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Space Structures III Design, Development and Verification (Orbital infrastructure for in orbit service & manufacturing, Robotic and Mechatronic systems, including their Mechanical/Thermal/ Fluidic Systems) (3)

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MORPHOLOGY AND BEHAVIOR CO-OPTIMIZATION OF MODULAR SATELLITES FOR ATTITUDE CONTROL

Abstract

The emergence of modular satellites marks a significant transformation in spacecraft engineering, introducing a new paradigm of flexibility, resilience, and scalability in space exploration endeavors. In addressing challenges like attitude control, both the satellite's morphological architecture and controller play equally important roles in performance optimization. However, despite the extensive study of optimal control, relatively little attention has been placed on making an optimized and practicable assembly plan for a modular satellite within mission-specific constraints. This research gap primarily arises from the inherently complex nature of co-optimizing design and control, a process known for its notorious bi-level optimization loop. Conventionally tackled through artificial evolution, this issue entails optimizing morphology based on the fitness of individual controllers, which is sample inefficient and computationally expensive. In this paper, we introduce a gradient-based approach to the co-optimization of morphology and behavior for modular satellites, aiming to maximize their performance and efficiency in attitude control missions. Specifically, to parameterize the 3D modular design space, we propose utilizing a scalable 3D Neural Cellular Automata (NCA) as the design policy. This NCA encodes local update rules in a Multilayer Perceptron (MLP) neural network, generating different developmental outcomes while using a smaller set of trainable parameters, enabling gradient-based optimization and design pattern regeneration. For control optimization, we focus on a reaction-wheel-based attitude control system, modeled using a Long Short-Term Memory (LSTM) neural network to improve the generalization ability through the integration of memory-reliant internal states. We formulate the design and control processes into a unified Markov Decision Process (MDP), facilitating the exploration of a vast design space. To achieve the concurrent training of both policies, aligned with the mission requirements and environmental conditions, we employ Proximal Policy Optimization (PPO) reinforcement learning with safety constraints. Monte Carlo simulations demonstrate that our co-optimization method not only generates modular satellites with better mission performance compared to those designed by evolution-based approaches and human experts but also offers the potential for autonomous repair in cases of partial damage.