

氏 名	ブリトン ナタン ジョン BRITTON, Nathan John		
研究科, 専攻の名称	東北大学大学院工学研究科 (博士課程) 航空宇宙専攻		
学 位 論 文 題 目	Teleoperation of Lunar Micro Rover with Monocular Omni-Camera (全方位カメラを用いた小型月面探査ローバのテレオペレーション)		
論 文 審 査 委 員	主査 東北大学教授 吉田 和哉	東北大学教授 小菅 一弘	
	東北大学教授 岡谷 貴之	東北大学准教授 永谷 圭司	
	(情報科学研究科)		

論文内容要約

The research presented here covers the design and operation of a lunar micro rover, codenamed Moonraker. The optimal maneuvering efficiency of wheeled skid steer mechanism is established and a slip prediction method presented. A virtual reality teleoperation interface is introduced, and methods of optical feature tracking and autonomous localization are proposed as a means to mitigate the hazards of time lag in the control loop and to provide a tele-operator with uninterrupted actionable information needed to conduct a lunar mission with high time efficiency.

Chapter 1 - Introduction

In Chapter 1, the history of lunar exploration is reviewed, and a micro rover mission, designed to win the Google Lunar XPRIZE competition, is introduced. Lunar exploration is becoming cheaper and the Moon will potentially be accessible to University research within the current decade, the GLXP is largely regarded as the first step in this new level of lunar access. A literature review is conducted on planetary rover design, terramechanics, catadioptric sensors, computer vision, and rover teleoperation.

Chapter 2 - Moonraker: Micro Rover Design and Construction

The design of Moonraker, a novel lunar micro rover prototype is introduced. Mass is still the driving force in lunar mission design, so Moonraker is presented as a model to achieve significant mobility on the surface of the Moon for 1 lunar day at under 10kg. A minimalist sensor suite of an omnidirectional camera and an inertial measurement unit are, along with wheel odometry sensors, proposed as the only sensors needed for constant situational awareness during a lunar mission. The system

architecture and space qualification tests of a pre-flight model are discussed, and a socket-based multi-threaded scalable software architecture is presented.

Chapter 3 - Mobility & Soft Soil Slip Hazard

The mobility system of the rover is discussed in detail and a slip model is proposed. Using a time-of-flight tracking mechanism for a high accuracy ground truth, the slip characteristics of the rover were measured and a slip model to predict longitudinal slippage is proposed. This model can be used to tune the navigation systems' estimation of traveled distance for mission safety, position estimation, path planning and 3D reconstruction of the environment.

Additionally, a set of laboratory experiments was conducted to determine the effect of grouser length in a 4-wheel skid-steer mobility system (Moonraker) on various turning maneuvers. It was discovered that longer grousers improve performance, even for spot turn maneuvers which remain efficient in loose soil. Gradual course adjustments, however, are determined to be less efficient when grouser length is increased. A theory to explain these results is proposed.

Chapter 4 - Feature Tracking and EgoMotion Localization Method

A feature tracking algorithm is presented, which allows for stable long-term tracking of feature objects through an omnidirectional camera. The method builds upon on existing implementations of keypoint detectors and descriptor extractors, namely the Star-ORB combination, which was determined to be the best available solution for the mission presented in Chapter 1, with the monocular omnicaamera of Moonraker. The tracking function presented uses the extracted keypoints from the Star-ORB combination to recognize features over a series of consecutive frames for as long as the feature is visible. This provides invaluable data for the localization process.

A highly accurate egomotion localization method is then introduced, using the catadioptric omnidirectional camera. This method makes use of features on the skyline to keep an accurate heading, and uses a proposed Motion Field Isolation method to isolate the fundamental axes of rover motion from the perceived motion of the feature set. Together with the attitude estimation from the IMU, and the wheel odometry, this system is able to maintain 97% positional accuracy in a feature-rich environment. Additionally, this method is able to detect subtle side-slip events.

Chapter 5 - Teleoperation System

A two-person semi-autonomous teleoperation system is presented, which mitigates the threat of the time gap between the Earth and Moon when roving at high speeds. The system, which divides tasks between two operators, allows the team to have uninterrupted situational awareness and conduct the mission efficiently. This is important to maximize the value of the mission, which is limited to 14 Earth days, and to win the GLXP as Moonraker will need to travel faster than competitors to win.

Chapter 6 - Field Testing & Evaluation

A set of field tests conducted at a lunar analogue site is presented as an evaluation of the work presented in previous chapters. The mobility performance and work conducted in Chapter 3 are evaluated and the design of Moonraker itself as presented in Chapter 2 is validated by the high performance of the system on steep slopes of soft soil. The localization system presented in Chapter 4 is implemented and evaluated in real-time, and the results confirmed to be sufficient for the requirements of the teleoperation system presented in Chapter 5. The teleoperation system itself proves through the shared roles model to be able to improve the operational efficiency of a mission by a factor of 4, when speed and distance traveled are used as a metric.

Contribution Statement

This work is expected to contribute to the field of extra-terrestrial exploration through micro-rovers, specifically for use on the moon. The mobility analysis and slip model presented help to validate the skid-steer system which will save mass and reduce slippage on steep slopes for any mission. Additionally, the optimal maneuvering strategy of focusing on spot turns over course adjustment for skid steer mechanisms is proven. The work presented in localization reduces the need for heavy sensors and highly redundant systems which dramatically increase the mass and cost of a mission. Furthermore, the work presented here in teleoperation will be important for any micro-rover mission to the Moon in the near future. While all missions to date are conducted in a slow and laborious manner, when exploring the moon on a limited budget, a fast-paced mission is essential. Having

access to hardware which can survive the lunar night will not be feasible for many decades to come; In the meantime, limited 2 week missions will be possible soon, and for these missions operating with high time efficiency, as facilitated in this work is incredibly important.