Algorithm-Driven Design and Optimization of Reusable SMA Origami Honeycomb Structures for Heavy Space Robotics

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Abstract

To address the stringent requirements for multiple landing and docking buffers in heavy space robotics, this study aims to develop a reusable energy-absorbing metamaterial by integrating Miura-origami patterns into Shape Memory Alloy (SMA) honeycombs. The methodology employs a highly interdisciplinary approach combining structural mechanics with advanced aerospace robotics algorithms. Physically, the origami creases are strategically designed to induce plastic hinges and control structural deformation, thereby preventing the SMA from exceeding its recovery limits. Computationally, an integrated algorithmic framework was developed to evaluate and optimize the landing processes. This includes a machine learning-based mathematical model to accurately capture the metamaterial's nonlinear reusable energy absorption, a dimensionless prediction formula derived via dimensional analysis for rapid performance forecasting, and a specialized optimization design algorithm tailored to space robotic mission profiles. Key findings demonstrate extraordinary mechanical enhancements: the reusable plateau stress in the in-plane direction increased by up to four times, and the out-of-plane reusable specific energy absorption (SEA) improved by up to nine times. Furthermore, the optimization algorithm successfully automated the extraction of key performance indicators. The significance of this research lies in bridging structural hardware with robotic software evaluation. By providing an algorithm-driven, predictive, and scalable design workflow, this study delivers a practical framework for engineering resilient, reusable buffering systems in future aerospace robotics.

Keywords

Heavy Space Robotics, Machine Learning, Optimization Algorithm, Reusable Energy Absorbing, Origami Metamaterial, Shape Memory Alloy (SMA), Dimensional Analysis.