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On the treatment of soft soil parameter uncertainties in planetary rover mobility simulations

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Abstract

Nowadays soft soil–wheel contact models are widely used for predicting the mobility of rovers in off-road applications. However, most of the contact models used in computer simulations are based on semi-empirical laws for which soil parameters can be assessed only with large uncertainty. This lack of knowledge results in significant uncertainty on the rover position predictions. Applied to a planetary rover model, this paper illustrates probabilistic and non-probabilistic techniques for efficient treatment of soil parameter uncertainty for rover position predictions.

Keywords: Planetary rover; Terramechanics; Soft soil contact model; Uncertainty analysis

1. Introduction

Planetary exploration activities received a new impulse after the successful NASA missions on the Martian surface. In the recent years, besides the NASA rovers, also the Chinese rover ‘Yutu’ succeeded in landing on the lunar surface and traveling shortly. Yet, European Space Agency plans to launch its autonomous rover for Mars exploration in 2018. Past experience proved that a crucial aspect in planetary exploration is connected with the rover trafficability on sandy terrain, largely present on the Moon and Mars surface. Indeed, sandy terrains may produce very high wheel sinkage, which compromises the rover mobility. For this reason extensive experimental programs have been carried out and numerical models have been developing for better understanding and predicting the behavior of a wheel on soft soils. Early works in this area were conducted by Bernstein Plackett (1985) who proposed a pressure-sinkage semi-empirical model for studying the wheel–soil contact dynamics based on the behavior of a rectangular plate penetrating into the soil. In the course of years the Bernstein model underwent improvements. Noticeable work was done by Bekker (1956, 1969) who introduced the dependency on the size of the contact patch and developed an experimental technique, called bevameter test (Wong, 2010), for measuring soil parameters. Later Reece (1965) included cohesion effects in the model. More recent works considered the effect of the wheel geometry and curvature (Ishigami et al., 2007; Meirion-Griffith and Spenko, 2011). Besides semi-empirical models, finite element method (Hambleton and Drescher, 2008) and discrete element method (Nakashima et al., 2010) have also been presented. These last approaches describe better the physics behind the contact phenomenon therefore they are potentially advantageous in terms of accuracy. However, they require an important computational burden, which currently limits their application. For this reason

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semi-empirical models still ensure the best trade-off between simulation time and accuracy and at the moment represent the most used tool for the analysis of rover mobility on soft soils.

Wheel–soil contact models can be integrated into a multi-body model for predicting the dynamic and mobility performance of a rover traveling on soft soils. Examples of full planetary rover simulations on sandy soils are given for instance in Patel et al. (2005), Schäfer et al. (2010), Li et al. (2013), and Zhou et al. (2014). Computer simulations can be extremely useful in the design and operating phases because they can predict the rover behavior without resorting to costly experimental tests. However, computer simulations give deterministic outcomes, which do not reflect the lack of knowledge inherently present in any physical process. Thus, reliable predictions can be achieved as long as uncertainties are taken into account. In rover mobility applications two different kinds of uncertainty are of major interest: Uncertainty and variability of the properties of the soil where the rover travels on; Uncertainty on the model adequacy and performance in environments different from the ones where the models have been validated. In the last decade various works have been published in these areas. For instance in Sandu et al. (2006,), Kewlani and Iagnemma (2008), and Ishigami et al. (2009) the problem of quantifying the uncertainty in the rover position for given variability of the soil parameters is addressed. In these studies polynomial chaos has been proposed for a probabilistic description of uncertainty. Still in the context of soil parameters uncertainty propagation, the application of the first-order second moment method to Bekker-based contact model has been presented in Jayakumar et al. (2014). In Sandu et al. (2005) and Lee and Sandu (2009) the authors focused on the inclusion of the terrain profile variability in the rover trajectory prediction. Another important topic of research concerns with the identification of simulation parameters. For instance in Iagnemma et al. (2002) and Hutangkabodee et al. (2008) a least square analysis has been proposed for real-time soil parameters identification. More works advocated the utilization of the Kalman filter for the identification of soil friction angle (Ray, 1997), traction forces (Ray et al., 2009) or rover pose and position (Seegmiller et al., 2012). In Gallina et al. (2014) a Bayesian approach for Bekker-based contact model parameter updating is described. In Leite et al. (2012), along with the presentation of a novel Bekker-based contact model, a stochastic model updating procedure is employed for assessing the soil parameters variability which explains the scatter of the responses measured in repetitive single wheel tests. Finally, the issue of validating soil–wheel contact models for off-road applications has been examined in Lee and Gard (2014). Here a stochastic procedure, which explicitly accounts for both parametric and model uncertainty, is illustrated.

The present paper deals with the uncertainty analysis of planetary rover computer simulations in two different aspects: rover position prediction and soil parameter identification. Extending a recent study (Gallina et al., 2015), in this work the effect of soil uncertainty on path predicted by a computer model of a planetary rover is addressed. Probabilistic (frequentist and Bayesian) and non-probabilistic (interval and fuzzy) approaches are investigated and compared with experimental results in order for checking the validity of the methods. Each procedure shows its own advantages and disadvantages. However, a probabilistic frequentist description of the soil parameter uncertainty evidences very poor performances. Conversely, a Bayesian probabilistic procedure reveals to be much more powerful. Bayesian approach is also employed for off-line identification of soil parameters along the rover path by post-processing data from experiments. Relevant to this last part or the work is the study presented in Blanchard et al. (2009) where a Bayesian framework and a Kalman filter procedure is employed in combination with polynomial chaos method for parameter identification. However, differently from Blanchard et al. (2009), in the present application an enhanced Markov chain Monte Carlo procedure is adopted for solving the Bayesian formulation, resulting in a fully probabilistic description of the soil parameter uncertainty. The present work includes both experimental tests and numerical simulations. Rover experiments are initially conducted for measuring a reference rover path to be compared with numerical simulations. Bevameter tests are also carried out for assessing expected range of variations for the properties of the soil. Recorded signals from rover experiments and measured soil properties are the input for a multi-body model of the rover used to predict the rover position in condition of soil uncertainty. Although the paper does not introduce new theoretical aspects on computational or numerical methods, it proposes the application of Bayesian inference for a correct probabilistic description of the rover position uncertainty when assuming random soil parameters. It is also believed that the comprehensive character of the research may give a contribution to the research committee.

The paper is structured as follows. The experimental part is described in Section 2. Section 3 focuses on the numerical setup. Uncertainty analyses are illustrated in Section 4. Section 5 summarizes the work and draws conclusions.

2. Experimental program

2.1. Rover experiments

Experiments have been carried out at the planetary exploration laboratory (PEL) at DLR, Robotics and Mechatronics Center. The DLR facility is equipped with the breadboard model of the ExoMars rover locomotion subsystem that was used for mobility performance analyses in mission phase B2 (http://exploration.esa.int/mars/47088-exomars-timeline/). The breadboard rover used for the experimental program has identical vehicle kinematics parameters as the expected flight model (wheel