Inflatable Fingertips with Stretchable Pressure Sensors for Adaptive Grasping and Manipulation

Hongyang Shi, Rutav Shah, Zhengjie Li, Heeyong Hah, Yuke Zhu, and Nanshu Lu

***Abstract*—The development of robotic hands that closely emulate the capabilities of the human hand has been a long-standing pursuit in the fields of robotics, prosthetics, and human-robot interaction. The key to achieving this goal lies in the creation of touch-sensitive, adaptive, and compliant fingertips. This proposal presents an approach by introducing inflatable fingertips integrated with stretchable pressure sensors to address critical challenges in robotic manipulation. We begin by highlighting the limitations of existing tactile sensing technologies and the necessity for intrinsically stretchable yet highly responsive electronic skins. Our work tackles two central challenges: first, the creation of soft, rugged, and highly pressure-sensitive materials suitable for highly deformable surfaces, and second, the development of electronic skins with the innate ability to modulate their interaction modalities. We delve into the design, fabrication, and integration processes of these inflatable fingertips, showcasing their potential to revolutionize adaptive grasping and manipulation. By emulating the human hand's nuanced touch, our approach bridges the gap between mechanical efficiency and delicate handling, facilitating safer human-robot collaboration and more versatile robotic interactions with the physical world.**

I. Introduction

In recent decades, the fields of robotics, prosthetics, and human-computer interaction have witnessed remarkable advancements that have brought machines closer to mimicking and augmenting human capabilities. A critical challenge in these domains is replicating the intricate and dexterous nature of the human hand's tactile perception and manipulation abilities. The human hand's adaptability, sensitivity, and ability to grasp objects of varying shapes and sizes [1-3] have made it an object of intense study, inspiring innovative approaches to imbue artificial hands with similar capabilities. However, such versatility in sensing modalities, sensing ranges, and capabilities of adaptation are not yet available to conventional robotic fingers. While traditional robotic hands have made significant strides in industrial settings, their inherent stiffness and lack of tactile sensitivity have limited their applicability in unstructured environments. Conversely, the human hand's intricate tactile feedback mechanism enables not only stable grasping but also fine-tuned adjustments during object manipulation, making it ideal for a wide range of tasks [3].

This work introduces a pioneering development in the realm of robotic manipulation: the integration of inflatable fingertips combined with stretchable pressure sensors. By emulating the characteristics of the human fingertip, this technology aims to revolutionize adaptive grasping and manipulation in robotics and prosthetics. The synergistic fusion of soft robotics, sensor technology, and biomechanical insights has led to the creation of a system that enables robots and prosthetic devices to interact with the environment and objects in a remarkably human-like manner.

The remainder of this proposal is organized as follows: Section II provides an overview of related work in the fields of tactile sensing and adaptive manipulation. Section III delves into the methodology, detailing the design, fabrication, and integration processes of the stretchable pressure sensors and inflatable fingertips. Section IV presents the experimental setup, results, and performance analysis. Finally, Section V concludes the paper by summarizing the contributions and discussing potential future directions in the realm of adaptive robotic manipulation.

II. Related Work

A. Tactile Sensing

In recent years, the emergence of soft robotics has catalyzed innovative developments in tactile sensing. Soft tactile sensors, characterized by their compliance and flexibility, closely mimic the deformable nature of human skin. Researchers have explored various materials, including elastomers and conductive polymers, to create sensors that can be integrated into robotic grippers and fingertips. These sensors offer real-time feedback on pressure distribution, object shape, and surface texture, enabling robots to interact with objects delicately and adaptively. For example, Rao et al. integrated pressure-sensitive rubbers to construct a tactile sensing skin for the robotic hand [4]. Besides mechanical pressure sensors[4-7], magnetic field sensors[8], barometers [9], and thermistors[10] have also been utilized for pressure sensing. However, close physical interactions between humans and robotic hands remain untamed due to the lack of human-hand-like robotic hands which are touch-sensitive, strong yet soft feeling. The first challenge to achieving human-like robotic fingers is the lack of intrinsically soft e-skins, which also have to be able to perform accurate, high-spatiotemporal-resolution pressure sensing as well as being compact and rugged. Stretchable pressure sensors are necessary for covering highly deformable surfaces such as the palm and the fingers of the robotic hand. The second challenge is the lack of e-skins that have the ability to tune

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the interaction modality of themselves[3]. These e-skins should have the versatility to adjust their tactile sensitivity, feedback mechanisms, and response dynamics in real time, depending on the object being manipulated or the task at hand. Achieving this level of contextual adaptation within the e-skin itself would represent a significant advancement in enhancing the robotic hand's ability to interact seamlessly and intelligently with its surroundings.

B. *Adaptive Manipulation*

Adaptive manipulation strategies leverage tactile sensing to enhance grasping and manipulation capabilities. Traditional robotic grippers often struggle to handle objects with variable shapes or uncertain properties. Tactile sensors provide crucial feedback that enables robots to adjust grip strength, finger positions, and contact forces in real time. This adaptability is especially useful for tasks involving delicate objects, unknown environments, or uncertain object positions. By integrating tactile information into their control algorithms, robots can achieve more reliable and versatile manipulation[11], mirroring the human hand's ability to adjust grip based on sensory input.

III. Methods

To address these afore-mentioned challenges, our research delves into the development of inflatable fingertips with integrated stretchable pressure sensors, offering a promising solution to these long-standing limitations. First, it can favor the sensing region actively. Second, it can enable sensing with different sensitivities. Third, it can activate different interaction models by changing the contact stiffness. Last but not least, it can simplify the control scheme of the robotic hands because pneumatic inflation at the fingertip is much simpler and computationally cheaper than motion controls of all finger joints. In return, the stretchability characteristics makes this stiffness-tunable e-skin possible.

A. *Stretchable Hybrid Response Pressure Sensors*

A highly innovative stretchable hybrid responsive pressure sensor (SHRPS) was devised in our previous work [12]. This sensor combines hybrid piezoresistive and piezo-capacitive responses under pressure with a capacitance-dominated response under stretch. The SHRPS consists of four stretchable layers, namely top and bottom electrodes, a barely conductive porous nanocomposite (PNC) layer with carbon nanotubes (CNT) doped in Ecoflex 00-30 elastomers, and a dielectric layer inserted between the PNC and the bottom electrode (**Figure 1**).

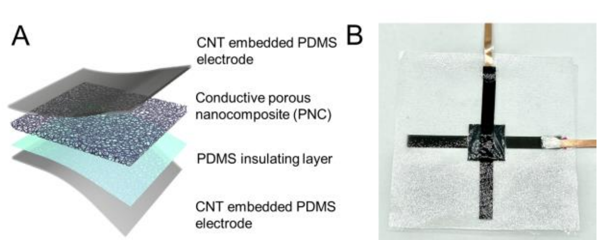

Figure 1. Stretchable hybrid responsive pressure sensor (SHRPS). A) Schematic representation of the different layers in a SHRPS. B) A photograph of a SHRPS with a 15 mm × 15 mm patch of PNC, and two 5 mm × 60 mm CNT-embedded PDMS electrodes.

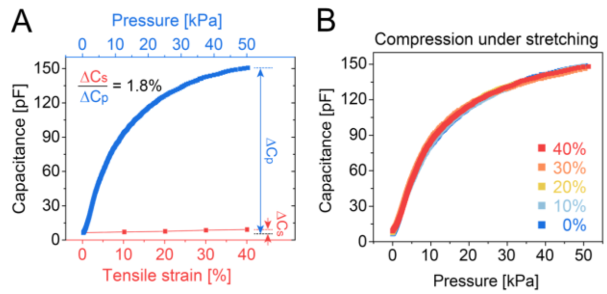

Figure 2. Pressure and stretch responses of SHRPS. A) Pressure (blue) and stretch (red) were applied separately. B) Pressure and stretch were applied simultaneously.

The SHRPS with 0.4-wt%-CNT-doped PNC boasts an impressive sensitivity of 2.13 kPa-1 within 0 kPa^{-1} kPa, 1.55 kPa^{-1} within 1 kPa - 5 kPa, 0.82 kPa^{-1} within 5 kPa-10 kPa, 0.42 kPa^{-1} within 10 kPa-30 kPa, and 0.21 kPa^{-1} within 30 kPa-50 kPa, and remains sensitive up to 300 kPa. It is also stretchable up to 70% under both uniaxial and biaxial tension, showing only a small, normalized capacitance change compared to the pressure response. Despite its high stretchability, the SHRPS's high sensitivity to pressure overcomes its stretch response, resulting in accurate pressure readings even under stretching conditions (**Figure 2**).

Robotic systems usually run at a high sampling frequency (100 Hz) to update its policy and collect data from all the sensors. In order to implement soft tactile sensing with our SHRPS sensor array, a higher scanning frequency is also required. Our previous analytical modeling and experimental results have shown that the SHRPS with a higher CNT doping ratio in the PNC at higher AC excitation frequency [13]. For example, 0.8-wt% doping ratio PNC at 16 kHz excitation signal, can present higher pressure sensitivity than the SHRPS with a lower CNT doping ratio in the PNC, such as 0.4-wt% doping ratio at 3 kHz. Therefore, first, a 16 kHz excitation AC was selected which facilitated a maximum sampling rate of 317 Hz. Second, to achieve higher spatial resolution of a soft pressure sensor array, the area of each pixel and the spacing between adjacent pixels should be as small as possible, but with still high pressure sensitivity. For a single pixel SHRPS, we investigated the effect of different widths on the pressure response (**Figure 3**). The results show that when the PNC patch adopted the same dimensions of 15

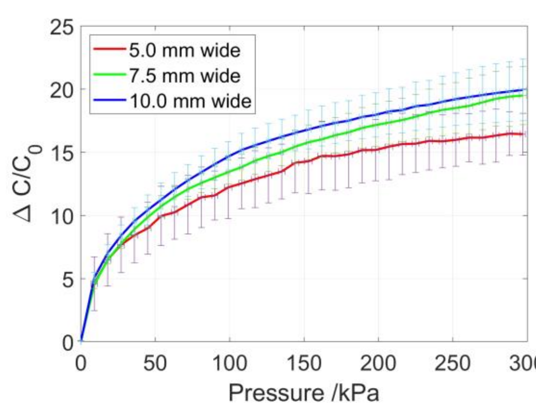

Figure 3. Pressure responses of SHRPS with different widths of CNT-embedded PDMS electrodes.

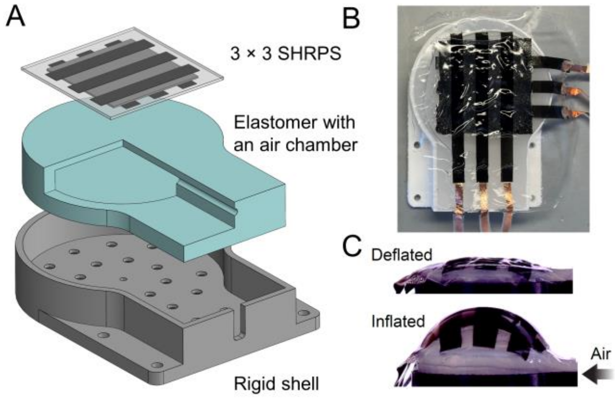

Figure 1. A 3×3 array of SHRPS on a soft inflatable fingertip. A) Schematic illustration of the components of the inflatable fingertip. B) A photograph of the inflatable fingertip with a 3×3 array of SHRPS attached on the membrane surface. C) The fingertip in deflated and inflated modes.

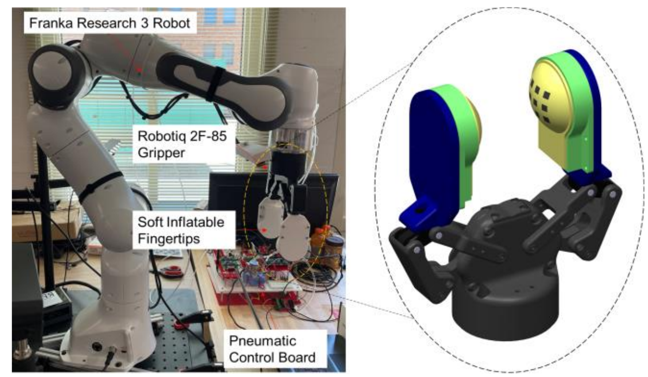

Figure 2. Experimental setup for adaptive grapsing and manipulation of delicate objects.

mm × 15 mm, the SHRPS with 10 mm wide CNT-embedded PDMS electrodes exhibits the highest sensitivity and largest relative change in capacitance, about 20 times under 300 kPa compression, while the SHRPS with 5 mm wide electrodes presents a lower sensitivity, reaching about 16 times of change in capacitance at 300 kPa pressure. This difference is due to the area mismatch between the PNC area and the overlapping area of the crossbar CNT/PDMS electrodes. But overall, the sensitivity of SHRPS with 5 mm wide electrodes are still high enough to be used for tactile sensing.

B. Design and Fabrication of the Inflatable Fingertips

To demonstrate SHRPS' large stretchability and relative insensitivity to stretch, a 3 x 3 array was laminated on a soft, inflatable fingertip as illustrated in **Figure 4A-B**. The inflatable fingertip was bonded on the rigid shell in order to be mounted on the robotic grippers for further grasping tasks. Unlike conventional rigid fingertips that have a fixed geometry and property, this soft fingertip can adjust its shape (from flat to half-dome, **Figure 4C**) and stiffness (from 0.07 N/mm to 0.36 N/mm) through inflation to suit various applications.

IV. Experiments

With the optimized structural design and characterization of the SHRPS pressure sensors and the inflatable fingertips, the performance of robotic grasping and manipulation of objects such as plastic cups, soft fruits, curve-shaped containers, and many other delicate objects, could be investigated.

A. Experimental Setup

The experimental setup was composed of five parts (**Figure 5**):

Robotic arm: A Franka Research 3 collaborative robot (Franka Emika) was used in this experiment with open-loop control. The robotic arm was controlled by a set of virtual reality headset and a touch controller (Meta Quest 2) to achieve large range motion during the object picking and placing process.

Robotic gripper: A Robotiq 2F-85 robotic gripper was installed on the Franka Research 3 robot. The gripper had a wide stroke of 85 mm with integrated position, speed, and force control.

Inflatable fingertips: The SHRPS-attached inflatable fingertips were mounted on the Robotiq 2f-85 gripper by replacing its original fingertip pads with our customized 3d-printed parts. The wires of the two 3×3 SHRPS arrays were separately connected to two customized data acquisition boards to determine the capacitance at each pixel. Impedance was measured by a 12-bit impedance converter (AD5933, Analog Devices) after calibration. A 16 kHz AC frequency was used to stimulate external impedance, and the response signals were sampled and digitally converted to impedance data a sampling rate of 317 HZ. In order to acquire information from multiple channels within the grid, two analog multiplexers (SN74LV4051A, TI) were used to provide row- and column-selection capability. The data were recorded by a nearby PC for post-processing.

Pneumatic control system: The Soft Robotics Toolkit Control Board was used as our pneumatic control system to operate and control the inflatable soft fingertips. The board consisted of a mini pump and a set of solenoid valves. The pressure in the system was regulated by Pulse-Width Modulation (PWM), which involved the controlled timing of the opening and closing of the valves. Commercial pressure sensors (ASDXAVX100PGAA5, Honeywell) provided feedback on the behavior of the system. The board was controlled automated via PID control.

Computer: A laptop was used to record the measured impedance data and visualize the capacitance change simultaneously for those two 3×3 SHRPS arrays through a Python program.

B. Results

A plastic cup was tested in the experiment due to its softness, flexibility, and curved shape. The robotic gripper was first controlled to find the position of the plastic cup, and then started to decrease its gap and grip the cup gradually. **Figure 6** shows the visualization of the grasping when the soft fingertips were set in the deflated mode, which means the internal chamber was enclosed without air leakage or

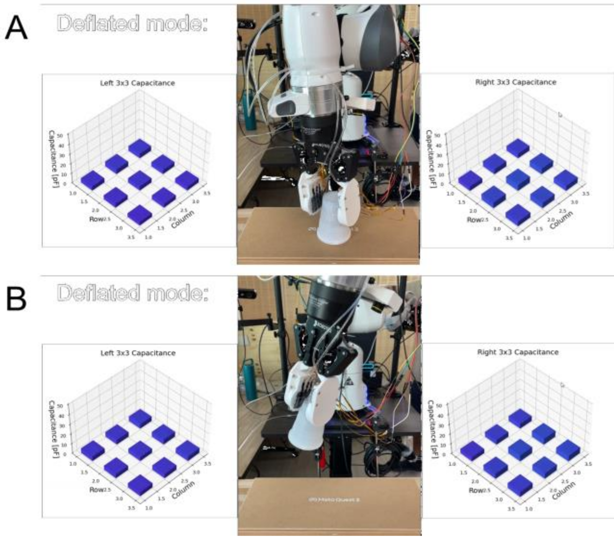

Figure 3. Mapping of pixel-wized capacitance change during the grapsing of a plastic cup using the soft inflatable fingertips in the deflated mode. A) The visualization results when the deflated fingertips first grasped the plastic cup before lifting off. B) The visualziation results when the plastic cup was moved and tilted in air.

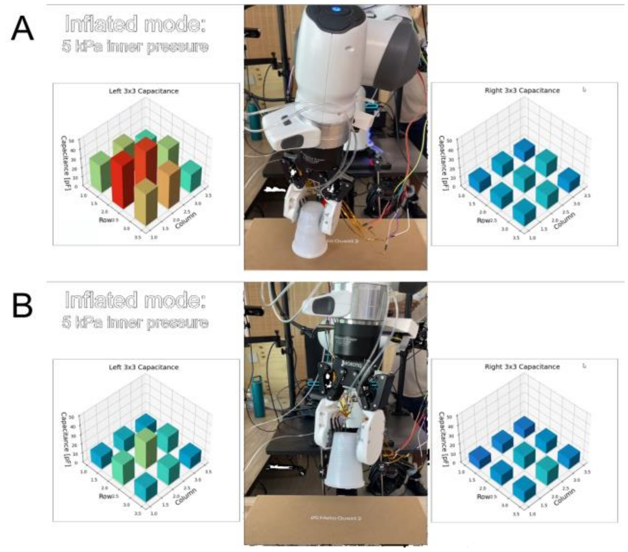

Figure 4. Mapping of pixel-wized capacitance change during the grapsing of the same plastic cup using the soft inflatable fingertips in the inflated mode (internal pressure kept at 5 kPa by PID control). A) The visualization results when the deflated fingertips first grasped the plastic cup before lifting off. B) The visualziation results when the plastic cup was moved and tilted in air.

external air input. When the deflated fingertips grasped the bottom of the plastic cup (upside down) before lifting it off, the capacitance measurements on each side of the grippers were quite small, at about 8 pF at each pixel (**Figure 6A**). After the plastic cup was gently grasped between the soft fingertips and was moved in a titled pose in the air, the capacitance at each pixel was still about 8 pF without obvious change. This results were mainly resulted from the tapered and curved shape of the plastic cup, where its conical wall was compressed to contact the outside elastomer boundaries of the soft fingertips, while the 3×3 array of SHRPS did not have a good contact with the plastic cup during the whole grasping procedure. This usually leads to the missing of critical contact force/pressure information, and sliding of the object is easily to happen without prompt feedback.

For the inflated-mode grasping, the fingertips were first inflated to an internal pressure of 5 kPa and kept dynamically at this level via PID control. As the SHRPS sensors were compressed and stretched by the internal air pressure, the capacitance gained to around 20 pF. When the fingertips contacted the bottom and wall of the plastic cup, the capacitance of the central pixel within the left SHRPS array immediately escalated from 20 pF to 50 pF, while the other pixels also increased by some (**Figure 7A**). This resulted from the shape conforming of the inflatable fingertips where a direct contact between the central pixel of the SHRPS array and the plastic cup was formed. Also, as the membrane of the fingertip was inflated to a dome shape, the central pixel exhibited a more concentrated pressure during the grasping. This significant change in capacitance upon contact can expedite the detection of objects during exploration, and can help monitor the grasping status of the objects in order to prevent sliding.

V. Conclusion and Future Work

This work shows the initial developments towards a robotic system for adaptive grasping and manipulation of objects based on inflatable fingertips with stretchable hybrid response pressure sensors that can provide tactile sensing with tunable shape and stiffness. One current limitation of the work involves the spatial resolution and scanning frequency of the SHRPS sensor arrays. To make the inflatable fingertips with better performance, we need to implement a multiprocessing data acquisition system that measures the capacitance of each sensor array using multiple impedance converter or capacitance-to-voltage converters simultaneously.

As we move forward, the first objective is to implement a close-loop feedback control based on the tactile sensing information such that the grasping tasks can be guided with optimal inflation pressure and gripper opening distance. Grasping and detection of objects with different shapes, sizes, stiffness, and textures will be investigated. Then the safety, robustness, and success rate of the system performing physical human body manipulation, such as limb repositioning actions, will be evaluated.

Acknowledgment

This research was mainly sponsored by the Cockrell School of Engineering at the University of Texas at Austin. N. Lu acknowledges partial support from the US Office of Naval Research through Grant N00014-20-1-2112, the US Army Research Office through Cooperative Agreement No. W911NF-19-2-0333, and the US National Science Foundation through Grant ASCENT-2133106.

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