IAF SPACE EXPLORATION SYMPOSIUM (A3)
Interactive Presentations - IAF SPACE EXPLORATION SYMPOSIUM (IP)

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MODULAR SELF-RECONFIGURABLE ROBOTIC SYSTEMS FOR AUTONOMOUS MARS EXPLORATION

Abstract

Mars's diverse terrains—from loose regolith on crater slopes to twisting lava tubes—pose significant challenges for conventional rovers like Curiosity and Perseverance. This paper presents a Modular Self-Reconfigurable (MSR) robotic system that overcomes the limitations of the traditional rocker-bogie mechanism by enabling real-time, autonomous reconfiguration for enhanced mobility and adaptability. Drawing inspiration from existing MSR platforms such as M-TRAN and NASA's ATHLETE, our system is composed of multiple interconnected modules equipped with high-torque brushless DC motors and universal docking interfaces. Each module includes robust latches and alignment guides for precise coupling, allowing configurations such as elongated chains for navigating narrow spaces, compact formations for stability on loose surfaces, or limb-like assemblies for tackling uneven terrain. To address the elevated power demands of these motors, the system employs high energy-density lithium-ion batteries with thermally adaptive battery management systems (featuring cell balancing and real-time state-of-charge estimation) and a model predictive motion planning approach that optimizes both mobility and power usage in resource-constrained environments. A decentralized control framework handles swift reconfigurations, ensuring overall functionality even if individual modules fail. Sensor capabilities include LiDAR and advanced 3D depth cameras, which provide comprehensive topographical data via a fault-tolerant, high-speed bus. To optimize navigation and reconfiguration in rapidly changing conditions, we integrate an advanced Reinforcement Learning (RL) paradigm. Combining Proximal Policy Optimization with Hierarchical and Multi-Agent RL, the system leverages real-time environmental feedback to refine locomotion and shape transformations. A detailed mathematical model underpins the RL algorithms, describing the kinematics, dynamics, and module interactions during reconfiguration to maintain stability and responsiveness in challenging Mars-like conditions. Energy management is further supported by high-efficiency solar panels, while active cooling systems protect sensitive electronics from temperature extremes. Looking ahead, in-situ resource utilization methods—such as localized energy generation and regolith-based component repairs—will bolster mission endurance and reduce reliance on Earth-based resupply. This MSR robotic system integrates multi-modal locomotion, structural adaptability, decentralized control, and advanced energy management to meet the demanding needs of planetary exploration. Its shape-shifting capabilities open access to previously unreachable locations on Mars and can be adapted for the Moon and asteroids. As mechanical designs, reconfiguration speeds, and AI-driven autonomy continue to improve, these versatile robots stand ready to revolutionize humanity's capability for deeper and more resilient interplanetary exploration.

Keywords: Modular Self-Reconfigurable Robots,Autonomous Navigation, Decentralized Control, Reinforcement Learning, Proximal Policy Optimization, Hierarchical Reinforcement Learning, Multi-Agent Systems, Mathematical Modeling, Energy Efficiency, In-Situ Resource Utilization, 3D Depth Cameras, Planetary Robotics