Modelling and Control of a Novel Foldable Fabric-Based Soft Robot for Minimally Invasive Surgery

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Abstract

Fabric-based soft robotic manipulators offer significant advantages in load-bearing capability compared to elastomer-based soft robots. However, proportionally controlling their bending angle and stiffness remains challenging. This research presents a dual-chamber fabric-based soft manipulator for precise bending control and stiffness modulation.

Approach: A parallel combination of bending and straightening chambers modulates the bending angle and stiffness. Three- (3S) and five-segment (5S) designs were compared on angle control, settling speed and stiffness.

Key Finding: Antagonistic chamber pressures enable proportional angle holding. 5S offers a wider angle-control range and a stiffer, more predictable response, whereas 3S settles in ~40% less time.

Keywords: fabric-based robot, soft robot, variable stiffness actuator.

Introduction

Soft robot manipulators offer safety and adaptability but lack precise control and load-bearing capacity. Fabric-based actuators offer higher load-bearing capacity and simpler manufacturing than elastomer-based soft robots, but typically rely on asymmetric geometric structures that result in non-linear bending responses.

This study proposes a mechanism utilizing two parallel chambers: one to induce bending (grooved) and another to counteract it (straight) (Figure 1). By balancing these opposing forces, the system achieves proportional bending angles and variable stiffness.



Figure 1. The dual-chamber configuration. The bending chamber mold (right) is placed directly on top of the straight chamber layer (left), fusing them into a single integrated actuator.

Objective: To overcome the limitations of fixed asymmetric structures by utilizing antagonistic pressure between dual chambers to achieve precise angle control, variable stiffness, fast settling and optimized geometric stability.

Research Method

Design & Manufacturing

The manipulators were fabricated from Thermoplastic Polyurethane (TPU) coated fabric for its high durability and weldability. A "sandwich" technique was employed: the top layer of the Straight Chamber serves as the bottom layer of the Bending Chamber, creating a compact, integrated unit (Figure 1).

Prototypes

Two manipulators were investigated with the same designed maximum bending angle of 150°:

- **3S**: 3 segments, 50°/joint (Figure 2).
- **5S**: 5 segments, 30°/joint (Figure 3).

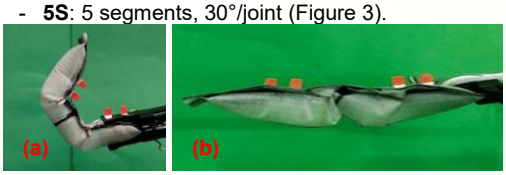


Figure 2. 3S in (a) fully bent and (b) straight states.

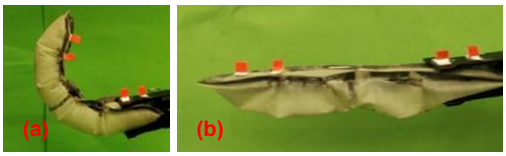


Figure 3. 5S in (a) fully bent and (b) straight states.

Experimental Setup

Bending angle was tracked with four red markers and video processing in MATLAB. Pressures were set by electrical regulators (ITV 0030, SMC, Japan); the Bending Chamber (BC) input was varied over PWM 1200–1650. Settling time was measured between settled plateaus for fall (bent → straight) and rise (straight → bent).

Discussion & Result

Angle Control

At a fixed BC input, raising the Straightening Chamber (SC) pressure progressively straightens the robot, so any angle between bent and straight can be held (Figure 4). Higher BC input shifts the curves to higher SC pressure.

- **5S**: bends to ~100°; its transition shifts from ~20 to ~60 kPa as BC input rises, giving a wide, well-ordered control range.
- **3S**: bends to ~77°; curves are steeper and crowded at low SC pressure (PWM 1200 and 1350 nearly overlap), with slight over-straightening.

Each BC level shows two curves ~15–25 kPa apart, reflecting fabric hysteresis.

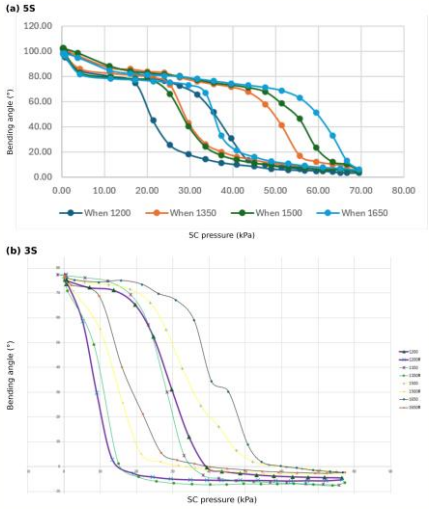


Figure 4. Bending angle vs. SC pressure at four BC input levels for (a) 5S and (b) 3S manipulators.

Settling Speed

3S settles faster in both directions (Figure 5): fall 2.46–2.99 s vs. 4.22–4.33 s for 5S, rise 3.89–4.39 s vs. 6.86–7.06 s. Rising (bending) is slower than falling in both designs. BC input barely affects 5S settling, while for 3S a higher input slows the fall but speeds the rise.

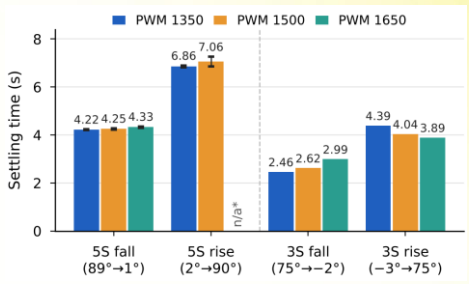


Figure 5. Settling time per BC input (5S: mean ± SD, n = 4; 3S: single run).

Geometric Effects on Stiffness

Stiffness was measured as reaction force vs. displacement.

- **3S**: large folds formed on the fabric during actuation (Figure 6), giving unpredictable stiffness.
- **5S**: minimal deformation and a stable, linear force–displacement response, stiffer than 3S (Figure 7).
- The stiffness of both can be tuned via the SC/BC pressure combination while holding the angle.

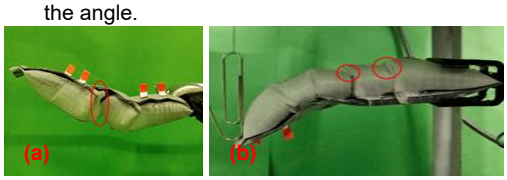


Figure 6. Local deformations (circled) act as notches: (a) 3S folds more than (b) 5S.

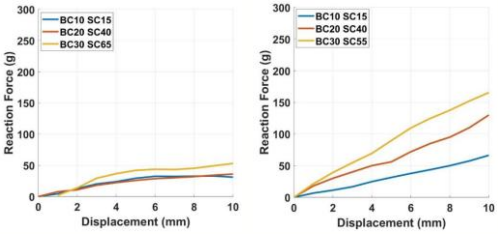


Figure 7. Stiffness of (left) 3S and (right) 5S: 5S is linear and stable, 3S less predictable.

Conclusion

A fabric-based soft robot with proportional angle control and variable stiffness was demonstrated. The number of segments sets a trade-off: 5S gives a wider angle-control range and higher, more predictable stiffness, while 3S settles in ~40% less time.

Future Works

We will investigate simultaneous control of stiffness and position. In addition, the dynamics model for soft robots that has been used for silicon-based soft robots will also be adapted for fabric-based soft robots.