Sensing and Analysis of Wheel Performance on Loose Soil for Lunar/Planetary Exploration Robots

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論 文 内 容 要 旨

Since the 1970s, lunar/planetary exploration missions have used mobile robots (rovers). Of the ten missions to have successfully landed wheeled vehicles on the surface of the moon and Mars, seven have employed wheeled rovers. Currently, a wheeled rover has covered its total distance on other planets that exceeds a marathon. Many of scientific discoveries, such as the presence of water in past Mars, have been performed during rover missions. This fact indicates that rovers are of great importance for lunar/planetary exploration. In the past, lunar/planetary exploration missions have mainly adopted unmanned mobile rovers with rigid metallic wheels for their locomotion gear, because wheel-based mechanisms excel in the mobility and are mechanically simple. However, the surfaces of the moon and Mars are covered with fine-grained regolith. Gravel and rocks are also widespread. Hence, the wheels of these rovers can easily slip while traveling in such environments. When the wheel slippage occurs, the rovers struggle to follow their desired path. In the worst situation, the rover gets stuck in loose soil, rendering it unable to move. Indeed, NASA/JPL's Mars Exploration Rover-A (Spirit), which landed on Mars in 2004, was buried in loose Martian soil in 2009. In 2010, NASA/JPL gave up trying to free the rover and converted it to a static observation station. Thus, wheel slippage is a serious problem for rover missions. To avoid such situations, an understanding of wheel-soil interaction and accurate online estimation of wheel performance are essential.

Once the wheels get stuck, the rover’s original missions must be terminated. Currently, ongoing NASA/JPL missions have mainly targeted a safe environment in which wheel sinkage and slippage is less likely. However, the most interesting locations are generally in more challenging environments, such as the rims and interiors of craters. Therefore, future exploration missions will need to overcome this issue to explore such challenging targets. For this purpose, getting stuck should be avoided. Getting stuck is induced by a lack of information in the current wheel-soil interaction model, unexpressed phenomena in wheel-soil interaction, unknown terrain characteristics, and so on. Therefore, to prevent lunar/planetary rovers from getting

stuck, the classical wheel-soil interaction model must be reconsidered, and the terrain characteristics of the target environments should be re-evaluated.

In this study, stress distribution of the contact patch of a wheel and the wheel sinkage/slippage phenomena are investigated. These aspects are the key to understanding the wheel-soil interaction. The stress distribution at the contact patch is of great importance, because this determines the wheel-soil interaction mechanism. Therefore, knowing the stress distribution will help to identify the soil characteristics. From the perspective of terramechanics, we can precisely estimate the mobility performance if the forces and torques acting on the wheels can be precisely estimated in-situ. However, the classical terramechanics models have targeted heavyweight vehicles that have large-scale running gears. These models have also been applied to small and lightweight vehicles since they can be tuned using several parameters related to the wheel-soil interface. This results in inaccurate mobility predictions. To accurately estimate the wheel performance on loose soil, the classical model must be reconsidered.

Moreover, practical rovers have lugs on their wheel surface. These plate-like lugs, called grousers, develop greater traction than that on the wheel surface. The resultant forces of a wheel with grousers have been discussed by related works, but the interaction between the wheel with grousers and soil has not yet been identified. To model a wheel with grousers, we must clarify the interaction mechanism. The stress distribution at the contact patch contains information about the terrain because the stress distribution is a product of the wheel-soil interaction. Thus, measurements of the stress distribution of a wheel with grousers is useful for modeling the wheel-soil interaction of wheeled rovers.

In a practical situation, it is not sufficient only to consider the wheel-soil interaction mechanism. Although terramechanics models have been used to estimate wheel performance (such as wheel sinkage, slippage, forces, and torques), these models are only effective when the terrain characteristics are known. However, the soil characteristics of the target environment of the rovers are unknown. Rovers need to travel on heterogeneous soil and rough terrain. The wheel performance varies in such environments. Therefore, online estimation techniques should be developed to measure wheel performance.

With the motivation described above, this research addresses two issues for lunar/planetary exploration robots: A) experimental clarification of the wheel-soil interaction mechanism, and B) online estimation of the wheel performance on loose soil. Moreover, to elucidate the wheel-soil interaction mechanism, issue A) considers the stress distribution of a slick wheel on loose soil and the stress distribution of a wheel with grousers on loose soil. Thus, this research is composed of three parts: 1) clarification of the wheel-soil interaction by precisely measuring the stress distribution on the wheels, 2) clarification of the interaction between a wheel with grousers and soil by measuring the stress distribution of the wheel with grousers over the contact patch, and 3) development of an online wheel performance estimation technique that estimates wheel sinkage and slippage, reaction force and torque.

This dissertation consists of six chapters.

Chapter 1: Introduction

This chapter introduces the background, motivation, purpose, and approach to this research. A literature review is also given in this chapter.

Chapter 2: Classical Model of Wheel-Soil Interaction

This chapter reviews existing models in the field of terramechanics. To confirm their characteristics, the normal and shear stress distributions are calculated under different wheel slip conditions. From the results, it is confirmed that the shear stress model depends on normal stress. The limitations of applying the classical models to lightweight vehicles are also explained.

Chapter 3: Stress Distribution of a Wheel on Loose Soil

This chapter presents an experimental investigation of the stress distribution of a wheel on loose soil. Normal, circumferential shear, and lateral shear stress distributions over the contact patch are precisely measured using a special measurement device. These measurements are compared with the stress distribution calculated using the classical model. Furthermore, the possibility of updating the classical stress model is discussed based on this comparison. In particular, a possibility of updating the normal stress model is discussed. From the viewpoint of the contact angle of the wheel, the parameters of the maximum stress angle model should be revised. As the contact angle depends on the normal stress, the normal stress model is compared with the measured values. A comparison of the maximum normal stress showed that the classical normal stress model could not express the normal stress distribution of a lightweight wheel. In particular, the classical normal stress model cannot express the forward shift in the maximum stress angle and the entry angle of the wheel as the wheel slip increases, or the decrease in the maximum normal stress. From this perspective, it is possible that updating the normal stress distribution model would provide better wheel performance estimates.

Chapter 4: Stress Distribution of a Wheel with Grousers on Loose Soil

This chapter experimentally elaborates the stress distribution of wheels with grousers. By representing the stress distribution based on six locations of the specific sensing area, the stress distribution at the contact patch of a wheel with grousers is identified. Based on these measurements, the tractive components exerted by the grousers and the wheel surface are quantitatively evaluated. Moreover, the traction developed by the grousers is discussed and compared to the passive earth pressure theory of a flat cutting blade in the soil. Thus, the traveling performance of a wheel with grousers can be approximated by considering the grousers' bulldozing effect. This enables the passive pressure developed by a grouser to be estimated.

Chapter 5: Online Estimation of Wheel Performance on Loose Soil

This chapter proposes an online estimation technique for wheel performance on loose soil. A ToF camera-based estimation method for wheel sinkage and slippage is introduced for use with various field robot applications. Practical applications of accurate slippage estimation using a ToF camera are discussed based on the characteristics of this sinkage/slippage estimator. Moreover, a real-time measurement method for the forces and torques acting on the wheel axle is proposed by fixing a low-profile force/torque sensor to the wheel axle. Drawbar pull, normal force, and wheel torque were well projected by the angle of wheel rotation. The online estimation of wheel performance on loose soil in future lunar/planetary exploration rovers is also discussed.

Chapter 6: Conclusions and Future Work

This chapter summarizes the outcomes and results of this research. The contribution of this dissertation and directions for future study are also presented in this chapter.

The research outcomes in this dissertation are expected to contribute to future lunar/planetary rover missions. First, accurate measurements of the three-dimensional stress distribution of a wheel, particularly for lightweight vehicles, demonstrate that the classical model cannot express the actual normal stress distribution of a wheel. Experimental results specifically indicated the possibility of more accurate estimates of mobility performance by updating the normal stress model for lightweight vehicles. The stress distributions of a wheel with grousers at arbitrary wheel rotation angles were highlighted the interaction mechanism at the contact patch. It was shown that the shear stress exerted by a grouser can be effectively estimated by calculating the passive pressure of a flat cutting blade. An online estimation method for determining the wheel performance on loose soil was presented for future lunar/planetary exploration robots. A technique for estimating the wheel sinkage/slippage online using a ToF camera was proposed. A practical application that detects large wheel slippage was presented, and a system for wheel performance estimation, which can be implemented in a wheeled robot, was developed.

論文審査結果の要旨

月や火星などを移動探査する車輪型ロボットが研究開発されているが，レゴリスと呼ばれる粒子の細かな砂で覆われた地形においては，車輪が空転しロボットが思い通りに走行できなくなる問題が指摘されている。このようなスリップしやすい軟弱地盤において適切な走行制御を行うためには，車輪と地盤の力学的相互作用を理解し，車輪個々の走行状態を適切に把握することが不可欠である。本論文は，実験的計測に立脚して車輪と軟弱地盤との相互作用を明らかにすることを目的としたものであり，全編 6 章よりなる。

第 1 章は序論であり，本研究の背景および目的を述べている。

第 2 章では，1950 年代より行われてきたテラメカニクスと呼ばれる研究分野において構築されてきた車輪の力学モデルを整理し，その問題点について論じている。従来のモデルは重量が 1 トンを越えるような農業機械，建設機械が主な対象となっており，そのモデルをそのまま月惑星探査ロボットに適用するには限界があることが述べられている。これは重要な問題提起である。

第 3 章では，車輪踏面に発生する応力分布について論じている。車輪踏面に力センサを組み込むことにより，車輪の回転角方向および幅方向に対して，踏面における垂直応力およびせん断応力を様々に条件を変えて詳細に計測を行っている。その結果，車輪踏面の応力分布は従来モデルで仮定されていた分布とは大きく異なることが明らかにされ，モデルの修正が必要であることが述べられている。特に，車輪のスリップ率の増大にともなって応力分布が進行方向前方にシフトする様子が，従来モデルでは適切に表現できていないことが示されている。これは重要な成果である。

第 4 章では，グラウザと呼ばれる平行平板を取り付けた車輪の応力分布について論じている。車輪踏面にグラウザを取り付けると牽引力が増大しスリップ率を低減できることが知られているが，詳細な力学計測は十分になされていなかった。本論文では，車輪内に力センサを組み込むことによりグラウザ発生力を直接計測することに成功し，その結果に対して考察を行い，テラメカニクスで用いられている平刃排土抵抗モデルを用いてグラウサの発生力の定量評価ができることが述べられている。これは有用な成果である。

第 5 章では，ロボットが走行中に牽引力やスリップの状態をオンライン計測することを目指した，実用的なセンサ組込法について論じている。車輪牽引力の計測には車軸部での 6 軸力計測，スリップ率の計測にはカメラ画像を用いたオプティカルフロー計測，および画像距離センサをによる車輪沈下量の計測を行い，これらの情報を統合することによりスリップを早期検出して車輪空転を避ける方法が論じられている。これは有用な成果である。

第 6 章は結論である。

以上要するに本論文は，月惑星探査を目指す車輪型ロボットについて，軟弱土壌走行時の車輪と土壌の力学的相互作用を実験計測により詳細に明らかにし，ロボット走行中に牽引力やスリップの状態をオンライン計測する手法を具体的に示したものであり，航空宇宙工学および宇宙探査工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。