An Origami-Based Soft Actuator and the Application as A Soft Gripper

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Abstract of Thesis

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This study aims to investigate characteristics of origami-based elastomeric actuator and its application to soft gripper. The employed lightweight paper-elastomer structure demonstrates features of efficient actuation in three ways: (1) It experiences nearly 20% less pressure for equal bending amplitude than pneumatic network actuator (Pneu-Net) of the same weight does; and even less pressure than other actuators with non-linear bending behavior; (2) It bends fully in 50 milliseconds under pressurization at the rate of 2.4 L/min; (3) less energy is dissipated in the inflation-recovery cycle as ballooning effect is minimized in the design. Additionally, controllability is discussed by validating associations between pressure and bending angle, and between interaction force and pressure at a fixed bending angle. A soft robotic gripper comprised of three actuators is designed. Enveloping and pinch gripping experiments that performed on various shapes imply the potential of grasping a wide range of objects for many applications.
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List of Abbreviations

Pneu-Net pneumatic network actuator iii
YP Yoshimura pattern 4
MYP modified Yoshimura pattern 4
COS combination of two basic origami structures 4
TPU flexible Thermoplastic Polyurethane 8
SLS selective laser sintering 8
SLA stereolithography 8
FDM fused Deposition Modeling 8
FEA finite element analysis 9
PWM Pulse-Width Modulated 15
EMG Electromyogram 27
List of Symbols

\[ P \] air pressure 6
\[ \theta \] an angle 9
\[ l_1 \] length of the inner enveloping curve 10
\[ l_2 \] length of the outer enveloping curve 10
\[ n \] Number of pleats 10
\[ s_1 \] Distance between glued inner pleats 10
\[ s_2 \] Outer pleat width 10
\[ d \] distance between edges of outer and inner pleats 10
\[ \alpha \] bending angle in radian 10
\[ r_1 \] radius of inner enveloping curve 10
\[ r_2 \] radius of outer enveloping curve 10
\[ h \] Fold length 11
Chapter 1. Introduction

Soft actuation units have attracted increasing research interest. They can be widely applied to biomedical area such as endoscopy devices, soft wearables and protheses due to the inherent superiority of safe interaction with external environment. Pneumatically powered soft actuators are of particular interest because they are made of biocompatible materials, lightweight and can be actuated at low pressure [1], capable of complex movement with simple input [2], not impacted in the presence of radioactivity and magnetic fields and are compatible with magnetic resonance imaging [3]. A major concern, however, for a pneumatically actuating device to be used internally in medical diagnosis and surgery is the “ballooning” effect under inflation [4], where expanding balloons increase the friction between the actuator and organ wall and may exert excessive local pressure on tissue [5]. Furthermore, the ballooning effect consumes energy on radial expansion rather than longitudinal motion [4]. Optimized Pneu-Net design that minimizes radical strain dissipated nearly 30 times less energy than the original design in one actuation cycle [6]. Such optimization also experienced less volume change for equal motion amplitude, thus enabled faster actuation at the same fluidic rate. Another emphasis of optimization has been on varying the thickness of chamber wall. Actuators with thicker walls require larger pressure to be inflated to a certain extend [7].

New materials and structures have been introduced in this area. Pneumatically actuated origami chamber eliminates “ballooning” effect by actuating origami structures with transformation of flexible facets, instead of material deformation [8]. Origami robots have other advantages: (i) built-in compliance because of the geometry of the folds and the creases in the material [9]. (ii) folded structure constructed following the principles of
origami that is lightweight, scalable and inexpensive. (iii) rapid prototyping and efficient manufacturing [10]. Combining the approach of Pneu-Net and origami, a pneumatic origami actuator made of paper-elastomer composite generates a wide range of motions by introducing controlled anisotropy into the response of elastomers to air pressure [11].

Pneumatically-driven actuator is also the most popular in developing soft grippers [12] – [17]. Traditional rigid gripper has its limitation in planning prior to grasping objects in different locations of a variety of geometries. Soft grippers, in the contrast, passively conform to unique object geometries, can grip widely varying objects without readjustment, including soft and delicate objects [18].

Hence, this study focuses on a pneumatically actuating gripper made from silicon-paper folded structure. The aims are to evaluate properties of origami-based soft actuators in bending with one degree of freedom in terms of actuating pressure, speed and generated force, and to implement a control system of the movement and force, validating the linear controllability that is a challenging topic in soft robotics. Since feedback is necessary in control, sensory has been widely explore in soft robot applications. Commercially available flexible sensors usually suffer from low sensitivity, high hysteresis, and signal drift. The liquid – metal – based soft sensors are well compatible with soft actuator providing high sensitivity, but the embedded microchannels require expensive material and a multistep construction process [19] – [20]. Computer vision can provide high-quality position sensing, but the camera systems rely on laboratory setup and can interfere with the user's motion. Due to these sensor limitations, many soft robots do not use the camera systems; instead they are open loop [21]. The proposed design aims to provide bending angle and force estimation with an off-the-shelf pressure sensor.
This paper highlights the following contributions: (i) a simple soft gripper architecture consisting of a soft origami structure; (ii) two distinct fabricating approaches for the origami skeleton that demonstrate the process is scalable and programmable (iii) performance characterization of the gripper and grasping test on a set of objects with various geometries.
Chapter 2. Methods

2.1 Prototype Design

The proposed actuator chamber was designed by investigating and combining several primitive origami patterns for desired behavior. Origami patterns and their modeling have been well studied [22]-[27], among which four basic patterns are mainly used on engineering applications: the Yoshimura pattern, the Miura-ori pattern, the waterbomb pattern and the diagonal pattern. Structure design in this study was assisted by online origami simulator [28], where the 3D structure and strain analysis are generated from 2D pattern. Actuators of three patterns were fabricated: the Yoshimura pattern (YP), modified Yoshimura pattern (MYP) and combination of two basic origami structures (COS): the reverse fold and the accordion fold [26].

The YP and MYP were creased manually with paper-elastomer composite. MYP was modified from YP, providing a smooth surface on one side of the structure that suits better as the gripper. COS was designed in CAD software before it was 3D-printed in elastomeric material, implying the potential to program and fabricate more complicated origami structure that is strenuous to be handcrafted.

2.2 Materials and Fabrication of Paper-elastomer Actuator

Inspired by soft robotic extensor based on pleated structures [11], the actuator was constructed with folded paper structure embedded in elastomer. I used a silicone elastomer (Ecoflex 00-30, Smooth-on, Inc.) and a polyester/cellulose blend paper (Spec-Wipe 5 Wiper, VWR). Ecoflex of 00-30 shore hardness is skin safe silicon rubber that can withstand 900% elongation at break [29]. The material comes in two parts that were mixed
at a 1:1 mass ratio. VWR Spec-Wipe 5 Wiper has a high tensile strength of more than 50 Nm$^{-2}$ and absorbs elastomer four times of its own weight [30]. Besides, the wiper is semi-soft, that is, it is rigid enough to maintain 3D pattern and compliant as fabric.

Figure 2.1 describes the fabrication process. The classic Yoshimura pattern (Figure 2.1a) is employed to form the foldable cylinder as shown in figure 2.1b, which folds under axial loading. The cylinder was evenly spread with degassed Ecoflex until it was saturated with Ecoflex. It was cured at 70 °C for 1 min. Then the partially cured structure was completely folded and held with paper clips, before being fully cured at 70 °C for 20 min. Top and bottom hexagonal caps (Figure 2.1c) were made of paper-elastomer composite and connected with an elastomer strip. The cylinder was sealed with caps to form a pneumatic chamber (Figure 2.1d), which extends when pleats unfold under pressurization. The elastomer strip that connects top and bottom caps provides a restoring force to fold the structure when unpressurized. The fabricated actuator weighs 9.3 g in total.

One side of each pleat is glued with Ecoflex to constrain the elongation, forcing the actuator to bend towards this side on pressurization. Figure 2.2 demonstrates actuation behavior of origami actuators under different actuation pressures.
Figure 2.1. Fabrication of the YP actuator. (a) The crease pattern. Valley folds are shown as solid, blue lines and mountain folds are shown in dashed red. (b) The pattern paper was rolled to form a foldable cylinder. (c) The molded top and bottom caps. (d) Glued the roll with caps connected by an Ecoflex strip to form a pneumatic chamber with sixteen folds.

Figure 2.2. Actuation behavior of origami actuator under Patm, $P_1 = 60$ mbar, $P_2 = 90$ mbar, $P_3 = 120$ mbar

A modified Yoshimura pattern (Figure 2.3a) is employed in the proposed soft gripper. This pattern is investigated for the worm robot in previous study [24]. The fold in the red circle between two intersecting folds adds a flat surface to the folded structure in the
bending direction, providing larger contact area when the actuator is applied as a finger of the gripper. The following modeling and experiments are based on the MYP as well.

Fabrication of the paper-elastomer origami actuators is inexpensive and programmable, achieving versatile structures. The process, however, has its limitation in terms of efficiency, repeatability, and reliability. For instance, leakage occurs at intersections where multiple folds coincide, through small holes caused by high stress during folding. In the following section, more scalable and repeatable methods are explored to overcome the problem.

Figure 2.3. Fabrication of the MYP actuator. (a) The crease pattern. Valley folds are shown as solid, blue lines, mountain folds in dashed red and added folds are shown in red circle. (b) The patterned paper was rolled to form a foldable cylinder with added fold shown in red circle (c) The mold for top and bottom caps. (d) Glued the cylinder with caps connected by a Ecoflex strip to form a pneumatic chamber.
2.3 3D Printing Origami Model

3D printed model with flexible filament has ductility that are not achievable with rigid material. Applying 3D flexible printing to the origami-based structure allows for increased durability, precision, and efficiency compared with manually folded paper. Additionally, more complex 3D structure can be realized with 3D printing. For example, in the proposed COS design, sum of adjacent angles with a common vertex, $\theta_1$, $\theta_2$, $\theta_3$, $\theta_4$ is smaller than 360°, that can hardly be creased by hand considering the small size.

Commonly used flexible material are flexible Thermoplastic Polyurethane (TPU) and flexible resin, printed through technologies including selective laser sintering (SLS), stereolithography (SLA), fused Deposition Modeling (FDM) and PolyJet printing. The COS prototype was designed in CAD software and was printed in PolyJet shore hardness 50A (Figure 2.4a, 2.4b) which has proper flexibility for bending motion.

The manual fabrication of origami structure is, on one hand, significantly simplified with 3D printing. On the other hand, the leakage problem through the surface is reduced. However, the allowed wall thickness for 3D printed cavity is at least 1.3 mm and inner supporting material can hardly be eliminated or removed after printing through a small opening.

Since the COS prototype is being improved and the characterization is ongoing, the actuation is undertaken in finite element analysis (FEA) in a simulating environment instead of the real world. The result is illustrated in Section 3.2.
Figure 2.4. Fabrication of the COS actuator. (a) printed actuator in natural state, (b) printed actuator in deployed state, (c) adjacent angles with a common vertex.
Chapter 3. Modeling

In this chapter, the motion range of MYP is characterized with dimensional parameters and a quasi-static analytical model for MYP is developed to investigate bending angle with respect to internal pressure. Additionally, controllability is discussed considering air flow dynamics. The model is validated in experiments that demonstrate that the analytical model captures the correlation of supplied air pressure and actuator bending angle. Comparatively, a finite-element model is created for the proposed COS actuator design.

3.1 Workspace Definition for MYP

The bending range of the proposed actuator can be characterized with parameters of one pleat (Figure 3.1a). Meaning of symbols is explained in Table 1. Enveloping curves of the inflated actuator chamber (Figure 3.1b) are assumed to be concentric and length of the curves are: \( l_1 = 2ns_1 \), \( l_2 = 2ns_1 + d\alpha \), where \( l_1 \) is constant and \( l_2 \) is linearly associated with evolving angle in radians, \( \alpha \).

The actuator at maximum bending is shown as a ring shape (Figure 3.1c), where the inner radius \( r_1 \), outer radius \( r_2 \) and bending angel \( \alpha_{\text{max}} \) are defined by dimensional parameters. By properly choosing the parameters, desired bending behavior and range can be realized. In this design, dimensions are chosen as seen in Table 1 to achieve \( r_1 = 17\text{mm} \), \( r_2 = 34\text{mm} \) and \( \theta_{\text{max}} = 240^\circ \).
**Figure 3.1. Prototype characteristics** (a) dimensional parameters of one pleat, (b) enveloping curves of inner and outer pleats, (c) defining actuator workspace at maximum bending, (d) simplifying actuation volume to a cylinder

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1$</td>
<td>Distance between inner pleats (glued)</td>
<td>5 mm</td>
</tr>
<tr>
<td>$s_2$</td>
<td>Outer pleat width</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>$d$</td>
<td>distance between edges of outer and inner pleats</td>
<td>18.96 mm</td>
</tr>
<tr>
<td>$h$</td>
<td>Fold length</td>
<td>18.67 mm</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of pleats</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 1.1 Design Parameters**

### 3.2. Analytical Model for MYP’s Motion

In this section, kinematics and air-flow dynamics of MYP’s motion are investigated when simplifying the bending actuator to a cylindrical shape (Figure 3.1d).

The chamber volume $V$ can be expressed as:

$$V = \frac{1}{2} \alpha h (r_2^2 - r_1^2)$$  \hspace{1cm} (3.1)
Assuming the inner air is adiabatic ideal gas [31], which follows ideal gas law:

\[ P = \frac{mRT_a}{V} \]  
(3.2)

\[ PV^\gamma = \text{const} \]  
(3.3)

where \( P \) is the pressure of the gas, \( R \) is the ideal gas constant, \( T_a \) is the absolute temperature of the gas, \( m \) is air mass in the origami chambers.

Combining (3.1) and (3.3), \( P, \alpha \) correlation can be expressed as:

\[ \frac{\partial P}{\partial \alpha} = \frac{\partial P}{\partial V} \frac{\partial V}{\partial \alpha} = -\gamma \frac{P}{\alpha} \], where \( \gamma = 1.4 \)  
(3.4)

Actuator dynamics is derived from (3.2) and (3.3):

\[ \dot{P} = \frac{\gamma RT_a}{V}(\dot{m}_m - \dot{m}_\text{out}) - \frac{\gamma P}{V}\dot{V} \]  
(3.5)

where \( \dot{m}_m \) and \( \dot{m}_\text{out} \) are respectively the rate of air passing in and out through the valve, which follows air-flow dynamics [32] :

\[
\dot{m} = \begin{cases} 
\frac{C_f A_1 C_1 P_u}{\sqrt{T_u}}, & \frac{P_d}{P_u} \leq P_{cr} \\
\frac{C_f A_1 C_2 P_u}{\sqrt{T_u}} \left( \frac{P_d}{P_u} \right)^{\frac{\gamma}{2}} \sqrt{1 - \left( \frac{P_d}{P_u} \right)^{\frac{(\gamma-1)}{\gamma}}}, & \frac{P_d}{P_u} > P_{cr}
\end{cases}
\]  
(3.6)

where \( C_f \) is a nondimensional, discharge coefficient, \( P_u \) is the upstream pressure, \( P_d \) is the downstream pressure and \( C_1, C_2, P_{cr} \) are constant for a given fluid. For air \( C_1 = 0.040418, C_2 = 0.156174, \) and \( P_{cr} = 0.528. \)
The association between pressure and airflow rate in (3.5) implies controllability of the inner pressure by manipulating flow rate, i.e. $\dot{m}$, which can be implemented by changing valve on-and-off frequency.

### 3.3 FEA Model for COS

Actuation of COS prototype is simulated in FEA. CAD model of the fabricated actuator is shown in Figure 3.2a, with the uniform wall thickness of 1 mm. Hyperelastic – Blatz Ko rubber model is employed for non-linear FEA simulation. For hyperelastic material such as rubber, the stress–strain relationship follows a strain energy density function rather than a linear model. Blatz-Ko strain energy density function [33] is one of the most commonly used functions. The same pressure is applied perpendicularly to every surface. It is noticeable in strain analysis under 10 mbar and 20 mbar (Figure 3.2b and 3.2c) that the actuator acts more like soft beam than origami; that is, the facets cannot rotate very flexibly around edges, but are deformed when actuating the model, and the pleat next to the fixed head has the largest strain and displacement while other pleats barely extend around the bending axis. To improve the design, the facets’ shape is modified so that it can generate larger bending torque. Re-designed model has an initial bending angle in natural state as shown in Figure 3.1d (COS2, the original prototype will be referred to as COS1). More significant angular displacement is noticed in COS2, but facets deformation and edges rigidity still compromise its flexibility as an origami structure. A possible solution is cutting notches along the edges or reducing edge thickness in printing, which will be explored in future work.
Figure 3.2. FEA model of two COS prototypes (a) CAD model of COS1, (d) CAD model of COS2, (b)(c)(e)(f): FEA results for strain and deformation (b) COS1 inflated under 10 mbar, (c) COS1 inflated under 20 mbar, (e) COS2 inflated under 10 mbar, (f) COS2 inflated under 20 mbar.
Chapter 4. Experiments and Results

4.1 Pressure Control System

In order to run quasi-static experiments where the module ought to be actuated under constant pressure, I built a pressure control board generating regulated pressure with solenoid valve (VQ110U-5M, SMC), using a diaphragm pump as air source and observed feedback with pressure sensor (ASDXRRX030PG2A5, onlinecomponents). Control performances using two pumps, i.e. Parker D737-23-01 and D1008-23-01 are compared as follows. Figure 4.1 describes the routing of air flow. A PWM (Pulse-Width Modulated) output is produced to switch valve in response time of 3.5ms to turn on and 2ms to turn off [34]. The experiments were undertaken on actuator of constant volume to ensure pressure and air flow followed linear relationship.

![Pressure control system](image)

Figure 4.1. Pressure control system
Pressure control was firstly performed with D737-23-01 pump, whose outlet flow is regulated non-linearly to environment pressure as shown in Figure 4.3a. The maximum flow is 11 L/min and maximum operation pressure is 20 psi, which presents challenge in maintaining pressure inside actuator of low volume: (1) As validated in tests, the inner pressure increases much faster than valve and pump can response, thus is not controllable; (2) Pump responses slower than valve, building pressure larger than 30 psi between the pump and the valve if pump is open while valve is not actuated. Therefore, when valve is re-open, a spike downstream causes pressure rises. (3) Additionally, the accumulated air pressure exceeds pump’s limit, forcing its actuation to stop and delay further when the pump is turned on again. Pump was programmed to actuate earlier than valve, which reduces the delay but cannot eliminate it. One failed control case is illustrated in Figure 4.3b.

To tackle the challenges, the pneumatic system was modified to slow the actuation: another pump with smaller flow rate and larger pressure tolerance is employed (Parker
D1008-23-01, Figure 4.4b); a 100 cm³ chamber is added between valve and actuator as buffer to prevent pressure surge, resulting much slower pressure climb. For example, inner pressure increases from 0 psi to 3 psi in around 500 ms. Due to the improved controllability, a PID controller can be used to regulate the pressure. P, I and D coefficients were tuned in Simulink (Figure 4.4a) and the resulted control performance is demonstrated in Figure 4.4c. Though fluctuation is observed around setpoint, the pressure can be maintained within a ± 0.5 psi window.

**Figure 4.3.** pressure control performance with D737-23-01 pump (a) pump air flow - pressure relationship [35]. (b) one failed control case and caused analysis
Figure 4.4. pressure control performance with D1008-23-01 pump (a) PID controller built in Simulink. (b) pump air flow - pressure relationship [36]. (c) control performance test result

4.2 Actuator characterizing

4.2.1 bending angle – pressure

The bending angle is measured as the angle between tip and horizontal surfaces (Figure 4.5a). In the experiment, images were recorded and calibrated using Computer Vision System Toolbox in Matlab.

Figure 4.5 compares Angle-Pressure curve of a semi-circular chamber [4] and the origami soft actuator of comparable size. noticeable results are: (i) origami – based module has a larger range of motion, that can reach nearly 360° by choosing proper geometry; (ii)
Smaller pressure is required for origami – based module to a certain bending amplitude; (iii) origami – based module can achieve smooth and continuous bending motion from its natural resting position to around 240°; bending angle and pressure are of linear association in most range of motion. The result conforms to analytical model built in section 3.1, making it possible to measure the degree of bending by monitoring the pressure.

**Figure 4.5. angle-pressure relationship** (a) origami – based actuator at different bending states: $P_1 = 85$ mbar, $P_2 = 161$ mbar (b) Angle - pressure curve of rubber actuator with semi-circular chamber [4] (c) Angle - pressure curve of the origami – based module

### 4.2.2 actuation speed

A high-speed camera was employed to record the actuation. the origami module bends fully in 50 milliseconds under pressurization at the rate of 24 L/min.
4.2.3 tip force – pressure

To measure the fingertip force, the end of the actuator was fixed (Figure 4.6a) and the tip of the actuator slowly bended downward as actuation pressure increases. The exerted tip force reads zero until the actuator reached the curvature enabling it to touch the scale. The measured tip force is converted from the unit of gram to Newton using the relationship 1g: 0.0098N. Three sets of experiments were undertaken, where the tip of the actuator was actuated to an angle of 90°, 120° and 150°. The tip force vs. actuation pressure shows an approximately linear relationship and slope coefficient tends to increase as bending angle decreases. Therefore, knowing the bending angle, the pressure reading could provide a real-time force estimation without a force sensor. According to the pressure-angle association, the bending angle can be acquired by watching load-free pressure change.

![Figure 4.6. Force Exerted at Tip of Pneu-net](image)

(a) setup for tip force measurement. (b) force vs. pressure relationships at different bending angle

4.3 Application

A gripper comprised of three origami-based modules as fingers was fabricated. The gripper can be attached as an end-effector on a manipulator with a connector (Figure 4.7).
Each actuator is connected to pneumatic source through a 0.06" OD tube (McMaster, Miniature EVA Tubing) and a syringe.

4.3.1 Object gripping capability

Grasp tests demonstrate the gripper’s capability of picking up objects of various geometries. Two types of grasp were tested: enveloping grasps that the objects entirely contact the gripper inner surface and pinch grasps that objects are held by the tips of the fingers.

In enveloping grasp test, the object is contained within fingers and palm. Tests were conducted on caps, a tape, a cylinder of 6 cm diameter laid parallel and a ball (Figure 4.8 a, b, d, e). Pinch grasp test was performed on small or thin objects that cannot be held firmly in palm, including paper, a sponge, a screw and a cylinder of 4 cm diameter stood upright (Figure 4.8 c, f, g). Allowable load in pinch grasp is relatively low compared with that in enveloping grasp.
The gripper is able to pick up and hold a variety of objects without damaging delicate surfaces due to compliance of the soft material. We should note the slight behavior differences between three fingers caused in fabrication process, leading to orientation change of lifted object and location shift after replacement.

**Figure 4.8. Gripper picking up various objects:** (a) plastic cup, (b) tape, (c) screw, (d) paper cup downwards, (e) paper cup upwards, (f) cylinder (g) paper (h) weight in bubble wrap with bubbles outward (i) weight in bubble wrap with smooth side outward
4.3.2 load test

The gripper lifted a range of weights reaching nearly 60 g in enveloping grasp where pressure was limited to 6 psi to protect the thin structure. Three major factors influence load capacity: (i) actuation pressure, (ii) object dimension and (iii) object’s surface condition. The influences were investigated in experiments:

(i) Load tests were performed under different pressures on objects in the same shape and of various weights. Maximum loads that can be held under pressure 1.5 psi, 3 psi and 6 psi were tested, where weights were put in a cup with 6 mm diameter opening. Direct relationship between pressure and maximum load can be noticed in Figure 4.9.

(ii) The load is influenced by object dimension as well. The maximum diameter of the cup-shape object grasped and lifted by the gripper was 8 cm, nearly two times of the range the gripper can reach in natural resting position, attributed to pleats inside the gripper that hold the object edge.

(iii) Another factor to consider in evaluating load capacity is object’s surface condition. Objects with smooth surfaces are more likely to slip. Tests on different surfaces conditions were performed on weights in bubble wrap that is textured on one side but smooth on the other side (Figure 4.8 h and j). The gripper lifts 2 times more weight contacting the side with bubbles.
4.3.3 Contact Sensing

As demonstrated in section 4.2, unloaded bending angle is associated with pressure reading (Figure 4.5c), so as interaction force with pressure at certain bending angle (Figure 4.6b). Therefore, it is possible to monitor grasping force by observing pressure, knowing to what extend the actuator has bended. Since the actuator bends freely before touching the object, if the moment of contact can be identified, the finally reached bending angle can be implied from pressure reading.

I performed three rounds of gripping tests on different objects. Nonmonotonic pressure increase was observed. As can be noticed in Figure 4.10, significant slow-down in pressure increase occurs for each of the three fingers at the point of contact. Therefore, with mere pressure sensor reading the contacting moment and correspondent angle can be recognized.

Further research will explore haptic object identification that has been realized using unsupervised learning with feedback from bending sensor attached to the finger [13]. However, previous study mostly focused on gripper comprised of pneuNet. Machine
learning performed on origami-based actuator has not been researched. Challenges could be variations between fingers from fabrication discrepancies. As indicated in Figure 4.10, pressure – time behaviors of three fingers are not identical. Previous characterizations in Figure 4.5c and 12 b are also based on one finger and don’t apply to others, such that identification model trained for one finger may not be reusable for another finger. Further work is to improve consistency of the fabricated actuator or learn the behavior of each finger through reinforcement learning.
Chapter 5. Conclusion

In this study, I have fabricated a lightweight, agile and energy-efficient soft actuator based on Yoshimura crease pattern and prototyped a 3D printable origami structure. A pneumatic pressure control system was built for experiments. Performance of the actuating module can be characterized with four parameters: (i) pressure required for a given degree of bending; (ii) time to actuate from linear shape to fully-bended extend; (iii) force exerted for a given pressure, when interacting with the environment. (iv) linearity of fitted line to Angle-Pressure and Force – Pressure data.

Compared with other pneumatic soft actuators, the origami-based actuator improves in actuation pressure and speed and behavior linearity relative to Pneu-Net and pneumatic device with semi-circular chamber. The associations in angle – pressure and force – pressure curves enable simple and accurate linear control.

The maximum force can be generated, however, is smaller than actuators made of pure silicon rubber chamber, because of tear strength limitation of thin paper-elastomer composite. Force capability can be improved by increasing the stiffness of the elastomer, though. Performances of silicone and polyurethane elastomers in the market with a large range of material properties are to be explored in future work. Proposed actuator in this study can be useful as a small-scale medical device that exerts force ranging in 1 N. More specifically, the bellows structure is possible to pass thin channel when it is folded and unfold itself in organ chamber to interact with tissue. Small pressure is required for actuation. Therefore, possible applications of the actuator can be tasks in biomedical environment of limited space such as minimum invasive surgery and drug delivery.
Another application of the actuator can be an end effector to operate delicate apparatus, which is validated by the gripper prototype comprised of three fingers. The soft gripper demonstrates abilities of compliant gripping for various shapes. Contact sensing simply with pressure sensors implies the possibility of haptic object identification without the assistance of motion and vision capturing devices.

In the future, following tasks are planned for the next step:

(i) Improve fabrication consistency and mechanics performance of the actuator in aspects of material stiffness and durability;

(ii) Validate contact sensing and force estimation with force sensor embedded in the actuator;

(iii) Deploy the actuator with motion sensing system, where EMG (Electromyogram) signals of the user’s muscles directly reflect the user’s motion intention [37]. A motion indicator was developed by processing and classifying EMG signals. The actuator will be activated based on indicated motion, thus will automatically assist users according to the users’ intention. This motion assistance system can be further applied to area such as rehabilitation and prothesis [21];

(iv) Develop haptic sensing algorithm to control grasping force either by training model for each finger, or by learning to control exerted force without knowing the analytical model. Dynamic control of soft robotic manipulators is an open problem. A reinforcement learning method has been explored for close-loop dynamic control. [38]
Reference


