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A multi-mode real-time terrain parameter estimation method for wheeled motion control of mobile robots ☆

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ABSTRACT

For motion control of wheeled planetary rovers traversing on deformable terrain, real-time terrain parameter estimation is critical in modeling the wheel-terrain interaction and compensating the effect of wheel slipping. A multi-mode real-time estimation method is proposed in this paper to achieve accurate terrain parameter estimation. The proposed method is composed of an inner layer for real-time filtering and an outer layer for online update. In the inner layer, sinkage exponent and internal frictional angle, which have higher sensitivity than that of the other terrain parameters to wheel-terrain interaction forces, are estimated in real time by using an adaptive robust extended Kalman filter (AREKF), whereas the other parameters are fixed with nominal values. The inner layer result can help synthesize the current wheel-terrain contact forces with adequate precision, but has limited prediction capability for time-variable wheel slipping. To improve estimation accuracy of the result from the inner layer, an outer layer based on recursive Gauss-Newton (RGN) algorithm is introduced to refine the result of real-time filtering according to the innovation contained in the history data. With the two-layer structure, the proposed method can work in three fundamental estimation modes: EKF, REKF and RGN, making the method applicable for flat, rough and non-uniform terrains. Simulations have demonstrated the effectiveness of the proposed method under three terrain types, showing the advantages of introducing the two-layer structure.

1. Introduction

In planetary exploration missions, rovers or wheeled mobile robots (WMRs) need effective wheel motion control to traverse on deformable terrain with efficient energy consumption autonomously [1,2]. Slipping of the wheels is inevitable,

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making the traversing a difficult task. To establish the energy-efficient control of slipping motion on soft terrain, it is a prerequisite to model the wheel-terrain interaction precisely for slip compensation [3–5].

The problem of wheel-terrain interaction modeling has been researched under various constraint situations in the terramechanics literature. Foundation of the wheel-terrain mechanics was laid by Bekker in his studies on off-road vehicle dynamics [6,7]. Based on Bekker's principles, Wong [8] proposed an analytical model to clarify the relationship between the mechanical and kinematic states of a rigid wheel driven longitudinally on soft terrain [9]. Steering maneuver was considered in [10] where a skid-steering tracked vehicle on a firm surface is investigated. Tran et al. [11] utilized the models built in [9,10] into a wheeled unmanned ground vehicle (UGV) and established an integral wheel-terrain interaction model with consideration of multiple steering wheels and loose soil. Ishigami et al. [12] incorporated the wheel-level model into multi-body frame and generated a framework of vehicle-wheel-terrain dynamics. Jia et al. [13] rebuilt the model with an assumption of isotropic shear stress and took grousers into consideration. Noticing that the terrain surface is probably rough, Iizuka et al. [14,15] studied the influence of circular and pentagon wheels to the performance of a lunar rover traversing on a sloped terrain.

The establishment of a wheel-terrain model is insufficient to determine the terrain force under wheel slipping, because in the model, there are several terrain parameters which dominate the projection accuracy from wheel slip to wheel-terrain force, and these parameters depend on specific terrain type of the wheel location that is usually unknown and cannot be predetermined. In order to compensate the influence of wheel slip to the wheel control, it is desirable to introduce a mechanism for acquiring and updating the values of terrain parameters during rover traversing motions, and terrain parameter estimation has become a key prerequisite technique for the autonomous motion control of wheeled rovers on unknown deformable terrains.

Recently, several methods have been presented to determine the terrain parameters. Ding et al. [16] decomposed the wheel-terrain model and classified the terrain parameters into three unrelated sets to calculate them in sequence, providing a series of methods to identify those parameters with in-situ data [17]. Xue et al. [18] dealt with the same problem of in-situ identification by using a least-square support vector machine. Hutangkabodee et al. [19], [20] adopted the composite Simpson's rule to fit the integrals in model, and then Newton-Raphson method to solve the approximated nonlinear equations iteratively. Considering the large computation load and inflexibility of those off-line methods, Iagnemma et al. [21] used linear least-square method to online update the cohesion of soil and internal friction angle in each processing time span. Ray [22] deemed parameter sets of possible terrains as hypotheses of wheel-terrain model and provided a multi-model based Bayesian estimation method to find the parameter set with the highest probability. The success of this method greatly depends on the practicability of the hypotheses.

However, the above mentioned methods estimate terrain parameters by offline or online processing data of wheel-terrain interaction, which cannot be used for real-time slip compensation. For this reason, the authors recently developed a real-time method of soil parameter estimation as presented in [23]. The method aims to estimate the wheel-terrain interaction forces in real time by focusing the estimation on two dominant parameters, sinkage exponent and internal friction angle, which dominate the normal stress and sheer stress that constitute the interaction forces on the wheel-terrain contact surface. By utilizing an adaptive robust extended Kalman filter (AREKF) presented in [24], the dominant parameters are updated in real time, which supports the implementation of real-time control, while the others are fixed with nominal values, reducing the complexity of onboard computation. However, the estimation result of the method is actually a function of the slip ratio, not the true value of parameters. It can help synthesize accurate wheel-terrain forces at the current slipping state of wheel, but the prediction capability is limited. That means, for the result at arbitrary time, the synthesis error from the slip ratio to the wheel-terrain force or vice versa will increase if the slip ratio or the wheel-terrain force remarkably deviates from its current value. That leads to the deviation of the desired value of slip ratio when calculated by the real-time estimation result of terrain parameters and the desired traction force from rover body, and augments the wheel traction control error.

When a rover runs stably without significant change of the desired wheel traction, deviation of the desired slip ratio is negligible, and the real-time estimation method in [23] can gain adequate accuracy of traction control. However, terrain is sometimes rough with various shapes, which makes the rover body generate a fluctuated desired traction force for each wheel. For large magnitude fluctuations, the calculated desired slip ratio probably contains a remarkable deviation, which will reduce the accuracy of slip compensation and the steady state error of the wheel traction force control.

To achieve desirable wheel motion control on a deformable rough terrain, the terrain parameter estimation accuracy is important. Hence, in this paper, a new real-time estimation method with multiple modes is proposed. This method is built on a two-layer structure. The AREKF method presented in [23] is used to design the inner layer to obtain real-time estimation of terrain parameters. A recursive Gauss-Newton (RGN) algorithm [25] is introduced as the outer layer to online update the inner-layer estimates. The RGN algorithm is chosen because its cost function utilizes observed and estimated history values which can help improve the accuracy of real-time estimation. In addition, it has a recursive form, without the need for large memory.

With the two-layer structure, the proposed method can work at three modes for various terrain situations, including RGN and the two modes of AREKF: extended Kalman Filter (EKF) and robust extended Kalman filter (REKF). For terrains with flat surface, the wheel slip due to terrain is almost invariant. The estimation method works only as an EKF. RGN does not update terrain parameters in the inner layer due to the lack of measurement innovation. When the terrain has variable slope angles, RGN layer is activated and works with REKF cooperatively. If the terrain is non-uniform and changes significantly, the method switches to REKF status to fast follow the terrain parameter variation, and RGN is reset to renew the online update