A Modular Bio-inspired Robotic Hand with High Sensitivity

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Abstract— While parallel grippers and multi-fingered robotic hands are well developed and commonly used in structured settings, it remains a challenge in robotics to design a highly articulated robotic hand that can be comparable to human hands to handle various daily manipulation and grasping tasks. Dexterity usually requires more actuators but also leads to a more sophisticated mechanism design and is more expensive to fabricate and maintain. Soft materials are able to provide compliance and safety when interacting with the physical world but are hard to model. This work presents a hybrid bio-inspired robotic hand that combines soft matters and rigid elements. Sensing is integrated into the rigid bodies resulting in a simple way for pose estimation with high sensitivity. The proposed hand is in a modular structure allowing for rapid fabrication and programming. The fabrication process is carefully designed so that a full hand can be made with low-cost materials and assembled in an efficient manner. We demonstrate the dexterity of the hand by successfully performing human grasp types.

I. INTRODUCTION

Dexterous manipulation and grasping have been and are still being actively explored in robotics, including motion planning in high dimensional space [1], finger contact model [2], in-hand manipulation with visual feedback [3] or tactile sensing feedback [4]. While it is a common daily task for humans to interact with various objects, manipulation and grasping activities in the real world are still challenging for robots. In order to successfully deploy a robot that can handle manipulation and grasping tasks in daily life, an intelligent system that is capable of adapting to various scenarios and utilizing different strategies is needed. Robotic hardware is fundamental for achieving this goal.

In order to handle more general manipulation tasks, more complex robot hand designs are usually required. More degrees of freedom (DoFs) are helpful to address various scenarios but may not be practical in real applications. On the other hand, simple hands are often more robust and can usually offer more reliable performance but have limited applications. For example, grippers are commonly deployed in industry. Vacuum grippers are easy to use for moving packages and are also suitable for picking up and placing small components. Parallel jaws with single actuators are also popular, e.g. Willow Garage Velo 2G [5]. Simplified multi-fingered hands could offer more dexterity. These hands are simple and nonanthropomorphic leading to low cost. However, they usually can perform a restricted class of tasks

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and cannot achieve generality. Highly articulated robotic hands are promising for handling a much wider range of tasks. Many researchers have been trying to replicate human hands by using more sophisticated mechanism designs and adding more actuators and sensors, e.g. Shadow robotic hand [6]. However, these hands are expensive and difficult to fabricate, calibrate, and maintain. One solution to reduce the complexity and also maintain the anthropomorphic design is to use underactuation, namely using fewer number of actuators to achieve more DoFs. For these designs, cabledriven approaches have been commonly used.

Compliance and safety are critical for robots when interacting with the physical world, especially with human beings. Using soft materials is a promising solution to make compliant robots. Such robots could be more adaptive to different tasks without relying on sophisticated control strategies. Moreover, soft materials have greater interaction safety by absorbing impact energy. However, soft robots usually require heavy actuation systems (pneumatic or hydraulic), and are also difficult to model due to the lack of precision. Because of the design and the fabrication techniques of soft robots [7], soft robotic hands are usually limited to several single-DoF fingers and are not capable of doing dexterous inhand manipulation tasks compared with rigid robotic hands.

In nature, it is common that soft materials and rigid bodies are combined together to construct tissues. This combination can create strong, precise, and also compliant biological systems. This fact has inspired the robotics community to explore soft-rigid structures. In this paper, we show that the combination of soft materials and rigid elements can generate novel robotic tissues that are able to inherit the benefits of both materials leading to performance that cannot be achieved by either one independently. The topological connection of the rigid elements defines the kinematic structure. The electronics can be integrated for sensing and measurement. A multi-layer silicone casting process is presented in order to mix the soft materials with the rigid elements while also maintaining the structural architecture of these rigid elements. The resulting robotic tissue integrates soft materials for compliance and shaping with an articulated rigid skeleton for structural strength and pose measurement. Using this approach, we created a bio-inspired robotic hand. We precisely cloned the shape of a human hand and all the bones. We converted the hand skeleton into several carefully designed bone-style linkage systems. These linkage systems are cable-driven and have integrated position sensors. The finger design has three joints and can be easily customized for different number of actuators. One significant advantage of this solution is low cost. Low-cost sensors and devices

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are important for rapid prototyping and research exploration that can provide easy customization and facilitate robotics benchmarks. For example, low-cost position sensors using paints can be easily customized to fit into highly space constrained modular robots [8]. Furthermore, low-cost robot platforms made by servo motors and simple mechanical components can be easily set up for benchmarks [9]. The robot tissue can be made using 3D printed components and low-cost materials (cables, pins, tubes, silicone, and magnets) easily by following our fabrication procedures. The modular design of the robotic hand also allows customization to generate robotic grippers in various morphologies, including the human hand morphology. Furthermore, after mounting all five fingers on a palm, we can derive a robotic hand that is highly similar to a human hand and is able to generate more natural gestures rather than simple motions, such as waving arms [10]. This capability could benefit human-robot interaction with better performance.

II. RELATED WORK

Grippers usually have simple designs and have been deployed in many scenarios. In addition to common parallel grippers, some specially designed grippers with more complicated cable-driven mechanisms have shown with more capability, such as the Barrett Hand [11], the iRobot-Harvard-Yale Hand [12], the M² Gripper [13], and an underactuated gripper that can grasp objects sequentially [14]. These grippers are aiming for a set of tasks rather than general purpose use.

In order to derive human-level dexterity, the human hand has been the design objective for general-purpose robotic hands. The Utah/MIT hand was first presented in [15] to facilitate machine dexterity research. The joints of human hands were analyzed that inspired the design of the DLR hand [16]. Due to the complexity of the human hand structure, underactuation is commonly used and the joint motions are usually coupled. Many robotic hands make use of cabledriven mechanisms with incorporated pulleys, e.g. [17], [18], [19], or springs [20] in which actuators and electronics can be installed inside a forearm. However, carefully designed structures are needed for cable routing. The linkage-driven approach is an alternative [21] but is more difficult to achieve larger workspace. To avoid sophisticated mechanism designs, some robotic hands are driven directly or through a gear or a timing pulley [22], [23], but these hands are usually much larger.

Compliance is important for providing more adaptive grasping capability – this property is innate for soft robots. The PneuNet technique [24] is commonly used for developing soft fingers, e.g. [25], [26], [27], in which fingers are driven by pneumatic control systems. More DoFs can be added by increasing the complexity of the molding structures to contain more chambers, such as [28], [29], [30]. Other soft materials and foams have also been explored to construct soft robotic fingers [31].

Inspired by human hands, various skeleton structures have been developed. Finger bones can be cast or 3D printed, and then they can be connected with silicone [32] or rubber bands [33], [34]. A passive skeleton structure is made by a multimaterial 3D printing process [35] and the joint stiffness can be controlled by jamming particles [36]. These approaches require complex fabrication process and do not include sensing capabilities.

In this work, we propose a novel way to combine soft materials and rigid elements to create bio-inspired robotic tissues. The articulated rigid skeleton defines the kinematic structure and electronics are embedded. The silicone casting process determines the shape of the tissue that can be highly customized and also provide compliance. We demonstrate this method by designing and fabricating a low-cost humanlike soft robotic hand. Compared with other soft robotic hands, the design can be easily customized, the fabrication process is simple and efficient, and the hand pose can be precisely measured in real time and further visualized using the MANO model [37].

III. DESIGN AND FABRICATION

Our proposed design is bio-inspired, compliant, low-cost, and modular. The finger design integrates soft compliant skin that mimics a human finger with an articulated rigid skeleton that provides structural strength. The hand is lowcost and utilizes standard components and digital manufacturing methods (e.g., 3D printing, laser-cutting) with a simple and fast assembly process. Furthermore, the hand design is modular — fingers can be added and removed from the design and can also be arranged in various configurations for different scenarios.



Fig. 1. (a) The design of the bones for the index finger is based on the human index finger bones. There are four bones connected with three pin joints. (b) A diametrically magnetized magnet is placed inside the joint of the distal phalange. (c) An angle sensor board is designed and installed inside one joint of the middle phalange.



Fig. 2. Fully assembled index finger skeleton with electric wires for angle sensors.

A. Cable-Driven Skeleton Design

The key idea is to embed articulated rigid skeleton into soft materials to form a controllable and sensible finger. The design of the robotic skeleton is shown in Fig. 1a. Each finger has four rigid bones connected by the pin joints which allows us to easily measure the joint angles. In every pin joint, we added a magnetic encoder (Fig. 1b) and a diametrically magnetized magnet (Fig. 1c) to measure the joint angle. This skeleton structure is cable-driven. We added attachments to the front and the back side of the bones for driving cables which are tied to the bones through holes on their bottom and top sides (Fig. 1b). Our skeleton design is bio-inspired. Our bones are based on human finger bones, including the dimension and the shape. Pin joints are used as ligaments and cables are used as finger tendons. Currently two cables are attached to every finger — one on the front side fixed at the finger tip and the other one on the back side fixed at one end of the proximal phalange shown in Fig. 1a and Fig. 2. One cable is used to bend the finger forward and the other is used to bend it backwards. We can easily add more tendons if necessary by adding holes to the bone and fixing more cables.

B. Fabrication Process

We first assemble bones to form the finger skeleton shown in Fig. 2. All the bones are 3D printed. Specifically, we use Nylon 12 (PA 2200) material (tensile strength 46 MPa, tensile modulus from 1600 MPa to 1700 MPa, elongation at break 14–20%). Magnets and angle sensor boards are installed inside the bones. Each sensor board requires six wires which are surrounded by a silicone tube. Then we connect all the bones with pins and attach cables to the skeleton. Before molding the fingers, we insert the cables through a silicone tube and then through the attachments on the sides of the bones, to keep the cable secure and away from silicone while molding.

We use a two step molding process to create the compliant skin for the finger. The CAD models for the mold are created based on the finger bones and the finger shape (Fig. 3). We 3D print three mold pieces that are used to create a complete finger using Onyx material (tensile modulus 2.4 GPa, elon-

TABLE I Cost of the Finger Components

Material	Quantity	Price(\$)
Silicone	$15\mathrm{ml}$	≈ 2
Bones	4	28
Mold	3	35
Angle Sensor Electronics	3	60
Cables, Pins, Screws, Wires		≈ 1
Total		126

gation at break 25%, tensile stress at yield 40 MPa). We use room temperature curable silicone (Smooth-On Ecoflex 00-20). In the first step, we mold the bottom part of the finger using two mold pieces (bottom and a top with outdents which match the bones) by pouring the silicone into the mold shown in Fig. 3a and Fig. 3b. After the curing (4 hours), the top part of the mold is removed and the bones with tendons are placed into the created intends for the bones (Fig. 3c). The third molding piece is screwed on and used for the top of the finger. After filling the silicone into the new mold and curing for 4 hours, we remove the hollow silicone tubes holding the cable and the finger is complete (Fig. 3d). Our finger design is low-cost. All the components to fabricate a fully functional finger are listed in Table I.

C. Mechanical Advantages

Embedding rigid skeleton structure into soft silicone can provide mechanical advantages over pure rigid robots and soft robots. First, the soft body is helpful to maintain the structure of the rigid skeleton. The assembled rigid skeleton is delicate and cannot be driven by cables without being surrounded by the soft body. The pin joints can break easily under external load but the silicone can tightly maintain the positions of all bones so that they can maintain their pin joint connections well. Reversely, the rigid skeleton can significantly increase the strength of the soft body made by silicone because the bones are strongly connected via pin joints. In addition, the rigid skeleton can define the shape of the soft body when bending. The comparison between with and without the skeleton is shown in Fig. 4. We applied forces to the tip of both fingers, and the finger with the rigid



Fig. 3. (a) A top mold is designed to include outdents that match the finger skeleton shape. In the first step, connect this mold with the bottom mold. (b) Pour the silicone into the mold for 4-hour curing, then remove the top mold and keep the cured silicone inside the bottom mold. (c) Place the bones with tendons into the created intends for the bones and screw on the other top mold. (d) Pour the silicone into the mold and, after 4-hour curing, the compliant skin surrounds the finger skeleton.



Fig. 4. (a) Bend a finger without rigid skeleton embedded. (b) Bend a finger with rigid skeleton embedded.



Fig. 5. Control architecture of the modular hand system.

skeleton is able to mimic the human finger behavior well, namely the finger curves on the joint locations and all the finger segments are straight. This mechanical advantage is unique among previous soft finger designs and can be helpful for human hand grasping and manipulation imitation.

IV. CONTROL AND POSE ESTIMATION

A. Control Architecture

We design all fingers in a modular way — every finger has its own processor to handle low-level control and communication and can be running independently. All the fingers are controlled by identical driving systems and control boards. A central computer is communicating with all fingers, including sending commands and obtaining finger hardware state. The general control architecture is shown in Fig. 5. This architecture makes use of distributed computing power and also allows users to easily add or remove finger modules.

The control board (Fig. 6) contains one customized ESP32 microcontroller for communicating with three angle sensors (MagAlpha MA782 from MonolithicPower, 16 Bit resolution, SPI interface) and controlling two brushless DC motors. The control commands are sent by users. The pose of the finger is updated at around 200 Hz and the current angular positions of motors are updated at around 20 Hz. This real-time performance can be useful for developing real-time grasping strategies. And the resolution of the angle sensors enable a robotic finger to have high sensitivity — detecting tiny change of its shape and capturing high-frequency



Fig. 6. The electronics board for finger control. The board is able to control three brushless DC motors and communicate with three angle sensors.



Fig. 7. Kinematics model of the index finger skeleton.

tiny motions. This high sensitivity can be shown from the experiment in Sec. V-B.

B. Pose Estimation

The kinematics model of the robotic skeleton of the index finger is shown Fig. 7 and the state of the finger can be fully defined by $[\theta_1, \theta_2, \theta_3]^{\mathsf{T}}$ and the position of the finger tip $p_{\text{tip}} = [x_{\text{tip}}, y_{\text{tip}}]^{\mathsf{T}}$ with respect to the root of the finger can be calculated by the following

$$\begin{bmatrix} p_{\rm tip} \\ 1 \end{bmatrix} = H_3 H_2 H_1 \begin{bmatrix} l_0 \\ 0 \\ 1 \end{bmatrix}$$
(1)

in which $H_i = \begin{bmatrix} \cos \theta_i & -\sin \theta_i & l_i \\ \sin \theta_i & \cos \theta_i & 0 \\ 0 & 0 & 1 \end{bmatrix}$

All finger poses are passed to a MANO model for realtime visualization. In MANO model, each finger contains 3 joints and each joint is considered as a ball joint defined by 3 parameters. In our finger design, every joint is restricted to one DoF, so we just need to update 3 parameters out of 9 for a single finger module. The visualization result is shown in Fig. 8.

V. EXPERIMENTS

A. Modular Design Versatility

The modularity of our finger design allows us to easily build various configurations using our fingers that is similar to modular robots since the fingers can be rearranged into different morphologies similar to [38]. We fabricated all five fingers (index finger, middle finger, ring finger, little finger, thumb) and first assembled them in a human hand configuration shown in Fig. 9a. We can also easily mount four fingers on a laser-cut acrylic base shown in Fig. 9b.



Fig. 8. A full hand (a) is visualized using MANO model (b).



Fig. 9. (a) A full hand configuration with five fingers mounted on a palm. (b) A full hand configuration with five fingers mounted on an acrylic base.

B. Accurate Pose Estimation and High Sensitivity

Although the rigid skeleton is fragile, surrounding it by silicone is able to provide precise and real-time pose estimation capability. We commanded the index finger to first bend and then extend to an intermediate pose. The angle sensors can estimate the finger pose in real time: the MANO model (Fig. 10b) and the real hardware (Fig. 10a) matched well, and the sensor measurement is shown in Fig. 11a.

Our finger can further detect tiny external loads, such as human touch. In this experiment, a person slightly touched



Fig. 10. (a) Command the index finger to first bend and then extend. (b) Visualization result of MANO model.



Fig. 11. (a) Angle sensor data during the motion of the finger. (b) Angle sensor data while the finger tip being touched.



Fig. 12. A person slightly touched the index finger tip multiple times.

the robotic index finger tip multiple times as shown in Fig. 12. The quick and tiny change of the finger shape can be clearly captured by the finger sensing capability shown in Fig. 11b.

C. Grasping Taxonomy

Human grasp types are synthesized into a grasp taxonomy that contains 33 different types [39]. We set up five fingers shown in Fig. 8a. In this setup, compared with a human hand, the palm is missing and the thumb is able to bend but not capable of rotating around. Hence, this robotic hand cannot handle grasp types that require the palm and different positions of the thumb with respect to the other four fingers. Some grasp types are shown in Fig. 13.

VI. CONCLUSIONS

In this paper, we present soft modular robotic fingers. Our design is bio-inspired — embedding rigid skeletons into soft tissues. We cloned and modified the human finger bones to create robotic finger skeletons with high resolution angle sensors embedded. A carefully designed fabrication process is introduced to quickly mold silicone around rigid robotic



Fig. 13. (a) Large diameter. (b) Small diameter. (c) Ring. (d) Distal. (e) Tip pinch. (f) Tripod. (g) Quadpod. (h) Parallel extension.

skeletons to form human-like fingers. The combination of the rigid elements with the soft materials is able to create a robotic finger with real-time precise pose estimation and high sensitivity. We further constructed a robotic hand with five fingers and demonstrated its grasping capability by performing several human grasp types. Future work includes a palm design with an additional rotation DoF for the thumb, a compact design of the wrist to hold the electronics, and the development of the control strategy for dexterous manipulation and grasping.

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