Low Cost Robotic Hand that Senses Heat and Pressure

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Abstract

Human beings interact with their surroundings through mechanical manipulation assisted by sensory receptors located throughout the body. In order for robots to behave and interact with the outside world in a similar way, humanoid robots must be equipped with sensors. Many research articles have been presented on the design of humanoid systems capable of dexterous motion and sensing. However, less have been focused on low cost designs with integrated sensors. This paper outlines the design and fabrication of a low cost 3D printed robotic hand equipped with off-the-shelf temperature and pressure sensors that are integrated into the five fingertips. It can be used as a mechatronic education project for schools. An under-actuated design scheme which is capable of 15 degrees of freedom of simple, yet facile mechanical movement, is utilized, allowing the hand to grip a variety of household items while using only five actuators housed in the forearm. The servos are controlled using Arduino Mega microcontroller hardware, which utilizes feedback from the temperature sensors and pressure sensors to respond to external stimuli.

Keywords:

Robotic Hand, Low-Cost, 3D Printing, Temperature sensing, Pressure sensing

I. Introduction

In this paper, the design, fabrication and implementation of a low-cost, 3D printed robotic hand that uses commercially available components to sense both temperature and pressure, is discussed. Research work that has been performed on robotics, humanoid robotics and prosthetics throughout the years, has culminated in humanoid systems that are very human like in appearance and in action. However, well-known systems such as Honda's ASIMO[1] or NAO from the French company Aldebaran-Robotics[2], with prices varying from over $1 million for ASIMO and $8000 for NAO, are very expensive and could not be sold directly to a wide consumer base. In an effort to reduce cost, a variety of 3D printed options has become available. The HBS-1 robot, presented by Wu et al.[3], a small child-sized humanoid, designed to interact with autistic children and costing approximately $10,000, is a good example. The life-size, open-source Inmoov robot demonstrated by Gael Langevin[4], that has been used by many amateur robot enthusiasts, is another example of the cost effectiveness of 3D printing, as it cost only approximately $1,000[5]. However, some of the humanoids, such as Inmoov, do not have integrated sensors and most still fail to effectively mimic the dexterity of human movement.

In order to improve the mobility and sensory functionality of humanoid robots, researchers have performed focused studies on various selected parts of the robot structure. For example, Tadesse et al.[6-7] worked on improving the design and functionality of a child-sized human head using shape memory alloy actuators (SMAs) and the facial response to external stimuli by

changing the properties of silicone skin. While Xu and Todorov[8] have worked on designing a highly anthropomorphic robotic hand in order to increase the capability of robotic hands to manipulate objects similar to human beings. Kim et al.[9] increased similarities between human beings and humanoids, by designing a human-like silicone skin capable of sensing heat, pressure and moisture, which can be used on prosthetics or robots. Similarly, Tomar and Tadesse[10], designed an artificial silicone skin capable of actuation, as well as sensing heat and pressure, using piezo electric pressure sensors and analog temperature sensors.

Another way to reduce the cost of a humanoid, is using an under-actuated design scheme, which, as is described extensively in *Underactuated Robotic Hands*[11], means simply to use fewer actuators than degrees of freedom. The hand is an area of the robot where this design scheme is especially well suited, and can be used to reduce the complexity of the design, while still allowing for moderate to high dexterity and gripping ability as is shown by Deimel and Brock[12] as well as Wong et al.[13].

It is therefore clear, that both adequate actuation and the integration of sensing capabilities in the designed humanoids, are needed to improve the robotic system and contribute to the pursuit of low-cost solutions to their design and fabrication. This will allow for increased access and distribution of the technology, to academic programs at high schools and universities, for example, as well as bring humanoids ever closer to accurate simulation of the human experience. In order to accomplish this goal, this paper presents a 3D printed human-like robotic hand and arm (figure 1**),** which uses temperature and pressure sensors that are readily available for purchase. The sensors are mounted in the fingertips and covered in a layer of silicone, which allows for better gripping ability and also provides a malleable surface that allows the sensors to work optimally. All the hand and arm parts were designed using CREO Parametric 3.0™. Some parts of the hand, in addition to the fingers, were also covered in a layer of silicone to give the hand enhanced gripping as well as a more human-like appearance. The design could be a great asset to teaching mechatronics since it involves the selection of actuators, sensors, controllers, CAD modeling, simulations, 3D printing, programming and testing.

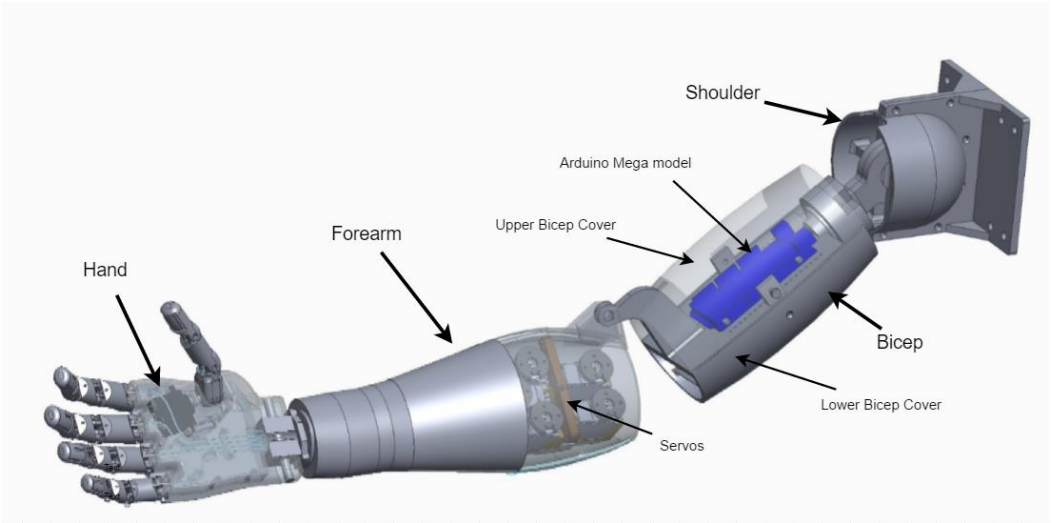

Figure 1: *The full robotic hand and arm includes the forearm, the bicep and the shoulder, each housing the servos, controller and sensors.*

The paper is organized in the following way. In section II, the design of the hand and the fingers, as well as the actuation methods are discussed. The design of the forearm, sensor integration, hardware and software control are also discussed in this section. In section III, fabrication methods and test results are explained. Section IV explains why the project is well suited as a mechatronics project and in section V discusses conclusions and future work.

II. Hand and Forearm Design and Sensor Integration

Sensor Selection

Heat and pressure sensing are two of the most important human senses; therefore, these two were chosen to integrate with the 3D printed hand design. A variety of heat and pressure sensors present possible design solutions, such as digital temperature sensors, analog temperature sensors, as was used in Tomar and Tadesse, as well as custom designed sensors. Similarly, pressure sensors come in a variety of types and form factors. MEMS pressure sensors were considered for their small size, as were piezoelectric plate sensors, as was used in Ross Miller[14], for their low cost. Low-cost, ease of implementation and small size were the most important factors considered while choosing the sensors.

10K thermistors were chosen as the temperature sensors, because of their durable nature, robust sensitivity, simple assembly and small size. Silicone elastomer is used as a covering for the sensors in the distal phalanxes. It is known that silicone is very heat resistant, therefore the performance of the heat sensor when covered in a layer of silicone was a concern early during the selection phase. However, it was found that thermistors responded well, even when embedded in a thin layer of silicone. For example, the time constant for the chosen thermistor with no silicone covering was 15 seconds and the time constant of a thermistor covered with a 0.05 – 0.07 inch layer of silicone was 16.5 seconds, with a two degree reduction in its steady state temperature value.

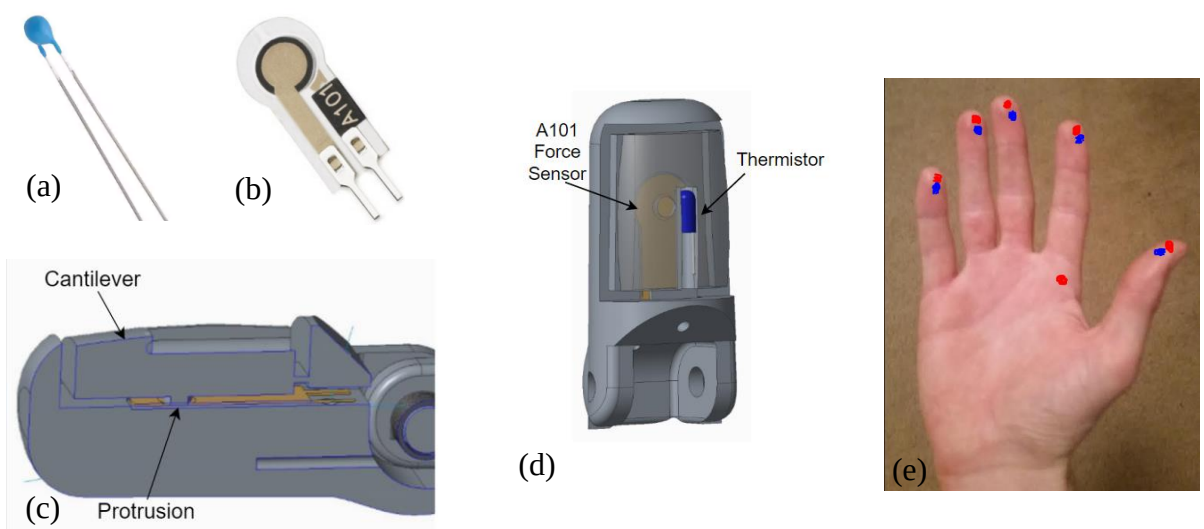

Figure 2: *Sensors in the hand and their placements are shown in the figure.* **(a)** *The temperature sensor - PT502J2 from U.S Sensors.* **(b)** *The pressure sensor - A101 FlexiForce from Tekscan.* **(c)** *The cross section of the finger shows the cantilever structure can be seen here.* **(d)** *A representative CAD design of a fingertip is shown here and* **(e)** *sensor placement on fingers- 6 temperature sensors (red) and 5 force sensors (blue) is also shown. Figure 2 (e) was adapted from Ref 10, where optimal placement of heat and pressure sensors are depicted on the human hand.*

The pressure sensors chosen were A101 FlexiForce sensors. These are resistive force sensors that change resistance when pressure is applied to them. Thus, the force is read by a change in resistance, in the same way the thermistor works. These sensors were found to be durable and easily implementable. A convenient characteristic of these force sensors is that the sensitivity varies with the applied bias voltage. Figure 2 (a) and (b) show the selected temperature and pressure sensors for the robotic hand. Figure 2 (d) shows the placement in the fingertip.

Fingertip Design

To give the hand sensing capabilities, the selected sensors were integrated into the distal phalanxes of the fingers. Figure 2 (d) shows the sensors placed on the fingertip where the active area of the sensor is in the mid portion of the phalanx. This choice of sensor placement was influenced by the work of Mirkovic and Popovic[15], who, as one can see in figure 2 (e), indicated pressure sensor placement should be primarily in the fingertips for optimal sensing capability with limited sensor quantity. Therefore, the fingertips were designed to comfortably house a pressure and temperature sensor. As can be seen in figure 2 (c) and (d), the distal phalanxes were designed by "carving" out a space for the pressure sensor and thermistor to fit. However, one difficulty with utilizing only one pressure sensor per fingertip, is that the "sensing" area of the A101 sensor is small, only 0.15 inches. In order to increase the size, part of the fingertip was designed as a cantilever beam, hovering above the sensor, with a small protrusion that concentrates the force applied anywhere on the cantilever onto the center of the force sensor. In the figure 2 (c), the cross section of the cantilever is shown and the protrusion can be seen. Also, in figure 2 (d), the cantilever is shown transparent, to better see how the A101 sensor fits underneath the cantilever, while the thermistor rests on top. With the addition of the cantilever, the sensing area of the fingertip is increased, allowing pressure application on any place on its surface to give a pressure sensor reading, as is shown clearly in figure 3.

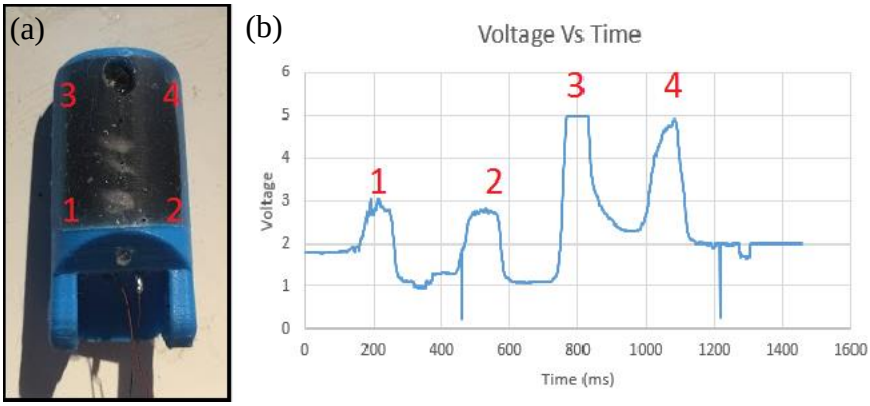

Figure 3: **(a)** *The fingertip with a pressure sensor embedded and four places labeled where pressure was applied to induce a response.* **(b)** *The response of the pressure senor in volts due to the application of a small force applied to the fingertip is shown in the graph.*

The graph in figure 3 (b) was generated by applying pressure on the finger to the four locations on the distal phalanx labeled in figure 3 (a). As can be seen, the cantilever responds to pressure applied at even its corners. Also visible, is that the far side of the cantilever (location 3 and 4) deflect more easily and therefore there is a larger voltage response.

Under-actuated Design for Fingers and Thumb

As can be seen in figure 4 (a – c), the fingers are designed to be similar to the size and shape of adult male human fingers. Their shape is broader at the base than the tip and the finger is divided into three phalanxes. To hold the phalanxes together, a 3D printed pin is inserted into the common joint of two adjacent phalanxes.

Under actuated design is key for simplicity and low cost, while at the same time offering adequate grasping capability. Using an under-actuated design scheme allows for the controlled motion of each finger phalanxes, while using only one actuator per finger. In this robotic hand, the selected actuators were HS-35HD HiTech servos, housed in the forearm. The standard servo horns that came with the servos were replaced with 3D printed circular servo horns as can be seen in figure 4 (d). A braided fishing line, which acts similarly to a tendon in the human body, runs from the servo, to the tip of each finger by passing through the holes in the front of the finger. The holes in which the tendon runs through can be seen in the CAD model of the finger in figure 4 (a).

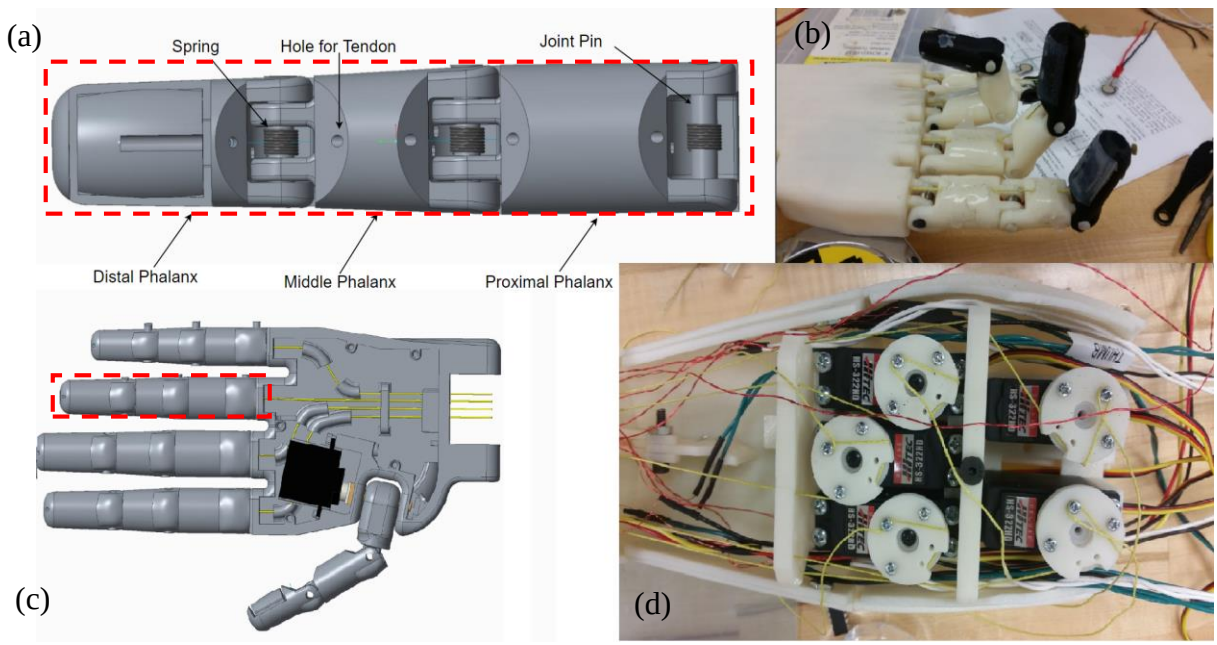

Figure 4: *Design of the hand.* **(a)** *Each finger of the robotic hand is composed of three tapered phalanxes held together by plastic pins. The distal phalanx holds both sensors.* **(b)** *The finger phalanxes close at different rates yielding the ability to control how the finger closes with only one actuator.* **(c)** *The CAD model of the entire hand seen from palm facing down is shown here. The small HiTech HS – 82MG servo that drives the thumb can also be seen as well as the guides for tendons strings.* **(d)** *The servos that are housed snugly in the forearm, rotate to wrap the tendon around the circular servo horns to move the fingers.*

The string (tendon), is wrapped around the circular servo horn and tied to one edge of the horn so that when the servo is actuated, it rotates and the string is wrapped further around the horn's edge which in turn pulls the tip of the finger in toward the palm. Thus, at the first stage in the motion, the tension of tendon causes the distal phalanx to bend inward. Then, as the tension increases, caused by the torque of the servo motor, it causes the middle phalanx to curl in as well (second stage of motion) and then finally, the proximal phalanx (third stage), curls in. Additionally, springs housed in each of the three finger joints, cause this motion to be smooth and add to the control. In this way the curling motion of the fingers, which accounts for 3 degrees of freedom,

can be controlled by only one actuator. Figure 4 (b) shows the robotic fingers in 3 different stages of closing. To return the fingers to the outstretch position, the servos simply rotate in the opposite direction, relaxing the tension of the tendon, which allows the torque of the springs housed in the joints of the fingers, to pull the phalanxes back into their resting, outstretched position.

As explained earlier, each finger is actuated by one servo motor, but the thumb requires two servos for effective grasping motion. In order to simplify the actuation mechanism for the thumb, a small servo is housed in the hand itself and directly drives the thumb in one degree of freedom along an axis parallel to the palm of the hand. The closing motion of the thumb's distal and middle phalanxes is controlled by a tendon the same way the other fingers are. As one can see in the figure 4 (c), the hollowness of the palm allows for the small servo to fit comfortably inside, as well for wire guides for the tendons leading to the servos in the forearm. A cover for the back of the palm was also designed (not pictured). Both the fingers and the palm were designed to be in the 99th percentile of male adult human hand sizes as found in, *Human Factors Engineering* data[16].

Arm Design

The forearm was designed, using inspiration from the Inmoov open source robot, to house the servos that drive the motion of the fingers and thumb. The tray that holds the five servos is designed to house standard servos that can be replaced, depending on the servo torque and size desired.

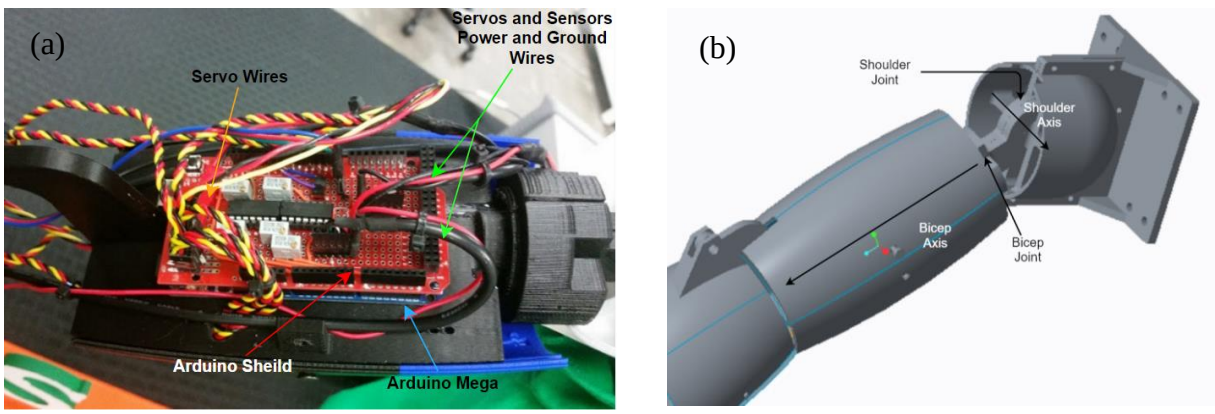

***Figure 5**:* **(a)** *The Arduino Mega, Arduino Shield, Servo wires, power and ground wires for servos and sensors are all housed in the bicep of the arm whose top cover can be removed for easy access.* **(b)** *The bicep and shoulder together have two degrees of freedom to better position the arm.*

The upper arm, including the bicep and the shoulder, was designed to house the Arduino Mega used for actuation and data acquisition, and for mounting the arm on a testing station for characterization. The bicep of the upper arm is composed of three different pieces, the top cover, the bottom cover and a center piece. In figure 5 (a), it can be seen that the Arduino Mega microcontroller, wiring and Arduino shield used to implement the needed circuitry for data acquisition is house comfortably in the bicep area, where the microcontroller can be attached to the center piece via bolts. The top cover can be removed for easy access to the Arduino Mega and Arduino shield. The bicep and shoulder together have two degrees of freedom. The shoulder joint rotates around the shoulder axis seen in figure 5 (b) to give the arm vertical lift when mounted and the bicep joint can be rotated around the axis labeled bicep axis in the figure to position the arm.

Control and Data Acquisition

Control and data acquisition was performed using both an Arduino Mega microcontroller, as was previously mention, and LabVIEW software. The Arduino Mega was chosen for its simple yet powerful platform and large community support. LabVIEW allowed for easy-to-achieve graphical displays of the sensor data. The sensors were fabricated by soldering magnetic wire onto the electrodes of the sensors and connecting the sensors to the analog pins of the Arduino Mega. The servos were controlled via the digital pins of the Arduino Mega. All the circuitry for data acquisition was wired to an Arduino shield that can be seen in figure 5 (a).

To program the Arduino, LabVIEW 2015 with the LINX toolkit was used. The LINX toolkit is a library of functions written for LabVIEW that allows for communication with an Arduino. This allows the use of a graphical programming environment. LabVIEW was chosen to use over the standard Arduino Sketch programming environment because it is easier to work with and make changes to programs. There is also more easy to access functionality for handling the analog sensor inputs, such as built in filtering functions. Additionally, the LINX toolkit has built in functions for controlling servos.

III. Fabrication and Testing

Fabrication

The parts for the hand and arm were 3D printed on a Fortus 3D printer, using acrylonitrile butadiene styrene (ABS) material. The overall volume of the hand and arm is 78 $\boldsymbol{in^3}$. Using the price for a spool of ABS P430 material, ($250 for 56 $\boldsymbol{in^3}$) from Argyle Materials, the approximate cost of 3D printing the hand and arm is $350.

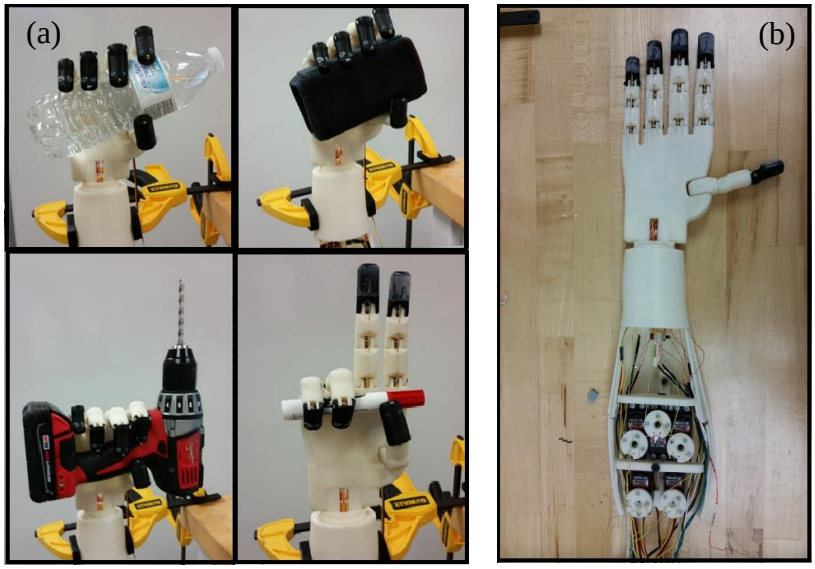

Figure 6: **(a)** *The hand is capable of grasping a variety of different objects, even heavy objects like the drill, while using only five actuators.* **(b)** *The hand is approximately the size of a male human's, while the forearm was designed to be slightly larger in order to house the standard sized servos.*

Once the parts are fabricated, some additional work had to be done, such as sanding rough areas in order to make the parts fit smoothly together. Although an attempt was made to make as many parts from 3D printed material as possible, standard metal screws were used to fasten certain of the arm.

Grasping Test

A full view of the hand with the palm and the upper forearm is shown in figure 6 (b). The hand was tested for grasping a variety of different objects of different sizes and as shown in figure 6 (a), the hand grasped the objects very well. The hand is clearly capable of grasping medium to small sized objects, however, small sized objects are grasped in an awkward fashion in the upper palm. This is because the hand is incapable of a pinching grasp commonly used by humans to hold small objects. The servos, however supplied excellent force to hold even heavy objects. A video of the hand while grasping objects can be found in the HSB Lab YouTube channel using the following link: https://www.youtube.com/watch?v=dUz22337CVA .

Sensing Test

Testing the sensing characteristics of the robotic hand was also performed. The first test was on the pressure sensors and the second test was on the temperature sensors. Figure 7 (a) shows the response of the pressure sensors while grasping a screw driver. As can be seen in figure 7 (a), the pressure sensors in the fingertips all showed approximately a 5V response.

To run the test for the temperature sensor, a water bottle was filled with hot water and the hand was actuated to grasp the bottle. Figure 7 (c) shows the response of the temperature sensors while the hand gripped the bottle, as seen in figure 7 (d). When the fingers of the robotic hand close around the bottle, the temperature sensors report a sharp climb, in degrees, from room temperature to the temperature of the bottle.

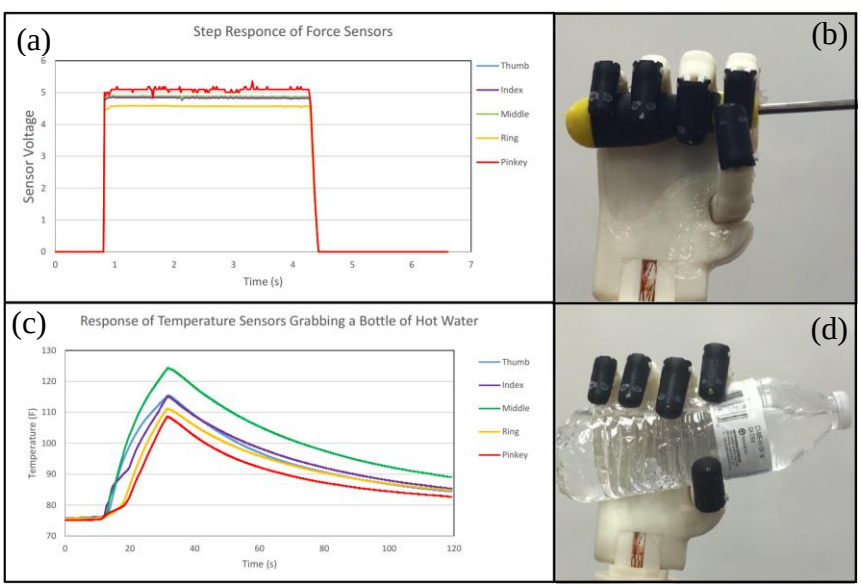

Figure 7: *Test results and test conditions are shown here.* **(a)** *When pressure is applied, the change in resistance caused in the A101 is changed to a differential voltage output displayed by the Arduino.* **(b)** *Grasping screw driver caused pressure in the sensors to respond.* **(c)** *The change in temperature of the sensors* **(d)** *while holding a hot water in a bottle, is a much slower response.*

Once the bottle is released, the values fall back to room temperature. It is clear from figure 7 (c), that the cool down rate of the temperature sensors is rather slow, which represents an unfortunate characteristic of the thermistors used.

Therefore, as can be seen the hand's sensors respond readily to heat and pressure stimuli. The successful testing of the heat and pressure sensors allow for a basis upon which future work involving more extensive testing can be founded. The drawback to the current temperature selection is the slow cool-down time as previously noted. This prevents accurate readings in quick succession and needs further study.

IV. Use of the Robotic Hand as an Educational Tool

This work can potentially be used for educational purposes in many schools, as senior design projects or for project based courses, to expose students to the mechatronics field. There are several reasons for this, firstly, the project is low cost, with estimated material cost of approximately $470, which gives academic programs the ability to afford the expense associated and incorporate it in their curriculum. Secondly, it provides a well-rounded mechatronics experience for a team of students that have different majors. For example, it involves CAD work for mechanical engineering students; circuits, sensors and data acquisition for electrical engineering students; as well as potential programming work suitable for computer science students. These students can learn from each other working on such projects. In another view, a team of one major (e.g. mechanical engineers) can learn all components of mechanical design, circuit, sensors & actuators, and programing through such a robotic hand project. Thirdly, students can learn additive manufacturing, which is becoming one of the most promising manufacturing solutions. Hence, this project has tremendous potential for mechatronic education.

V. Conclusion and Future Work

In conclusion, the design and fabrication of a low-cost, 3D printed robotic hand that senses pressure and temperature in the fingertips is presented with applications for mechatronics education as well as an example of a low cost solution to humanoid robotics hand and arm design. 3D printing was found to be effective for reducing cost and controlling the design of the finished product, while offering a very fast turn-around time. Off-the-shelf sensors were used in the design and required some assembly as well as casting in an elastomeric material that served as cushioning and protecting layers, but were found to be very easy to fabricate and implement. The overall assembly time took about 5-7 hours, with the molding of the silicone distal phalanxes being the most difficult and lengthy task to complete. Preliminary test on the sensing indicated that the hand could identify hot objects and different loads while grasping objects. The overall material cost was $470 in total, with approximately 25% of the cost going toward the five powerful HiTech Servos; therefore, the under-actuated design was proven to be a good cost saving measure. Future works include feedback control and characterization of the hand under different scenarios.

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