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Development of Low-Cost Automatic Soft Robotic Finger and Experimental Applications

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Abstract— **This paper introduces a novel soft robotic finger (SRF) fabricated from Polydimethylsiloxane (PDMS), designed to perform controlled bending and yaw movements. Various experiments are conducted to demonstrate the SRF's performance in real time. The bending movement is driven by an internal actuation channel, where the yaw movement is performed by a dual-motor system. Embedded sensors continuously monitor and adjust bending and yaw movement, improving control during gripping, lifting, and turning objects. This work advances to design a SRF at a low cost by enhancing continuous control operation with material flexibility.**

I. Introduction

Soft robotics has seen significant advances in recent years, driven by the need for robots that can safely and effectively interact with delicate objects and complex environments [1]. The SRF has broad applications in fields requiring gentle handling, especially in biomedical sectors, where it is used for tasks such as tissue manipulation and surgery [2]. Its flexible nature minimizes the risk of damage as compared to traditional rigid robots [3]. Moreover, in agriculture and manufacturing fields, SRFs mimic human fingers to handle fragile items without causing damage [4]. Recent advancements in material design and sensitivity have further enhanced its adaptability to perform complex tasks while adjusting to different shapes and textures [5].

In medicine, SRFs effectively perform delicate tasks such as tissue manipulation and minimally invasive surgeries greatly reducing the risk of damage compared to traditional rigid systems [6]. In industrial environments, their flexibility allows for the safe handling of sensitive materials like electronic components and glassware, minimizing the risk of breakage [7]. In agriculture, SRFs with their gentle grip help to protect crops during harvesting [8]. However, there are still challenges in enhancing the durability and reliability of SRFs, particularly in environments with fluctuating temperatures and humidity. Addressing these challenges is important to improve the applicability of SRFs.

A key innovation in this work is integrating a feedback-based closed-loop control system. This system utilizes embedded flex and temperature sensors to monitor and adjust the SRF's position in real-time. This approach addresses the limitations of earlier open-loop control systems, where robot movements were pre-programmed without real-time environmental feedback [9]. In our work, the SRF with feedback dynamically adjusts its movements, ensuring more accurate and reliable performance during bending, object handling, and temperature sensing. The main advantages of this work are as follows:

- We present a low-cost unified automatic SRF system integrated with flex and temperature sensors.
- The developed SRF system is suitable for biomedical and agricultural applications.
- Moreover, its low manufacturing cost makes it ideal for educational purposes, such as lab equipment to conduct control, robotics, and sensor experiments.

II. Overview of Developed Automatic SRF System

The block diagram, shown in Fig. 1, illustrates different components of the developed SRF system.

A. Fabrication of SRF

The SRF is fabricated using Polydimethylsiloxane (PDMS), a silicone-based elastomer, which is popular for its flexibility and compatibility with biological systems [10]. It adds the following advantages to an SRF:

- *Elasticity:* PDMS can undergo extensive stretching and bending without deforming its original shape.
- *Durability:* The extended lifetime of PDMS facilitates the consistent performance of SRF systems under repetition.
- *Flexibility:* PDMS can be conformed into various shapes that enhance the flexibility of SRF in different applications

Figure 1(a) shows the fabrication process. The PDMS gel is poured into a 3D-printed mold (Fig. (a)(i)). After curing the SRF is removed from the mold and a polyethylene thread (actuation wire) is inserted (Fig. 1(a) (ii)).

B. Modeling and design

The design of the SRF aims to create an autonomous system that can handle both bending and yawing.

- Its bending and yaw movements are controlled by using two servos (MG90S)—Servo 1 and Servo 2.
- The integrated flex and temperature sensors, shown in Fig. 1(c), provide the controller with continuous real-time feedback of bending angle and temperature.
- Figure 1(b) illustrates a schematic of the closed-loop automatic SRF system comprising SRF, sensing elements, and servos with their controllers.

The proposed design presents a unified automatic control system for an SRF integrated with a sensing facility. The forward path represents control of SRF's position depending upon the error signal. In the feedback, output are measured continuously and fed to the controller to execute the required control action.

C. Experimental setup

We develop a custom-made electronic setup to automate the SRF system for performing desired tasks. As shown in

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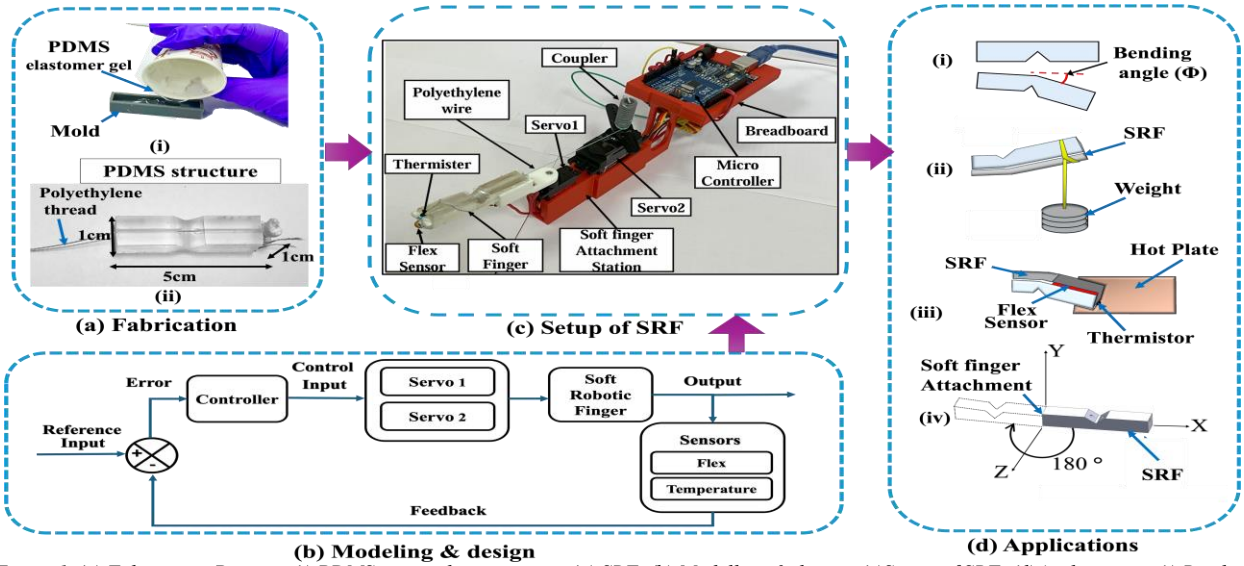


Figure 1:(a) Fabrication Process, (i) PDMS material preparation, (ii) SRF, (b) Modelling & design, (c)Set up of SRF, (d)Applications: (i) Bending response, (ii) Lifting capability, (iii) Temperature sensing, (iv) Yaw movement.

Fig. 1(c), the overall hardware setup of the proposed automatic SRF system is assembled with an ATmega328P microcontroller, dual servo motor (MG90S) system, flex sensor, and temperature sensor (thermistor).

- Two motors are used to execute the bending motions and yaw motions of the unified SRF system.
- The industrial sensors integrated with the SRF can detect bending movements and temperature.
- The entire setup is aligned with a 3D-printed attachment station, shown in Fig. 1(c) that is placed to a base of dimension 40mm × 30mm × 30mm, alongside the SRF.
- A vertical coupler, with a thickness of 3 mm and height of 28 mm, is positioned on top of the motor.

Servo 2 integrates the SRF's bending movement by activating the controller signal. This tension in the polyethylene wire causes the SRF to bend up or down while reversing the motor to its original position. Servo 1 manages the yaw movement (rotation along the X-axis) of the SRF system, as shown in Fig. 1(d) (iv).

D. Bending and yawing mechanism

The control of bending and yawing is driven by a dual-motor system: one motor for the bending motion, while a second motor at the base of the SRF handles the yaw movement. This setup makes the SRF suitable for handling objects in an environment with space constraints.

- *Bending:* The SRF bends along its Y-axis based on the controller output (see Fig. 1(d)). The flexibility of the PDMS material enables pneumatic actuation, illustrated in Fig. 2(a) and (b). A polyethylene thread runs through a hollow channel in the SRF to create tension, resulting in bending. Experimental results show that the bending angle (Section III-A). However, the SRF faces a trade-off while handling high forces repetitively. As it can lead to plastic deformation of the SRF.
- *Yawing:* The SRF features yawing shown in Fig. 2(c), (d). The incorporation of yaw control enables another degree of freedom to the overall SRF system. As a result, the SRF can execute smooth lateral movement without compromising its mechanical structure.

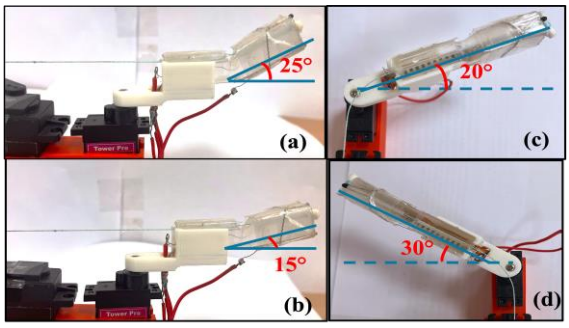


Figure 2: (a) SRF bending at 25° (b) SRF bending at 15° (c) SRF yawing right with 20°, (d) SRF yawing left with 30°

Cost comparison with the state-of-the-art [11-13]

Table 1 compares the manufacturing costs of SRFs in the existing literature [11-13]. The total equipment cost of [11-13] is approximately \$96.05, \$128.75, and \$86.95, respectively. Note that the manufacturing cost of [11-13] is increased due to the usage of pneumatic actuators and sensors like strain and pressure sensors.

However, our proposed SRF designed for the same tasks has a cost of \$33 approximately. Thus, the manufacturing cost of the developed SRF system is at least half of the

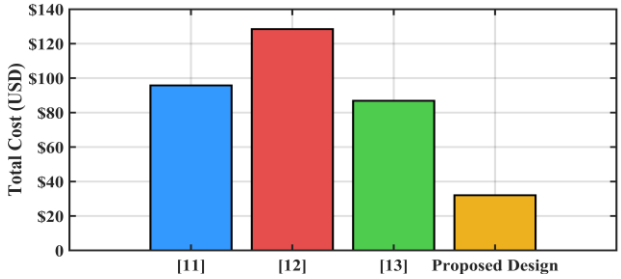


Figure 3: Cost comparison with the state-of-the-art [11-13].

Table 1: Cost comparison

Category	Components	[11]	[12]	[13]	Proposed
Sensors	Strain Sensor (Liquid Metal)	$7.15	$14.30	–	–
	Pressure Sensor (US9111)	$29.80	$29.80	–	–
	Flex (REES52) and NTC Thermistor	–	–	–	$8.30
Controller Components	Instrument Amplifier (AD8237)	$4.20	–	–	–
	PID Controllers	–	$17.90	–	–
	Control Board (Valves, Sensors)	$29.80	$29.80	–	$4.75
	Dual-Servo Motors	–	–	–	$7.15
Actuation Components	Pneumatic Actuators	–	$17.90	$17.90	–
	Polyethylene Wire	–	–	–	$1.20
	Actuation Channel	$4.80	$7.15	$9.55	$2.40
Materials	Polydimethylsiloxane (PDMS)	–	–	–	$5.95
	Silicone	$11.90	–	–	–
	3D Printed Molds	$8.40	$11.90	$59.50	$2.40
Total		$96.05	$128.75	$86.95	$32.15

earlier works [11-13]. The same is depicted using a bar diagram in Fig. 3. This strategic component selection for designing the SRF (shown in Table 1) reveals that there is no compromise with its applicability to make it cost-effective. Here, the proposed SRF design not only meets the operational requirements but also presents a more accessible financial option for cost-effective applications.

III. Experiment Results and Discussion

This section presents the experimental results to illustrate the performance of the automatic SRF system under two different practical scenarios.

A. Repeated lifting of weights

The lifting capability of the designed SRF is assessed through repetitive experimental runs. These experiments are aimed to evaluate the efficiency, reliability, and adaptability of the SRF while executing consistent lifting operations.

1) No load: In the no-load condition, the bending angle (Φ) of the SRF is proportional to the applied force. The blue colored line of Fig. 5 illustrates the relation between the bending angle and applied force. Figures 4(a) and 4(b) depict the SRF with no load in resting and 25° bending positions without any load.

2) With load: During load testing, the SRF is subjected to different loads with weights of 5g, 10g, 15g, 20g, and 25g. Figures 4(c) and 4(d) illustrate its ability to lift a 25g object at bending angles of 25° and 40°, respectively. These findings confirm SRF's effectiveness in delicate lifting tasks while maintaining precision and structural integrity.

Applications

1. The bending capability of the SRF is useful in chemical laboratories, allowing it to hold chemicals at a specific angle for an extended time period while performing certain experiments.
2. It can be applied in industrial settings to handle delicate objects, carefully moving them from one location to another without causing any damage.

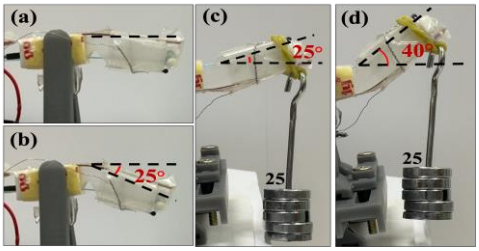


Figure 4: (a) SRF at rest, (b) SRF bent at 25°, (c) SRF lifting a 25g load at 25°, (d) SRF lifting a 25g load at 45°

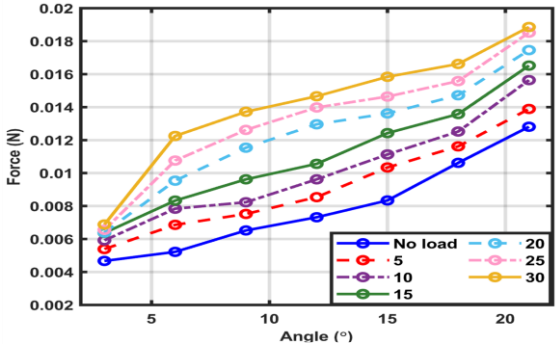


Figure 5: Relationship between servo and finger bending angles during forward and reverse cycles

B. Automatic temperature sensing and control

The temperature sensor, integrated into SRF's tip, is a key component of the feedback control (shown in Fig.(1)(c)).

1) Temperature sensing: In this experiment, the SRF detects the temperature of a hot plate. During this process, the temperature sensor on the SRF will give feedback to the control system. If the hot plate temperature is greater than 35°C (36.4°C as shown in Fig. 6(c)), the feedback control instantly operates and the SRF moves to its rest position (OFF position, Φ = 0°). The same is shown in Fig. 6(a). Otherwise, when the hot plate temperature is less than 35°C

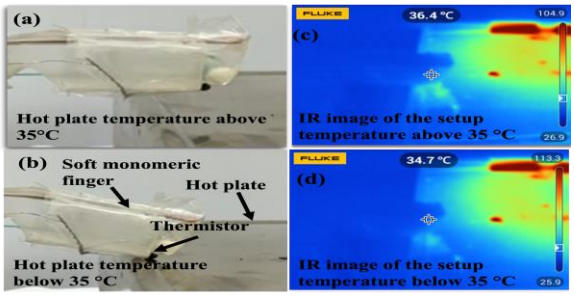


Figure 6: Temperature Sensing (a) SRF bending towards at hot plate above 35°C,(c)IR image above 35°C (b) Finger response to a hot plate below 35°C,(d)IR image below 35°C.

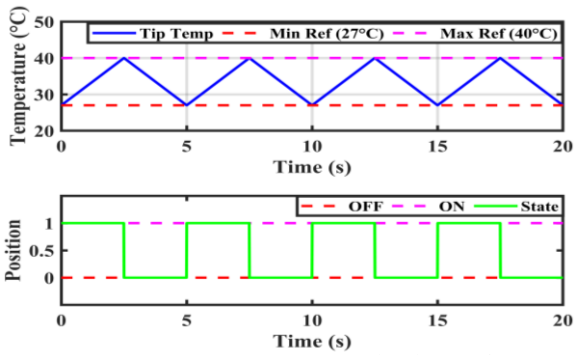


Figure 7: Temperature vs. time graph indicating finger's state (0 = rest, 1 = contact).

(34.7°C as shown in Fig. 6(d)), the SRF keeps touching the plate surface (ON position), which is depicted in Fig. 6(b).

2) Automatic temperature control: This experiment shows automatic temperature control. The integrated thermistor (temperature sensor of this system) on the SRF tip continuously feeds the temperature value to the controller to actuate the motor. Initially, the hot plate temperature is fixed at more than 40°C. During this time, the temperature of the thermistor is 27°C (room temperature). This is SRF's ON position (from 0s to 2.5s as shown in Fig. 7), and it is touching the hot plate surface. When the temperature of the thermistor reaches 40°C, the SRF goes ON to OFF position (at 2.5s shown in Fig. 7). It stays at the OFF position till the thermistor temperature reaches 27°C (from 2.5s to 5s refer to Fig. 7). When the temperature becomes 27°C, the SRF again automatically moves to the ON position (from 5s to 7.5s, see Fig. 7), and the SRF touches the hot plate. These cycles keep repeating in this experiment.

Applications

1. The SRF can detect soil temperature, which is useful for monitoring the irrigation of the plants to prevent crop damage. This continuous monitoring maintains proper soil temperature and can increase crop production.
2. In chemical laboratories, the SRF is useful for detecting the chemical temperature, while conducting experiments without harming to human resources due to high temperature.

Discussions

This automatic SRF can be applied in various fields. In biomedical use, it handles delicate tissues in surgeries. In industry, it lifts and manages components in robotic system. In agriculture, it helps with tasks like fruits picking. Its low cost also make useful for education in robotics and sensors.

The experimental video captures the following test sequences at the indicated time stamps:

- Weight-lifting capability with different loads of {15g, 20g, 25g, 30g, 35g} (Referring to Section III-(A)): Duration: [0.05s-1.05s].
- Automatic temperature sensing (see to Section III-B): [1.10s-1.28 s].
- Yaw movement (see Section II-D): [1.30s-2.04s]

The complete video documentation of all these experimental procedures is given in the following link: https://youtu.be/X3bT4LGYYF0.

IV. Conclusion

This study presents a new SRF developed using PDMS focusing on its flexibility and autonomy in a broad range of applications. The SRF with dual-servo motors allows to control of bending and yawing. A key feature of the SRF is its integrated feedback controller including flex and temperature sensors. This system provides real-time monitoring and adjustment of SRF's position, managing tasks such as lifting weights and regulating temperature. The experimental results reveal that the developed SRF system has potential applications in industry, agriculture, and biomedical fields.

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