Design of an origami-based manipulator for grasping objects with complex geometries

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Abstract

This research explores an innovative approach to manipulator design inspired by the traditional Japanese art of origami, specifically the Miura-ori fold pattern. The proposed algorithm takes the contour of a complex shape as input and generates a corresponding Miura-ori fold design for 3D printing. The resulting 3D-printed manipulator, with rigid nylon layers and flexible TPU hinges, demonstrates the ability to replicate complex shapes through controlled actuation. This study highlights the adaptability of origami-based designs for creating simple yet versatile manipulators with a detachable manipulator system that allows for easy customization to grasp objects with diverse geometries.

In the realm of mechanical manipulators, conventional designs often rely on numerous linkages to achieve specific motions (Meneses Martínez et al., 2015), posing challenges in the design complexity and adaptability of the manipulator. For example, a simple endoscopic end effector can consist of many rotating joints, sliding linkages, and frames to achieve a 2-degree-of-freedom motion (Krishnan and Saggere, 2012). Most traditional manipulators convert a rotational or translational input into a gripping motion via linkages, gear and rack, cam-motion, or ropes and pulleys. The intricate contours of complex shapes further compound these challenges, as complex linkage patterns and a large number of actuators will be required to manoeuvre the gripper to conform to the complex shape (Grebenstein et al., 2011). As a result, there is an interest in developing a simple manipulator that can grasp objects with complex shapes.

Origami, the traditional Japanese art of paper folding, provides a rich source of inspiration for innovative solutions in manipulator designs. Several origami-based and origami-inspired manipulators have been previously studied, ranging from pneumatically actuated reconfigurable grippers using origami waterbomb folds (Robertson et al., 2021) to soft end-effectors using origami-folds and tendon actuators (Kan et al., 2019). While the focus of the research has been on creating a general compliant manipulator, little research has been done on a manipulator design that can specifically conform to the contour of an object with complex geometry. A particularly well-recognized fold pattern with great potential as a mechanical manipulator is the Miura-ori, shown in Fig. 1 first proposed in 1980 by Miura (Miura and Lang, 2009). For a given fold pattern defined by fold angle α and actuation angle θ, the output angle γ can be expressed as a function of the inputs α and θ where $k = 1$ for $\theta > 0$ and $k = -1$ for $\theta < 0$ (Equation (1)) (Kamrava et al., 2017). Figure 1 shows the variation of γ as a function of actuation angle θ for different values of fold angle α. For a constant actuation angle θ, increasing the fold angle α towards 90° leads to an increase in the absolute value of the output angle γ.

$$\gamma = 2k \cos^{-1}\left(\frac{\cos\alpha}{\sqrt{1 - cos^2\theta \sin^2\alpha}}\right) \tag{1}$$

Conversely, given a particular output angle γ and actuation angle θ, the fold angle required α can be back-calculated using Equation (2).

$$\alpha = \sin^{-1}\left(\sqrt{\frac{\cos^2\frac{\gamma}{2k} - 1}{\cos^2\theta\cos^2\frac{\gamma}{2k} - 1}}\right) \tag{2}$$

The advantage of a Miura-ori fold pattern is its single degree of freedom over multiple hinges: when two of the modules are connected in series with an aligned central path, they exhibit the same actuation angle θ, but the sign is reversed from one module to the next. This allows multiple Miura-ori modules with different fold angles α to be placed in series such that a corresponding set of output angles γ can be generated for a given actuation angle θ (Kamrava et al., 2018).

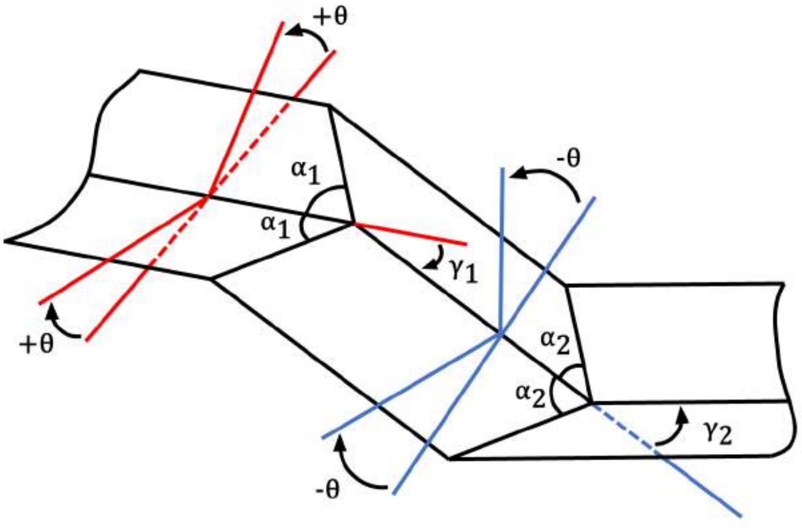

Figure 1: Two Miura-ori modules connected together. The actuation angle θ is reversed from one module to the next. The output angle γ is dependent on the fold angle α for each module

With this insight, a Miura-ori-based fold pattern can be designed using a series of unique fold angles α such that when all the modules are actuated to a specific actuation angle θ, the series of output angles γ produced by the Miura-ori fold pattern conforms to the vertex angles of a desired complex shape. Henceforth, a rigid version of the fold pattern with flexible hinges as folds can be fabricated to create a mechanical manipulator capable of replicating the desired complex shape.

This research proposes an algorithmic approach for the design and fabrication of manipulators based on the principles of Miura-Ori origami. The algorithm takes in the contour of a complex shape as its input and generates the corresponding Miura-Ori fold design to achieve the input shape. The Miura-Ori fold pattern can subsequently be designed into a thick manipulator and 3-D printed. A summary of the approach of this paper can be seen in Fig. 2.

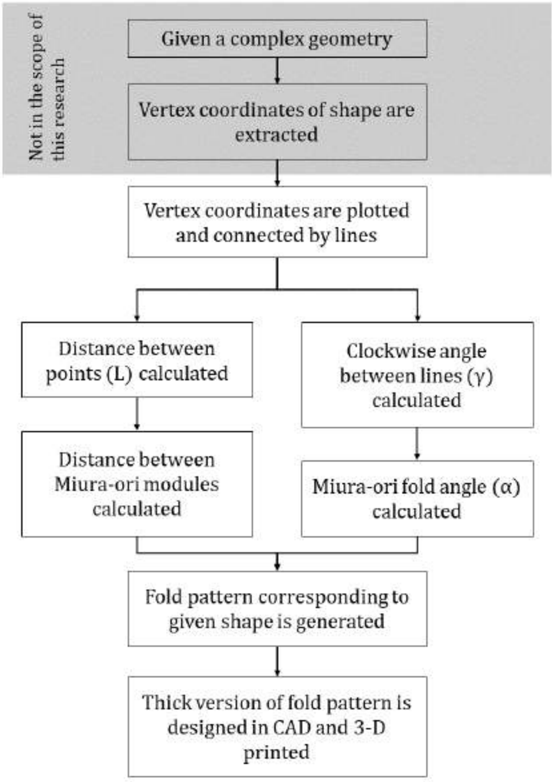

Figure 2: Flowchart summarizing the algorithmic approach of this paper in designing a Miura-Ori-based origami manipulator

Firstly, the vertex coordinates (x, y) corresponding to the desired complex geometry were input into the algorithm. As there exist algorithms capable of extracting the vertex coordinates given an image of a complex shape, this research does not focus on how the vertex coordinates were obtained. With the vertex coordinates, the algorithm plots the points, joining adjacent vertices with lines (Fig. 3).

Next, the distance L_i between two adjacent points was calculated. The clockwise angle γ_i between two adjacent line segments was calculated using a combination of the dot product and cross product of the two line vectors. Using the values of γ_i calculated, the corresponding Miura-ori fold angles α_i were back-calculated using Equation (2), taking note that the actuation angle θ alternates between θ and $-\theta$ for every fold. Each Miura-ori fold was also positioned a distance L_i away from the previous fold. The algorithm automatically generates a drawing of a fold pattern with the corresponding L_i and α_i values for a chosen θ (Fig. 4). The fold pattern generated from the algorithm was printed out and folded, which resembled the complex shape input into the algorithm (Fig. 5).

With an array of L_i and α_i values, the fold pattern can be translated to a 3-dimensional model via Computer Aided Design (CAD) software. Several thick Miura-ori designs were

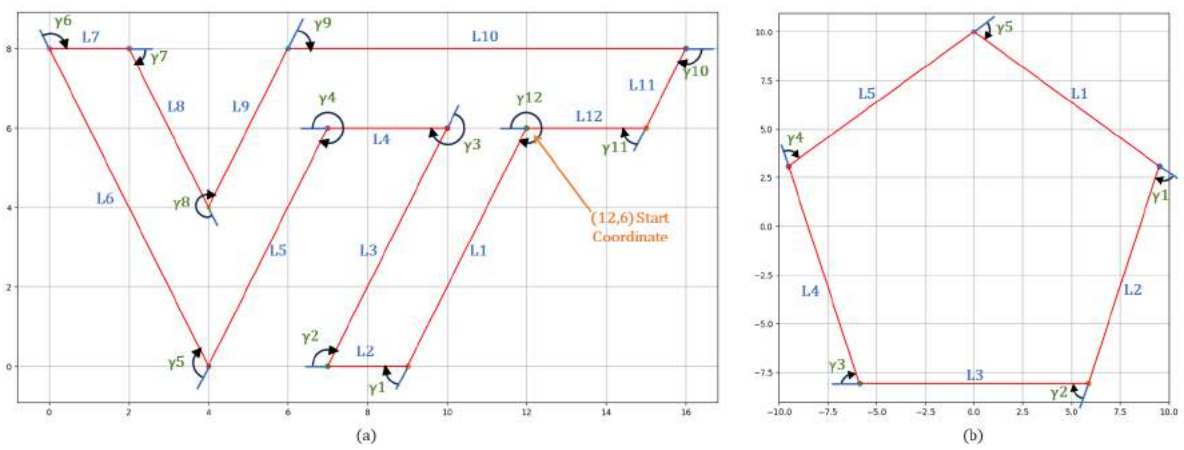

Figure 3: (a) Complex shape with 12 line segments and angles labelled with corresponding length L_i and clockwise angle α_i where $i = 1, 2, ..., 12$. (b) Pentagon with 5 line segments and angles labelled with corresponding length L_i and clockwise angle α_i where $i = 1, 2, ..., 5$.

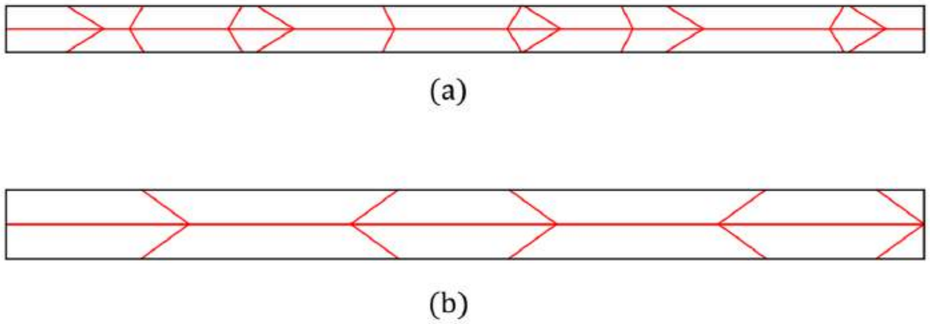

Figure 4: (a) Miura-ori fold pattern generated from the complex shape in Fig.3(a) given actuation angle $\theta = 90^\circ$ (b) Miura-ori fold pattern generated from the shape in Fig.3(b) given actuation angle $\theta = 90^\circ$

Figure 5: Origami fold pattern from Fig.4(a) printed on paper and folded.

trialled before settling on the design seen in Fig. 6. A thin (0.3mm) layer of TPU was positioned in the middle of 2 thick (1.85mm each) nylon layers. The thick nylon layers acted as rigid panels holding the shape of the mechanism while the thinner TPU layer acted as flexible hinges to allow for bending, similar to a paper Miura-ori module. To accommodate for the thick nylon layers in bending, they were tapered at the edges where folding occurs. The model comprising thick nylon layers and a thin TPU layer was 3-D printed using a dual-extrusion 3-D printer in a single print.

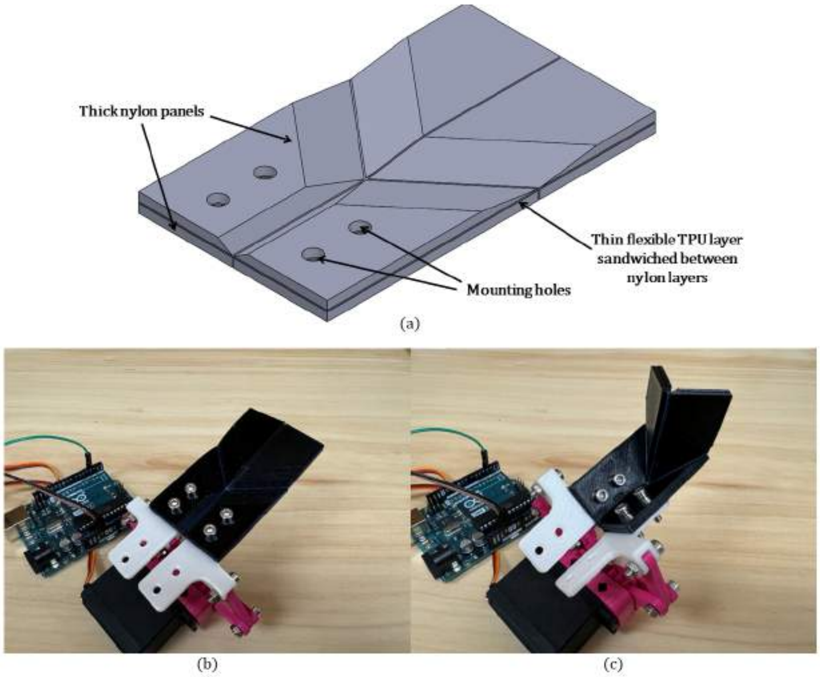

Figure 6: (a) CAD design of a single thick Miura-ori module using nylon and TPU. (b) 3D printed Miura-ori module mounted on actuator with actuation angle $\theta = 0°$. (c) Miura-ori module actuated to angle $\theta = 45°$

Lastly, an actuation mechanism was designed that allowed the rotational motion of a servo motor to be converted into the desired rotation from 0 to θ of the manipulator. Fig. 7. shows a 3-D printed manipulator attached to the actuator at an angle $\theta = 0°$ and $\theta = 45°$ respectively. Mounting holes were designed into the manipulator and the actuation mechanism, allowing for ease of installation and removal. This design allowed the manipulator to be easily detachable from the actuator, such that different manipulators with different fold patterns could be easily installed to grasp objects with different geometries as required.

A key limitation was the ability of the 3-D printer to print overhangs exceeding certain angles, as this limited the taper angle achievable on the thick nylon layer, hence limiting the actuation angle θ that could be reached when folding. The precision of the 3-D printer was also a limitation in achieving accurate folding angles and would have resulted in a drift away from the target shape as the number of folds required increased. Another inherent limitation was the fact that thick origami in itself limits the angles to which it can be actuated (Lang et al., 2018). With current origami models, it is assumed that all rigid panels have negligible thickness. Novel designs would be required, possibly using double hinges, to allow for a complete actuation between $\theta = 0°$ and $\theta = 90°$.

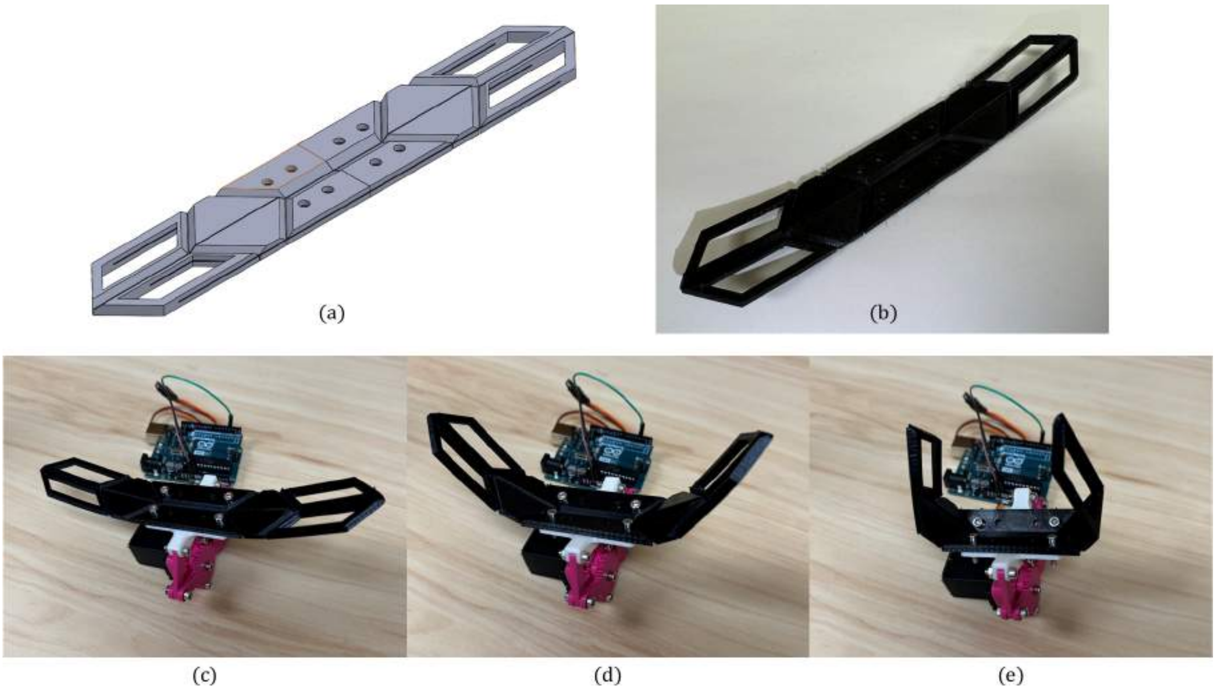

Figure 7: (a) CAD design of a Miura-ori-based manipulator. (b) 3D printed Miura-ori-based manipulator using nylon and TPU actuated to (c) $\theta = 0^\circ$, (d) $\theta = 20^\circ$ and (e) $\theta = 45^\circ$.

In this paper, the algorithmic approach for designing Miura-ori-based origami manipulators was proposed to grasp objects with complex geometry. A design algorithm for generating Miura-ori folds from vertex coordinates of complex shapes was presented, along with a 3D- printed prototype gripper using a single actuator. This is ideal for applications where a gripper is required to start from a flat or flush configuration, or when an object with a complex geometry has to be handled delicately. Given the scaleable nature of origami folds, the design could be applicable for millimetre-sized manipulators or meter-scale space applications. The current work paves the way to design origami-based manipulators, with the integration of sensors bringing about the possibility of dynamic control for more robust manipulation.

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