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Online estimation of terrain parameters and resistance force based on equivalent sinkage for planetary rovers in longitudinal skid

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ABSTRACT

Wheel-soil interaction mechanics plays a crucial role for wheeled mobile robots (WMR) on rough and deformable terrains such as Martian and Lunar surfaces. Skid terramechanics is an essential component for WMRs and generates resistance force when a WMR brakes or on downhill slopes. The basis of classical terramechanics theories for WMRs – Bekker's normal stress and Janosi's shear stress equations – are so complex that the wheel-soil interaction force/torque equations are not amenable to closed form solutions, which seriously limits the application of terramechanics theories to WMRs. To establish analytical wheel-soil interaction expressions, the normal and shear stresses that can be characterized linearly by the proposed terrain stiffness and shear strength, respectively, are presented in this paper. Terrain stiffness and shear strength can be used to characterize terrain mechanical properties. Compared with the experimental data, the maximum relative error of the resistance forces estimated using these expressions at steady state is less than 7%. These validated expressions can be applied to estimate terrain parameters and resistance force online with high accuracy. Terrain's stiffness and shear strength increase first, and then reach a constant. Before wheels entering steady state, the online estimated resistance force's relative error is much higher, which can be explained using wheel's vertical velocity.

1. Introduction

The analysis of wheel-terrain interaction mechanics has implications for the system's design [1,2], sensing subsystem [3,4], and estimation and control algorithms [5–7]. In most cases, this interaction is assumed to follow a simple Coulomb friction law [8–11], and the effects of such phenomena as wheel skid and vertical sinkage are ignored [12]. Although such an approach may be sufficient for some applications, operation near a system's performance limits - that is on challenging terrain - often requires more sophisticated analyses of wheel-soil interaction [13].

The images that were sent back by the YUTU Lunar Rover and NASA's Mars Rovers show that the Lunar and Martian surfaces are covered with fine and soft soil which are difficult to traverse, and their access presents an ongoing challenge for WMRs [14]. In the coming 2020, CNSA (China National Space Administration) [15], NASA [16], and the European Space

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Nomenclature

A	amplitude of oscillation
C	intercept when oscillation frequency is plotted versus skid ratio
F_{D}	Damp force caused by wheel vertical velocity (N)
F_{P}	pushing force from the vehicle (N)
F_{R}	resistance force (N)
$F_{\mathrm{R}\sigma}$	resistance force component integrated from the normal stress (N)
$F_{\mathrm{R}\tau}$	resistance force component integrated from the shear stress (N)
F_{V}	vertical force (N)
$F_{\mathrm{V}\sigma}$	vertical force component integrated from the normal stress (N)
$F_{\mathrm{V}\tau}$	vertical force component integrated from the shear stress (N)
K	shearing deformation modulus of soil (mm)
K_1, K_2	coefficients used to calculate resistance force
K_σ	terrain stiffness (Pa/m)
K_τ	shear strength (Pa/m)
T_{B}	braking torque (Nm)
W	wheel vertical load (N)
b	wheel width (mm)
c_1, c_2	coefficients used to compute maximum normal stress angle
c	soil cohesion (Pa)
d_1, d_2	coefficients used to determine angular position of the transition point of shear stress
$f_1(\theta)$	function used to calculate equivalent wheel sinkage
$f_2(\theta)$	function used to calculate normal stress
$f_{\mathrm{o}}(t)$	function used to describe oscillation
h_{L}	lug height (mm)
j	soil shearing deformation (mm)
k_1, k_2, k_3	coefficients used during the analytical modeling process
k_{11}, k_{12}	coefficients used to calculate equivalent wheel sinakge
k_{21}, k_{22}	coefficients used to calculate normal stress
k_c	cohesive modulus of soil (kPa/m^{n-1})
k_φ	frictional modulus of soil (kPa/m^n)
N	sinkage exponent of soil
n_0, n_1, n_2	coefficients used to compute sinkage exponent
n_{L}	lug number
p	pressure between plate and soil (Pa)
r	wheel radius (mm)
s_{d}	skid ratio
t	time (s)
v	wheel forward velocity (mm/s)
z	plate sinkage (mm)
z_1	wheel vertical sinkage (mm)
z_2	soil rebounding height (mm)
z_{F}	wheel vertical sinkage caused by the vertical force (mm)
z_{M}	measured wheel vertical sinkage (mm)
z_{V}	wheel vertical sinkage caused by its vertical velocity (mm)
z_σ	equivalent wheel sinkage (mm)
α	slope angle (rad)
ω	wheel angular velocity (rad/s)
ω_{O}	oscillation frequency (rad/s)
θ	wheel-soil contact angle (rad)
θ_0	angular position of the transition point of shear stress (rad)
θ_1	wheel entrance angle (rad)
θ_2	wheel leaving angle (rad)
θ_{m}	angular position of the maximum normal stress (rad)
λ_{PRC}	resistance force coefficient
τ	tangential stress (Pa)
φ	soil internal friction angle (°)
ϕ	phase shift (rad)
σ	normal stress (Pa)
σ_1	normal stress in the front region (Pa)
σ_2	normal stress in the rear region (Pa)