# From Cylinders to Complex Shapes: Nematic Multi-Stable Shape-Morphing Cylindrical Actuators

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Shape-morphing actuators and structures are central to soft robotics [1], [2], [3] and deployable structures [4], [5]. These systems are often subject to severe geometric constraints, imposed, for example, by the limited diameter of payload fairings in space applications [6], [7], [8] or by surrounding biological tissue in medical settings [1], [2], [3]. Consequently, cylindrical shape-morphing structures have attracted significant attention. Existing approaches include kirigami-based inflatables [9], [10], hinged flexible lattices [11], shape-memory polymers [12], and three-dimensional curved wire metamaterials [13]. However, achieving large, programmable, and complex shape changes that remain stable without continuous force input remains challenging.

A powerful paradigm for programmable shape morphing is nematic design, which exploits locally anisotropic stretches to produce prescribed global geometries [14]. To date, this approach has been limited to initially flat structures. Separately, structural multi-stability has been used to enable deployed configurations that persist without sustained actuation [15], [16], [17]. A prior study combined nematic design with multi-stability [18], but relied on assembling multiple rigid components, complicating fabrication and miniaturization.

Here, we introduce *cylindrical multi-stable nematic metamaterial actuators*, algorithmically designed from compliant bi-stable elements to morph an initially cylindrical constant-thickness shell cutout into prescribed geometries. The proposed architecture enables rapid, single-part fabrication via 3D printing or laser cutting, without assembly. Numerical simulations and preliminary experiments demonstrate the diversity of achievable shapes and the practicality of the approach, enabling new capabilities for soft robotics and deployable structures.

## NEMATIC CYLINDERS

Nematic shape-morphing designs are based on prescribing locally anisotropic surface stretches, which collectively induce global curvature changes. At each surface point, a director $\hat{n}$ defines the direction of maximal stretch $\lambda$, while the perpendicular stretch is assumed negligible. The local stretch tensor is therefore written as

$$\mathbf{U} = \mathbf{I} + (\lambda - 1)\, \hat{n} \cdot \hat{n}^T, \tag{1}$$

where $\mathbf{I}$ is the $2 \times 2$ identity matrix. The stretch tensor is used to compute the metric tensor $\mathbf{g}$, which governs changes in lengths and angles of surface tangent vectors:

$$\mathbf{g}\,(h, \theta) = \mathbf{J}\mathbf{U}\mathbf{U}^T\mathbf{J}^T, \quad \mathbf{J} = \begin{bmatrix} 1 & 0 \\ 0 & r \end{bmatrix}, \tag{2}$$

where $\mathbf{J}$ is the Jacobian, $h$ and $\theta$ parameterize height and angle, and $r$ is the radius of the undeformed cylinder.

For axisymmetric stretch fields, $\mathbf{g}(h, \theta) = \mathbf{g}(h)$, and the deformed surfaces are surfaces of revolution characterized by their deformed radius $R(H)$ and height $H$. Given the director field $\hat{n}(h)$ and stretch magnitude $\lambda$, the metric tensor defines a mapping between the undeformed cylinder and the morphed surface, allowing computation of $R(h)$ and $H(h)$.

Designing a structure to achieve a desired target geometry requires inverting this mapping. By prescribing $R(H)$, the director angle $\alpha\,(h) = \arccos\left(\hat{n} \cdot \hat{h}\right)$ can be computed. For axisymmetric surfaces, this reduces to solving (3)–(4):

$$\frac{\mathrm{d}\alpha}{\mathrm{d}h} = \frac{R\,(H)}{\Lambda r^2 \cos(\alpha)\sqrt{\frac{1}{\Lambda}\left(\left(\frac{R(H)}{r}\right)^2 - 1\right)}} \frac{\mathrm{d}R}{\mathrm{d}H}\frac{\mathrm{d}H}{\mathrm{d}h} \tag{3}$$

$$\frac{\mathrm{d}H}{\mathrm{d}h} = \frac{-B\,(H) + \sqrt{B\,(H)^2 - 4A\,(H)\,C\,(H)}}{2A\,(H)}, \tag{4}$$

where $\Lambda = \lambda^2 - 1$, and $A(H)$, $B(H)$, and $C(H)$ are functions of $\lambda$, $R(H)$, and $\mathrm{d}R/\mathrm{d}H$. A feasible solution exists when $R(H)$ is differentiable and satisfies $r \leq R(H) \leq \lambda r$. Fig. 1a presents inverse-design examples for several target geometries with $\lambda = 3$ (i-iv) and $\lambda = 5$ (v).

## MULTI-STABLE COMPLIANT DESIGN

Nematic theory assumes a continuum in which every surface point follows the prescribed stretch tensor. To realize mechanically multi-stable metamaterials, the surface must be discretized. One approach assembles multi-stable straw-like tubes connected by rigid links [18]. While effective, such assemblies are difficult to miniaturize and mass-produce. Here, we instead employ a single-part design composed of compliant bi-stable mechanisms, which have been shown to be highly miniaturizable [19]. The resulting architecture exhibits no variation in the radial direction, enabling fabrication via both 3D printing and laser cutting.

Bi-stable elements are connected in series to approximate the integral curves of the director field (Fig. 1b). Elements are placed sequentially, oriented tangentially to the curve and positioned as close as possible to prior elements without

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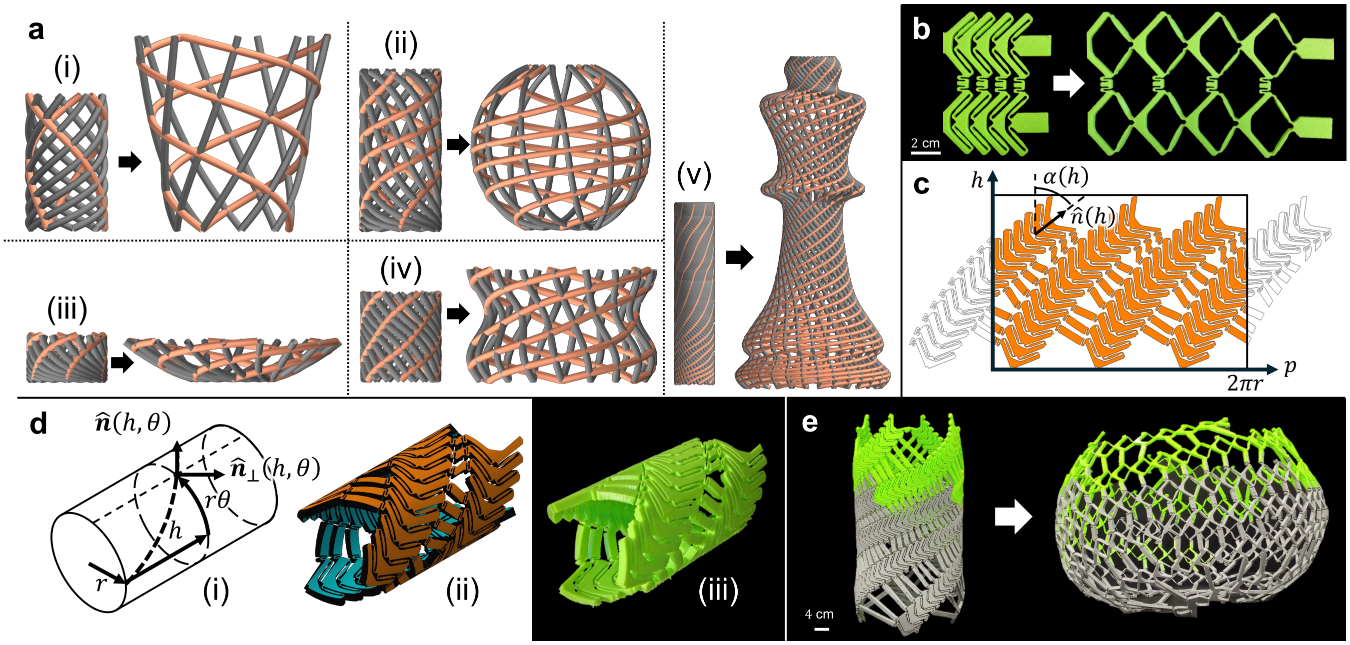

Fig. 1. Multi-stable nematic cylindrical actuators: (a) Inverse-designed director curves (pink) and fixed-length normal curves (gray) morph cylindrical surfaces into, e.g., (i) cone, (ii) sphere, (iii) parabolic, and (iv) sinusoidal surfaces, (v) chess queen. (b) Design of bi-stable element chains with perpendicular connections for anisotropic stretch. (c) Unwrapped layout approximating director curves using bi-stable elements. (d) 3D design process: (i) director curves wrapped onto a cylinder surface, (ii) wrapped multi-stable layout, (iii) 3D-printed structure. (e) Deployment of an actuator into a stable convex surface.

overlap. The resulting chain is replicated uniformly around the circumference. The algorithm then identifies pairs of elements from adjacent chains that lie approximately along common normal curves and connects them to constrain deformation in the normal direction (Fig. 1c). Both elements and connections are designed to allow out-of-plane bending, enabling curvature changes.

Once the planar layout is generated, it is wrapped onto a cylindrical surface. A curve in the plane, parameterized by $t$, is mapped onto a cylinder of radius $r$ via

$$[p\left(t\right), h\left(t\right)] \rightarrow \left[r\cos\left(\frac{p\left(t\right)}{r}\right), r\sin\left(\frac{p\left(t\right)}{r}\right), h\left(t\right)\right]. \quad (5)$$

To form a solid structure, the wrapped pattern is extruded radially to a second cylindrical surface of radius $r_2$. Each planar curve is projected accordingly, and the surfaces connecting corresponding curves form ruled surfaces. Fig. 1d shows a representative 3D-printed prototype.

For a more rapid manufacturing process, flat layouts can be manufactured before wrapping the design on a cylindrical surface. End points of the planar cutouts are then connected to create approximate cylindrical bodies. This methodology may additionally enable significant miniaturization by using micro manufacturing techniques such as photolithography.

## PRELIMINARY EXPERIMENTAL RESULTS

Experimental prototypes of individual bi-stable elements and full cylindrical actuators were fabricated using a Bambu Lab X1 Carbon printer with TPU for AMS material. The bi-stable elements featured a 45° angle between flexures and a flexure length of 20 mm. A cylindrical actuator designed to deploy into a truncated sphere was manufactured. The undeformed cylinder had radius $r = 100$ mm and was designed for a stretch factor $\lambda = 3$. Fig. 1e shows the closed and deployed configurations. The deployed structure exhibits the prescribed radial variation with height.

We observe that wrapping bi-stable elements onto cylindrical surfaces can significantly alter their force-displacement behavior, in a manner that depends on the director angle. This effect becomes more pronounced when the ratio of element size to the surface radius of curvature increases. The chosen geometric parameters account for this behavior and provide a practical baseline for future implementations. Additionally, when flat layouts are manufactured and then wrapped onto cylinders, this phenomenon is significantly diminished.

## CONCLUSIONS

We present a practical, algorithmic design methodology for initially cylindrical, multi-stable, shape-morphing actuators based on nematic design principles and compliant bi-stable mechanisms. The approach enables single-part fabrication, avoids assembly, and supports rapid prototyping. Numerical results demonstrate the ability to design a wide range of target geometries, and preliminary experiments validate the feasibility of the method.

Future work will explore additional target shapes, alternative fabrication techniques, actuation strategies, and non-axisymmetric designs. We anticipate that this framework will enable previously unattainable capabilities across applications ranging from soft robotics and medical devices to deployable space structures.

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