Robust Wireless Networking of Multiple Micro-Rovers for Lunar Exploration Missions

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論文内容要約

Space exploration remains at the pinnacle of human endeavor. The idea of exploring outer space has always occupied a special place in the public imagination since the dawn of the Space Age in the late 1950s. Back then, the main driving force for interplanetary exploration was the desire to satisfy humanity's curiosity. Nowadays, instead of just being curious about what lies beyond the confines of our planet, we humans have started to entertain the idea of exploring other worlds to guarantee the enduring continuance of our species. Here on Earth, we are dependent on a limited quantity of natural resources and space. It is no longer a question of "if" but of "when" these resources would run out. Hence, we have to look into the possibility of mining these resources from otherworldly locations. Venturing outside our atmosphere is no easy feat, however, as the space environment is harsh and unpredictable. A key enabler for making such challenging explorations possible is the use of robotic vehicles, also known as rovers, that allow us to collect information about extraterrestrial environments prior to sending human-crewed missions. These rovers, therefore, are an indispensable component of the initial phase of space exploration, and significant research is currently being conducted to develop new systems and technologies involving these rovers.

Almost five decades since humans last walked on the Moon, it is now beckoning for us to return. An increasing number of experts from government, industry, and academe now view Earth's lone natural satellite as an "eighth continent" full of natural resources, sitting at the edge of Earth's gravity well, waiting to be mined. A particular lunar resource being looked at is water ice, believed to exist in substantial concentrations within the permanently shadowed regions near the lunar poles. This water ice can be split into hydrogen and oxygen via electrolysis, thus providing a means for human life support and fuel for rocket propulsion. Aside from water ice, several chemical and mineralogical resources on the Moon have been identified for possible in-situ resource utilization applications. Surveying the lunar surface for pockets of water ice and precious metals will be an enormous undertaking that will involve gathering samples over vast areas. Therefore, the current approach of using a single large and expensive rover platform will likely be ill-suited for this task.

Multi-rover systems composed of simple and low-cost micro-rovers now present a flexible and cost-effective solution for large-scale lunar surface resource prospecting. With multi-rover systems, lunar exploration missions can be completed in a shorter amount of time. However, in these missions, the rovers will be distributed across a wide area and must communicate wirelessly over long distances to accomplish their objectives. Hence, a requirement for lunar multi-rover systems would be to establish and maintain a reliable wireless network between the robotic agents. Numerous factors can easily disrupt lunar multi-rover networking. For one, the motion of the rovers can interrupt inter-agent connections. This interruption could happen if the rovers move out of the radio connectivity range from other agents. Another potential cause of disruption is that rovers are fallible and are likely to break down in the harsh lunar environment. Therefore, there is a need to address these issues to enable multi-rover systems for lunar exploration.

This dissertation explores the ideas of network connectivity and network robustness for lunar multi-rover systems. This work uses a comprehensive strategy that combines elements from both realistic channel-based and graph theory-based approaches currently found separately in the literature to investigate how the connectivity and robustness of lunar multi-rover networks evolve during large-scale lunar exploration missions. The overall goal of this research is to develop schemes for lunar multi-rover systems to (1) maintain their connectivity while the rovers are exploring and (2) improve the robustness of the network against rover failures.

Chapter 1 presents an introduction to rovers for lunar and planetary exploration. It provides a brief survey of single-rover platforms involved in past and upcoming space missions. It then offers the concept of using multi-rover systems as a compelling alternative for employment in future lunar exploration scenarios. The chapter also outlines the significant challenges that need to be addressed to implement such a system. Finally, it provides details on the research approaches and other relevant content included in this dissertation.

Chapter 2 reviews the different radio propagation phenomena present in the lunar environment that can affect the quality of communications between lunar robotic agents. It then presents the development of a radio propagation model specifically designed for predicting the total path loss for point-to-point wireless communication links between robotic agents operating on the surface of the Moon. The proposed model is deterministic and is based on sound theoretical models that account for various lunar radio phenomena (such as free-space propagation, reflections, and diffractions) expected to impair radio transmissions over the irregular lunar terrain. The model is also designed to be terrain-aware and takes advantage of the recent availability of high-resolution digital terrain maps of select lunar regions of interest. Furthermore, it accounts for parameters relevant to lunar radio propagation, such as the electrical properties of the lunar regolith, operating frequency, antenna heights, and polarization. Simulations were performed to evaluate the performance of this model compared to a modified version of the well-established semi-empirical Longley Rice Irregular Terrain Model (ITM) for lunar radio propagation. High-resolution digital terrain maps of the Apollo 15 and Apollo 17 landing sites were downloaded from the NASA PDS archives to facilitate these simulations. Results indicate that the proposed model closely agrees with the modified ITM, with the latter estimating slightly higher path loss values at farther distances. The development of this lunar radio propagation model is expected to aid in designing and analyzing wireless communication systems for lunar applications.

Chapter 3 introduces the idea of representing lunar multi-rover networks via accurate communication graphs. These communication graphs were derived by combining standard Graph Theory formulations with the realistic lunar radio propagation model from the previous chapter. This chapter also discusses how to use these graph-based representations to assess the network connectivity and network robustness of lunar multi-rover systems. In particular, by using simple graphs to represent lunar multi-rover networks, the connectivity and robustness of such networks were equated to their topological graph-based counterparts. This approach allows us to abstract out the higher-level technical aspects of a network and its components to focus on modeling the network via low-level physical layer wireless interactions between its agents. Finally, a new metric for evaluating the robustness of lunar multi-rover networks was introduced in this chapter. The new metric, Network Vulnerability, is easy to compute, is intuitive and unambiguous, and is specifically formulated to quantify the robustness of multi-rover networks against single-rover failures.

Chapter 4 consolidates the ideas presented in the previous chapters towards developing coverage path planning algorithms for multi-rover exploration of the lunar surface. These algorithms were explicitly designed to impose constraints on the rovers' motions to maintain the connectivity and improve the robustness of multi-rover networks for large-scale lunar exploration missions. Extensive simulations studies were conducted, which involved multi-rover systems composed of a single fixed lunar module and several micro-rovers performing a large-scale collaborative sweep of the Apollo 15 and Apollo 17 lunar landing sites. These simulations assume that the micro-rovers have limited sensing, computation, and communication capabilities, which they use to autonomously take measurements of their immediate environments, localize themselves, and share data with other agents in the network. A myopic coverage path planning algorithm from previous work was adapted as a reference algorithm to facilitate the simulations. Modifications to this reference algorithm were then gradually introduced to build towards a path planning solution that achieves the previously stated goals without significantly prolonging the mission duration.

Three different constrained coverage path planning algorithms for lunar multi-rover networks were developed in these simulation studies: (1) Connectivity-Constrained Algorithm, (2) Biconnectivity-Constrained Algorithm, and (3) Vulnerability-Constrained Algorithm. The Connectivity-Constrained Algorithm was able to maintain network connectivity, but it regularly resulted in network configurations that are highly susceptible to network fragmentation due to single-rover failures. On the other hand, the Biconnectivity-Constrained Algorithm was able to enforce both network connectivity and strict network robustness, but at the cost of severely increasing the mission duration. Finally, the Vulnerability-Constrained Algorithm performed the best out of the three algorithms by maintaining network connectivity and achieving an acceptable level of network robustness without significantly increasing the exploration duration. These simulation results show that the connectivity and robustness of lunar multi-rover networks can be managed by imposing simple constraints on the movement of the micro-rovers.

Lastly, Chapter 5 summarizes the previous chapters and states the conclusions and contributions of this dissertation. It also identifies possible directions for future work. The work presented in this thesis contributes towards the robust wireless networking of lunar multi-rover systems. It is intended not as a complete solution readily applicable to upcoming lunar missions but as a stepping stone towards the future of lunar and planetary surface exploration via multi-rover systems.