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Bi-stable Meta-Rod Structures with Designable Shape Transformation for Medical Robots

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ABSTRACT

From large space antennas to medical balloon catheters, we rely on the deployability of rod-shaped structures. Deployable rod structures enable designs that can be compactly assembled into a cylindrical form for transport and then rapidly deployed to achieve the desired shape transformation. For example, in robotic-assisted surgeries, concentric tube continuum robots are designed to provide precise shape transformations, which make it possible to perform intricate maneuvers and complex procedures with greater accuracy. However, the deformations achieved by currently used compliant mechanisms are highly susceptible to environmental disturbances, particularly in fluid-filled confined spaces. To attain and maintain a desired shape requires a triggering mechanism, which occupies valuable space, and a constant applied force, which consumes extra energy. Current rod concepts in literature are thus less suitable for complex missions, such as motions in medical soft robots.

Recent efforts have produced bi-stable meta-structures with morphing functionalities by mimicking the snap-through mechanism of the Venus Flytrap in nature. This work presents a new class of bi-stable metastructures named “Meta-Rod”. Meta-Rod structures can transform their shapes from a rod-shaped stable stage to a desired deployed stable stage, realizing linear, bending, twisting, radial, volumetric changes, or combinations of them. The desired deformation can be programmed into the layout of the bi-stable structures. Designing distinct deformation modes, such as translation and twisting, can be achieved by studying the relationships between building block symmetry and achievable deformations. The developed bi-stable can maintain precisely programmed motion and deployment at the second stable stage, thus freeing the space and energy required for shape locking.

Via a combination of numerical simulations and mechanical experiments, this study developed prototypes that demonstrated effective deformation in a range of shape reconfigurations. The proposed Meta-Rod can achieve 57.2% of linear deformation, 45° of bending, and 18° of twisting. An umbrella-shaped areal model and a balloon-like volumetric structure were developed and evaluated, with the deformation stabilized by a locking mechanism. By evaluating these combinations in both static and dynamic environments, including a left ventricle duplicator that replicated physiological conditions, the designs' stability and adaptability were further validated. The outcomes demonstrate how Meta-Rod can take the place of conventional systems in applications that call for accurate and stable deformations, offering scalable and energy-efficient solutions. With future efforts focused on improving manufacturability, durability, and application-specific designs, this study establishes the foundation for developments in biomedical engineering, soft robotics, and deployable systems.