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ADAPTIVE MECHANICAL ARCHITECTURES AND AI-ENABLED CONTROL STRATEGIES FOR A 4-ROBOT SWARM IN LUNAR RESOURCE UTILIZATION AND LIFE SCIENCES

Abstract

Long-duration lunar missions require robotic systems capable of executing complex tasks such as in-situ resource utilization (ISRU) and life sciences research under harsh environmental conditions. This paper introduces a four-robot swarm featuring adaptive mechanical architectures and AI-enabled control strategies designed to balance functionality, scalability, and logistical feasibility. The proposed system aims to ensure efficient task distribution, fault tolerance, and robust operation in the Moon's rugged terrain. Each robotic unit is built around a compact, articulated chassis designed to traverse craters and uneven regolith. The chassis employs a modular, reconfigurable design made from lightweight titanium alloys, with lattice-based topology optimization maximizing the strength-to-weight ratio while resisting dust abrasion and thermal extremes from 173C to 127C. High-torque, low-power actuators with compliant joints power the robotic arms, enabling precise manipulation of regolith or scientific payloads. Prior to fabrication, finite element analysis (FEA) will be conducted to validate structural integrity against micrometeoroid impacts and thermal stress. The swarm operates under a decentralized control architecture powered by Distributed Consensus-Based Optimization (DCBO) algorithms, enabling dynamic task allocation and real-time scalability. Each robot incorporates a reinforcement learning (RL) framework implemented through Deep Q-Networks (DQN), allowing individual units to adapt to environmental uncertainties. RL training occurs in high-fidelity lunar simulations accounting for gravity gradients, regolith behavior, and terrain variability. A multi-layered sensor fusion system merges data from optical cameras, LiDAR, and inertial measurement units (IMUs). An Extended Kalman Filter (EKF) processes these inputs, achieving sub-centimeter localization accuracy and producing a shared, real-time terrain map. For ISRU applications, each robot includes spectrometers and X-ray diffraction (XRD) sensors, providing on-the-spot identification of water ice and volatiles within the regolith. The swarm can merge into a single configuration for tasks like heavy load transport, employing docking mechanisms and distributed power-sharing. Alternatively, it can de-swarm for resource mapping, sample collection, and microbial experimentation in specialized life sciences modules, investigating the effects of lunar radiation, micro-gravity, and temperature extremes on biological systems. Aligned with NASA's Artemis program and commercial lunar initiatives, this four-robot swarm exemplifies scalable, autonomous technologies vital for establishing sustainable lunar habitats. By uniting advanced mechanical architectures with AI-driven control methods, this research advances the potential of multi-robot swarms in resource extraction, scientific

inquiry, and mission readiness for deeper solar system exploration.

Keywords: Lunar Exploration, In-Situ Resource Utilization (ISRU), Multi-Robot Swarm, Life Sciences, Artificial Intelligence, Distributed Consensus-Based Optimization (DCBO), Sensor Fusion, Autonomous Navigation, Regolith Analysis, Microbial Cultivation