Design and Fabrication of a Soft Robotic Hand and Arm System

Alexander Alspach, Joohyung Kim, and Katsu Yamane

***Abstract*— We present the hardware design and fabrication of a soft arm and hand for physical human-robot interaction. The six DOF arm has two air-filled force sensing modules which passively absorb impact and provide contact force feedback. The arm has an inflated outer cover which encloses the arm's underlying mechanisms and force sensing modules. An internal projector projects a display on the inside of the cover which is visible from the outside. On the end of the arm is a 3D printed hand with air-filled, force sensing fingertips. We validate the efficacy of the outer cover design by bending the arm to reach out and grasp an object. The outer cover performs as intended, providing enough volume and range of motion for the arm to move, and stretching at the elastic relief features in the cover. We also validate the hand design by implementing a grasping algorithm in which the fingers follow a closing trajectory, make contact, then maintain a given range of fingertip pressure. Using this algorithm, the hand is able to gently grasp a soft object.**

I. Introduction

No longer confined to cages in factories, robotic systems designed to exist among humans can be found interacting in diverse settings providing information, entertainment, education, therapy and physical assistance [1]–[6]. In these scenarios, physical interaction may substantially enhance human-robot communication, productivity, and affinity [7].

Where physical human-robot interaction is expected, robots should be compliant and reactive to avoid human injury and hardware damage. To meet the requirements for both passive and active compliance in a robotic system, we previously developed 3D printed soft skin modules which sense force via an air-filled cavity connected to a pressure sensor [8], [9]. These force sensing modules are designed to cover the various links of a small humanoid or other robot, enabling the robot to sense force over a large area of its body while requiring less cumbersome electronics and wiring than other tactile sensor networks.

While these soft, force sensing modules enable various modes of physical interaction, scaling the design for use on larger robots is impractical due to the limited build volume of the 3D printer, as well as the cost and durability of the materials. Further, due to the porosity of the rubber-like material used, these modules can not be pressurized for extended periods of time, and are therefore limited in their sensing sensitivity and range of detectable forces.

Our goal is the realization of a robot arm and hand system which can physically interact with humans and gently manipulate objects. The arm comprises air-filled force sensors, as well as an inflated outer cover. While numerous other inflated robots exist, for instance BYU's "King Louie" and "Grub" [10], [11], Sanan's inflatable manipulator [12] and Marchese's soft continuum manipulator [13], these robots employ soft actuation mechanisms which require complex control schemes. We are focused on outfitting traditionally actuated "hard" robots with soft and easy-to-integrate sensor systems.

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Fig. 1. Soft robotic arm system with inflated outer cover, underlying pressurized force sensing modules and soft 3D printed hand. Our goal is the realization of a robot that can safely and robustly physically interact with people.

The system detailed in this paper employs soft, pressurized heat-sealed polyurethane force sensing modules on two of the arm's links. In our study of children's hugging for interactive robot design [14], heat-sealed polyurethane air-bladders were found to be simple to fabricate and durable when used to record hugging forces. The force sensing modules on the arm, when connected via tube to a pressure sensor, provide contact force feedback and passive absorption of impacts.

The arm and force sensing modules are covered by an inflated polyethylene bag which is shaped by heat-sealing. This cover does not sense contact, but provides a soft barrier between an interacting human and the robot's internal mechanisms and electronics. Inside of this translucent cover

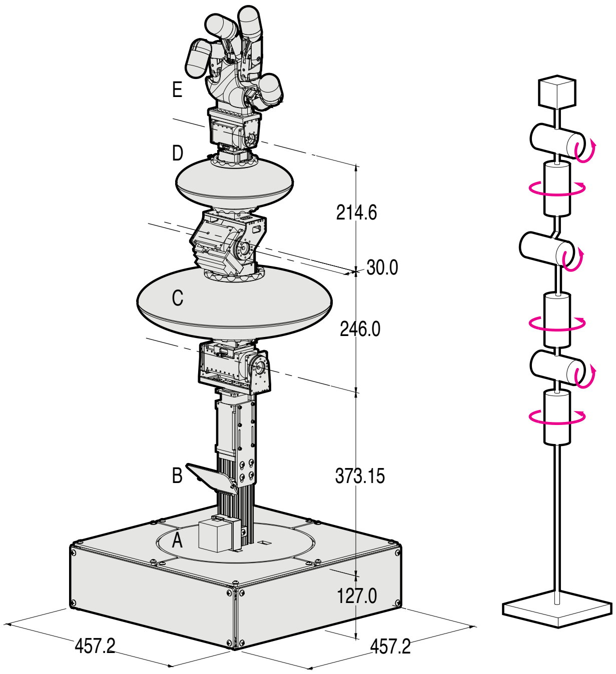
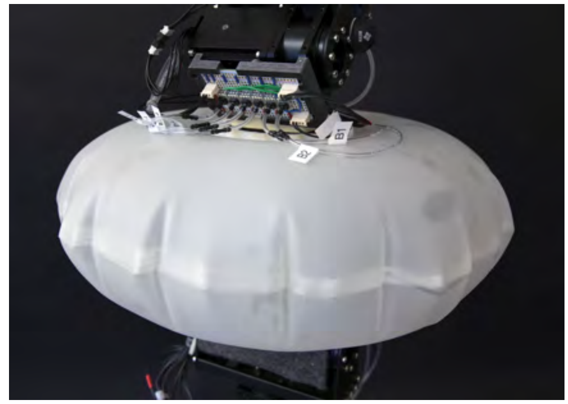
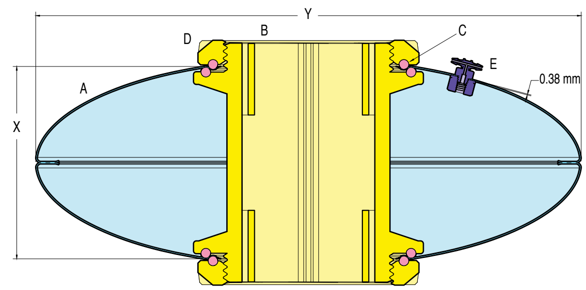


Fig. 2. Soft robotic arm system dimensions and kinematic description. The system includes a projector (A), mirror (B), large (C) and small (D) force sensing modules, and a 3D printed soft hand (E). All units in (mm).



(a) Force sensing module on arm



(b) Cross-sectional diagram of module

Fig. 3. Air-filled force sensing modules encircle two links of the robot arm. These modules consist of a heat-sealed polyurethane membrane (A), a rigid 3D printed core (B), sealing O-rings (C) and caps (D), and a barbed tube fitting (E). The sensors are connected via tube to a 34.5 kPa pressure sensor. The larger of the two modules has a diameter (Y) of 36 cm and a height (X) of 13 cm. The smaller module has a diameter of 25 cm and a height of 8.5 cm.

is a projector that projects a display onto the cover visible from the outside.

Also presented here is a 3D printed robot hand with similar air-filled force sensing modules on each fingertip. These modules, each connected to a pressure sensor, provide force feedback and compliance when grasping.

In Section II of this paper, we present an overview of our interactive arm and hand system. In Sections III and IV, we present the design and fabrication of the air-filled force sensing modules and the inflated outer cover. Section V describes the design and fabrication of our 3D printed, soft robotic hand. Section VI reports the implementation details and results of a soft grasping experiment requiring simultaneous control of the arm and hand. Our conclusions and future work are discussed in Section VII.

II. System Overview

The soft, force sensing robot arm depicted in Fig. 1 is built upon a six degree of freedom (DOF) Dynamixel-Pro servo-based arm [15]. The configuration of this arm, as well as various components of the system can be seen in Fig. 2. Two air-filled, pressurized force sensing modules consisting of a heat sealed polyurethane membrane and a 3D printed rigid core surround two of the arm's links (Fig. 3). These soft, air-filled modules act as impact absorbing bumpers and each provide independent contact force feedback via an attached pressure sensor. Enclosing the arm and force sensing modules is an inflated polyethylene cover which defines the outer shape of the robot arm, conceals internal components and provides a soft barrier between humans and the inner mechanisms of the robot arm. When projected upon by the robot's internal projector, this translucent-white external cover doubles as a surface on which information can be displayed. At the end of the arm is a seven DOF, four-fingered, 3D printed hand with soft, air-filled force sensing fingertips. A power supply, computer, air blower and other necessary electronics are housed within the base of the robot.

III. Air-Filled Force Sensing Modules

As part of our previous research, we have developed a soft, 3D printed force sensing module that contains a flexible air-filled cavity. This module, designed to fit over an off-the-shelf servo, helps absorb impacts, reducing the likelihood of hardware damage and human injury. These air-filled modules, when connected to a pressure sensor, also provide force feedback. Distributing individual modules over the various links of a robot provides contact force sensing over a large area of the robot and allows for the implementation of spatially aware, engaging physical human-robot interactions. The independent sensing areas also allow a human to communicate with the robot or guide its motions through touch.

In order to scale these force sensing modules to a larger robot, we moved from 3D printed membranes to heat-sealed

Fig. 4. The soft membranes of the force sensing modules on the arm are made of two laser-cut polyurethane circles heat-sealed around the outside edge. This image shows a partially sealed membrane during module fabrication. The left half of the membrane is heat-sealed

polyurethane membranes. The use of polyurethane allows us to make much larger sensors without the 3D printer's limitations of build volume, material cost and material durability. Another benefit of polyurethane is its air impermeability. The 3D printed modules leak air slowly and are therefore operated at atmospheric pressure. Sealed polyurethane modules hold pressure without leaking. Pressurizing the module enables higher sensing sensitivity, as well as a larger upper limit for detectable forces. As determined in hugging force experiments with children [14], heat-sealed polyurethane air bladders are robust to prolonged, forceful physical interaction.

Two of the robot arm links are encircled by differently sized air-filled force sensing modules, the larger of which is shown in Fig. 3(a). The outer force sensing surface of each module is fabricated from flexible 0.38 mm thick polyurethane sheet. A nonporous, 3D printed rigid core seals the module, provides structure and mounts to the underlying servo. The core was printed on a Stratasys Objet260 Connex using VeroWhitePlus material [16]. A cross section of the sensor module can be seen in Fig. 3(b). The larger of the two modules has a diameter of 36 cm and a height of 13 cm. The smaller module has a diameter of 25 cm and a height of 8.5 cm. The cross-sectional view shows that each module contains a heat-sealed polyurethane membrane and rigid inner core, as well as O-rings and threaded caps which create an airtight seal between the polyurethane membrane and the core. Each module also has a barbed fitting which is used to connect a pressure sensor via an air tube.

A. Module Fabrication

The polyurethane membrane is fabricated from two flat, equally-sized circular pieces of polyurethane sheet, shown in Fig. 4, which are cut using a CNC laser cutter. These two circular sheets each have a circular hole cut from the center with a diameter matching that of the outer diameter of the threads on the module's rigid core. This center hole is where the core protrudes through the membrane and seals. On one of the two sheets, a second 4 mm hole is cut 50 mm from the inner circle's edge where the tube fitting will be fixed.

Before the membrane and core are assembled, the two circular pieces are aligned flat one on top of the other, then heat-sealed along the outer edge, as shown in Fig. 4. The sheets are sealed together using a 30 cm (12 in) Uline Impulse Sealer. Sixteen or more overlapping line-seals are used around the circumference of the sheets to create an airtight circular result. The sealed sheets are then turned inside-out so that the seam is on the inside. A 1.588 mm (1/16 in) tee tube fitting with two barbs on one end and 10-32 threads on the other is placed in the hole and fixed with a nylon flange nut. Epoxy is applied between the fitting and the polyurethane to ensure an airtight connection. Once the sealant is dry, the module's core is positioned between the polyurethane sheets so that the threads on either side of the core protrude through the holes while the adjacent flanges remain inside of the polyurethane membrane.

For each force sensing module, two different sized O-rings are used, two of each. The larger of the two O-rings, coated in Molykote 111 silicone lubricant, creates the airtight seal between the core's flange and the polyurethane membrane. The smaller is epoxied to the outside of the membrane to create a lip by which the cap can hold the membrane in place. The caps on either end are tightened to seal the airtight module.

B. Module Installation

Each completed module is placed over its respective link and fixed into place. The larger of the modules is pressurized to 5 kPa and the smaller to 8.6 kPa. Each module is connected via 3.175 mm (1/8 in) OD, 1.588 mm (1/16 in) ID tube to a 34.5 kPa Honeywell ABPDANT005PGAA5 analog pressure sensor. Each of these pressure sensors is connected to one of four analog to digital ports on an adjacent Dynamixel-Pro.

IV. Inflated Outer Cover

An inflated cover, pictured in Fig. 1, envelops the arm's force sensing modules and servos, as well as the internal projector and mirror. The main purpose of this cover is to provide a soft barrier between humans and the internal mechanisms of the robot. The cover is not airtight, allowing air to escape and the volume to change for bent arm configurations. An Attwood Turbo 3000 Blower located in the base moves over 90 CFM of air to produce a positive pressure within the cover. This positive pressure inflates the cover and provides a restoring force which pushes outward.

The cover is made of 0.0635 mm thick inelastic polyethylene sheet. Its overall shape is achieved through heat-sealing. Elastic features heat-sealed into the cover, seen on the side of the cover in Fig. 1, gather excess material in certain configurations and let material out in other configurations, maintaining the cover's intended form during robot articulation. An elastic drawstring at the bottom fixes the cover to the base of the arm. Further, the translucent-white material allows an image projected on the inside of the cover to be clearly viewed from the outside.

A. Cover Fabrication

The basic form of the cover is cylindrical with a domed top from which the hand protrudes. The cover is 30 cm

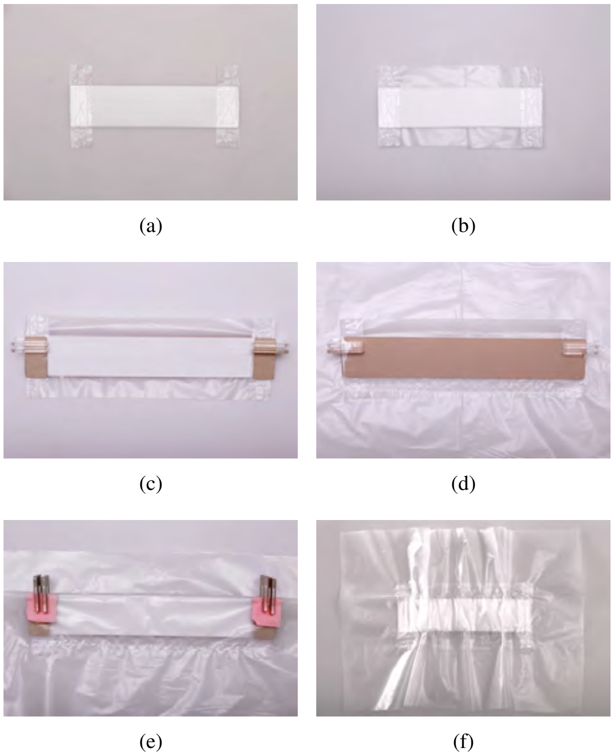


Fig. 5. (a) Plastic tabs are folded over the end of the elastic and sewed in place. The tabs are heat-sealed so that they bond with the stitching and elastic. (b) The inside layer of the casing, which is the length of the fully stretched elastic, is heat sealed to the tabs at either end. (c) The elastic and casing are fully stretched and clamped to an an acrylic jig. (d) The casing is then heat sealed down one side to the interior of the inflatable cover. (e) The casing and cover materials are folded over, re-clamped, and the original clamps are removed so that the cover material can lay flat against the elastic. The casing is then sealed down the other side. The pink paper protects the plastic from damage when clamping (f) The clamps are removed and the elastic contracts, gathering the cover material with it. The two short edges are then heat-sealed to the arm cover.

taller than the arm in its upright (zero) position, leaving extra material for when the arm bends. Three equally spaced vertical elastic bands are located halfway up the cover which contract and gather this excess material when upright. When the arm bends, the elastic on the outside of the joint stretches and allows the cover to lengthen where necessary. The elastic bands are 5 cm wide, gather 10 cm of excess material when upright, and stretch from 20 cm to 30 cm when bending.

The three vertical elastic bands are heat-sealed to the cover while the cover is still a flat sheet. The step-by-step fabrication procedure is illustrated in Fig. 5. These elastic relief areas are fabricated by first sewing a polyethylene tab to each end of the band. A 5 cm by 10 cm piece of cover material is folded along its long axis and positioned with one layer on either side of the elastic band's end. Using a sewing machine, the thin sheet is attached to the elastic (Fig. 5(a)). This plastic is then heat-sealed over the interface to melt the plastic into the stitching, strengthening the connection. This procedure is repeated for the other end of the elastic band.

Incorporating a casing, or enclosed channel, into the cover for the elastic to stretch within prevents buckling of the elastic, constraining it to remain in contact with the cover when contracted. This produces more predictable material gathering with smaller wrinkles. The casing consists of polyethylene material on the front and back of the elastic band. The front part of the casing is the arm cover itself. The back part of the casing is a 30 cm by 10 cm sheet heat-sealed to the elastic's two sewn-on plastic tabs (Fig. 5(b)). After the back casing is attached, the elastic band is stretched to a length of 30 cm and clamped to an acrylic jig (Fig. 5(c)). While stretched, one edge of the back casing is heat-sealed to the inside of the arm cover (Fig. 5(d)). The cover is then folded back behind the acrylic jig and the elastic assembly fixed with a second set of clamps. The original clamps are then removed, enabling the heat-sealing of the flattened casing's second edge (Fig. 5(e)). All clamps are then removed and the elastic assembly is heat-sealed to the cover on the two remaining short edges (Fig. 5(f)).

After all three elastic bands are attached, the bottom edge of the cover is folded towards the inside and heat-sealed to create a 2.5 cm wide channel for the elastic drawstring.

The polyethylene sheet is then folded in half, with the outer surface of the cover inside, and heat-sealed to create a tube. While the cover is still flattened, the top opening of the tube is sealed along a curve to produce a rounded top when inflated. All excess material outside of the seal lines is cut away, then the cover is turned right-side out so that the sealed seams are on the inside. A 6 mm-wide elastic rope is then fed through the drawstring channel around the bottom of the cover. With the hand detached, the cover is pulled over the arm and the drawstring cinched at the bottom. The hand and hand mount plate are then placed over the centered cover material at the wrist and fixed by screwing through the cover into the arm's terminal link. Wires and tubes are routed to the hand through a small hole in the cover behind the hand. The blower, ducted though an acrylic plate at the base of the arm, feeds air directly into the cover.

B. *Projected Display*

A RIF6 Cube mobile projector is mounted at the base of the arm, pointing upward. Mirrored acrylic, laser cut to size and mounted 6 cm above the projector at 45°, reflects the projected image onto the inside of the translucent cover. The mirror flips the image for proper viewing from the outside and enlarges the projected image by increasing projection distance. The projector receives HDMI input from the computer in the base. The robot can be seen displaying a heart in Fig.1.

V. Soft Hand

A 3D printed, seven DOF hand with air-filled, force sensing fingertips, developed for gentle, controlled grasping, can be seen in Fig. 7. The hand consists of four fingers. The thumb, index and pinky fingers each have two actuated DOFs, and the middle finger has one actuated DOF. In each finger, the pitch servo drives two coupled pitch joints by means of a four-bar linkage.

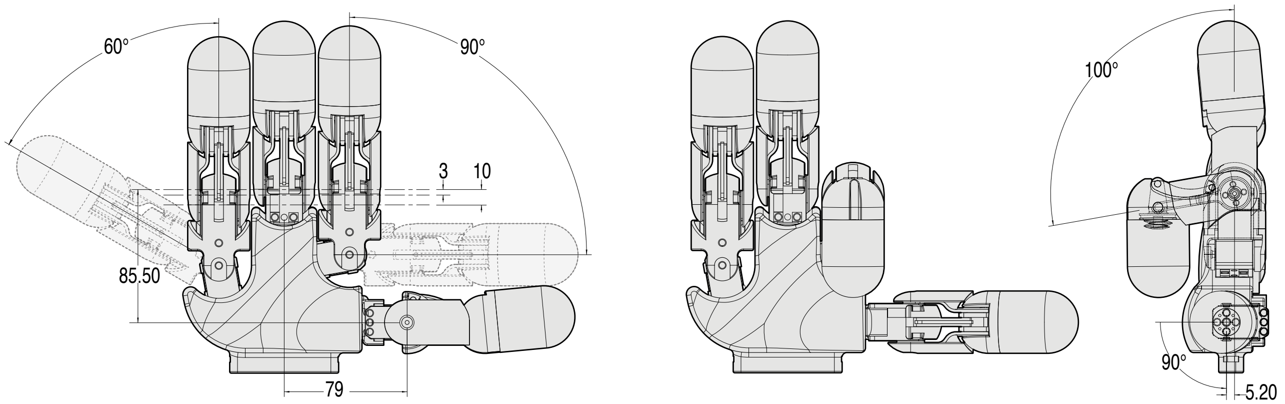
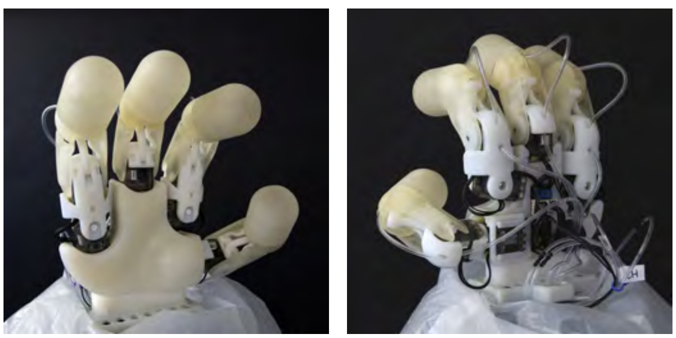


Fig. 6. The roll ranges of motion of the index and pinky fingers are 90° and 60°, respectively. The range of motion of the index finger's four-bar linkage-coupled pitch joint is 100°. The thumb pitch joint has a range of motion of 90°. Joint locations dimensioned relative to the middle finger pitch servo are shown. All units are (mm)



(a) Front (b) Back

Fig. 7. A 3D printed seven DOF hand with air-filled, force sensing fingertips developed for gentle, controlled grasping. Each finger contains a four-bar linkage driven by a Dynamixel XL-320 servo with a soft, air-filled force sensing module at the tip.

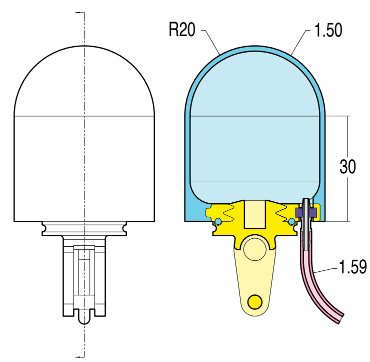


Fig. 8. The 3D printed force sensing fingertip module is comprised of a rubber-like membrane, rigid female screw threads, 3D printed gasket for tube attachment and a 3D printed O-ring. The module is sealed when screwed onto the end of a finger linkage. A barbed fitting and 1.588 mm (1/16 in) ID tube connects the sensor module to an analog pressure sensor. All units are (mm)

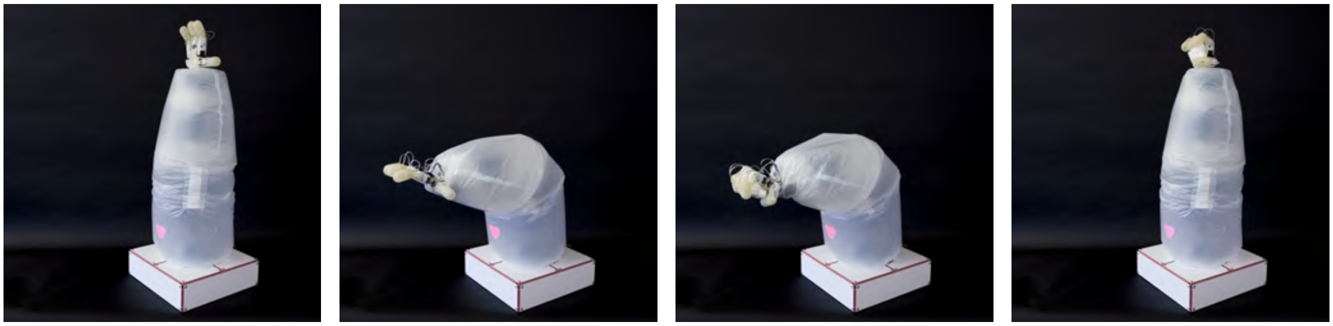
The entire hand, except for the cast silicone palm, is printed in a single run on a multimaterial 3D printer [16]. With this printer, both rigid and flexible features can be printed in a single part. The materials used are VeroWhitePlus (rigid) and TangoPlus (rubber-like). These materials can also be combined to form a range of material hardnesses.

A. Fingers

The seven actuated joints in the hand, shown in Fig. 6, are each driven by a Dynamixel XL-320 servo. The index and pinky fingers each have an actuated roll DOF. The pinky has a roll range of motion of 60° and the index finger has a roll range of motion of 90°. Each finger has an actuated pitch DOF which drives a four-bar linkage, shown in Fig. 7. The range of motion of the actuated pitch joint is 100°. When at the extent of its range of motion (closed grasp), the end link of each finger is parallel to the palm.

The finger components are designed to snap onto the the servos for screwless, toolless assembly. A rear view of the fingers is shown in Fig. 7(b). The rigid four-bar linkage on each finger is flanked by rubber-like material that conforms during contact and provides friction when grasping. The linkage assembly, including the four rigid links, the soft outer features and the interfaces to the servo body and horn, are all printed as a single articulating part which can not be disassembled.

At the end of each finger is a soft air-filled force sensing module which provides contact and grasping force feedback [8], [9]. As detailed in our previous work, each 3D printed sensor comprises a 1.5 mm thick rubber-like membrane, rigid female screw threads, 3D printed gasket for tube attachment and a 3D printed O-ring. Photos and a detailed cross section of this module can be found in Fig. 7 and Fig. 8, respectively. This unit, when screwed onto the threaded end of each finger's four-bar linkage, creates an airtight seal. The gasket (Shore 60 Digital Material) is the interface to the module's air-filled cavity and is required to withstand repeated plugging and unplugging of a barbed fitting to which a tube and pressure sensor connect.



(a) (b) (c) (d)

Fig. 9. The images above are taken during the grasping of a bag of soft marshmallows. The hand modulates the grasping force of each finger independently based on the internal pressure of each fingertip force sensing module.

Each of the four fingertip modules is connected via a 1.588 mm (1/16 in) ID tube to a separate 34.5 kPa pressure sensor located on the arm within the inflated cover.

B. Palm

Each finger slides into a channel in the palm of the hand and is held in place by a friction fit. This assembly method allows fingers to be easily installed or quickly swapped without tools. The palm of the hand is cast in Dragon Skin 30 [17] silicone and provides compliance and friction when grasping an object. The complex curves of the soft palm are designed in CAD. A mold is created based on this design and 3D printed. The two-part silicone is mixed in a plastic cup, degassed for ten minutes in a vacuum chamber, then poured into the mold. The mold lid has three holes in it to allow air and excess material to escape as the lid is placed on top of the mold and bolted down. After baking the mold and cast for an hour at 50° C, the silicone palm is removed from the mold and glued onto the hand.

VI. System Integration and Grasping

The two large air-filled force sensing modules are each mounted onto their respective arm link and attached via 3.175 mm (1/8 in) OD, 1.588 mm (1/16 in) ID tube to a 34.5 kPa analog pressure sensor. Six of these pressure sensors reside on a PCB mounted to the arm link between the two force sensing modules.

The smaller force sensing modules on the hand's fingertips are connected to the remaining four pressure sensors on the PCB. The analog output signal of each sensor is wired to one of eight independent analog-to-digital converter (ADC) ports on the arm. The four fingertip sensors are wired to the Dynamixel-Pro nearest the sensor PCB, while the other two are wired to an adjacent servo. All sensors share the same 5V input and ground, which is regulated by the power supply in the base.

To validate the design of the hand, a finger trajectory modification control scheme for gentle grasping is implemented based on pressure information from the fingertip force sensing modules. The controller for the n^{th} finger pitch angle ($\theta_n(k)$) is described as

$$\theta_n(k) = \begin{cases} \theta_n(k-1)+a & \text{if } P_n(k) \leq P_c \\ \theta_n(k-1) & \text{if } P_c < P_n(k) \leq P_p \\ \theta_n(k-1)-b & \text{if } P_p < P_n(k) \end{cases}, \quad (1)$$

$$\text{where } \theta_{min} \leq \theta_n(k) \leq \theta_{max}.$$

In Eq. (1), $P_n(k)$ is the sensed pressure of the n^{th} finger, a and b are the grasping and releasing velocities, and θ_{min} and θ_{max} are the minimum and maximum angles of the finger pitch servo. Once the grasping motion is initiated, $\theta_n(k)$ begins moving inward, closing the finger onto an object. If the pressure of a given module exceeds P_c, the corresponding finger pitch joint stops and maintains its current angle. If the pressure exceeds P_p, the joint rotates outward, releasing the corresponding finger. Using this simple control scheme, each finger moves to contact the object, then modulates its angle to maintain a pressure value within the given range, enabling the hand to hold an object gently between its fingers and palm.

To verify the successful integration of the arm and hand systems, as well as the efficacy of the inflated outer cover, a controller is implemented to bend the arm and grasp an object. The implemented controller commands all XL- and Pro-series servos and reads all six pressure sensors. Using this controller, the arm's three pitch servos are commanded from their upright zero position to 60°, 60° and -60°, from base to wrist, respectively. Once bent over, a user hands a soft object to the robot. The gentle grasp controller is initiated and the hand receives and holds the soft object. The arm then moves back to its upright zero position. Throughout this motion, the inflated outer cover provides enough volume and range of motion for the arm to move. When bending, the cover stretches at the elastic reliefs to elongate where necessary. The elastic then gathers the excess cover material again when upright. While the arm's force sensing modules are not used in this experiment, the sensors are fully integrated and the pressure data is available.

VII. Conclusion and Future Work

The hardware design considerations and fabrication details for a large-scale robotic arm and hand for physical human-robot interaction were presented. The six DOF arm has two air-filled force sensing modules which passively absorb impact and provide contact force feedback. The system also includes an inflated outer cover which encloses the arm's underlying mechanisms and force sensing modules. An internal projector projects a display onto the inside of the cover which is visible from the outside. At the wrist is a 3D printed hand with soft, air-filled, force sensing fingertips.

We validated our integrated system and outer cover design by bending the arm to grasp a soft object. The outer cover acted as intended, providing enough volume and range of motion for the arm to move, stretching at the elastic features when bending and gathering excess material when upright.

The hand design was validated by implementing a grasping algorithm in which each finger follows a given trajectory until a certain fingertip pressure threshold is met. Using this control scheme, the hand was able to gently grasp a bag of soft marshmallows.

A limitation of the current force sensing modules, both on the arm and in the hand, is their inability to sense the direction of a contact force. The sensors currently provide only force magnitude. Future interactive functionalities will incorporate the data available from the large force sensing modules, as well as current-based torque feedback from the arm servos, to determine the rough magnitude and direction of an external force.

The inflated cover was fabricated from an inelastic material with elastic features added to gather or release excess material, depending on the arm's configuration. A larger survey of applicable materials may yield a more appropriate lightweight, elastic material for covering the robot.

For the hand, more sensing areas are desired, starting with the palm. The palm is currently solid cast silicone. A future iteration of the hand will incorporate an air-filled force sensing palm module as well.

Acknowledgment

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