

Foldable Body, Unfolded Capability: Structural Properties and Functional Applications of a Novel Yoshimura Origami Tubular Robot

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Abstract. The Yoshimura origami tubular robot offers high deformability and a large fold-to-span ratio, making it promising for confined-space applications such as disaster rescue. However, its practical extension ratio is often much lower than the theoretical limit due to internal constraints, such as facet interference and node stress concentration, rather than the negative Poisson's ratio itself. In this study, we systematically investigated the effects of material thickness, aspect ratio, cross-sectional shape, and structural modifications (facet optimization and node refinement) on the compression and bending performance of paper-based Yoshimura origami robots. A geometric constraint model was established to derive feasible polygonal configurations, and theoretical models for the fold-to-span ratio, bending angle, and tendon-driven shape estimation were developed. Experiments on prototypes made from four types of paper showed that material thickness dominates compression height, an aspect ratio above 1.2 is favorable, and quadrilateral/hexagonal cross-sections outperform octagonal ones. The proposed structural modifications improved the fold-to-span ratio by up to 32.2% and the maximum bending angle by 29% (reaching 92° under SMA actuation), with good agreement between predicted and measured bending angles. Two functional prototypes were demonstrated: a decimeter-scale SMA-driven robot with an onboard camera successfully navigated a simulated rubble environment, and a centimeter-scale magnetically driven robot achieved wireless crawling and pinching. These findings provide design guidelines and validate the potential of Yoshimura origami robots for confined-space exploration, search-and-rescue, and future medical applications.

Keywords: Yoshimura origami, paper-based tubular robot, fold-to-span ratio, structural optimization, confined space exploration

1. Introduction

Compared with rigid-link robots, continuum robots offer greater flexibility in confined spaces due to their multiple degrees of freedom, yet their limited axial extensibility often restricts workspace and adaptability [1–4]. Yoshimura origami, characterized by reconfigurability [5], a negative Poisson's ratio [6], and a high fold-to-span ratio [7], provides a promising solution. Through modifications in fold arrangement [8], structural design [9], and materials [10, 11], Yoshimura-inspired origami

structures have been widely applied in deployable systems [12], grippers [13], actuators [14], bionic devices [15], and continuum robots [16]. However, the actual extension ratio of Yoshimura origami structures is often limited by facet interference and stress concentration at crease nodes, preventing full deployment. This reduces flexibility and adaptability in confined environments, making improvement of the fold-to-span ratio while preserving stability a key challenge.

This study models Yoshimura origami structures using node-edge-facet elements and constraint equations to identify feasible configurations, revealing that limited axial extension arises mainly from internal constraints, such as surface interference and node restrictions, rather than the negative Poisson's ratio. Facet optimization and node refinement are introduced to alleviate these constraints, and experiments examine the effects of paper aspect ratio, material thickness, and cross-sectional shape on fold-to-span ratio and bending performance, identifying an optimal design range. Based on this optimized structure, two prototypes—a decimeter-scale SMA-driven continuum robot with a miniature camera and a centimeter-scale magnetically driven multi-segment crawling robot—are developed and tested in confined environments, providing insights into the structural behavior of Yoshimura origami tubular robots and guiding future designs for constrained spaces.

2. Methodology

2.1. Principle of the Yoshimura origami robot

The proposed Yoshimura origami robot forms a 3D tube from a 2D diamond-faceted sheet (Fig. 1), enabling large axial contraction via folding, not stretching. Under compression, it shortens and expands radially, showing negative Poisson's ratio. Its high fold-to-span ratio results from geometric reconfiguration with minimal strain, and circumferential symmetry ensures stable deformation and reduced buckling—ideal for compliant robotic applications requiring large deformation.

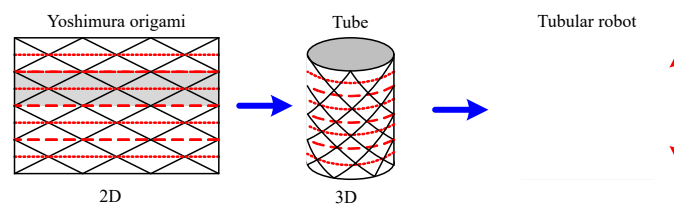


Figure 1. Geometric configuration of Yoshimura origami from 2D crease pattern to 3D tube

2.2. Geometric constraints and feasible configurations

The Yoshimura origami structure was analyzed using two geometric elements (Fig. 2): nodes (intersections of creases controlling local deformation) and creases (valley lines for inward folding, peak lines for outward). Nodes can extend into levels—continuous straight lines of collinear creases aligned circumferentially. Nodes have higher effective degrees of freedom due to multi-crease coupling, while levels have fewer due to constraints. Valley creases drive axial contraction; peak creases drive radial expansion. Their alternation ensures geometric compatibility and prevents torsional instability.

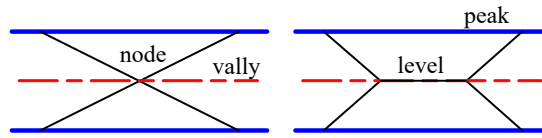


Figure 2. Nodes (junctions), peak (outward/radial), valley (inward/axial)

Based on the above, the configuration of a Yoshimura origami structure can be expressed by:

$$4N_{\text{node}} + 5N_{\text{level}} - P_{\text{side}} - P_{\text{node}} = N_{\text{side}} \quad (1.1)$$

where N_{node} is the number of nodes, N_{level} is the number of horizontal line elements, P_{side} is the number of splicing elements, P_{node} is the number of common nodes, and N_{side} is the number of edges of the convex polygon. These parameters satisfy the following constraints:

$$0 \leq P_{\text{node}} \leq P_{\text{side}}$$

$$2 \leq P_{\text{side}}$$

$$N_{\text{node}} + N_{\text{level}} = P_{\text{side}} \quad (1.2)$$

Table 1. Feasible regular polygonal configurations satisfying the constraints

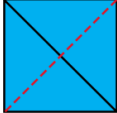
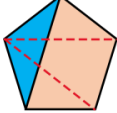
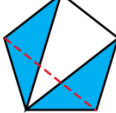
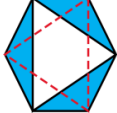
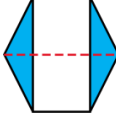
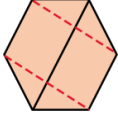
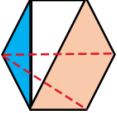
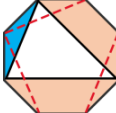
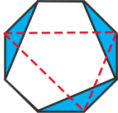
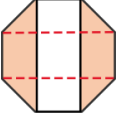
Shape	Scheme	
Regular Quadrilateral		$N_{\text{side}} = 4$ $N_{\text{node}} = 2$ $N_{\text{level}} = 2$
Regular Pentagon	 $N_{\text{side}} = 5$ $N_{\text{node}} = 1$ $N_{\text{level}} = 1$  $N_{\text{side}} = 5$ $N_{\text{node}} = 2$ $N_{\text{level}} = 0$	
Regular Hexagon	 $N_{\text{side}} = 6$ $N_{\text{node}} = 3$ $N_{\text{level}} = 0$  $N_{\text{side}} = 6$ $N_{\text{node}} = 2$ $N_{\text{level}} = 0$  $N_{\text{side}} = 6$ $N_{\text{node}} = 0$ $N_{\text{level}} = 2$  $N_{\text{side}} = 6$ $N_{\text{node}} = 1$ $N_{\text{level}} = 1$	
Regular Octagon	 $N_{\text{side}} = 8$ $N_{\text{node}} = 4$ $N_{\text{level}} = 0$  $N_{\text{side}} = 8$ $N_{\text{node}} = 1$ $N_{\text{level}} = 2$  $N_{\text{side}} = 8$ $N_{\text{node}} = 3$ $N_{\text{level}} = 0$  $N_{\text{side}} = 8$ $N_{\text{node}} = 0$ $N_{\text{level}} = 2$	

Table 1. (continued)

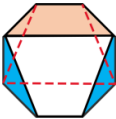
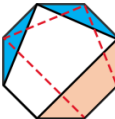
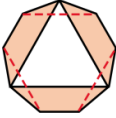
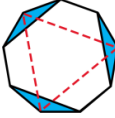
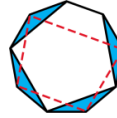
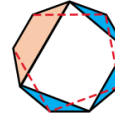
Regular Octagon		$N_{side}=8$ $N_{node}=2$ $N_{level}=1$		$N_{side}=8$ $N_{node}=2$ $N_{level}=1$				
Regular Nonagon		$N_{side}=9$ $N_{node}=0$ $N_{level}=3$		$N_{side}=9$ $N_{node}=3$ $N_{level}=0$		$N_{side}=9$ $N_{node}=4$ $N_{level}=0$		$N_{side}=9$ $N_{node}=3$ $N_{level}=1$

Table 1 lists feasible regular polygons (quadrilateral to nonagon) for kinematic analysis and prototype selection.

2.3. Structural design and optimization

Based on the configurations in Table 1, crease patterns for regular quadrilateral, hexagonal, and octagonal Yoshimura structures were designed (Fig. 3). In the original closed structure, adjacent facets interfere during deformation, generating internal forces that reduce the fold-to-span ratio and may cause non-uniform deformation. To mitigate this, two modifications were introduced: facet optimization and node refinement (Fig. 4). Facet optimization created diamond-shaped openings on facets to break surface continuity, while node refinement removed material near nodes to relieve stress concentration and increase local degrees of freedom. Additionally, the effect of the length-width ratio of the folding unit was investigated. These structural variations were implemented in paper-based prototypes to compare mechanical performance under axial loading and bending, aiming to enhance flexibility without causing instability.

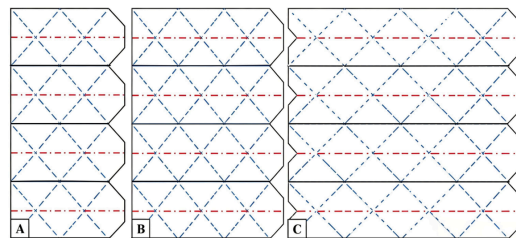


Figure 3. Crease patterns: (A) quadrilateral, (B) hexagonal, (C) octagonal Yoshimura structures

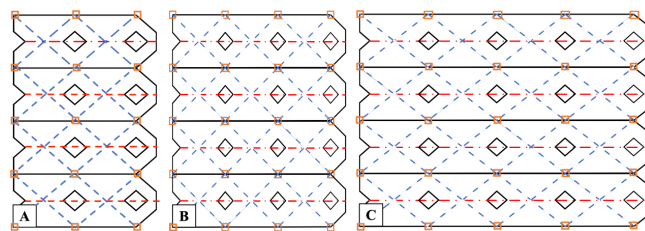


Figure 4. Optimization methods: (A) Diamond cutouts on facets; (B) Node material removal (orange box) to reduce stress and increase local DOFs

2.4. Theoretical modeling

2.4.1. Symbols

The following symbols are used throughout the theoretical modeling: I_C (ideal compressed length, mm), I_E (ideal extended height, mm), N_U (number of folding units), h (half-height of a crease unit, mm), P_T (paper thickness, mm), λ (fold-to-span ratio), θ (bending angle between end planes), l (central axis arc length, mm), r (radius of curvature, mm), l_1, l_2, l_3 (driving wire lengths, mm), l_{avg} (average wire length, mm), b (tube radius, mm), ϕ (twist angle).

2.4.2. Fold-to-span ratio

Assuming negligible compression gaps and fold thickness, the theoretical fold-to-span ratio λ is:

$$\lambda = \frac{I_E}{I_C} = \frac{2N_U h}{4N_U P_T} = \frac{h}{2P_T} \quad (2.1)$$

This ratio depends only on the crease unit height and material thickness, providing a design guideline: increasing h or reducing P_T enhances the extended capability. In practice, the actual ratio is lower due to surface interference, node constraints, and material properties.

2.4.3. Bending angle

The bending angle θ (radians) is defined as the angle between the two end planes under uniform curvature (Fig. 5), where l is the central axis arc length ($\approx$ ideal extended height I_E) and r is the radius of curvature. The ideal bending angle is thus given by:

$$\theta = \frac{l}{r} = \frac{2hN_U}{r} \quad (2.2)$$

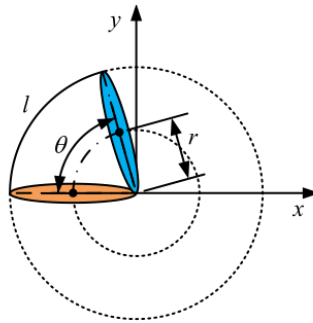


Figure 5. Bending geometry (constant curvature): arc length l , angle θ , radius r . Orange: base plane, blue: end plane

2.4.4. Shape model for tendon-driven robot

For a tendon-driven robot with three wires spaced 120° at radius b , wire lengths l_1, l_2, l_3 . Under constant curvature, The central axis arc length l_{avg} is the average of the three wire lengths. The bending angle θ (rad) is derived from the squared deviations of wire lengths from the average, yielding:

$$\theta = \frac{1}{b} \sqrt{\frac{2}{3} \sum_{i=1}^3 (l_i - l_{avg})^2} \quad (2.3)$$

The direction (twist angle) φ of the bending plane is obtained from the asymmetric part of the length differences:

$$\varphi = \text{atan2}\left(\frac{\sqrt{3}}{2} (l_3 - l_2), \frac{l_2 + l_3 - 2l_1}{2}\right) \quad (2.4)$$

The radius of curvature r of the central axis follows from the arc length:

$$r = \frac{l_{avg}}{\theta} \quad (2.5)$$

Finally, with the robot initially aligned along the z -axis and the bending plane rotated by φ , the coordinates of the end-effector point (Fig. 6) are:

$$\begin{aligned} x &= r(1 - \cos\theta)\cos\varphi \\ y &= r(1 - \cos\theta)\sin\varphi \\ z &= r\sin\theta \end{aligned} \quad (2.6)$$

This model assumes ideal conditions: uniform curvature, no node stiffness, negligible material thickness, and no surface interactions. Nevertheless, it provides a useful kinematic basis for shape estimation and endpoint position prediction in confined environments.

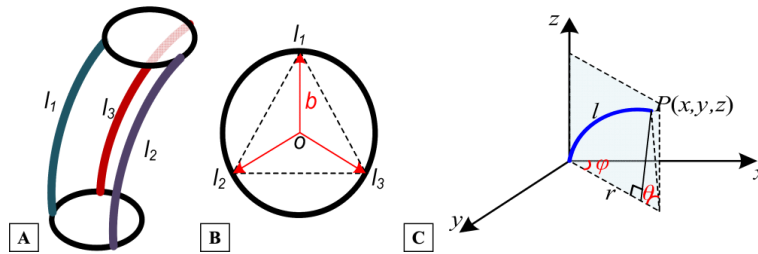


Figure 6. Schematic of the 3D coordinate system and kinematic parameters used for endpoint position prediction

2.5. Fabrication

2.5.1. Paper materials

Yoshimura prototypes were made from four papers to assess stiffness and thickness effects: Japanese Washi (100 g/m², long kozo/gampi/mitsumata fibers, strong and lightweight), standard A4 (80 g/m², uniform and consistent), Japanese Unryu (40 g/m², long kozo fibers, pliable and low-mass), and cardstock (210 g/m², thick and stiff, high load-bearing capacity).

2.5.2. Actuation systems

Two actuation systems were developed: tendon-driven using SMA wires, and magnetically driven. In the tendon-driven system, three SMA wires (0.6 mm diameter, nickel-titanium alloy) were placed

120° apart around the tube, routed through node holes, with a PLA base at the bottom and a miniature camera on top; pulling wires enabled bending, extension, and compression (no heating applied). The magnetic system used permanent magnets at both ends; moving an external magnet produced worm-like crawling. Additionally, two opposite-pole magnets on one end created a pinching motion for simple grasping.

2.5.3. Prototyping process

The fabrication process consisted of three steps. First, the crease patterns were designed in SolidWorks and printed directly onto the selected paper using a standard printer. Second, the printed paper was cut along the outer contour lines with scissors, and each structural unit was folded carefully along the crease lines, paying close attention to symmetry and fold angle accuracy. Third, for the tendon-driven prototype, the folded structure was mounted onto the base, and the SMA wires and miniature camera were installed afterwards (Fig. 7A). For the magnetically driven prototype, small permanent magnets were embedded at both ends of the folded structure (Fig. 7B).

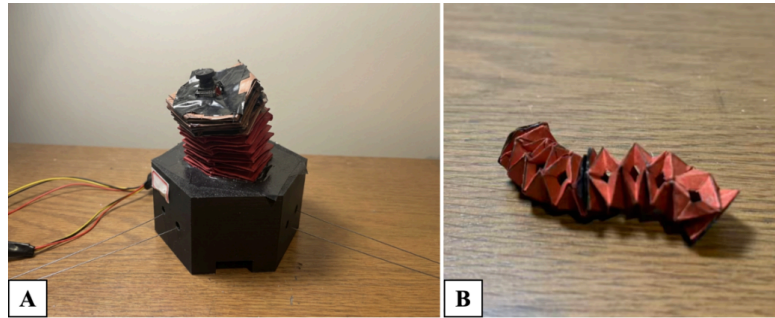


Figure 7. Tendon-driven (A) and magnetically driven (B) Yoshimura origami robot prototypes

3. Results and discussion

3.1. Nomenclature

The following symbols are used in the experimental results: P_L (paper length, mm), P_w (paper width, mm), $aspect\ ratio = P_L / P_w$, H_0 (initial height, mm), H_C (compressed height, mm), H_E (extended height, mm), $\lambda = H_E / H_C$ (fold-to-span ratio), C_{real} (actual compressed height, mm), C_{ideal} (theoretical compressed height, mm), θ_{pre} (predicted bending angle, deg), θ_{real} (measured bending angle, deg), $P_E = (H_E - H_0) / H_0$ (extension percentage), $P_C = (H_0 - H_C) / H_0$ (compression percentage).

3.2. Fundamental tests

3.2.1. Effect of aspect ratio on compression performance

To study the effect of paper *aspect ratio* on compression performance, A4 paper prototypes (0.07 mm thick, four folding units, no modifications) were fabricated with four length/width ratios. Results (Table 2) show that ratios of 1.28 and 1.867 achieved high fold-to-span ratios ($\lambda = 16.10$ and 15.47), while ratios near 1 (0.967) or below 0.7 (0.636) gave very low λ (1.26 and 1.05), indicating that low ratios restrict folding. An *aspect ratio* above 1.2 is favorable. The 1.28 configuration (Origami 03) was selected for subsequent modification studies.

Table 2. Fold-to-span ratio for different aspect ratios (unmodified A4 paper prototypes)

NO.	P_L (mm)	P_w (mm)	Aspect ratio	H_E (mm)	H_C (mm)	λ
Origami 01	140	220	0.636	200	190	1.05
Origami 02	145	150	0.967	132.5	105	1.26
Origami 03	145	113	1.28	80	4.97	16.10
Origami 04	140	75	1.867	65	4.2	15.47

3.2.2. Effect of material thickness on compression height

To investigate the influence of material thickness on compression performance, we fabricated prototypes using four different paper materials: Japanese Washi paper, standard A4 printing paper, Japanese Unryu paper, and cardstock. The design used was the regular hexagonal configuration with an aspect ratio of 1.28 (the same as Origami 03 in the previous section), without node or window modifications, to facilitate comparison. The fabricated prototypes for the four materials are shown in Fig. 8. The experimental results are summarized in Table 3. The theoretical and actual compression heights for the four materials were also compared (Fig. 9).



Figure 8. Four-unit prototypes: A4, Unryu, Washi, cardstock (left to right)

Table 3. Maximum compression height for different paper materials

Paper material	P_L (mm)	P_w (mm)	Thickness (mm)	C_{real} (mm)	C_{ideal} (mm)
A4 paper	145	113	0.07	1.3	1.12
Washi paper	145	113	0.08	1.5	1.28
Unryu paper	145	113	0.1	1.9	1.6
Cardstock	145	113	0.15	2.9	2.4

In Fig. 9, the blue line shows the theoretical minimum compression length (perfectly flush folding), while red points are actual measured maxima. Actual compression exceeds theoretical for all materials, with discrepancy increasing with thickness. A4 paper (0.07 mm) achieved the smallest actual compression (1.3 mm vs. ideal 1.12 mm), followed by Washi (0.08 mm, 1.5 mm), Unryu (0.10 mm, 1.9 mm), and cardstock (0.15 mm, 2.9 mm vs. ideal 2.4 mm). Despite deviations, a clear linear trend indicates thickness dominates compression limits, though fiber structure and stiffness also matter. For confined environments, reducing thickness while maintaining strength enhances compression capability.

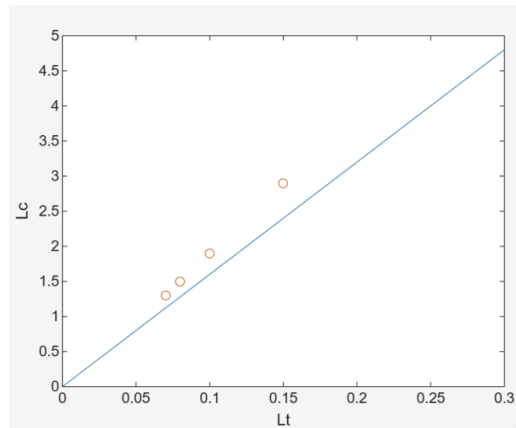


Figure 9. Theoretical vs. actual compression height for different paper materials

3.2.3. Effect of structural modifications on compression performance

Traditional Yoshimura structures suffer from facet interference and stress concentration at nodes. To mitigate these, we explored material removal at facets and nodes (openings $\leq 20\%$ of facet area). While facet optimization (20–30% removal) is known to improve deployability [17], node refinement at crease intersections has not been systematically studied. Thus, we focus on the effects of both facet openings and node refinement on fold-to-span ratio (λ) and bending performance.

Using Unryu paper (0.10 mm, aspect ratio 1.28, 4 units), four modified prototypes were tested (Figs. 10, 11). Relative to baseline Unryu 01, fold-to-span ratios (λ) improved: Unryu 02: 13.03 (+18.0%), Unryu 03: 12.6 (+14.1%), Unryu 04: 14.6 (+32.2%). Thus, facet optimization and node refinement enhance compression performance, with gains depending on modification details. The improvements stem from releasing inter-surface contact constraints and increasing node DOFs, which prevent premature locking seen in the baseline design. Systematic optimization of hole size and distribution remains future work.

Table 4. Fold-to-span ratio of unmodified and modified structure

No.	Aspect ratio	H_0 (mm)	H_E (mm)	H_C (mm)	P_E (%)	P_C (%)	λ
Unryu 01	1.28	22	37	3.35	68.2%	84.8%	11.04
Unryu 02	1.28	23	43	3.30	87.0%	85.7%	13.03
Unryu 03	1.28	23	42	3.33	82.6%	85.6%	12.6
Unryu 04	1.28	24	48	3.28	100%	85.9%	14.6

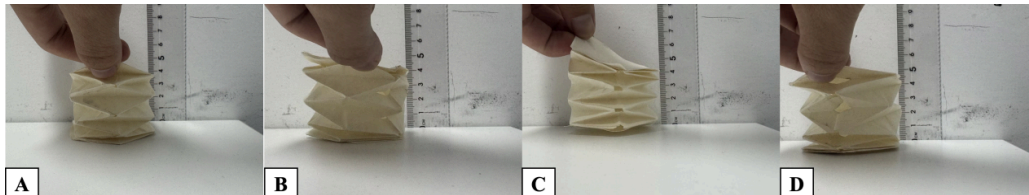


Figure 10. Max extension: (A) unmodified, (B) windows, (C) holes, (D) both

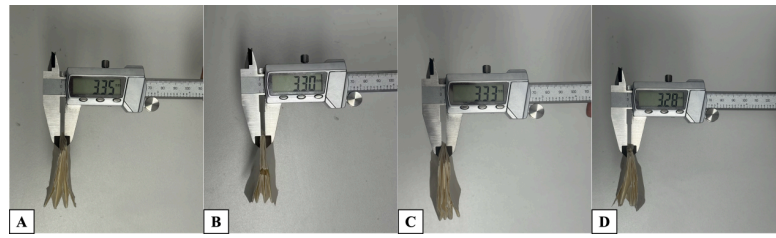


Figure 11. Max compression: (A) unmodified, (B) windows, (C) holes, (D) both

3.2.4. Effect of structural modifications on maximum bending angle

To investigate whether structural modifications can improve bending performance, we fabricated four sets of prototypes using Unryu paper (thickness 0.10 mm) with the same aspect ratio (1.28) and number of folding units (4). The four configurations were: Unmodified (closed surfaces and intact nodes), With windows only (window openings on facets, intact nodes), With holes only (node refinement, closed surfaces), With both (window openings on facets and node refinement) (Fig. 12).

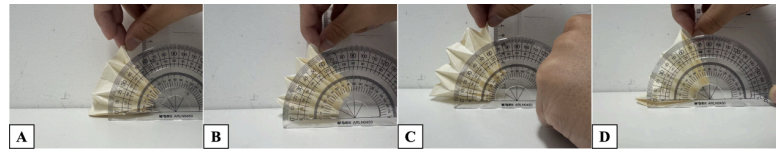


Figure 12. Max bending: (A) unmodified, (B) windows, (C) holes, (D) both

All modified configurations achieved higher maximum bending angles than the unmodified structure (55°). The combined window and node refinement design reached the highest angle (71°, +29%), followed by windows only (65°) and holes only (63°). These improvements stem from reduced surface interference and enhanced local rotational freedom, indicating that modifications beneficial for extension also enhance bending capability.

Table 5. Maximum bending angle for different structural modifications

Configuration	Maximum bending angle (deg)
Unmodified	55
With windows only	65
With holes only	63
With both	71

3.2.5. Comparison of predicted and experimental bending angles

To validate the theoretical bending model, a cardstock prototype with both windows and node refinement was fabricated. Three SMA wires threaded through symmetric nodes (Fig. 13) controlled bending; the base was fixed, and the bending angle measured between the top hexagonal plane and the table. Using the model from Section 2.4.4, predicted and measured angles for three configurations are compared in Table 6 and Fig. 14.

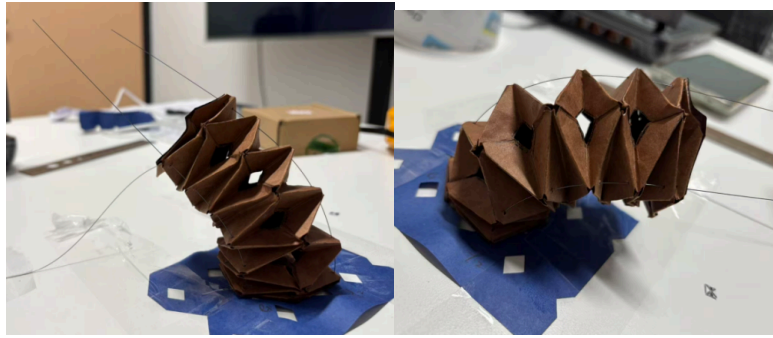


Figure 13. Setup for measuring the bending angle

Table 6. Bending angle measurements (modified structure with windows and holes)

No.	l_1 (mm)	l_2 (mm)	l_3 (mm)	θ_{pre} (deg)	φ (deg)	r (mm)	b (mm)	l_{avg} (mm)	θ_{real} (deg)
1	70	65	28	68.99	53.74	45.12	22	54.33	65
2	104	77	49	82.70	30.60	53.11	22	76.67	90
3	103	43	75	90.28	-32.20	46.75	22	73.67	92

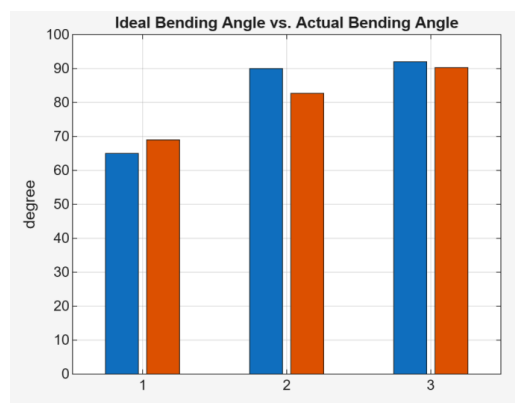


Figure 14. Modified structure: predicted bending angle vs. actual bending angle

Experimental bending angles (65° – 92°) agreed reasonably with theoretical predictions (69° – 90°). Discrepancies arose from asymmetric wire lengths, material stiffness, folding errors, and non-ideal cross-section. The prototype achieved a maximum bending angle of 92° under SMA actuation. Per ASTM E54 standards for response robots, a near- 90° bending capability is highly desirable for confined-space navigation and non-line-of-sight searching. This result demonstrates strong potential, and since bending angle increases with more folding units, the proposed modifications provide a promising foundation for future multi-unit designs.

3.2.6. Effect of cross-sectional shape on compression ratio

To investigate the influence of cross-sectional shape on compression performance, we fabricated Yoshimura origami tubular robots with regular quadrilateral, hexagonal, and octagonal cross-sections, as shown in Fig. 15. All prototypes were made from A4 paper (thickness 0.07 mm) with the same number of folding units.



Figure 15. Prototypes of three different cross-sectional shapes

The experimental results are summarized in Table 7. The results show that the theoretical ideal compression length (calculated using Eq. 2.1) is 1.12 mm for all three cross-sectional shapes, as the paper thickness and number of folding units are identical. However, the actual measured compression lengths differ substantially: the quadrilateral configuration achieved an actual compression length of 1.8 mm, the hexagonal configuration achieved 1.9 mm, while the octagonal configuration achieved only 4.0 mm. Based on these results, the quadrilateral and hexagonal cross-sections are recommended for engineering designs, as they offer superior compression performance compared to the octagonal configuration.

Table 7. Compression performance for different cross-sectional shapes

Shape	P_L (mm)	P_w (mm)	Aspect ratio	C_{ideal} (mm)	C_{real} (mm)
Quadrilateral	58	98	0.592	1.12	1.8
Hexagon	114	98	1.163	1.12	1.9
Octagon	138	98	1.408	1.12	4

3.2.7. Summary of optimal design parameters

Based on experimental results, the following design parameters are recommended for high fold-to-span performance in Yoshimura tubular robots: (1) aspect ratio > 1.2 ; (2) structural modifications (window openings + node refinement); (3) low thickness with high tensile strength (e.g., Unryu for flexibility, cardstock for load-bearing); (4) hexagonal cross-section.

3.3. Case study 1: SMA-driven continuum robot for confined environment exploration

The high-extension origami continuum robot uses a lightweight, compressible paper folding module with remote drive based on geometric and force constraints, resulting in low mass and space occupancy—ideal for unstructured environments. An SMA-driven hexagonal prototype with windows and node refinement was fabricated, and two experiments assessed its mobility and detection capability.

Mobility test in confined passages. A simulated ruined environment (Fig. 16) with narrow gaps was constructed. Using SMA actuation, the robot deformed to enter debris and traverse confined spaces inaccessible to rigid robots. Fig. 16 shows it navigating a narrow crevice, demonstrating its ability to pass through highly constrained environments.



Figure 16. Search-and-rescue test in ruins with origami continuum robot

Visual detection test. A second prototype with a miniature camera (wired through the robot to an external display) was tested in a 3D-printed ruined building model simulating collapsed walls and narrow openings (Fig. 17). The model had two openings: one elevated, one lower. The robot extended to reach the higher opening—inaccessible to a rigid robot of similar size—adjusted its bending angle, and captured clear internal images. It then contracted, reoriented, and entered the lower opening to capture additional images (Fig. 18). Despite confined geometry and low light, the camera provided real-time visuals, demonstrating the robot's potential for search and observation in post-disaster environments.

Based on the above objectives, we hope that this robot can be applied in the future to disaster scene search and rescue, unknown environment detection, space target acquisition, and other fields, such as collapsed buildings in earthquake rescue scenarios and non-cooperative space target capture.

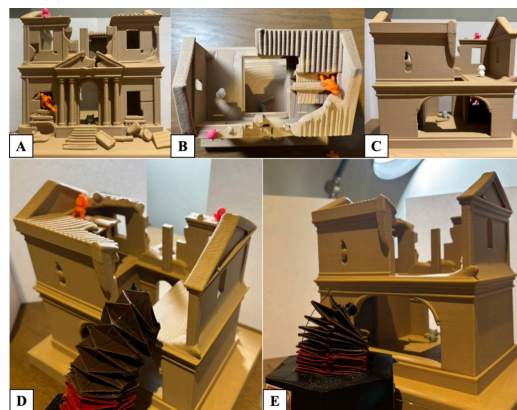


Figure 17. Ruined building model: (A) front, (B) top, (C) rear; robot imaging from (D) upper and (E) lower openings

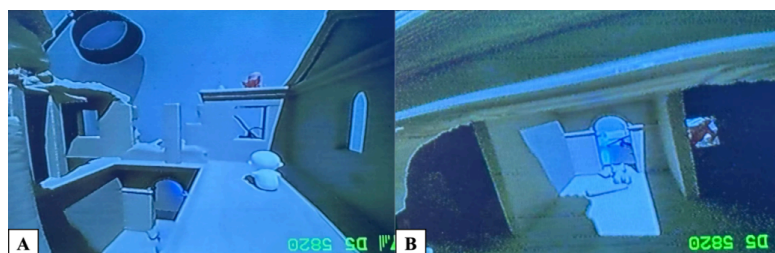


Figure 18. Captured views: (A) upper opening, (B) lower opening

3.4. Case study 2: magnetically driven miniature Yoshimura origami tubular robot

To explore alternative actuation strategies for miniaturized applications, we developed a magnetically driven Yoshimura origami robot. Magnetic actuation offers non-contact, wireless control, making it suitable for scale-constrained environments such as medical applications (e.g., foreign object removal, vascular examination) and confined-space exploration.

A paper prototype with embedded magnets at both ends (opposite poles facing) enables magnetic-field-driven compression and extension for crawling on flat surfaces (Fig. 19A, B); additional magnets at one end allow pinching (Fig. 19C). Inspired by ingestible origami robots, Fig. 20 shows the robot swallowed in compressed state (e.g., inside an ice capsule), which dissolves in the stomach; an external magnetic field then extends the robot (Fig. 20B) to reach and manipulate targets like a button battery or tissue. The magnets could retrieve objects or grasp samples. High foldability, wireless actuation, and compact-to-expanded transition make the Yoshimura robot a promising platform for minimally invasive interventions, including foreign object removal, tissue inspection, drug delivery, and wound repair.

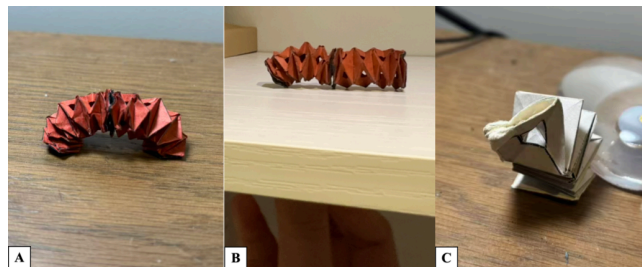


Figure 19. Magnetic robot: (A, B) crawling via bending/extension; (C) end magnets pinching

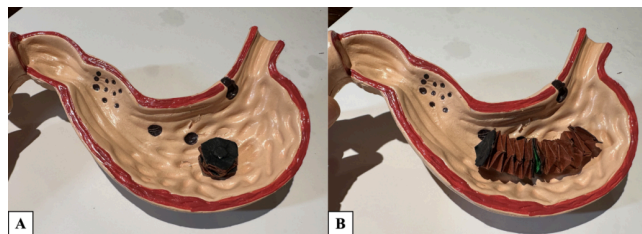


Figure 20. Magnetic robot stomach entry: (A) compressed in esophagus (ice capsule); (B) deployed in stomach

4. Conclusion

This study presents a comprehensive investigation of Yoshimura origami tubular robots, covering geometric modeling, material selection, structural modifications, bending characterization, cross-sectional shape analysis, and application validation. To address limitations of the closed-surface design—namely surface interference and node constraints—a hollow-out modification strategy with facet windows and node holes was explored. Experimental results showed that these modifications improved compression performance (fold-to-span ratio λ increased by up to 32.2%) and bending performance (29% improvement over the unmodified version). Under SMA actuation, the prototype achieved a bending angle of 92° , matching theoretical predictions. Systematic studies showed that an aspect ratio above 1.2 is favorable, material thickness linearly correlates with compressed height (A4 paper achieved 1.3 mm), and quadrilateral/hexagonal cross-sections outperformed octagonal ones (compressed heights: 1.8 mm, 1.9 mm vs. 4.0 mm). Two case studies demonstrated practical

potential: a decimeter-scale SMA-driven robot with a camera navigated a simulated ruin, while a centimeter-scale magnetically driven robot exhibited wireless crawling and grasping, suitable for confined environments.

Future work includes several directions: extending the theoretical model to real-time shape estimation and endpoint prediction for proprioceptive sensing; incorporating physical parameters like axial and bending stiffness; expanding actuation strategies via multi-segment SMA control, hybrid magnetic-thermal actuation, or embedded artificial muscles; and deeper investigation of fiber-based materials, including fiber orientation, anisotropy, and composite reinforcement. Addressing these will advance the design, modeling, and deployment of high-performance Yoshimura tubular robots in real-world applications.

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