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In situ identification of shearing parameters for loose lunar soil using least squares support vector machine

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A B S T R A C T

A method is presented for the online prediction of the terrain-shearing parameters for a wheeled Unmanned Ground Vehicles (UGVs) traversing on an unknown terrain. The method uses a trained multiple-output least squares support vector machine (LS_SVM) to map engineering data and predict the terrain-shearing parameters such as cohesion, internal friction angle and shear deformation modulus without requiring information on wheel sinkage. The predicted terrain-shearing parameters can be used to predict vehicle drawbar pull which can be used for trafficability prediction, traction control and performance optimization. Experiments were performed using a single-wheel soil bin to measure the sinkage, drawbar pull and torque for a griddle net wheel under different slip ratio. An additional experiment was performed under a continuous slip ratio from 0.2 to 0.6 with a wheel load of 50 N to validate the method. The experimental results show that the multiple output LS_SVM model can accurately predict the terrain-shearing parameters using the slip ratio, torque and wheel load without the need of wheel sinkage.

1. Introduction

Unmanned Ground Vehicles (UGVs) are an important method of data collection for conducting scientific research during lunar or Mars exploration missions. The planetary surfaces of the Moon and Mars are very rough, covered by loose regolith composed of dust and rock, which impedes the mobility of UGVs. For example, the Sprint and Opportunity rovers became deeply embedded in loose sand during their explorations of Mars [1,2]. Fortunately, after several weeks of attempts, the Opportunity rover was finally freed from Purgatory on Sol 484. The driving force generated by the wheels thrusting through soil is insufficient to overcome the resistance created by this kind of loose terrain, causing the slip ratio and sinkage to increase. Understand soil mechanics, such as the internal friction angle φ, cohesion c and shear deformation modulus K, is an important task for researchers. It is desirable to estimate terrain parameters online, since such knowledge, combined with a wheel–terrain interaction dynamic model, allows researchers to predict vehicle drawbar pull, which can be used for trafficability prediction, traction control and risk assessment [3]. Also, knowledge of terrain parameters would assure a safe landing for planetary lander [4].

Two main methods can be used to obtain planetary soil mechanics. The first method, which can provide exact information, is to collect samples of the planetary soil and return them to earth. The second method is in situ observation, which allows the soil mechanics to be obtained in the absence of planetary soil. Many research groups conduct research on soil mechanics through the online estimation of planetary soil based on terramechanics for planetary rovers.

Researchers from NASA and JPL have performed investigations to identify the parameters of Martian soil. They used Sojourner and MER rover wheels as a shear test device and the Mohu–Coulomb failure criteria to identify soil cohesion and internal friction angle [5–10]. However, this method not only exacerbates wheel wear, but could also threaten the safety of mobile systems. Also, the method was an offline analysis technique. Since the communication time delays from Earth to Mars is about 3–21 minutes in a one-way transmission, the method may limit the UGV's autonomy and reduce its efficiency.

Based on the classical terramechanics equations proposed by Bekker [11] and Wong and Reece [12–14], Iagnemma [15–18] used a linear-least squares estimator to estimate terrain parameters such as cohesion and internal friction angle using onboard sen-

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sors. However, at least two unique datasets combined with large-scale slip were required to estimate terrain parameters and shear deformation modulus should be pre-determined. Hutangkabodee [19–22] used Newton Raphson method to identify lumped pressure sinkage coefficient, internal friction angle and shear deformation modulus, while cohesion was set to 3 kPa. This method required at least three sets of measured data to identify three soil parameters. Cui [23] used Newton's iterative method for computing terrain parameters such as internal friction angle and press–sinkage parameter. However, the method also required a reasonable cohesion to be determined beforehand. Ding [24–29] proposed a set of closed-form analytical equations to identify three groups of planetary soil parameters: contact angle coefficients, bearing performance parameters and shearing performance parameters. A cyclic iterative parameter identification approach was applied to estimate the three sets of parameters step-by-step, using measured data obtained from a wheel–soil interaction test system. In this process, drawbar pull *DP* should be used as input data when calculating the contact angle coefficients. However, it is difficult to acquire precise *DP* information directly during planetary exploration missions [17]. Cross [30,31] proposed a trained neural network for estimating cohesion and internal friction angle online for a rigid wheeled rover. However, the terrain parameter of the shearing deformation modulus should be set to a suitable value before computing *DP*. A vibration-based technique was employed to classify terrain type but not to estimate terrain parameters [32]. Based on Newton–Raphson method, Tan [33] and Yousefi Moghaddam [34] done a lot of work to estimate terrain parameter online, however their application was for excavation and not based on wheel–terrain interaction.

The purpose of this study is to develop a method for predicting terrain-shearing parameters online. The multiple-outputs Least Squares Support Vector Machines (LS_SVM) method is used to map engineering data based on simplified classical terramechanics equations. The input data for the LS_SVM comprise wheel load W, torque T and slip ratio s, and output data include three terrain-shearing parameters: cohesion c, internal friction angle φ and shearing deformation modulus K. This method can be used to estimate for $[c, \varphi, K]$ with a set of data $[s, T, W]$, which can allow a vehicle to autonomously traverse the planetary surface and 'feel' changes of rough terrain in real time during traveling through deformable terrain. Using terrain-shearing parameters, *DP* and tractive efficiency η can be calculated, which can also be used for optimal route planning, traction control and traversability prediction of a vehicle on off-road terrain.

2. Terrain-shearing parameter estimation method

2.1. Mechanics of vehicle

Shear stress distribution acting on a point along a wheel rim can be obtained from the following Eq. (1) [14,35]:

$$\tau(\theta) = \big(c + \sigma(\theta)\tan\phi\big)\Big(1 - e^{-\frac{r}{K}((\theta_1-\theta)-(1-s)(\sin\theta_1-\sin\theta))}\Big) \qquad (1)$$

where $\tau(\theta)$ is shear stress, $\sigma(\theta)$ is normal stress, r is wheel radius, θ is an angular location, and θ_1 is entrance angle.

Fig. 1 shows a free-body diagram of a driven rigid wheel of radius r and width b traveling through deformable terrain, where z is sinkage. Fig. 1 shows normal distribution under the action of a driven wheel in terrain, presented as two regions, divided by the maximum normal stress σ_m. In region I, normal stress σ_1 occurs between θ_m and θ_1. In region II, normal stress σ_2 occurs between θ_2 and θ_m. Here, θ_m is maximum stress angle and θ_2 is leaving angle. Based on the force and moment balance, the interaction model for a rigid wheel can be given by

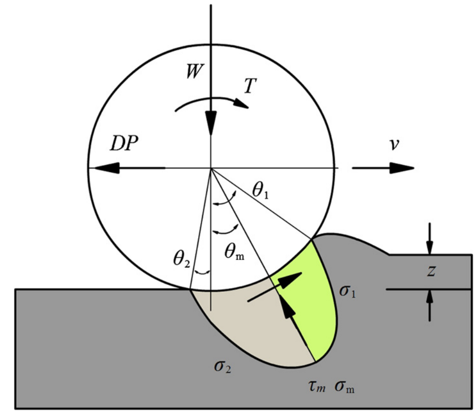

Fig. 1. Free body diagram of a rigid wheel on deformable terrain [14] showing the distribution of normal and shear stress.

$$\frac{W}{rb} = \int_{\theta_2}^{\theta_m} \big(\sigma_2(\theta)\cos\theta + \tau_2(\theta)\sin\theta\big)d\theta + \int_{\theta_m}^{\theta_1} \big(\sigma_1(\theta)\cos\theta + \tau_1(\theta)\sin\theta\big)d\theta \qquad (2)$$

$$\frac{T}{r^2 b} = \int_{\theta_2}^{\theta_m} \tau_2(\theta)d\theta + \int_{\theta_m}^{\theta_1} \tau_1(\theta)d\theta \qquad (3)$$

$$\frac{DP}{rb} = \int_{\theta_2}^{\theta_m} \big(\tau_2(\theta)\cos\theta - \sigma_2(\theta)\sin\theta\big)d\theta + \int_{\theta_m}^{\theta_1} \big(\tau_1(\theta)\cos\theta - \sigma_1(\theta)\sin\theta\big)d\theta \qquad (4)$$

where *DP* is drawbar pull, W is wheel load and T is torque.

2.2. Simplified analytic model

Eqs. (2)–(4) are too complex to be integrated. Thus, Iagnemma [17] proposed a simplified method for calculating the integrals, as illustrated in Fig. 2.

Fig. 2 shows that the shear and normal stress distribution curves are approximately linear for a diverse range of terrains [17,18]. Based on this observation, the simplified stress equations can be written as [36]

$$\sigma_1(\theta) = \frac{\theta_1 - \theta}{\theta_1 - \theta_m}\sigma_m \qquad (5)$$

$$\sigma_2(\theta) = \frac{\theta}{\theta_m}\sigma_m \qquad (6)$$

$$\tau_1(\theta) = \frac{\theta_1 - \theta}{\theta_1 - \theta_m}\tau_m \qquad (7)$$

$$\tau_2(\theta) = \tau_{offset} + (\tau_m - \tau_{offset})\frac{\theta}{\theta_m} \qquad (8)$$

where τ_{offset} is an offset term at $\theta = 0$, σ_m and τ_m are the maximum values of the normal and shear stress, respectively.

Furthermore, Iagnemma [18] proposed that the angular location of the maximum stress point occurs midway along the contact angle, $\theta_m = (\theta_1 + \theta_2)/2$. In practice, θ_2 is usually simplified to zero because it is generally small and not easy to determine. Then, two more equations can be obtained by setting $\theta = 0$ and $\theta = \theta_m$: