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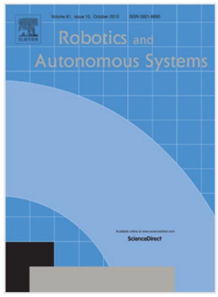

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Yuankai Li, Liang Ding, Guangjun Liu

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Attitude-based Dynamic and Kinematic Models for Wheels of Mobile Robot on Deformable Slope

Yuankai Li [a, b], Liang Ding [c], Guangjun Liu [b,*]

[a] School of Aeronautics and Astronautics, University of Electronic Science and Technology of China, Chengdu, China
[b] Department of Aerospace Engineering, Ryerson University, Toronto, Canada
[c] State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, P. R. China

Abstract: Deformable slope is a type of terrain that wheeled mobile robots (WMRs) and ground unmanned vehicles (GUVs) may have to traverse to accomplish their mission tasks. However, the associated terramechanics for wheels with arbitrary posture is rarely studied. In this paper, based on wheel attitude, dynamics of the wheel-terrain interaction for a rigid wheel on deformable slope is investigated. Through introducing the angular geometry of wheel attitude into terramechanics theory, a generalized dynamic model is developed, involving two inclination angles of slope and three attitude angles of wheel steering axis. Two representative cases are studied: the wheel runs straight forward and perpendicular to the slope, and the wheel is in a steering maneuver with an inclined steering axis. A generalized kinematic model for wheel-terrain contact point and wheel center is also provided, which analytically explicates that trajectory of wheel motion is coupled with wheel attitude while driven by angular rates. The proposed attitude-based models are valid for arbitrary wheel-terrain geometry and can lead to control purpose directly. Effectiveness of the models is confirmed by simulating the influences from attitude to wheel mechanics and motion.

1 Introduction

Wheeled mobile robots (WMRs) and ground unmanned vehicles (GUVs) provide a significant platform for many applications, such as searching and rescue and planetary exploration missions such as the Curiosity rover recently landed on Mars [1]. In these applications, real environment is usually complex and a priori unknown, so environment-robot interaction becomes fundamental in yielding robotic intelligence and determining robotic behavior [2-3]. Deformable and rough terrain are one of such environments that WMRs will encounter. For reducing the risk of mission failure, it is necessary to mathematically specify the dynamic interaction between wheels and terrains. For this reason, wheeled locomotion with its wheel-terrain interaction mechanics becomes one of the essential topics for the mobile robots on planetary or rough ground [4].

Theory of wheel-terrain interaction is built on terramechanics, which first appeared in Bekker's works [5-7]. Bekker studied the off-road vehicle dynamics systematically and laid the foundation of wheel-terrain mechanics. Wong [8] extended Bekker's principles and proposed an analytical model [9] to predict the mechanical and kinematic status of a rigid wheel driven on deformable soil with longitudinal motion. Shibly et al. [10] simplified the closed-form model by linearizing the normal and sheer stress through which soil parameter estimation, an inverse problem of modeling, and many other applications become expectable to solve with less computation load.

Steering maneuver is considered in [11], where a skid-steering tracked vehicle on a firm surface is studied. Shear deformations and stress distributions in the contact area are identified during steering maneuver. Tran et al. [12-13] utilized the methodology for wheeled UGV and established an integrated model of the interaction among multiple steering wheels and soft terrain. Ishigami et al. [14] incorporated this 2-dimensional wheel-soil model into multi-body frame and generated a framework of vehicle-wheel-terrain dynamics. Jia et al. [15] rebuilt the model assuming that the sheer stress is isotropic and took grousers into consideration. Due to the complexity of this model, quadratic approximation, unlike Shibly's linearization method, is introduced in [16-17].

Most of the above mentioned works assume that the surface is flat. However, mobile robot, such as planetary rover with rigid wheels, is inevitable to traverse on a slope terrain. Iizuka et al. [18-19] studied the influence of circular and pentagon shaped wheels to the performance of a lunar rover running on a slope, but the sloped soil surface contains only one inclined angle along straight-line of motion. This simplified

* Corresponding author. Tel: +1 4169795000 ext. 7648.
Email addresses: yuankai.li@uestc.edu.cn (Y. Li), liangding@hit.edu.cn (L. Ding), gjliu@ryerson.ca (G. Liu).