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Fully 3D printable Robot Hand and Soft Tactile Sensor based on Air-pressure and Capacitive Proximity Sensing

†Sean Taylor, †Kyungseo Park, Sankalp Yamsani, and Joohyung Kim

***Abstract*— Soft tactile sensors can enable robots to grasp objects easily and stably by simultaneously providing tactile data and mechanical compliance to robotic hands. If there are low-cost and easy-to-build robotic hands equipped with soft tactile sensors, they would be highly accessible and facilitate many robotics projects. To this end, we propose an accessible robot hand capable of tactile sensing, which can be produced through digital fabrication. We made the robot hand using commercial servo motors as well as components 3D printed from PETG, TPU, and conductive TPU. These materials allow the robot hand to have a soft, durable, and even functional structure. Specifically, the soft fingertip was crafted from TPU and conductive TPU, and their mechanical and electrical properties enable easy implementation of tactile sensing capabilities, such as force and capacitive touch, simply by adding off-the-shelf sensors (air-pressure and capacitance). The proposed robot hand could effectively sense interaction forces and proximity to conductive objects, and its utilization in various tasks was also demonstrated successfully.**

I. INTRODUCTION

As collaborative robots become more readily available, there is a growing interest in utilizing robots for object manipulation. This trend is driving an increased demand for robot hands and motivating numerous studies. In particular, there are active research projects on open-source robot hands, such as Yale OpenHand, OpenBionics, Pisa/IIT SoftHand, which can be easily customized according to users' needs and preferences [1]–[3]. These robot hands have a significant advantage over commercial robot hands in terms of affordability, ease of production, and modification.

However, the fabrication process of such robot hands can still be laborious from the perspective of an average person at times. For instance, creating soft components (silicone rubber) involves tedious steps such as making molds, casting, degassing, and curing. These processes require equipment such as ovens or vacuum chambers that are not always available. Furthermore, since these tasks are still carried out manually by individuals, the fabrication process can be arduous, and the results can also be influenced by human factors. PolyJet-type printers can alleviate these challenges to some extent, but their high cost remains a limitation [4].

To address these issues, Zhou et al. introduced an adaptive gripper (InstaGrasp) that significantly reduces fabrication and assembly time by utilizing 3D printable materials (PLA, TPU) and commercial motors [5]. The gripper was created using only a hobby-grade 3D printer, with a total cost of less than 100 GBP (125 USD), and the entire fabrication process took less than 18 hours (17.5 hours of printing time and 10 minutes of assembly time). Moreover, the exceptional mechanical properties of TPU impart flexibility and durability to the gripper, enabling it to securely grasp various objects. This clearly demonstrates the advantages and potential benefits of leveraging digital fabrication.

†These authors contributed equally to this work. All authors are with the KIMLAB (Kinetic Intelligent Machine LAB) at the University of Illinois Urbana-Champaign, Urbana, 61801 IL, USA. (e-mail: `seanlt2, kyungseo, yamsani2, joohyung`@illinois.edu).

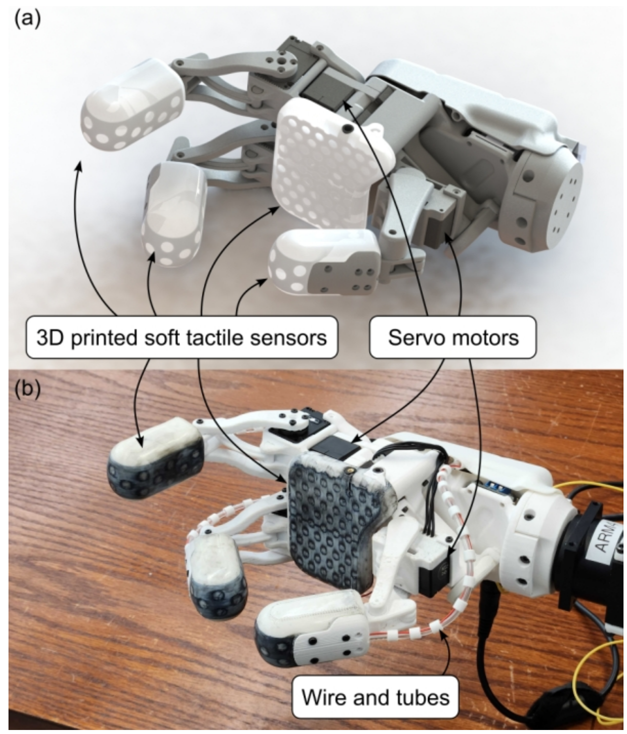

Fig. 1. Fully 3D printable Robot hand and soft tactile sensor (a) rendering image of the proposed design; (b) photo of the implemented robot hand and tactile sensors. The robot hand is installed on a robot arm.

Tactile data play an important role in grasping and object manipulation, as it informs how robot hands physically interact with the external environment. This has motivated research into various types of tactile sensors [6]–[10]. For example, vision-based tactile sensors obtain high-resolution tactile data by capturing a deformation of elastomer caused by tactile stimuli through a camera. Many studies have been reported utilizing high-quality tactile images obtained from vision-based tactile sensors for contact-rich tasks [11].

Meanwhile, Wettels et al. developed a multi-modal tactile sensor using conductive liquid, which was capable of sensing interaction force as well as vibration and temperature [12].

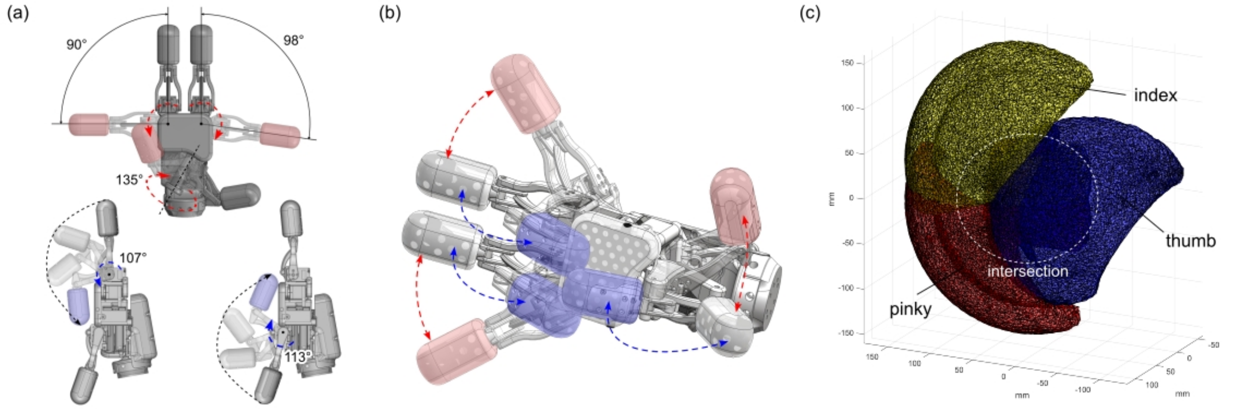

Fig. 2. (a) range of motion of the developed robot hand and (b) view from third-person perspective. Abduction and adduction are shown in red color while flexion and extension are shown in blue color; (c) workspace of the developed robot hand.

Despite its somewhat lower spatial resolution compared to the vision-based sensor, this system was usable not only for general tasks but also for material recognition or haptic feature extraction [13], [14]. Additionally, although it doesn't take the form of a finger, there is research that has achieved safe and gentle physical interactions by simultaneously implementing mechanical compliance and pressure measurement using a 3D printed soft shell and an air pressure sensor [15], [16].

In this context, our goal was to develop an accessible robot hand based on digital fabrication, embedded with a soft tactile sensor (see Fig.1). This approach will enable us to create a robot hand with the following advantages: (1) cost competitiveness, (2) easy and automated production process, (3) decent tactile sensing capabilities to boost the usability of robot hands.

The developed robot hand was fabricated using commercial motors and various 3D printable materials (PETG, regular TPU, conductive TPU). To leverage the properties of these materials, we integrated off-the-shelf ICS (air pressure and capacitance) with 3D printed parts. The air-pressure sensor perceives external forces by measuring the volumetric pressure changes within an airtight cavity, while the capacitive sensor recognizes adjacent conductive objects based on capacitance values.

Additionally, data acquisition and processing were carried out by a small MCU, and the resulting tactile data were set to be published via ROS. Leveraging the benefits of open-source and digital fabrication, these features will facilitate the seamless integration of the proposed robot hand with various projects. This paper is organized as follows: section II describes the hardware design and fabrication. Section III shows the experiments to test the characteristics of the developed soft sensor and the results. Section IV presents examples to demonstrate the usability of the developed robot hand. Lastly, the significance and limitations of this work, and future research directions are discussed in Section V.

II. Hardware Design and Fabrication

A. *Hand Design*

The hand consists of 3 fingers: one thumb, one index finger, and one pinkie (see Fig. 2.). Each finger has 2 degrees of freedom, meaning that the entire hand has a total of 6 degrees of freedom. Each finger has 2 joints which are actuated using Robotis XL 330 series servo motors, the most distal joint in each finger is controlled by a four-bar linkage mechanism. We choose three fingers since we wanted the hand to be compact yet capable of grasping robustly. The linkage mechanism was based off one used in similar work here [16]. Since this hand needs to be easily mounted to existing robot arms, we avoided using any sort of tendons which would have to be actuated outside of the hand.

With the thumb, index, and pinkie finger, the motors are use for flexion, adduction, and abduction. For the thumb, the adduction / abduction motion is created by a skewed roll joint. The skewed roll joint is positioned in a way that allows the thumb to move between the center of the hand for precision grasping and the side of the hand for power grasping.

By using MATLAB, we created a basic model of the hand, which was used to analyze the workspace and the maximum finger-span for each finger. To calculate the workspace, we first derived the theoretical maximum joint angles by checking for internal collisions within the robot hand itself. Once these limits were found, we determine the workspace for each finger by generating random joint values within this joint space and finding the position of the fingertip for each of these values. We then generated points which would be on the surface of the fingertip and created a point cloud. From this point cloud, we generated three envelopes to represent the workspace of each of the 3 fingers as seen in Fig. 2c.

By analyzing these workspaces, we were able to make initial comparisons among potential designs. We looked at both the total area of the three workspaces as well as the areas where the workspaces intersected. These intersections were important as they represent the areas where multiple fingers can be simultaneously used to grasp a same object.

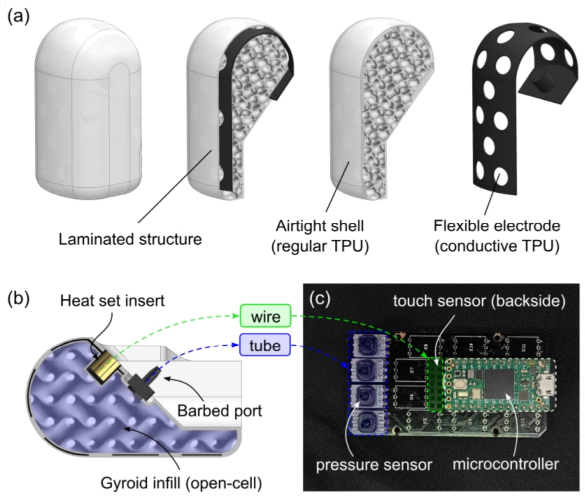

Fig. 3. (a) structure of 3D-printed soft fingertip; (b) connection between soft fingertip and sensing electronics; (c) sensing electronics (microcontroller and sensors).

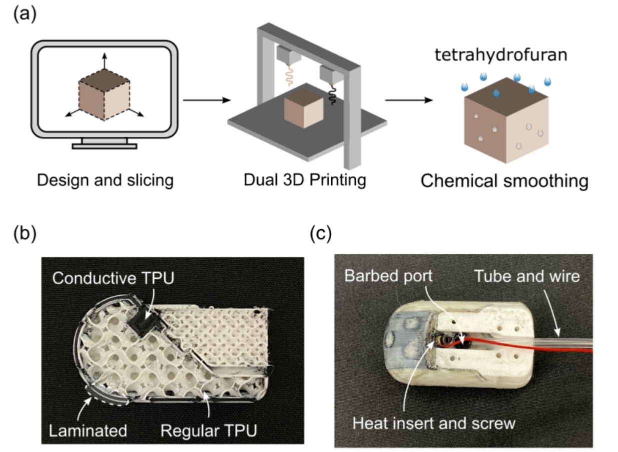

Fig. 4. (a) digital fabrication and post-process; (b) cross-sectional image of the soft fingertip captured during 3D printing; (c) assembly of soft tactile sensor.

In this design, we mainly varied these parameters: (1) the x and z coordinates of the adduction motors of the pinkie and index fingers, (2) the x and z coordinates of the roll motor for the thumb, and (3) the angle of the roll motor relative to the palm and the y-directional offset of the thumb.

B. Sensor Design

The developed robot hand contains a total of 4 sensors, one at the tip of each finger and on in the palm, as shown in Fig.3. Each sensor contains both a soft pneumatic shell for force sensing as well as a flexible electrode for capacitive-type proximity sensing. The pneumatic shell is compressible TPU structure printed with a gyroid infill. The infill is similar to an open cell foam structure in that it allows air to freely move inside the structure. Also, it helps prevent other parts of the shell from bulging when the internal pressure changes due to external forces, ensuring that deformation only occurs where the force is applied. The pneumatic shell is connected to a piezoresistive air pressure sensors (ABPDANT005, Honeywell) by tubing.

The flexible electrode is made of a conductive TPU. This layer is separated from the outside of the sensor by thin layer of non-conductive regular TPU. When a conductive object is close to the ground, there exists a capacitance between the object and the electrode (conductive TPU layer). Since the conductive TPU is somewhat stiffer and more fragile than regular TPU, we perforated the flexible electrode and laminated it between layers of regular TPU to ensure better flexibility durability of the shell. Also, the flexible electrode has a terminal where metal heat inserts could be installed, making it easy to connect to the capacitive-type proximity sensor (AT42QT1070, Microchip Technology) via wires.

Since the soft tactile sensor was made solely of flexible materials, we needed to add a rigid backbone to maintain the placement and shape of the sensor. We created the backbone using PETG due to its high durability and ability to chemically bond with TPU. Additionally, the tubes and wires were routed inside the structure of the robot hand, and they were connected to the sensing electronics.

C. Fabrication

To simplify the structure and fabrication process, we have used commercial servo motors (Dynamixel, Robotis) and FDM 3D printer. The robot links were printed in place out of PETG filament using a 3D printer (Creator 3 pro, Flashforge). We used PETG filament to facilitate bonding with the soft materials. The soft tactile sensor consists of regular TPU (NinjaFlex, Fenner) and conductive TPU (Eel, Fenner), and these parts were printed together as one part on a 3D printer equipped with dual extruder (E2, Raise3D). Printing these structures together in this manner greatly simplified the fabrication process, achieving a soft, durable, and functional structure. After each segment was printed, its surface was chemically smoothed with an organic solvent called tetrahydrofuran (THF); this step closed small holes that could cause air leaks and also removes any conductive material that was unintentionally deposited on the surface during the printing process.

A heat-set insert is added to a terminal of the flexible electrode for an easily removable yet secure connection with an M2 screw. A plastic barbed port is also added to a hole in the soft shell and is sealed using cyanoacrylate adhesive (superglue). Initially, we were concerned that the superglue might crack over time and cause a leak. However, this did not become an issue, likely because the barb is installed in a part of the sensor that is unlikely to undergo deformation. After the barb is added, we checked for air leaks by pressurizing the sensor and holding it under water where the presence of bubbles will reveal any defect. If no leaks are found, we added a PETG segment to provide and attachment point. This component is printed separately and fused to TPU shell using THF since it can dissolve both materials. When this occurs the the polymer chains of the two materials intermix, and as the solvent evaporates, a strong bond is formed.

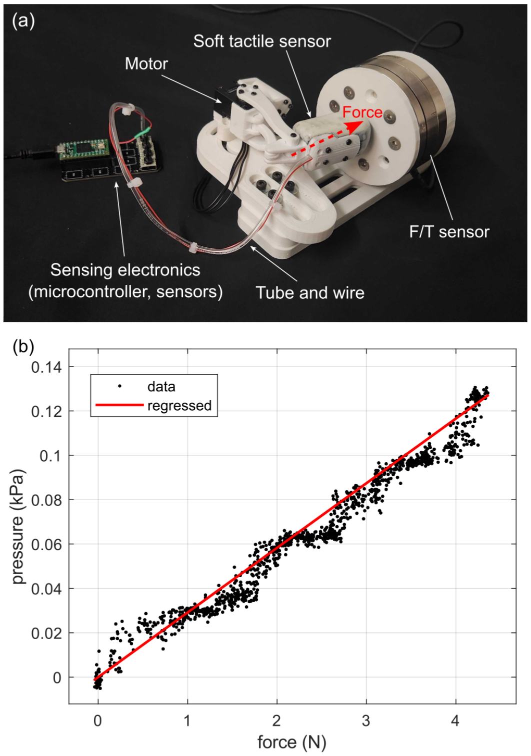

Fig. 5. (a) setup for loading test; (b) relationship between the applied force and the resulting changes in internal air pressure.

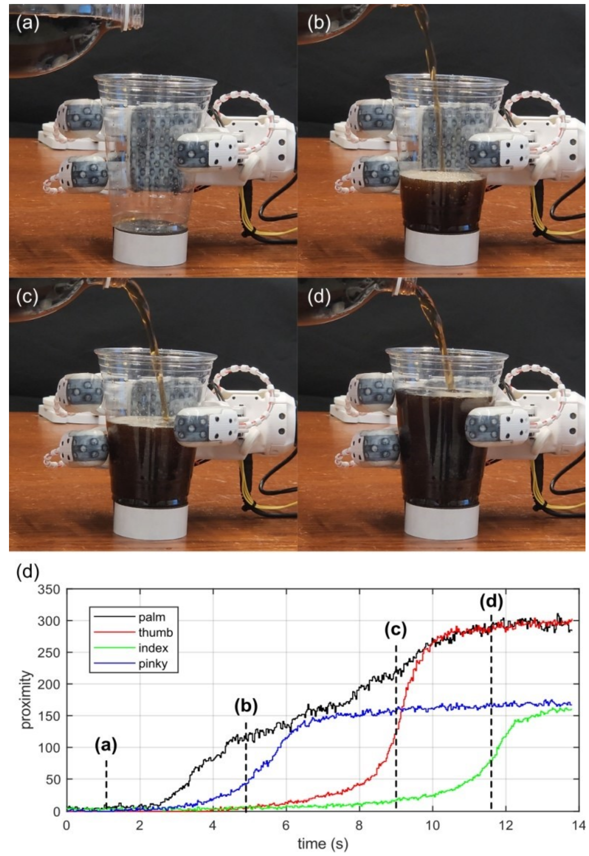

Fig. 6. Proximity sensing test and its result. The liquid level gradually rose from (a) an empty bottle up to the point where the (b) little finger, (c) thumb, and (d) index finger are positioned.

III. Experiment

A. Loading Test

Figure 5 shows an experiment setup to obtain the relationship between the applied force and the resulting air pressure change. The setup has a custom fixture that includes a force/torque sensor and a robotic finger with a tactile sensor. The fixture was 3D printed using PLA components and allowed the finger to be placed in different positions.

During the test, the robot finger firstly moved into a position where it made a contact between the force/torque sensor and fingertip sensor. Data logging then commenced, measuring values from both the force/torque sensor and the air pressure sensor. Subsequently, the robot finger was moved to follow a sinusoidal trajectory with an amplitude of 0.15 radians for one cycle, and the data logging stopped. In this setting, the contact was maintained for approximately one minute.

The results of the loading test are also presented in Fig. 5. As the force applied to the sensor increased, the resulting pressure within the shell likewise increased. This graph shows that the developed sensor is capable of sensing external forces by measuring volumetric pressure changes. The relationship was monotonic and somewhat linear; however, the data quality was not as ideal as that of other sensors. Also, we observed an issue that the sensitivity varies depending on the level of deformation and the location where contact is made. The likely reason for this is the variations in mechanical properties at different locations, so it can be fixed by adjusting the sensor's geometry and printing parameters.

B. Proximity Sensing Test

An experiment was conducted to demonstrate the efficacy of the capacitive-type proximity sensing in the fingertips and palm of the hand. The procedure involved firmly grasping a cup with the three fingers of the hand at three distinct levels. Following the secure grip, we start to log the data from the proximity sensors paired with flexible electrodes (conductive TPU), which is embedded in the palm and each of the fingertips. We then evaluated the sensors feedback by pouring liquid carefully into the cup.

The results of the proximity sensing test are presented in Fig. 6. The graph clearly illustrates the response of each fingertip's sensor as the liquid is poured into the cup (the signal is not calibrated here). As the liquid level gradually rises, the sensor begins to react once the liquid crosses the corresponding finger level. It should be noted that this function is only available only when the adjacent material is electrically conductive. Since each fingertip was placed on different position, the signals were changed at a different timing, allowing us to determine the precise moment at which the liquid reaches the height of each fingertip.

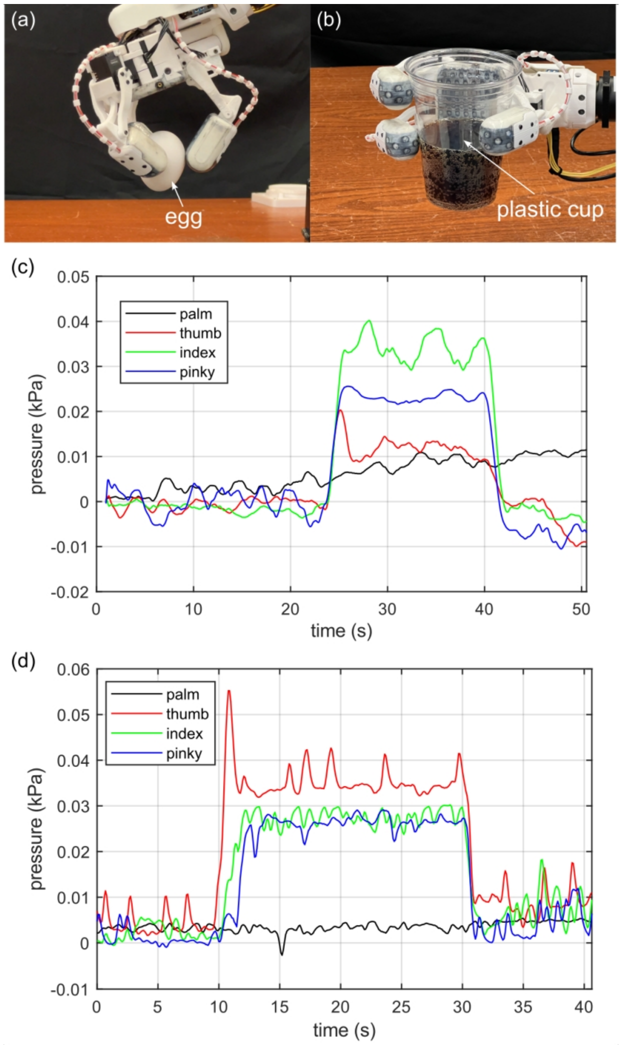

Fig. 7. Demonstration of grasping fragile objects using air pressure signals. (a-b) The robot hand could grasp fragile objects such as a flexible plastic cup and an egg. The finger position was adjusted to keep the air pressure signals lower than the threshold; (c) air pressure values when grasping an egg; (d) air pressure values when grasping a cup.

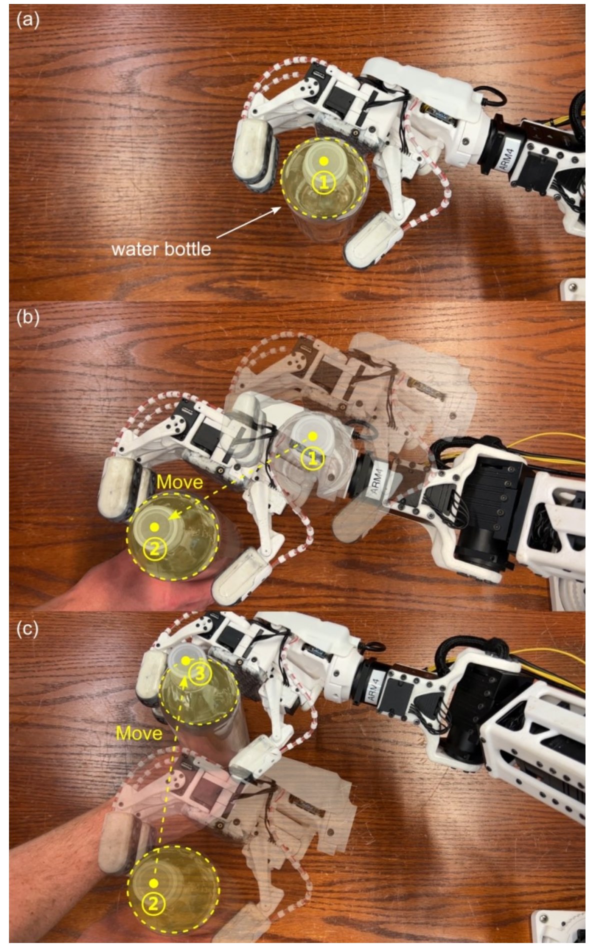

Fig. 8. Demonstration of pre-grasping using capacitive proximity signals (adjusting hand position before grasping). The cup was moved by hand, and the robot hand could chase it in real-time by leveraging the proximity values. (a) initial position; (b-c) pre-grasping result

IV. Demonstration

A. Grasping using Air-pressure Data

To demonstrate the force-controlled grasping capabilities of the hand, we employed two delicate objects: a plastic cup filled with liquid and a raw egg. We integrated the hand with a 6-DOF manipulator [17] and utilized the air pressure sensor in the fingertips to showcase the hand's ability to delicately grasp the objects of varying fragility. Each object was intentionally positioned to facilitate grasping. The plastic cup required a grasp from side (large diameter grasp), while the egg required a tripod grasp from to side [18].

The hand was placed in an ideal pre-grasp position, and the fingers gradually approached the object of interest. As the fingers contacted the object, the air pressure signal increased. Once the air signal reached a specific threshold, the fingers ceased movement. Each finger had different values for the contact pressure threshold that was heuristically set to ensure a stable and secure grasp of the object. Once a firm grip was achieved, the object was carefully lifted off the table and subsequently placed down. The result demonstrates that the developed tactile sensor is sensitive enough to delicately grasp and lift fragile objects (see Fig.7).

B. Pre-grasing using Proximity Data

To showcase the utility of the capacitive proximity sensing capabilities of the robotic hand, we conducted a demonstration to properly position the object between the fingers and the palm of the robotic hand (see Fig. 8). In this experiment, the hand is once again integrated with a 6 DOF arm. We then place the hand in an initial pre-grasp configuration, and an object is placed within a certain distance from the fingertips and palm of the hand. By leveraging the proximity sensors integrated into each finger and the palm, we were able to obtain real-time values proportional of the inverse of distance between the object and a corresponding sensor

TABLE I. Total fabrication cost of the robot hand

Part Type	Model Name	Qty.	Unit price (USD)
Air pressure sensor	ABPDANT005	4	31.46
Proximity sensor	AT42QT1070	1	1.20
Servo motor	XL330-M288-T	6	23.90
Comm. converter	U2D2	1	32.10
Microcontroller	Teensy 4.0	1	23.80
Circuit board	-	1	< 5.00
Miscellaneous	-	-	< 40.00
		Total	$<$ **370.00**

pad. By harnessing this proximity data, we could determine servoing commands to move the hand for pre-grasping task.

During the demonstration, the system strived to align the proximity readings from the index finger and thumb to achieve centering in the x direction. Simultaneously, the proximity values from the palm were used to adjust the distance between the object and the palm. Constraints were also imposed to restrict the system's motion solely to the x and y directions of the end effector.

As observed in the demonstration, the system showcased the ability to maneuver itself to center the object between the fingers and palm. This pre-grasping capability provides a huge benefit in grasping tasks, enabling a secure and stable grip on the object. For example, this would be advantageous in environments such as a kitchen, where manipulating containers filled with liquid is required. Additionally, the proximity value can be utilized to prevent overflowing by monitoring the liquid level in real-time.

V. CONCLUSIONS

This paper presents the design and implementation of a robotic hand equipped with soft tactile sensors, all of which are fully 3D-printable. The developed robotic hand consists solely of commercial servo motors and 3D-printed components, allowing the system to feature high accessibility through a simplified fabrication process and low production costs. Notably, the soft fingertip itself was fabricated from PETG, regular TPU, and conductive TPU, forming a structure that is soft, durable, and functional. This combination was selected because these materials can be fused together either through heat or organic solvents. The total fabrication cost for the proposed hand is less than 370 USD, as shown in Table I, which is quite affordable compared to other robotic grippers of similar actuation DOF and sensing capabilities.

For evaluation, we conducted experiments to test the characteristics of the soft tactile sensors. The results show that the developed sensors possess sufficient performance for grasping tasks, despite several drawbacks such as low pressure sensitivity, drift due to ambient temperature, and limited type of detectable materials. We also demonstrated grasping and pre-grasping tasks utilizing the tactile data and found that these data can offer benefits in handling fragile objects or liquids. Given its high accessibility and affordability, the developed system has significant potential for widespread adoption, offering immediate and substantial benefits to research endeavors requiring robotic hands.

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