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AUTONOMOUS TASK ALLOCATION IN MULTI-ROBOT NETWORKS FOR LUNAR RESOURCE EXTRACTION: INTEGRATING REINFORCEMENT LEARNING WITH MODEL PREDICTIVE CONTROL

Abstract

The new discipline of lunar resource utilization confronts a unique set of challenges that demand highly advanced autonomous systems capable of dealing with themselves well in adversarial and uncooperative environments. This work examines the application of reinforcement learning (RL) and model predictive control (MPC) to multi-robot networks for the management of the high-level task allocation problems characteristic of lunar mining operations. The ultimate objective is to develop a resilient, adaptive, and scalable framework that promotes cooperative decision-making among heterogeneous robotic agents and achieves optimal resource exploitation, energy efficiency, and safety of operation. In this article, we present a hybrid approach to take advantage of the complementarity of RL and MPC to address the lunar surface environment dynamic and non-deterministic behavior. Reinforcement learning is employed for learning the best policies for task allocation at higher levels based on direct feedback of the local environment, such as variations in regolith type, terrain roughness, and equipment wear. Model predictive control, on the other hand, enables planning and execution of lower-level paths to perform accurate motion and manipulation of robot limbs or excavation equipment subject to physical constraints and avoiding collision. To verify the proposed framework, we carried out large-scale simulations with a physics-based simulator of the lunar environment that implemented realistic gravity models, dust motion, and thermal fluctuations. The simulation results exhibit spectacular task success rate enhancement, energy efficiency, and system reliability compared to typical heuristic-based techniques. We also developed a prototype network of three rover-type robots with sensors, manipulators, and communications modules and tested it in a terrestrial

analog test bed that mimics lunar-like conditions. Experimental results derived from these experiments complement the simulation results, showing the framework's ability to react to unforeseen disturbances while still operating under growing uncertainty. The result of this research directly applies to future missions on the moon, namely those scheduled to have a permanent human settlement or to harvest precious materials like water ice and rare minerals. With the advanced technologies advancing in autonomous multi-robot systems, this work provides a foundation for the construction of more efficient, cost-effective, and resilient solutions to some of the most fundamental problems in space exploration. Future work will involve expanding the framework to other modalities, such as machine vision for object detection and natural language processing for human-robot communication. Further, its possible utilization in other celestial environments, for example, on asteroids and on Mars, will be considered.