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Optimized control for longitudinal slip ratio with reduced energy consumption

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ABSTRACT

Wheeled exploration robots (WERs) used for applications such as planetary exploration have to traverse loose terrain, often, during which time they may suffer longitudinal slip and side slip owing to the interaction between their rigid wheels and the loose soil. Longitudinal slip and side slip are the main causes for WERs delay or deviate from the ideal trajectory. But the presented work is indeed focused on longitudinal slip. By analyzing and simplifying the wheel–soil interaction terramechanics model for this case, the algorithm for an adaptive fuzzy control law based on slip ratio optimization is designed to optimize the tractive efficiency and minimize energy consumption. Its stability is proved, and conditions for control parameters are derived. Analytical and simulation results demonstrate that the proposed control system significantly improves the mobile performance of the WER.

1. Introduction

Wheeled exploration robots (WERs) are now being used for planetary exploration missions [1]. Their mobility control has attracted research attention because they often traverse loose terrain in such missions, and they may suffer longitudinal slip owing to the interaction between their rigid wheels and the loose soil. When the slip exceeds a certain degree, it can cause deviations from the predetermined trajectory, increased energy consumption, and even failures. WERs moving on loose terrain have already suffered problems. For example, the 2005 Opportunity Rover relapsed into loose sand dunes of Purgatory and took five weeks to escape [2]. Similarly, the 2009 Spirit Rover was jammed into the sandy soil of the Home Plate plateau of Mars, owing to which its mobile life ended and it became a fixed research platform [3].

Kawabe considered rigid wheel–terrain interaction to design a control strategy for mobility control of WERs on flat roads, with slip considered an external disturbance [4]; however, this approach is not applicable to loose soil, in which case the interaction differs greatly. A traditional control strategy assuming rigid interaction will cause the WERs to lose control [5–9]. Iagnemma used numerical analysis and experimental verifications to demonstrate that a traditional motion-planning and control algorithm assuming rigid interactions will cause WERs to suffer serious slip and sinkage problems [10], in addition to modeling wheel–soil interactions based on terramechanics and establishing a multiple physical model control strategy for WERs on loose flat terrain [11]. Michałek et al. design a control strategy for a mobile robot trajectory tracking with skid–slip compensation in the vector-field-orientation control system [12]. Yoshida et al. extended multiple physics-based approaches and proposed a traction control method to reduce the slip ratio [13]. An experimental test on loose soil such as dry sand

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confirmed that wheel-slip-based control effectively prevents serious sinkage and energy wastage [14]. Wang et al. proposed a velocity synchronization algorithm that avoids conflict among the wheels [15]. They experimentally verified that this method can reduce the required power and wheel slippage [16]. Ding et al. proposed an online soil parameters estimation method using the linear least-squares method [17,18] and the modified wheel–terrain interaction simplified model [19], and they compared the simplified and original integrals by numerical analysis [20]. The influence of wheel slip ratio on energy consumption and traction efficiency is well understood owing to the development of wheel–soil interaction terramechanics for WERs [21,22]. Moreover, better control algorithms can now be developed for both minimizing the energy consumption and compensating for the traction efficiency loss due to wheel slip. The present study focuses on mobility control of WERs traversing flat loose terrain [4,16,18,20], which has rarely been studied thus far. Available wheel–soil interaction mechanics models are too complex for control design. This study focuses on designing an effective control strategy based on wheel–soil mechanics for mobility control of WERs on sloped loose terrain.

This study investigates longitudinal slip-ratio coordinated of WER with a rocker bogie while climbing over different loose slopes by planning and tracking the slip ratio based on the analysis of the wheel–soil interaction mechanism. First, experimental motion analysis is conducted to determine a dynamic model for a six-wheeled WER with a rocker bogie climbing a loose slope. Second, a slip ratio planning algorithm is determined based on an energy optimization goal. Third, a tracking control method is proposed using the individual wheel slip ratios as state variables and the planning slip ratios obtained by energy optimization as desired inputs. To improve the robustness and adaptability of the tracking control system, a fuzzy adaptive control strategy is developed. Finally, the stability of the control law is proved using the Lyapunov method. Full-scale simulations are conducted for a six-wheeled lunar rover moving over a loose slope to demonstrate the capabilities of the proposed control scheme.

The remainder of this study is organized as follows: In Section 2, a simplified slope-based wheel–soil model for a WER with a rocker bogie is developed. In Section 3, energy-optimal-based slip ratio coordinated arithmetic is established. In Section 4, by using the coordinated slip ratio as the desired input and the real slip ratio as the state variable for establishing an equation of state, and by designing the coordinated slip ratio tracking system by adaptive fuzzy control, the stability of the control law is proved using the Lyapunov method. In Section 5, the capabilities of this control scheme are demonstrated via full-scale simulations conducted with a six-wheeled lunar rover moving over sloped loose terrain, with real-time computations being performed using RoSTDyn, a dynamic software developed by Vortex. Finally, in Section 6, the conclusions are presented.

2. Wheel–soil interaction terramechanics and simplification for control

2.1. Wheel–soil Interaction terramechanics for one wheel

The entire wheel is stiff and the slope soil is loose. Fig. 1 shows the wheel–soil interaction terramechanics of one wheel [24–26].

In Fig. 1, F_N is the normal force; F_{DP}, the draw pull force; T_R, the rolling resistance torque; θ_1, the wheel–soil interaction entry angle; θ_2, the departure angle; and θ_m, the angle of maximum normal stress. θ_P, the angle of longitudinal slope; $\tau$and σ are the shear stress and normal stress, respectively; z_1 and $z_2$are the wheel sinkage.

Based on terramechanics research [19–22] and theory [23], the normal forceF_N, drawbar pullF_{DP}, and wheel driving torque$T_R$are calculated as follows:

$$\begin{cases} F_N = b\{\int_{\theta_2}^{\theta_m}[r_s\sigma_2(\theta)\cos\ \theta + r_s\tau_2(\theta)\sin\ \theta]d\theta + \int_{\theta_m}^{\theta_1}[r_s\sigma_1(\theta)\cos\ \theta + r_s\tau_1(\theta)\sin\ \theta]d\theta\} = F_N(P_s, P_w, P_R) \\ F_{DP} = b\{\int_{\theta_2}^{\theta_m}[r_s\tau_2(\theta)\cos\ \theta - r_s\sigma_2(\theta)\sin\ \theta]d\theta + \int_{\theta_m}^{\theta_1}[r_s\tau_1(\theta)\cos\ \theta - r\sigma_1(\theta)\sin\ \theta]d\theta\} = F_{DP}(P_s, P_w, P_R) \\ T_R = r_s^2 b[\int_{\theta_2}^{\theta_m}\tau_2(\theta)d\theta + \int_{\theta_m}^{\theta_1}\tau_1(\theta)d\theta] = T_R(P_s, P_w, P_R) \end{cases} \tag{1}$$

where

$$\sigma_1(\theta) = \left(\frac{k_1}{b} + k_2\right)(r_s\ \cos\ \theta_P)^N(\cos\ \theta - \ \cos\ \theta_1)^N \quad (\theta_m \le \theta \le \theta_1)$$

$$\sigma_2(\theta) = \left(\frac{k_1}{b} + k_2\right)(r_s\ \cos\ \theta_P)^N \times \left\{\cos\left[\theta_1 - \frac{\theta - \theta_2}{\theta_m - \theta_2}(\theta_1 - \theta_m)\right] - \ \cos\ \theta_1\right\}^N \quad (\theta_2 \le \theta < \theta_m)$$

$$\tau_1(\theta) = [c + \sigma(\theta)\tan\ \varphi]\{1 - \exp[-j(\theta)/K]\} \quad (\theta_m \le \theta \le \theta_1)$$

$$\tau_2(\theta) = [c + \sigma(\theta)\tan\ \varphi]\{1 - \exp[-j(\theta)/K]\} \quad (\theta_2 \le \theta < \theta_m)$$

$$j(\theta) = r_s[(\theta_1 - \theta) - (1 - s)(\sin\ \theta_1 - \ \sin\ \theta)]$$

$k_1$and$k_2$are the cohesive modulus and frictional modulus of sinkage, respectively. b denotes the wheel width; c, the internal cohesion of the soil; φ, the friction angle; K, the shear modulus; r, wheel radius; r_s, wheel effective radius. The wheel lugs influence the rolling resistance, drawbar pull and slip, and they fluctuate with the discontinuity due to entrance into the