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学 位 論 文 題 目　Strategic Path Planning of Lunar Micro-Rover under Environmental Constraints
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# 論文内容要約

In recent decades, outer space has become more accessible as launch vehicle and space exploration system development started to shift from government agency's work to private entities and start-up. This movement was possible due to the emergence of space system research and development lead by university and the availability of Commercial-Off-the-Shelf (COTS) hardware. Some of these devices are intensively tested to qualify for flight readiness, and mass production of such electronics reduce the cost of development significantly compared to predecessor's hardware, where most of the devices were custom made for specific project using a trial and error process. This difference also comes from the degree in knowledge accumulated for space technology. Space travel and exploration was previously thought to be an impossible challenge to overcome. The Apollo mission proved human's capability by landing humans on the moon.

With the rise of affordable COTS hardware, low-cost space system became accessible where university can afford development at a minimal cost. Furthermore, a cash incentive challenge from Google Lunar XPRIZE (GLXP) competition stirred an increased attention from start-up and private entities to aim for potential resource prospecting on the Moon using the micro sized rovers. The Moon has resource rich lands that are expected to have an abundant amount of hydrogen volatiles, which will be beneficial for the reusability of manned lunar base on site.

When considering a mission scenario of a lunar surface exploration for resource prospecting, there are several environmental considerations that need to be accounted for the small compact rover. First of all, the locomotive technologies on the surface is critical as the lunar surface is filled with fine particles known as regolith. There have been reports that these granular soils can cause difficulty in mobility performance such as wheel slippage and burrowing during locomotion. This issue can potentially lead a stuck wheel, resulting to a permanent halt on site. Secondly, the lunar surface temperature can range anywhere between -200°C to 150°C, depending on the time of the day and the latitude condition. This high temperature variation requires a smart thermal control technique in order to regulate the onboard hardware temperature within

the operational temperature range. Thirdly, the Moon takes roughly one Earth month to complete one revolution. This means that the rover needs to consider whether it can survive the 2 weeks of lunar day or 2 weeks of lunar night. For most cases, the lunar night is extremely cold for survivability, making rover operations impossible with the current technologies that start-ups have access to. This allows operation only for the day time period. Furthermore, the insolation condition changes depending on lunar latitude, and this affects the effective lunar surface temperature and sunlit area at specific time domain during the mission. Lastly, the gravitational field at the Moon is about a sixth of the Earth. This again can negatively affect the locomotion performance on lunar ground. These environmental constraints are important elements to consider for the rover's pre-mission analysis, and these factors dictates the optimal path to the resources while maximizing the rover's survivability.

Considering the above conditions, an extensive study on motion planning is required to move from one point to another as safe as possible. In typical path planning idea in terrestrial application, the rover's main objective is to move as fast as possible for rapid surface coverage. However, in case of lunar/planetary exploration operation, accelerated exploration does not necessarily indicate an effective planning as the environment is different from terrestrial conditions along with difficulty in remote-operation in a distant place. To investigate the rover’s safest path in such environment, a path planning strategy for lunar micro-rover application is studied, where the details are described in the following chapters.

In Chapter 1, history of planetary and lunar rover is discussed to supplement background of this research. This subsequently introduces previous rovers developed for space exploration by space agencies and the start-up that emerged from the GLXP competition. The idea of exploring the lunar skylight is also introduced beside the main GLXP mission. Furthermore, literature review is studied to compare the pros and cons of thermal control systems used in planetary and lunar rovers and satellites.

Chapter 2 discusses the micro-rover model for mobility and thermal performance. For the former, the rover is tested under sandy terrain to mimic similar terrain condition as lunar surface, and the locomotive performances are quantified depending on slope and rover's orientation. For the latter, the thermal model incorporates all external thermal inputs in the lunar surface condition, and several key thermal parameters are briefly discussed.

Chapter 3 discusses the thermal design analysis associated with the lunar micro rover, developed by Space Robotics Lab (SRL). This rover uses a mixture of space legacy hardware, space heritage hardware from previous SRL satellite development, and COTS hardware inside the design. The materials and components are selected to develop a light-weight yet high performing rover. For thermal control technique, a passive (thermal interface material) and active system (heater) are incorporated to tune the rover's thermal performance depending on the target exploration site and the operation time window.

Chapter 4 proposes the path planning algorithm for the lunar rover application. Three different environmental constraints are considered with a customizable cost function, and each of them is examined carefully in a test case map scenario. From the results, the environmental constraints are weighted in a certain order from least to most important to tune the 'optimal' path selection for actual mission scenario.

Chapter 5 presents mission case scenario of the lunar polar region exploration. This section briefly discusses landing site selection, way point selections, and motion strategies utilized for the rover.

Chapter 6 summarizes the lunar micro-rover's path planning decision for the polar region exploration. The results from Chapter 5 show that a micro-rover is capable of performing lunar exploration at any latitude, showing promising results for a resource prospecting mission. This path planning methodologies are usable for any other applications such as on Earth or other planetary region such as Mars.