Analysis, Optimization, and Testing of Planetary Exploration Rovers: Challenges in Multibody System Modelling

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Abstract

Mobility analysis is of great importance in the area of planetary exploration with wheeled robots (rovers). Environmental uncertainties and the autonomous nature of operations require an adequate knowledge of system behaviour in complex motion scenarios. The wheel-soil interaction poses a main challenge in such analyses. Rovers have to negotiate unstructured terrain, their mobility depending heavily on the dynamics at the wheel-soil contact interface. Experience has shown that poor traction can result in significantly reduced mobility, limiting the manoeuvrability of the rover or even completely preventing it from moving.

Extensive research is being carried out to understand the way in which forces and moments develop at the wheel-soil contact. The problem can be approached from the point of view of terramechanics, via a detailed analysis of the wheel-soil interface that intends to provide realistic values of the reactions developed at the interface. The common approach relies on semi-empirical models based on the interaction of a single wheel with the terrain [1]. An alternative is the use of so-called *observative* models, which allows for the definition of performance indicators to characterize the behaviour of the system. For example, non-holonomic constraints can be used to describe the ideal form of mobility of the system and find its relationship to the real system behaviour [2]. Irrespective of which approach is chosen, validation of the model with

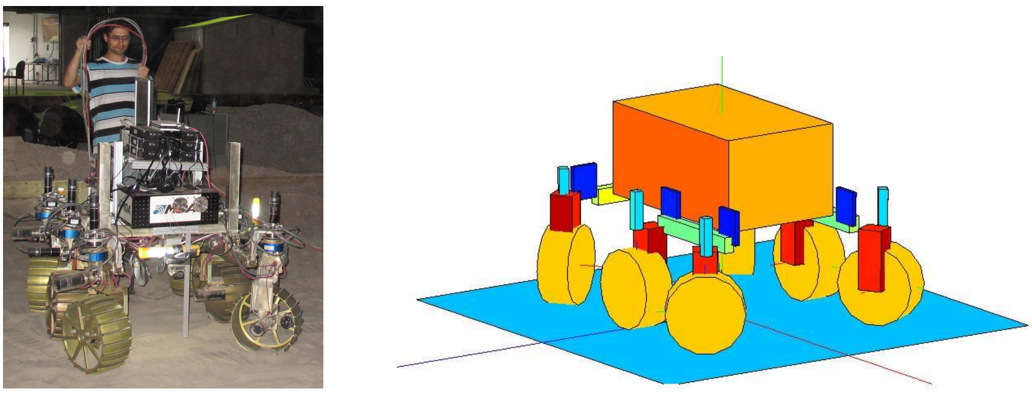

Figure 1. Rover prototype used in the experiments (left) and its computer model used in simulations and analysis (right)

experimental data is required. This will ensure that the model captures the relevant aspects of the real system with enough accuracy under the given conditions. Currently there is a lack of available experimental data describing the behaviour of an entire rover in various manoeuvres and under different terrain conditions. This was the motivation to perform a series of experiments with the Rover Chassis Prototype (RCP), a six-wheeled planetary rover shown in Fig. 1, on various types of terrain. The RCP is equipped with odometry and force/torque sensors; every wheel of the rover can be steered and driven independently. The wheel-soil reaction forces were characterized based on the readings of these sensors and used to validate two models for the analysis of the vehicle-terrain interaction. The first one is a recently developed terramechanics model [3] intended for realistic wheel-soil interaction in dynamic analyses and simulation studies that resort to multibody formulation. In this model the developed forces are calculated using elasto-plasticity theory and assuming a plausible

velocity field for the motion of soil particles under the wheel. Second, the experimental results were used to assess the suitability of the wheel-terrain reactions obtained with observative models as performance indicators. This requires a multibody model of the entire rover, as opposed to evaluating the forces developed at one single wheel-terrain interface, and the ability to incorporate different representations of the motion at the wheel-terrain interface. With some of these, the resultant multibody system model is redundantly constrained, even for the simplest rover topologies. The modelling and validation of such systems pose several challenges; in order to deal with them, a software tool for the analysis and simulation of generic multibody systems, implemented in MATLAB, was built. Using this software a 3-D multibody model of the RCP was generated. The code allows for choosing among several wheel-soil interaction models, as well as dynamic formulations and numerical integrators. Furthermore, it is designed to be able to yield reaction forces associated with redundant and velocity dependent constraints.

A set of experiments with the RCP was designed to capture the motion of the rover in different manoeuvres and record the forces involved, thus giving a full picture of the system behaviour. Preliminary tests were used to calibrate the multibody model of the rover used in the experiments. The prototype did not allow for geometric reconfiguration, but several modifications of the original design and operation scenarios were introduced by adding extra masses, varying the torques acting on the wheels, and applying different drag forces to the main chassis. Thus, different configurations and operating conditions of the same rover could be compared in terms of the performance indicators defined using observative models. The rover was operated on three different types of terrain such as rigid surface, hard soil, and soft soil. The purpose of these tests was to validate the multibody model of the rover in order to have reliable simulation results. These results will be used to evaluate the effectiveness of existing and new approaches to the problem of wheel-soil interaction in a multibody simulation environment. For example, the readings of forces and torques resulting from the interaction of the rover with the terrain were compared with the values predicted by the multibody model. Also, the variations of normal and traction forces due to addition of extra masses, dragging forces, and different ratios of actuation torques at the wheels were recorded to find the relationship between the mobility performance of the rover and the forces acting on it. Additional sets of tests, in which the rover was commanded to climb a slope, overcome obstacles, and describe curved trajectories were carried out as well. Figure 2 shows a sample of the readings of the force sensors in the

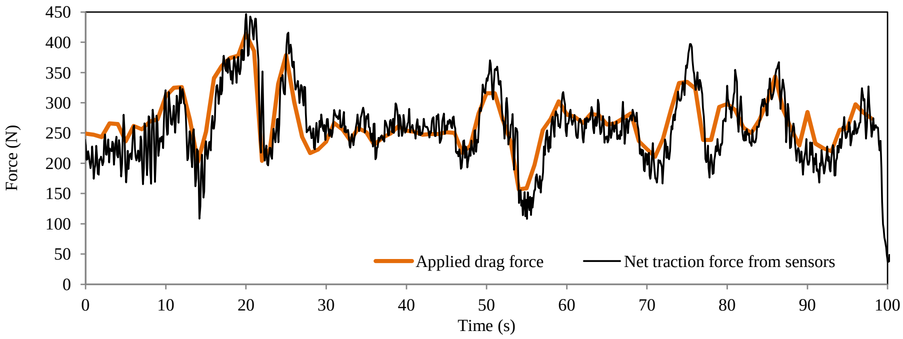

Figure 2. Drag force applied to the body of the rover as measured by the load cell (thick orange line) and net traction force read by the six force/torque sensors of the vehicle (thin black line)

tangential direction during straight motion on soft soil, as well as the applied drag force. The net traction force developed by the six wheels balances the drag force and the rover moves with no acceleration. Experimental data provide useful information to study the validity of the multibody modelling, the proposed performance indicators, and wheel-terrain interaction models. The work reported here should shed light on some open questions in the realm of rover mechanics.

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