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VIBRATION-ENABLED ORIGAMI PROBOSCIS FOR PARTICULATE TRANSPORT IN SPACE ENVIRONMENTS

Abstract

The transport of lunar regolith, granular media, and fluidic matter in extraterrestrial environments is hindered by the combined effects of microgravity, vacuum conditions, electrostatic interactions, and particle dispersion. Traditional methods relying on mechanical augers, pneumatics, or fluid pumps face challenges in these extreme conditions, including inefficient particle flow, clogging, and excessive power consumption, in addition to dispersion of dust above the surface causing wear and tear to any operating objects as seen in the Apollo missions. However, the in-situ resource extraction and utilization of regolith is inevitable, making a cost-effective scalable solution needed now more than ever.

This work covers the design and development of a bio-inspired, telescopic, vibration-driven origami proboscis, leveraging piezoelectric ionogels, thermal control fabrics, and flexible composite structures to enable controlled particle transport with minimal power input. The system consists of a Kevlar fabric tube embedded with piezoelectric ionogel actuators, forming an adaptive origami structure capable of peristaltic-like motion through localized vibrations. This mechanism offers a gravity-agnostic particle transport solution suitable for lunar In-Situ Resource Utilization), asteroid mining, and microgravity sample collection. The origami-based collapsible design ensures compact stowage and scalable deployment, while integrated thermal control fabrics and composites aid in passive dust mitigation, thermal and electrical insulation and resisting abrasion.

Analytical calculations for the unit pattern and tube sections are performed on MATLAB after a detailed trade-off of folds like the Kresling and Yoshimura patterns for this application. The design is then CAD modelled and simulated to tune the design for optimum mechanical, particle flow and thermal performance on Earth and Lunar gravity, atmosphere and thermal considerations. Possibilities to analyze particle dynamics, electrostatic charging effects, and wave propagation efficiency are also explored to a limited extent. The optimized actuation frequency, geometry and dimensions is cross-validated for material response and structural stability for effective transport. A functional prototype is fabricated using 3D-printed origami scaffolds, flexible composites, and ionogel filling, validated functionally using regolith simulant and ready for in-orbit validation.

This study introduces a scalable, low-power, and dust-tolerant transport mechanism tailored for in-situ planetary resource extraction, extraterrestrial construction, and space-based industrial applications. Future developments will focus on adaptive frequency control, integration to robotic systems and tools and energy harvesting integration, advancing the viability of soft robotic excavation and transport systems for planetary exploration.