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Innovative Control Paradigms For Space Vehicles: A Comprehensive Review And Future Prospects

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Abstract : Control systems are the cornerstone of space vehicle operations, ensuring stability, precision, and adaptability in challenging and dynamic environments. Despite the success of classical and adaptive control systems in traditional missions, emerging challenges such as nonlinear dynamics, multi-agent coordination, and scalability demand innovative solutions. This paper provides an in-depth review of current control strategies, including classical control, adaptive mechanisms, and artificial intelligence-based systems. It identifies their limitations in addressing scalability, uncertainty, and computational constraints. To bridge these gaps, three distinct paradigms are proposed: (1) a hybrid neural-adaptive control framework combining real-time reinforcement learning with classical adaptive techniques to improve disturbance rejection and trajectory precision, (2) dynamic morphing surfaces using shape-memory alloys to enhance thermal and aerodynamic performance during re-entry, and (3) decentralized swarm intelligence for satellite constellations using distributed reinforcement learning and low-bandwidth communication for collision avoidance. The proposed methods are validated through simulations, demonstrating significant improvements in performance metrics. The hybrid control framework reduces fuel consumption by 15% and enhances trajectory accuracy. Morphing surfaces reduce peak thermal loads during re-entry by 25%. The swarm intelligence system achieves collision-free operations under partial communication failures. This paper concludes with a discussion on implementation challenges, including computational constraints, integration with existing systems, and validation in real-world missions, providing a pathway for the next generation of space exploration technologies.

Keywords : space vehicles, adaptive control, neural networks, swarm intelligence, dynamic morphing surfaces, reinforcement learning, control systems
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