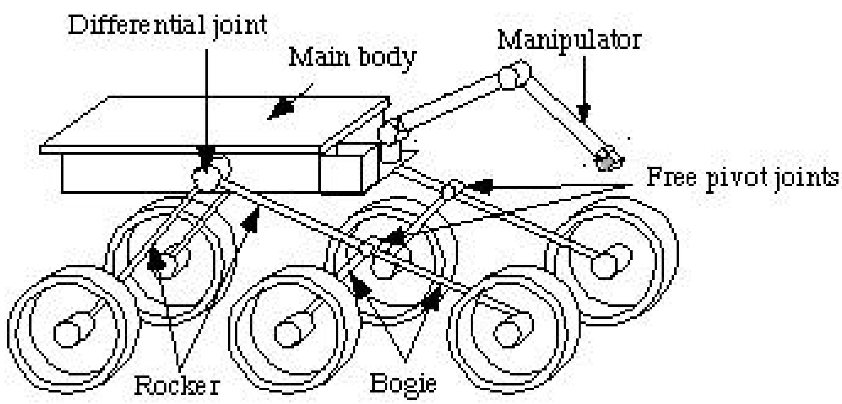

Figure 1: A Rocker-Bogie Rover (LSR-1)

3. Model description

One of the principal purposes of this analysis is to serve as on-board tool for action planning [5]. Hence it is important to keep the model as computationally simple as possible while maintaining an acceptable level of fidelity. A key to achieving these objectives is to recognize that the practical constraints of space systems, such as weight and power, require rovers to travel at slow speeds, approximately 3 cm/s (for the LSR-1). Therefore, dynamic effects are small and a quasi-static model adequately describes its behavior.

The terrain geometry is taken as input to the analysis. Rovers will have sensors such as stereo cameras and laser range finding systems capable of providing this informationin the form of maps of the local terrain [2,11]. The tire/soil characteristics are essential for the accurate modeling of rover behavior [12]. However, these characteristics can be difficult to obtain. On-line adaptive or identification methods, as well as pre-established estimates may be used to provide this information. This area remains an open research topic. The analysis developed here is intended to be sufficiently general to accomodate different soil/tire models.

3.1 Inverse Kinematics

The attitude and configuration of a rover as a function of the terrain on which it moves is required to calculate the load distribution on the wheels, the rover's stability, actuator outputs, etc. The rover's configuration, position and attitude can be fully defined by the following ten parameters (see Figure 2).:

x_B, y_B and z_B the inertial position of the vehicle;

ψ, Θ and φ: the yaw, roll and pitch angles

Θ_1, Θ_2, Θ_3 and Θ_4 : angles that define the configuration of the rocker-bogie mechanism

In the following kinematics analysis, the desired heading angle (ψ) and the inertial position of the middle right wheel (x_{2r},y_{2r}) are taken as input. Then, seven other independent variables must be determined. The variables z_{2r}, φ, Θ, Θ_1, Θ_2, Θ_3 and Θ_4 are chosen as unknowns. From this set of ten variables, the remaining three system variables x_b,y_b, and z_b can be easily calculated.

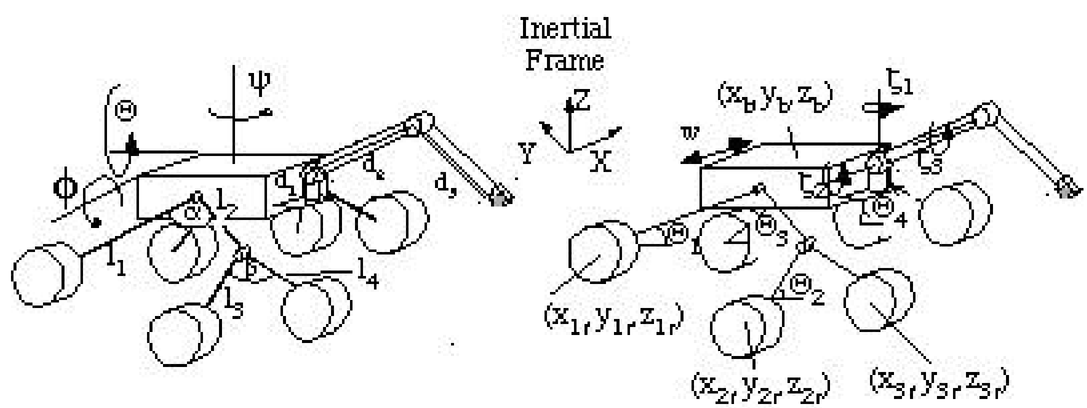

Figure 2: Kinematic parameters of the Rover

Since the six wheels are independently driven, the wheel motions along the ground are considered as inputs to the analysis. From this input, the rover position and configuration is calculated iteratively to satisfy these closed-loop equations [4]:

$$\Phi = \left(\Theta_1 + \Theta_3\right) / 2 - \gamma \tag{1}$$

$$z_{2r} = z_{\text{center,2r}} \tag{2}$$

$$z_{2r} - z_{3r} = \cos(\Theta)\ \ (l_3\ \ \sin(\Theta_2) - l_4\ \ \sin(\Theta_2 + \beta)) \tag{3}$$

$$z_{2r} - z_{1r} = \cos(\Theta)\ \ (l_3\ \ \sin(\Theta_2) + l_2\ \ \sin(\Theta_1 + \alpha) - l_1\ \ \sin(\Theta_1)) \tag{4}$$

$$z_{2r} - z_{1l} = \cos(\Theta)\ \ (l_3\ \ \sin(\Theta_2) + l_2\ \ \sin(\Theta_1 + \alpha) - l_1\ \ \sin(\Theta_3)) + w\ \ \sin(\Theta) \tag{5}$$

$$z_{2r} - z_{2l} = \cos(\Theta)\ (l_3\ \sin(\Theta_2) + l_2\ \sin(\Theta_1 + \alpha) - l_2\ \sin(\Theta_3 + \alpha) - l_3\ \sin(\Theta_4) + w\ \sin(\Theta) \quad (6)$$

$$z_{2r} - z_{3l} = \cos(\Theta)\ (l_3\ \sin(\Theta_2) + l_2\ \sin(\Theta_1 + \alpha) - l_2\ \sin(\Theta_3 + \alpha) + l_4\ \sin(\Theta_4 + \beta) + w\ \sin(\Theta) \quad (7)$$

where r and l refer to the right and left sides of the vehicle respectively, and γ is the angle Θ_1 when the rover is on a flat surface. The wheels centers positions are then deduced by solving this system. This gives seven equations in seven unknowns. These iterative solutions are obtained using numerical methods such as steepest descent and Newton's method. Because of the highly non-linearity of these equations and because the ground profile is not continuously differentiable, these methods can fail to converge to a solution.

It is possible to solve accurately the above inverse kinematics by simplifying the problem. From the profile of the ground, Θ can be approximated. Then, the model is broken into two problems. Using this approximate value of Θ, the models of the right and left sides are solved directly. Finally, Θ is corrected while maintaining the values for z_{2r}, Θ_1, Θ_2, Θ_3 and Θ_4. For a complete description of this approach see [4]. The average error between the wheel contact point and the ground profile is less than one percent of the wheel diameter (.2 cm). This error is on the same order as the errors due to other factors, such as tire compliance. The method is computationnaly very efficient (less than 10 iterations are usually enough to find a solution).

3.2 Force Analysis

With the pose of the rover calculated, the quasi-static force analysis can be performed. The quasi-static force balance is used to determine if the rover wheels will slip, if the rover will slide or tip over. It can also be used to estimate the amount of energy consumed and if any actuator are near saturation. The system center of mass position is computed and is input to the force analysis, as well as external forces. Through these terms the manipulator configuration and task forces enter the analysis. It is assumed that with the LSR's relatively rigid wheels, a large moment in any direction does not exist at the ground contact point. Ignoring these moments prevents the three-dimensional force analysis from becoming highly statically indeterminate.

The normal and the tangential forces between the i^{th} wheel and ground are N_i and T_i respectively, see Figure 3.

Assuming that the vehicle roll angle is small, The transverse forces acting at the wheel contact point (F_{y1} to F_{y6}) will be relatively small. Further, by assuming that each of these forces has the same magnitude, M_{xl}, M_{xr}, M_{zl} and M_{zr} can be computed (the width of each of the rocker-bogie assembly is small as compared to the width and height of the vehicle, hence M_{xl}, M_{xr}, M_{zl} and M_{zr} are only function of F_{yi}). The resulting equations of static equilibrium for the body are:

$$F_{xr} + F_{xl} = 0 \quad (8)$$

$$(F_{xr} - F_{xl})\frac{w}{2} + M_{zr} + M_{zl} = 0 \quad (9)$$

$$F_{zr} + F_{zl} - W_z = 0 \qquad (10)$$

$$(F_{zl} - F_{zr})\frac{w}{2} + M_{xr} + M_{xl} = 0 \qquad (11)$$

The system of equations (8)-(11) permits the values F_x, F_z, M_y that are applied from the body to each rocker to be calculated. These forces and moments are then considered inputs to the planar problem shown in Figure 3. The equations of equilibrium in the planar case are:

$$\sum \mathbf{F} \cdot \mathbf{u_x} = \sum_{i=1}^{i=3} \left(\mathbf{T_i} + \mathbf{N_i}\right) \cdot \mathbf{u_x} + F_x = 0 \qquad (12)$$

$$\sum \mathbf{F} \cdot \mathbf{u}_z = \sum_{i=1}^{i=3} \left(\mathbf{T_i} + \mathbf{N_i}\right) \cdot \mathbf{u}_z - F_z = 0 \qquad (13)$$

$$\sum \mathbf{M}_{\mathbf{y},body} = \mathbf{T}_1 \times \overline{\mathbf{RA}} + \mathbf{N}_1 \times \overline{\mathbf{RA}} + \mathbf{T}_2 \times \overline{\mathbf{MA}} + \mathbf{N}_2 \times \overline{\mathbf{MA}} + \mathbf{T}_3 \times \overline{\mathbf{FA}} + \mathbf{N}_3 \times \overline{\mathbf{FA}} + \mathbf{M}_y = \mathbf{0} \qquad (14)$$

$$\sum \mathbf{M}_{y,bogie} = \mathbf{T}_2 \times \overline{\mathbf{MB}} + \mathbf{N}_2 \times \overline{\mathbf{MB}} + \mathbf{T}_3 \times \overline{\mathbf{FB}} + \mathbf{N}_3 \times \overline{\mathbf{FB}} = \mathbf{0} \qquad (15)$$

These equations are solved with the following constraints on the wheel torques:

1) $\left|\mathbf{T_i}\right| \le \mu \left|\mathbf{N_i}\right|$: no slip ith wheel (or will just slip).

2) $N_i \ge 0$ insures ith wheel ground contact.

3) $\left|\tau_i\right| \le \tau_{max}$ to insure the ith wheel motor does not saturate.

Where τ_i is the ith wheel motor torque. Note that τ_i is related to the wheel tangential force T_i by the wheel radius. The method of finding a solution under these constraints is detailed in [4].

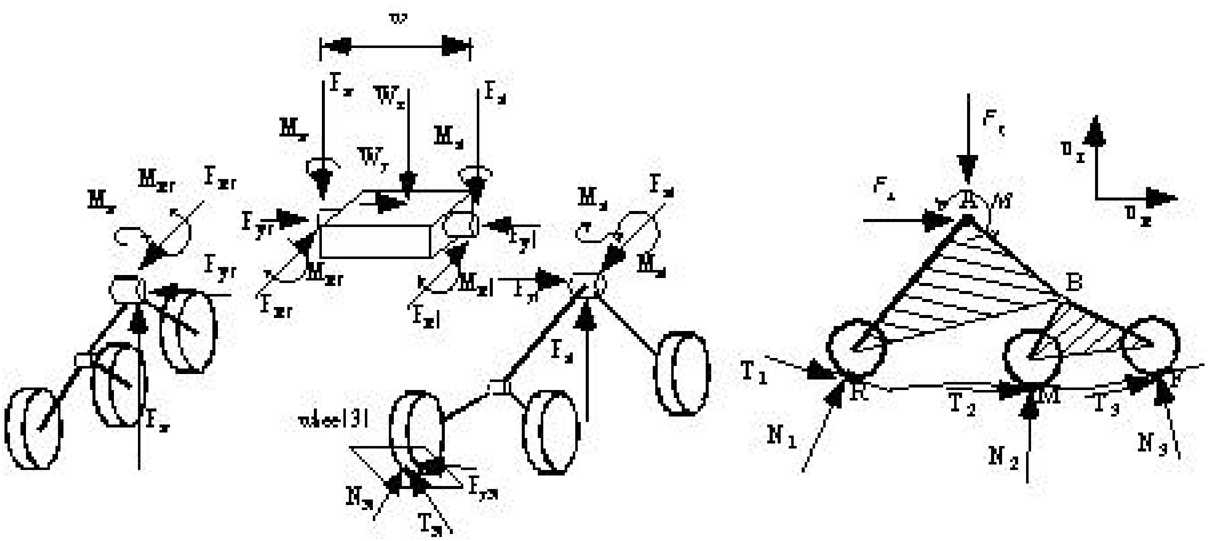

Figure 3: 3-D and 2-D Force Analysis

he set of equations (12-15) is underdetermined (four equations and six unknowns). Three of the unknowns are directly commanded (the wheel torques), therefore they affect the normal forces magnitudes. This interesting feature is used in the design of a traction controller based on fuzzy logic [4].

The model has been tested on the MIT MOD I rocker-bogie experimental test-bed. Figure 4 shows the results and the comparison to the analysis. For these experiments the rover was standing on a flat surface. The normal force changes with respect to torque changes have been measured with a load cell. The dashed line represents experimental results, and the solid line represents analytical model results.

In Figure 4, the changes in the rear, middle and front wheels normal forces as a function of the motor torques are plotted.

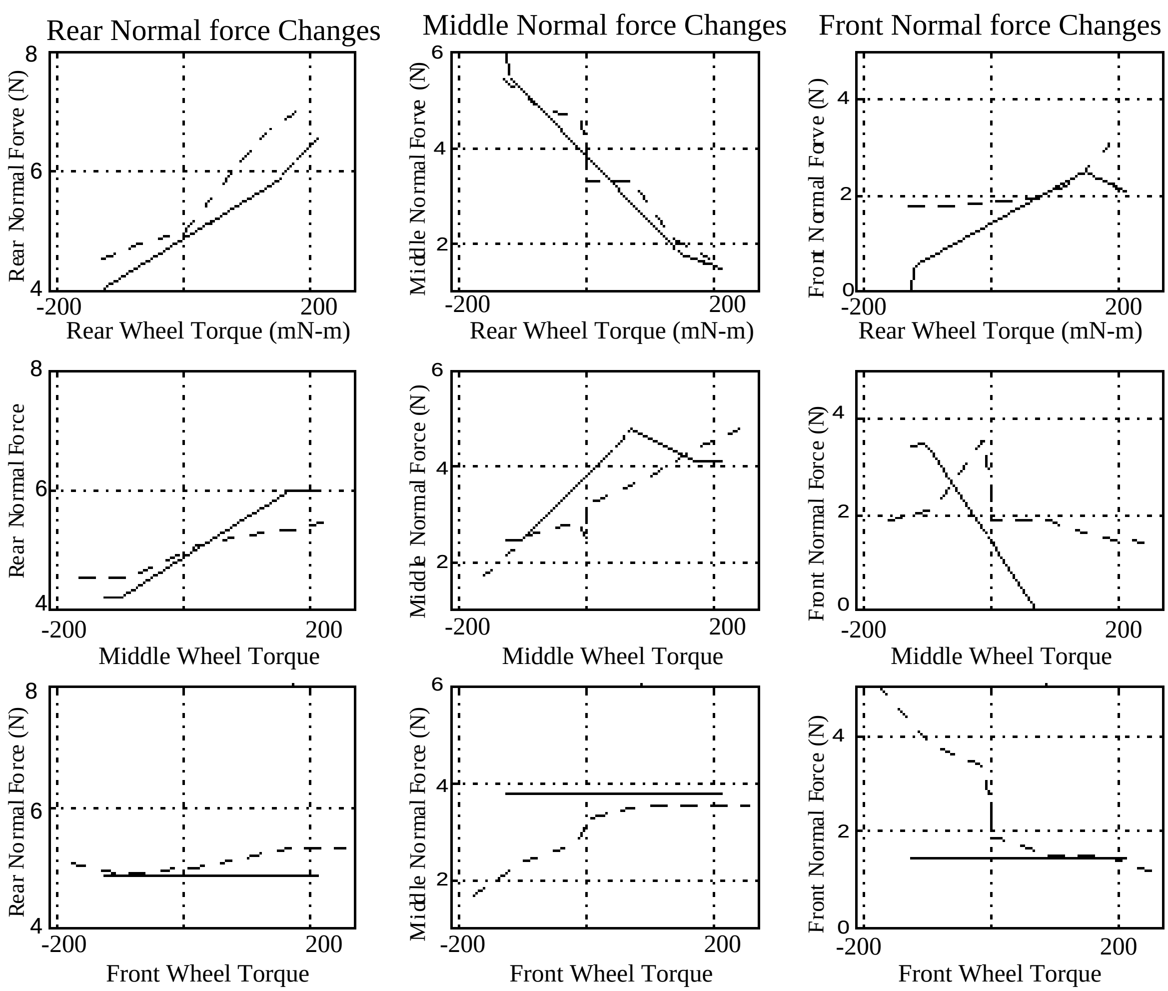

Figure 4: Measured and simulated variations of the normal forces on the wheels.

The errors between the model and the actual system are caused by several factors. In the analytical model, when the effect of a wheel torque is considered, the other motors torques are taken as zero. However, the friction of the highly geared motors creates an unknown static torque opposing the commanded torque. Also, since the experimental rover is not equipped with torque sensors, the output torque cannot be known very accurately. Finally, unmodeled friction in the rocker-bogie joint can also be shown to create some errors. Nonetheless analytical model predicts the trends seen in the experimental system quite well.

4. Simulation

The model has been implemented into a simulation. It shows the rover in its environment, moving over specified terrains and is a valuable tool for evaluation. A graphical interface has also been developed, to enhance the understanding of the system (see Figure 5). A number of variables useful for performance evaluation are computed and displayed including the normal forces on the rover wheels. The torque saturation for each wheel (the ratio between the actual torque and the saturation torque), the slip ratio S_r that is defined and computed as: $S_r = \quad \mu$, where T_i, N_i and μ are the traction and normal forces and the local coefficient of friction under the i^th wheel respectively are also shown. Stability margin is defined as the ratio between the angle necessary to tip over the rover at a given time and the angle to tip over the rover when on a flat surface [13].

The kinematics parameters (link lengths, etc) can be changed during the simulation, therefore the simulation can be used for optimisation studies. Other control panel keys interface with the user, such as Pause, Play Fast Forward, etc. buttons. This way, the user can focus on specific areas.

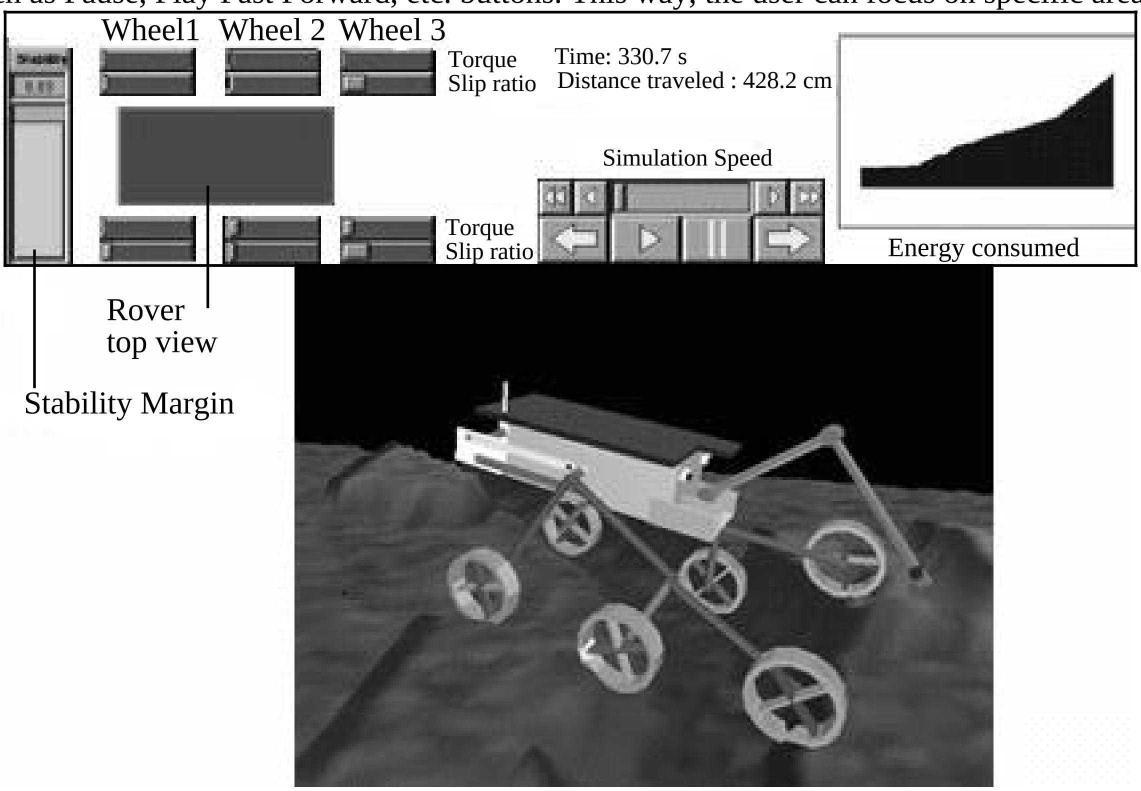

Figure 5: Rover Simulation Graphics Software

5. Summary and Conclusions

A simple and computationally efficient rocker-bogie rover model is presented. Under reasonable assumptions, it is possible to determine the rover attitude and configuration, given its position and ground characteristics, and whether the rover will slide, tip over or maintain its balance. The model includes the affect of the manipulator. The mechanics of the rover has been developed, and the over-actuation of the system leads to the ability to affect the normal forces by applying specific wheel torques. This property has been verified experimentally and can be used for the design of an active traction control. A graphical interface has been designed to enhance understanding of the system.

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