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Author: Mr. Christian Bellinazzi
Politecnico di Torino, Italy

Mr. Catello Leonardo Matonti
Politecnico di Torino, Italy

Ms. Marina Coco
Politecnico di Torino, Italy

Prof. Marcello Romano
Technical University of Munich (TUM), Germany

Dr. Chantal Cappelletti
University of Nottingham, United Kingdom

DESIGN, PROTOTYPING AND VALIDATION OF A SOLAR-SAIL DEPLOYMENT MECHANISM
FOR PLANETARY SUNSHADE PRECURSOR MISSIONS

Abstract

Design methodologies for Solar-Sail Deployment Mechanisms (SSDMs) remain poorly documented in literature, due to limited public disclosure and industrial confidentiality policies. This work addresses this gap by presenting a novel mechanism for Solar-Sail Satellites (SSSs) based on a counterclockwise, out-of-plane radial boom deployment technique. Specifically, this study experiments a scalable architecture incorporating a dedicated origami-inspired sail folding configuration.

This prototype supports the development of Planetary Sunshade infrastructures, a space-based solar geoengineering concept aimed to mitigate climate change on Earth, operating near the photo-gravitational L_1 equilibrium region. The mission scenario is defined within the Sun-Earth-Moon system, targeting insertion in proximity to this point. Due to its inherently perturbed dynamical environment, precursor missions are essential to demonstrate deployment reliability, to validate mission maneuvers, to assess long-term orbital degradation and to reduce technological risks prior to full-scale implementation. Following these design drivers, the precursor SSS is conceived for a 3U CubeSat platform, with sizing derived from trade-off analysis against comparable heritage missions.

The SSS features a 24.2 m^2 four-quadrant sail divided into triangular sectors, deployed by spiral-wrapped tape-springs of 3.48 m in length. The deployment technique exhibits a cutting locking system between booms and central hub through feather-keys, coupled to a rotating motor shaft for ensure reliable torque transmission. Moreover, structural components' design, material selection, and compact electrical actuation complete the discussion. The prototype incorporates geometrically-scaled sail sectors with a 1:3.48 factor, facilitating subsystem accessibility and inspections. The 3U platform is selected for its cost-effectiveness and rapid in-orbit development. The mechanism allocation complies with typical constraints of 3U CubeSats, requiring a volume of approximately 1.4U and total mass of 1.55 Kg.

To assess dynamical performance, a coupled numerical model evaluates both sail and boom strains over time. Sail structural response is modeled using classical Laminated Plate, whereas booms by Timoshenko beam, finally including time-dependent von Karmàn geometric non-linearities. The analysis examines the first three natural mode shapes with corresponding frequencies.

Results demonstrate limited transverse modal coupling and a predominantly directional structural response with respect to the SSS main axis triad. The absence of frequency overlap between mechanism,

sail and boom modes mitigates resonance risks, validating the SSDM robustness, feasibility and scalability for the imagined operational scenario.