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Estimation of terramechanics parameters of wheel-soil interaction model using particle filtering

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ABSTRACT

Accurate estimation of the parameters affecting the wheel-soil interaction terramechanics of an extraterrestrial rover is key to the success of its mission. Traditional approaches to estimating the relevant parameters based on laboratory tests lead to predictions that show significant deviation from experimental observations. The objective of this article is to apply dynamic Bayesian estimation techniques on the measurements from simple single wheel tests to estimate the terramechanics parameters. This ensures that the parameter estimation takes into account the scatter that invariably exists in physical measurements. A mathematical model for a rigid wheel driven on a dry (0% moisture content) granular soil medium is considered to model the planetary regolith. It is demonstrated that adopting Bayesian techniques for terramechanics parameter estimation leads to good predictions for the drawbar pull, torque and the wheel sinkage. This bypasses the need for using more complex models which in turn require additional parameters to be estimated.

1. Introduction

Successful deployment of rovers for planetary exploration demands a good understanding of the factors that affect mobility in unknown terrains with unknown terramechanical properties. This understanding is crucial in remotely navigating a rover across the unknown terrain. This implies that optimal controls should be imparted on the rover in terms of wheel torque and drawbar pull. Calculation of these quantities can be estimated based on simple wheel-soil interaction models; however, this necessitates the knowledge of the terramechanics parameters. While the development of mathematical models follows the principles of mechanics which are fairly well understood, the primary difficulty lies in estimating the soil-dependent parameters of these models. Estimation of the extra-terrestrial soil properties must be carried out using in situ tests that are simple enough to be conducted by the rover.

Mathematical models based on the empirical relationships developed by Bekker (1960) and widely used in the terramechanics community have been proposed by Wong and Reece (1967) to predict the behaviour of rigid wheels running on soil. The parameters of this model are usually estimated from plate sinkage and shear tests. Unfortunately, the lack of standards for these tests leads to considerable uncertainty in estimating the parameters (Oravec, 2009). Moreover, the tests themselves do not exactly mimic the stresses under the wheels of a planetary rover. For example, the parameters estimated through a plate sinkage test fail to obtain reasonable predictions for the wheel static sinkage (Meirion-Griffith and Spenko, 2013). In the case of dynamic sinkage, an additional slip sinkage parameter is necessary to fit the experimental data (Ding et al., 2010). There are considerable differences of opinion in using the parameters obtained from the shear tests (Senatore, 2011) as the actual stress condition under the wheel is quite different from those in the shear test. In spite of these shortcomings, Bekker's method is widely used in the design of planetary rovers (Gallina et al., 2014; Trease et al., 2011) on account of its ability to provide solutions that do not require expensive experiments or complicated mathematical models.

The problem in estimating the terramechanics parameters from physical measurements, is that considerable uncertainty exists, both in the measured data as well as in the terramechanical soil properties. The scatter that invariably exists in the measurements needs to be incorporated into the estimation analysis. Karl et al. (2004) used a least squares estimator in conjunction with kinematic analysis to determine the cohesion and internal friction of a soil; the necessary computations were carried out using onboard computational resources. In this study, only two parameters

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were considered to be unknown. For more complicated models that required estimating five soil parameters from measurements of the drawbar pull, sinkage and slip, the associated nonlinear coupled equations were solved using a generalised Newton-Raphson based method (Hutangkabodee et al., 2008). Stochastic based approaches in estimating the terramechanical parameters have also been used in the literature. A stochastic model updating technique has been implemented in Leite et al. (2012) for estimating the soil parameters from repeated single wheel test measurements. A Bayesian approach that uses principles of transitional Markov Chain Monte Carlo method presented in Gallina et al. (2014) makes use of the knowledge of the drawbar pull, wheel input torque and wheel vertical load for a given wheel sinkage to estimate the terramechanics parameters. The technique uses average values of the data rather than sequential data.

This study focuses on developing a methodology for estimating the terramechanics parameters from measurement data using the principles of dynamic Bayesian estimation. The unknown parameters are modelled as random variables with arbitrarily assigned probability density functions (pdfs). As more measurement data becomes available, this increase in knowledge is assimilated into the model, using Bayesian principles, leading to updated pdfs of these random variables. This enables predicting the most likely estimates of the parameters as well as obtaining error bounds on the predicted values. The methodology is numerically implemented using a boot strap variant of a particle filter algorithm. The goal is to demonstrate that the proposed approach leads to accurate estimates in a computationally inexpensive manner and significantly reduces the variability associated with the parameters estimated using conventional methods.

2. Problem statement

2.1. Mathematical model for wheel-soil interaction

A mathematical model for a rigid wheel driven on a dry (0% moisture content) granular soil medium is considered for the planetary regolith. The wheel load is W and a torque T is applied to the axle of the wheel. A schematic diagram for the wheel is shown in Fig. 1.

The linear wheel velocity of the axle is v. The variables θ_f and θ_r denote the front and rear contact angles made by the wheel with the soil surface that deforms due to the wheel motion. The dynamic wheel sinkage is z and the rear soil swelling, which is the vertical rebounding of the soil surface in the rut following the wheel pass, is z_r. Two failure zones are formed beneath the wheel demarcated by the line joining the wheel centre and the point on the soil medium where the maximum radial stress is developed. The line joining the wheel centre and the point of maximum radial stress on the wheel-soil interface makes an angle θ_m with the vertical and is expressed as

$$\theta_m = \theta_f\,(c_1 + c_2\,s) \tag{1}$$

where the coefficients c_1 and c_2 are typically taken to be $c_1 = 0.38$ and $c_2 = 0.44$ (Senatore and Iagnemma, 2014). The slip, s, for a driven wheel with an angular velocity, ω, is $s = (r\omega - v)/r\omega$, where r is the wheel radius. The normal stress $\sigma(\theta)$ developed on the wheel-soil interface is a function of θ - the angle that a point on the wheel makes with the vertical and is expressed mathematically as Wong and Reece (1967)

$$\sigma(\theta) = \begin{cases} k_{eq}\, r^n \left[\cos\,\theta - \cos\,\theta_f\right]^n, & \theta_m \leqslant \theta < \theta_f \\ k_{eq}\, r^n \left[\cos\left[\theta_f - \frac{(\theta-\theta_r)}{(\theta_m-\theta_r)}(\theta_f - \theta_m)\right] - \cos\,\theta_f\right]^n, & \theta_r < \theta \leqslant \theta_m \end{cases} \tag{2}$$

These expressions are generalised from plate sinkage relationship under a flat rectangular plate of dimension $a \times b$, where a is the smaller dimension of the plate and b represents the wheel width (Fig. 2). The relationship between sinkage and normal stress for flat plate is given as

$$\sigma(z) = \left(\frac{k_c}{a} + k_\phi\right) z^n = k_{eq}\, z^n \tag{3}$$

Here, k_{eq} and n are soil-dependent parameters and are obtained from plate sinkage tests, a schematic of which is shown in Fig. 2.

An expression for the shear stress $\tau(\theta)$ in terms of $\sigma(\theta)$ and the shear displacement $j(\theta)$ has been shown (Wong, 2010) to be of the form

$$\tau(\theta) = (c + \sigma(\theta)\,\tan\phi)\left(1 - e^{\frac{-j(\theta)}{K}}\right) \tag{4}$$

Here, c is cohesion, ϕ is angle of internal friction and K is shear modulus. The development of Eq. (4) is based on the empirical function,

$$\tau = \tau_{max}\left(1 - e^{\frac{-j}{K}}\right) \tag{5}$$

that relates $\tau(\theta)$ and $j(\theta)$ for plastic soil. The shear deformation is a derived quantity obtained by integrating the slip velocity at the wheel-soil interface. The slip velocity, which is the difference between the wheel circumference velocity and the wheel tangential velocity, is given as

$$v(\theta) = r\omega - v\,\cos\,\theta = r\omega[1 - (1-s)\,\cos\,\theta] \tag{6}$$

$$\begin{aligned} j(\theta) &= \int_{\theta}^{\theta_f} r\omega[1-(1-s)\,\cos\,\theta]\frac{1}{\omega}\mathrm{d}\theta \\ &= r[(\theta_f - \theta) - (1-s)(\sin\,\theta_f - \sin\,\theta)] \end{aligned} \tag{7}$$

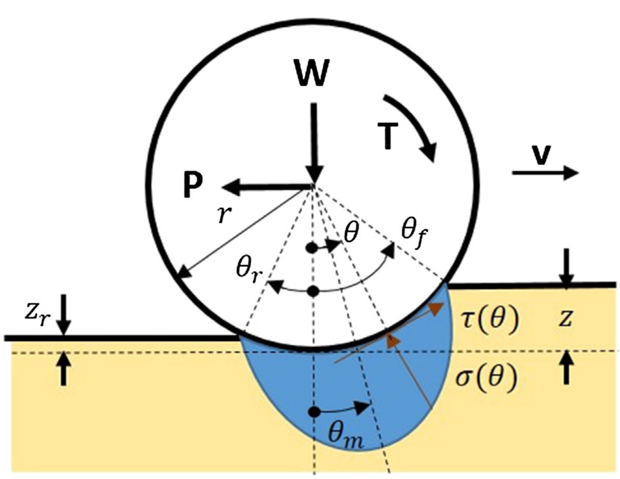

Fig. 1. Forces (W, P), torque (T) and stresses (σ, τ) acting on a driven rigid wheel; z_r is the vertical rebound of the soil in the wheel rut relative to the wheel sinkage z.

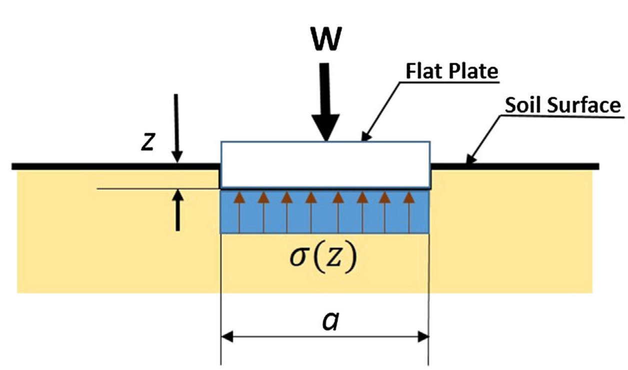

Fig. 2. Flat rectangular plate sinkage.