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Harnessing Multimodal Multistability for Next-Generation Soft Robotic Arms

Benyamin Shahryari[1], Hossein Mofatteh[1], Arian Sargazi[1], Armin Mirabolghasemi[1], David Meger[2], Alex Kalamkarov[3], Abdolhamid Akbarzadeh [1,4*]
[1] Department of Bioresource Engineering, McGill University, Montreal, Canada
[2] School of Computer Science, McGill University, Montreal, Canada
[3] Department of Mechanical Engineering, Dalhousie University, Halifax, Canada
[4] Department of Mechanical Engineering, McGill University, Montreal, Canada
hamid.akbarzadeh@mcgill.ca

ABSTRACT

Inflatable multistable materials have emerged as a transformative platform in the development of shape-preserving soft robotic arms, offering enhanced adaptability, energy efficiency, and safety. However, existing designs typically exhibit monomodal multistability, such as extension or extension-induced bending, thereby limiting their potential applications. Addressing this limitation, we introduce a novel platform that harnesses *multimodal multistability* through geometric frustration, enabling stable configurations in both tension and bending. Our approach utilizes a cylindrical unit cell with rotational symmetry, originally designed for extension bistability. By integrating a pneumatic actuator with multiple degrees of freedom (multi-DOF), the system achieves frustrated multistable states in bending, significantly expanding the range of stable deformation trajectories. The proposed design supports programmable and reversible shape changes, load-bearing capability, and precision local deformation control using a global pneumatic system. This study demonstrates that the multimodal multistable metastructures can achieve stable configurations across both pure extension and bending modes, facilitating previously unexplored deformation pathways in mechanical metastructures. The fabrication of a 3D-printed soft robotic arm using thermoplastic polyurethane (TPU) material showcases its practical applications. The arm, weighing only 20 grams, exhibits impressive load-bearing capacities, bearing weights between 250 grams and 1000 grams without external pressure once a stable configuration is attained. The pneumatic setup, comprised of four linear actuators, allows for an independent control of deformation, ensuring programmability and adaptability of shape changes. This innovative multimodal multistable platform offers unprecedented potentials for soft robots with applications spanning from aerospace and medical instruments to underwater exploration and emergency response.