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CCE 499X: Senior Design

DESIGN AND DEVELOPMENT OF A ROBOTIC ARM THAT SENSES TEMPERATURE, PAIN, AND PRESSURE

by

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"You can fool all the people some of the time, and some of the people all the time, but you cannot fool all the people all the time."

Abraham Lincoln
1809-1865

Abstract

New robotic arms that have one or more sensations are being studied and developed; however, no arm with combined sensations of touch, pressure, and pain has been designed yet. This aspect is important not only for robots to protect themselves from harm, but also to be developed in the future to prosthetic arms for amputees. Accordingly, the aim behind this project is to design and develop a robotic arm that senses temperature, pain, and pressure. The project consists of implementing multiple temperature and pressure sensors on the palm and fingers of a robotic hand and placing four servo motors on the elbow to control the arm's movements; the pain sensation is obtained according to human temperature and pressure thresholds, which were carefully studied before embedding them in a custom-developed software. What results are the measured values which are represented by a withdrawal reflex achieved by the servo motors in order to protect the arm from any potential damage, in addition to a voice signal depicting the resulted sensation, and a screen displaying the level of temperature, pain, or pressure, or any of them combined together. The arm should have a fast response since multiple sensors were tested before using any of them. In the future and as a first step, this arm may be implemented on a robot, and in later steps, it may be further developed in order to function as a prosthetic arm for amputees.

Acknowledgements

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PWM	Pulse Width Modulation

Chapter 1

INTRODUCTION

It is known that sensory receptors located in the human body assist mechanical manipulation that allows human beings to interact with their surroundings. Similarly, a robot should be equipped with sensors in order to behave with the outside world. Pressure and heat are two of the most important human senses. A human being is capable of picking up a light object with ease whereas it is hard for robots to know when to apply a strong or soft grip and mimic the delicate movement of the biological hand. This may result in injuring a person or breaking an object. A robot with the sense of touch is able to adjust its grip with respect to the object it holds. Moreover, enabling robots to react to pain is important since it helps protect humans by evading them from the source of pain and thus, not letting them get hurt. However, the 'pain' that the robots feel differ from the real biological pain. The robotic hand needs to identify physical states it is about to encounter, rate the damage it may cause, and react accordingly.

Accordingly, this report outlines the design and development of a robotic arm that senses temperature, pressure, and pain; where pain is a certain high level of temperature or pressure. In this project, the human reflex for pain is imitated and applied to the robotic hand. Although pain is not a very pleasant thing to feel, it is implemented in this project by the use of sensors since it is essential for protecting humans from further injuries. The system identifies the pain and swiftly responds by simulating the reflex motion that allows that hand to draw back from the hot object it encounters and to output a voice message 'Ouch, this is hot'. Moreover, almost every amputee aspires to regaining his feeling for temperature and pain that brings to him the sense of belonging to the world.

This project, a prototype for a more developed prosthetic hand, is equipped with pressure and temperature sensors integrated in the middle of the palm and into the five fingertips. It also has a screen to output the status of the hand, whether it is a normal, hot, or cold state along with the temperature and a voice message that claims that the object to be encountered is hot. The nine servos that move the hand and fingers are controlled using Arduino Mega controller hardware by acquiring feedback from the sensors and responding to the stimulus. The used components and applied methods are going to be further explained in the upcoming paragraphs.

A. Statement of the Problem

Many amputees dream of having their hand back. Even though feeling pain does not seem very encouraging, they do wish to get this feeling in order to feel normal again. While researchers are developing and inventing new robotic and prosthetic arms, none has come up with one that can feel temperature, pressure, and pain at once. In addition, the existing solutions are very expensive and cannot be bought by individuals with limited income.

Examples:

Many researchers and engineers have been studying this subject and finding many solutions. However, no arm with the three sensations combined has been developed yet.

Examples of similar designs include the hand with sensory feedback developed by Micera and colleagues (2013) and the DARPA hand (2015).

B. Hypothesis or Key Questions

The proposed project is expected to prove the following hypotheses:

- Adding pressure and temperature sensors to a robotic arm can make it feel both of these sensations with the help of custom-developed software.
- High temperature and pressure levels can cause pain to the robotic hand.
- The sensors and program used can be close to the human sensors and nervous system.

C. Proposed Solution

The design consists of four main parts:

i. Implementing the temperature and pressure sensors to a robotic hand.
ii. Studying the human temperature and pressure levels in order to embed them in a program.
iii. Outputting all of these three sensations using a voice signal, a screen, and a reflex.
iv. Performing multiple testing on the arm to see if the sensations are accurate enough to reach the function of a human hand.

D. Specific Objectives

The specific objective of this design is to implement accurate sensors with a fast time response on a robotic hand in order to make it as similar as possible to a human hand. The arm should be able to detect the sense of touch applied to it, and respond accordingly by performing both a withdrawal reflex and a voice signal representing what the hand is sensing at that time. Also, a screen will be displaying the levels of temperature, pressure, and pain if it occurs.

E. Relevance of this Work

The human's innate capability to feel pain and to pull away from a certain object that causes harm protects him from further injury. Hence, pain is the system that protects the human body and it is something that can be used to protect robots as well. This project focuses on forming robotic pain, or an artificial simulation of it, based on human pain research. Therefore, the robotic arm is able to identify the hot surface and refrain from touching it. Moreover, the robotic hand can also differentiate between the pressure it needs to exert when holding a light or a heavy object. In other words, it can hold an egg without crushing it. Thus, a certain high threshold of pressure exerted or temperature encountered is defined as robotic pain. This robotic hand is a step forward towards creating a more developed brain-controlled prosthetic hand that can be implemented on amputees.

F. State-of-the-Art

Throughout the past few years up until recently, scientists have developed sensor technology for prosthetic arms that detects signals from nerves in the spinal cord. This technology analyses the electrical signals sent from the spinal motor neurons and uses them as commands.

The DARPA's Revolutionizing Prosthetics program by DEKA Research and Development Corp developed the LUKE Arm, which was previously known as the DEKA Arm. It was set to hit the market after receiving marketing approval from the U.S Food and Drug

Administration (FDA). The LUKE arm is the first prosthetic arm that is able to translate signals from a patient's muscles into complex motions. Moreover, the system is integrated with a sensor that returns "grip-force" feedback information back to the patient about how much force is being grasped. It took DARPA around 10 years to come up with this advanced limb prosthetic natural control, over 10,000 hours of testing and nearly 100 amputees.

Moreover, two German researchers from the Leibniz University of Hannover are developing an "Artificial Robot Nervous System (aRNS)" which allows robot to be alert to dangers enabling them to react in time in order to avoid damaging their electronic or mechanical systems. This nervous system is similar to the network sensory neurons in human skin which is able to feel pressure and temperature. If a certain external stimulus exceeds the previously programmed threshold, a suitable response is activated.

Chapter 2

PHYSIOLOGICAL BACKGROUND

In order to design a human-like robotic arm, it is important to understand the human hand's physiology first.

In the human body, the arm is the organ located between the glenohumeral joint and the elbow joint. The arm has three parts: the part which extends from the shoulder to the elbow or the upper arm, the forearm that extends from the elbow to the hand, and finally, the hand [2].

Each hand in the human body contains 27 different bones which provide the body with flexibility and give the hand a great precision and an easy motion [2].

In addition to the bones, the hand has several muscles that help it move and keep posture. However, powerful movements are performed with the help of the forearm's muscles. The palm's muscles are subdivided into three groups: the thenar eminence, the hypothenar eminence, and the midpalm (Figure 1).

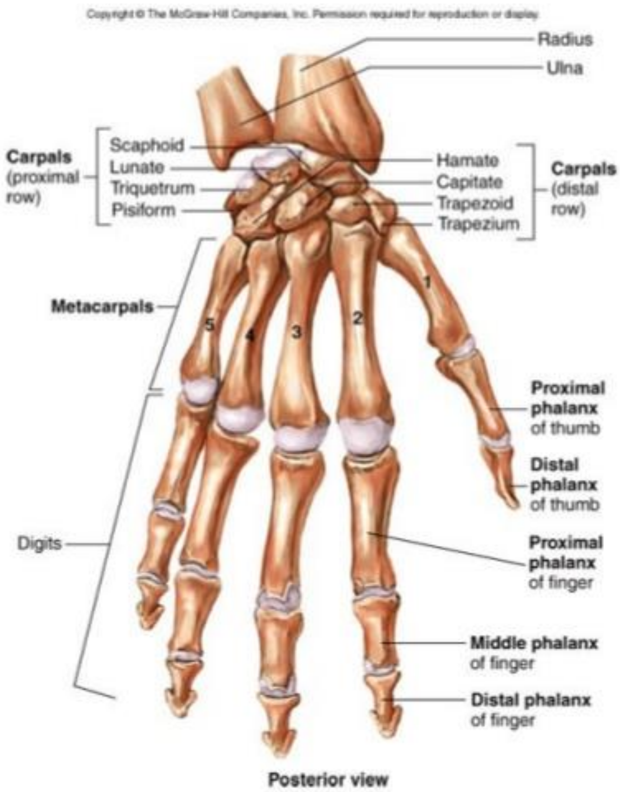

Figure 1. Bones of the hand. (Source: https://www.slideshare.net/hermizan84/bone-and-muscles-of-the-hand).

Moving to the control of the hand, it is performed with the help of the nerves. They receive the wide sensory information supplied by the sensors of the hands and fingers, and they also command the complex movements of the arm all the way down to the dexterous fingers [2].
The hand performs many tasks throughout the day and thus needs a great number of neurons; this is why even the smallest hand muscles are controlled by over 200,000 neurons [2].
Even though the hand seems very simple externally, it actually has a complex structure consisting of tendons, blood vessels, bones, nerve fibers, muscles, and nerves [2].
The hand is one of the most used body parts. It has been found that the fingers on one hand will be contracted and stretched over 25 million times over an average human lifetime [2].
In order to feel, the hand has very sensitive stimuli receivers. It has a total of 17,000 touch receptors and free nerve endings in the palm in order to pass on sensations for vibration, movement, and pressure. The skin is the most sensitive part of the hand and could be injured more than any other body part if high temperature or pressure are applied to it more than any other part [2].
Moreover, studies have shown that for a finite amount of time, a temperature of 44ºC can burn the skin. With temperatures ranging between 44ºC and 51ºC, the rate of burn is increased by a factor of four with each degree from six hours down to six minutes. For temperatures higher than 70ºC, the burn develops in less than a second; high or low temperatures can cause a reflex [3].
A reflex is a fast, involuntary response to any stimulus. Spinal reflexes are the most performed type of reflexes in the human body [1]. A reflex arc in the hand involves parts shown in the below figure.

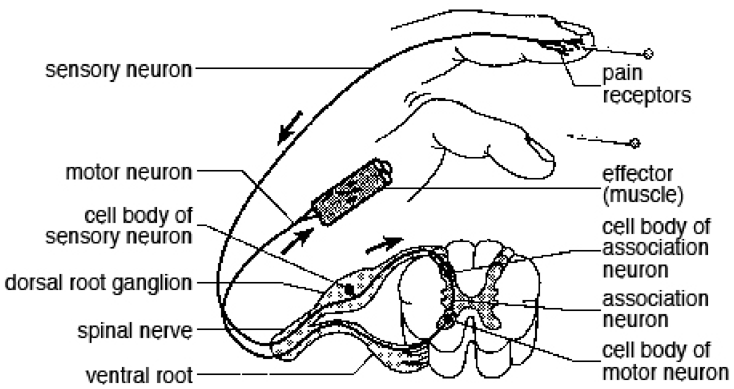

Figure 2. Reflex parts in the hand (Source: http://www.innerbody.com/anatomy/nervous/arm-hand).

The receptor detects he stimulus, then the sensory neuron transmits the impulse to the spinal cord. Next, a motor neuron sends a nerve impulse from the spinal cord to a peripheral region. The effector then receives this impulse from the neuron. In the case of a hand, the effector is the skeletal muscle that moves the hands fast in the case of a reflex [1].

In more details, a withdrawal reflex is an automatic withdrawal of a limb from a painful stimulus. This reflex starts when the sensory nociceptor is excited by a noxious stimulus such as pain; this signal then travels through a primary sensory neuron, which enters the dorsal horn of the spinal cord. Next, the neuron synapses with an interneuron within the spinal cord and this interneuron synapses with an alpha motor neuron; this leaves through the ventral horn, and then supplies excitatory input to the flexor muscle group on the same side. In parallel, motor neurons that supply the extensor compartment on this side receive signals from some inhibitory neurons and supply the antagonist muscles. This process is known as ‘reciprocal inhibition'. The result is pulling the limb away from the stimulus within half a second [1]. Figure 3 shows the multiple neurons involved in a withdrawal reflex of the arm.

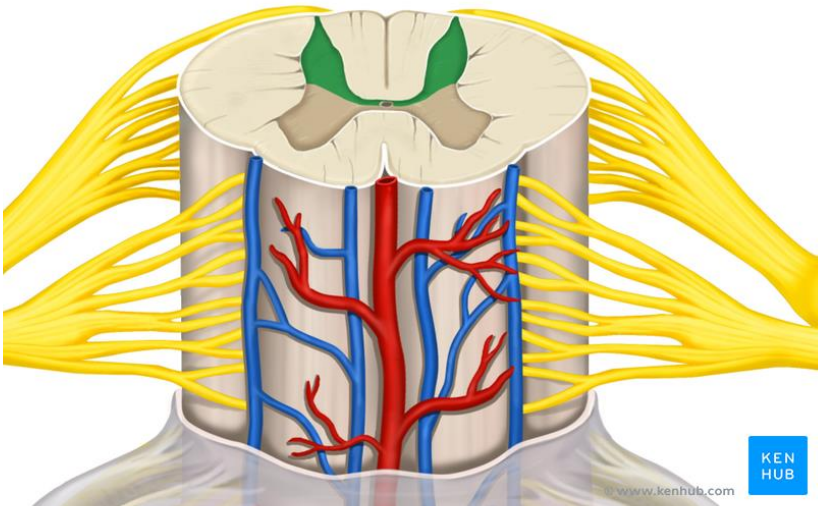

Figure 3. Posterior horn of the spinal cord. (Source: https://www.kenhub.com/en/library/anatomy/the-withdrawal-reflex#_=_).

Chapter 3

LITERATURE REVIEW

The robotic arm has evolved drastically throughout the past few decades. In this paragraph, the most important findings and developments about robotic arms are highlighted.

In 1938, Willard Pollard licensed a splash completing automated arm that had five degrees-of-freedom and an electrically controlled framework. However, this arm was never built because of the limitations at that time [1].

In 1962, George Devol introduced the first industrial arm that was installed at the General Motors Plant in Ternstedt, New Jersey (Figure 4).

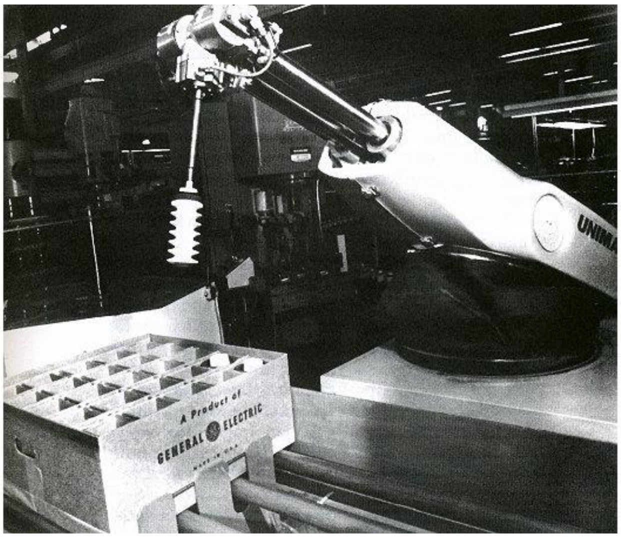

Figure 4. The first industrial robotic arm - 1962.
(Source:http://i.pinimg.com/originals/24/c6/56c65685b18f8302bfc45.jpg).

Ever since the 1960's, industrial robotic arms continued to evolve as the competition between companies around the globe continued to cause high demand on these types of inventions [1].

In 1963, the Rancho Arm having six joints was invented in order to assist handicaps (Figure 5).

Figure 5. The Rancho Arm. (Source: http://cyberneticzoo.com/tag/prosthesis/).

In 1968, Marvin Minsky created the tentacle arm which had 12 joints and was strong enough to lift a person [1] (Figure 6).

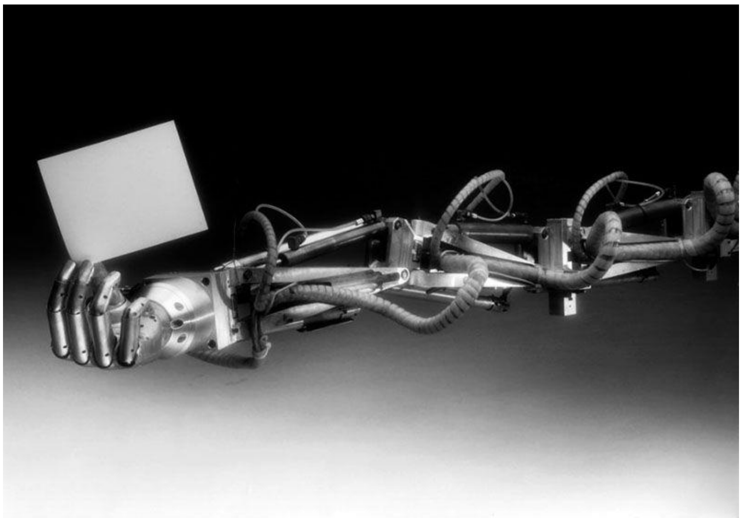

Figure 6. The tentacle arm. (Source: http://www.computerhistory.org/timeline/ai-robotics/).

In 1969, researchers at Stanford University designed a commercial robotic arm. It was one of the first computer-controlled, electronically-powered arms. It reached further development in 1974 when it was able to collect and assemble a water pump [1].

In the same year, David Silver from MIT University developed the Silver Arm. This arm was able to assemble anything precisely using pressure and touch sensors with the help of a microcomputer [1].
Ever since the mid 1970's, the robotic industry started to evolve and grow at rates around 30% per year [1].
In 2007, the Bionic Hand or i-LIMB was created. It was the world's first commercially available prosthetic hand. It was developed by Touch Bionics (Livingston, United Kingdom). Each finger of this hand was able to move on its own and to hold large objects (Figure 7).

Figure 7. The i-LIMB. (Source: http://www.opchealth.com.au/i-limb-ultra-revolution).

In 2008, scientists at the University of Tokyo developed a type of "e-Skin" with the help of carbon nanotubes in order to give robots a sense of touch. This was the first step towards creating human-like robots [1].
Silvestro Micera and colleagues at EPFL Center for Neuroprosthetics and SSSA (Italy) developed the revolutionary sensory feedback that allows feeling while handling objects. A prototype of this bionic technology was tested in February 2013 during a clinical trial in Rome under the supervision of Paolo Maria Rossini at Gemelli Hospital (Italy). This was the first time in neuroprosthetics that sensory feedback has been restored and used by an amputee in real-time to control an artificial limb.[6]

In 2014, the Open Hand Project was launched in order to supply amputees with lower cost robotic hands. Being very advanced, the Dextrus hand is a realization of the dream of many amputees [1].

In 2015, engineers at the Applied Physics Laboratory at Johns Hopkins University developed a new advanced robotic hand or the DARPA hand which is directly wired to a human brain in order to make it have the sense of touch. This hand contains sensors that are able to detect pressure applied to any of its fingers, and it mimics touch sensations by creating electrical signals (Figure 8).

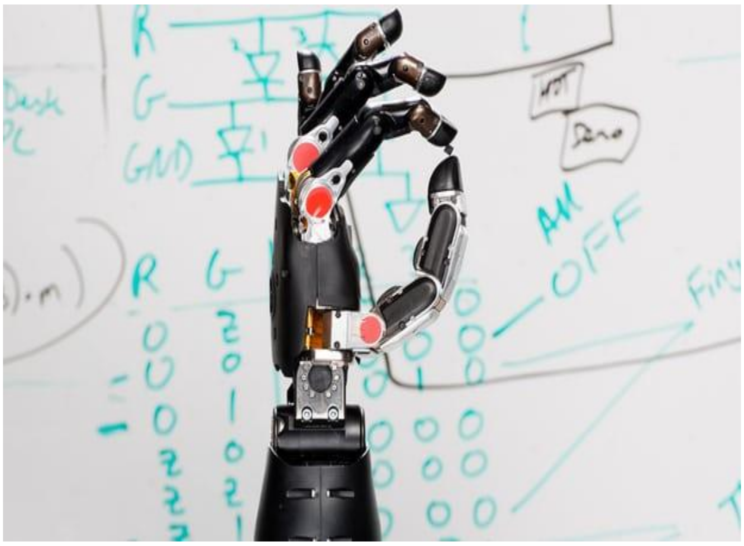

Figure 8. The DARPA hand. (Source: https://www.theguardian.com/technology/2015/sep/14/robotic-hand-wired-directly-into-brain-feel-again-darpa).

In 2016, Zhe Xu and co. from the University of Washington built the most detailed and accurate biomimetic anthropomorphic robotic hand, aiming to completely replace the robotic hand (Figure 9).

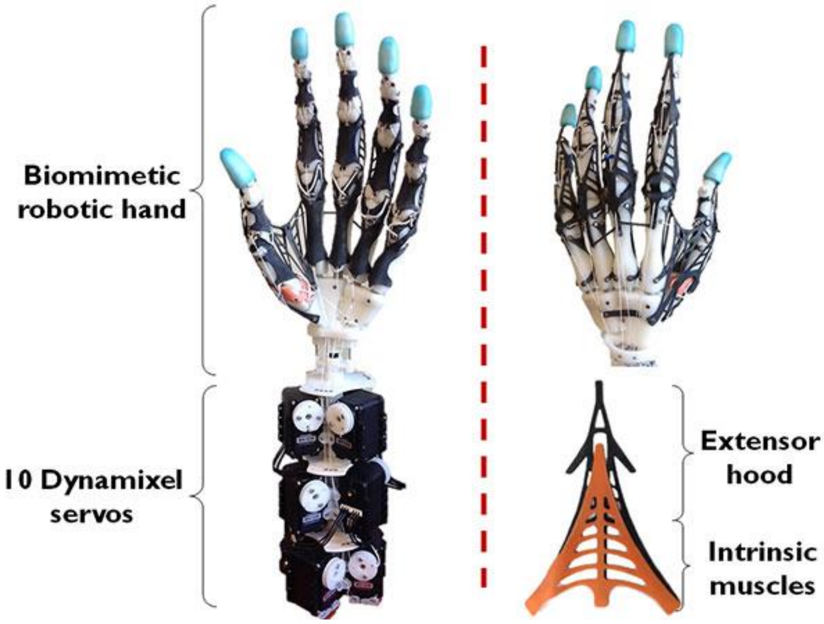

Figure 9. The first biomimetic anthropomorphic robotic hand (Source: https://spectrum.ieee.org/automaton/robotics/medical-robots/biomimetic-anthropomorphic-robot-hand).

In 2017, researchers at the University of Glasgow have developed what seemed to be impossible: a self-powered robotic skin that is sensitive to touch even more than a human hand [1].

The future of robotic and prosthetic hands seems to be very promising according to the huge developments and discoveries made every day. This field is unstoppable and can reach high measures in no time [1].

Chapter 4
MATERIALS AND METHODS

This is the most important part in any project since the designers have to do multiple research about what materials are suitable for their project and decide the most convenient methods to implement them in order to obtain the desired results.

A. Alternative Design Approaches

In order to start with a project, the engineer should take into consideration many alternative design approaches and then choose the most suitable one among them. This choice is made according to the engineer or group's knowledge, capabilities, and budget.

The following two tables represent the first, second and third alternative design approaches to the selected design approach.

Table 1. The First Alternative Design Approach.

Hardware	Peripherals	Programming language
Prosthetic arm	Sensors: thermocouple and force torque sensor	Raspberry Pie

Table 2. The Second Alternative Design Approach.

Hardware	Peripherals	Programming language
Robotic arm	Sensors: force torque sensor Temperature sensor: SHT1X	C++ / Arduino

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Table 3. The third Alternative Design Approach.

Hardware	Peripherals	Programming language
Robotic arm	Sensors: piezoelectric sensor for pressure Temperature sensor: thermocouple	C++ / Arduino

B. Selected Design Approach

Technical capabilities: all the group members are able to work as a unity, under pressure, rapidly, and accurately to design the desired project. They can draw and construct circuits, write several programming languages such as C++, Java, and Matlab, implement sensors, and troubleshoot for any errors.

Cost and experience: the cost of this project is set to be a maximum of 1,200$ for the whole group; the group consists of four members, which means that the cost per member should not exceed 300$. The students' four-year experience in subjects concerning biology, physiology, physics, chemistry, math, signals, electrical circuits and programming should provide a project with a good quality and accuracy.

Development time: if no errors occur and all components are working properly, the whole project should take up to four months of development including implementation, programming, troubleshooting, and testing. However, the team is taking into consideration the chances of encountering any errors, and thus working fast but attentively to prevent them from happening.

C. Design Specifications

The design consists of a robotic arm having five fingers (Figure 10). The arm is already assembled; it is made of Black Acrylic 5.0; it consists of a servo motor with a 5-6 V voltage, and it has the following dimensions: a maximum height of 189.27 mm and a total width of 66 mm.

The temperature and pressure sensors are implemented on this hand especially on the fingers and palm. The output is connected to a screen having a sound output and a signal representation.

Servo motors are also implemented on the arm to play the role of the muscles in moving the hand for reflexes. The hand is tested using hot objects, cold surfaces, objects with moderate temperature, low pressure, and high pressure. These ranges of temperature and pressure will lead to the pain output.

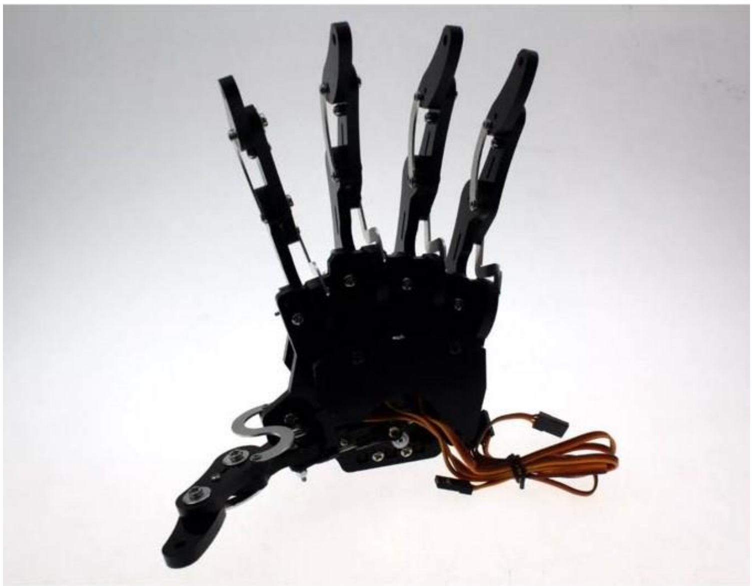

Figure 10. The chosen hand for the project.

Figure 11 shows a 3D design of the project.

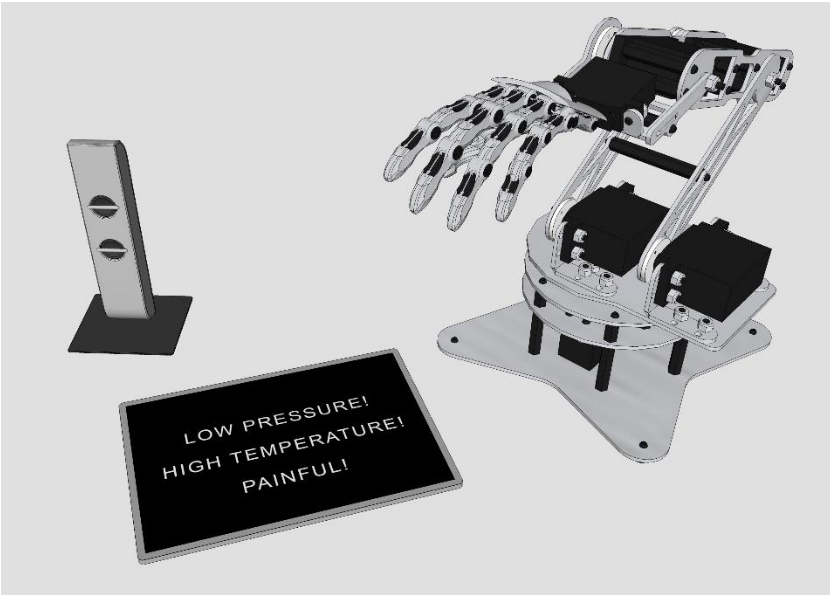

Figure 11. A 3D design of the robotic arm.

D. Multiple Realistic Design Constraints

This robotic arm project is of low cost, with estimated material cost of approximately 1040$. One of the constraints is having four buttons implemented on the robotic arm, which is not a practical way to control the arm.

Another constraint is the availability of the sensors since they have to be ordered from different countries and need time to be delivered.

One last constraint is the power limitation since the arm needs a lot of power because of the presence of nine servo motors and an Arduino; some serious problems were faced because of this constraints where servo motors stopped working and affected the arm's position and movement.

As for the ethical part, the project does not use any radioactive nor toxic materials and it is designed with low cost in order to lower the price of such designs.

The health and safety part is not a concern for this design since it is safe for workers and even consumers to work on and use, it does not cause any harmful noise nor uses hazardous materials. The control system of this arm is safe and cannot hurt anyone.

E. Materials

This project is basically composed of components that are already found in the market, and can be easily purchased.

i. Arduino Mega:

The core of this project is the Arduino Mega (Figure 12) board that has: 54 digital I/O pins, 14 of which (D0 to D13) can be used as PWM outputs, 16 of which are analog input pins and can also be used as digital I/O pins, adding to the existing 54 digital I/O pins, four serial communication lines UARL (pins D0, D1, and from D14 to D19), a 16 MHz crystal oscillator, a USB connection, a power jack and a reset button (Figure 12).

Figure 12. Arduino Mega. (Source: https://store.arduino.cc/usa/arduino-mega-2560-rev3).

ii. Flex Sensor FS-L-0055 (2.2”length):

A flex sensor (Figure 13) is a variable resistor whose terminal resistance increases when the sensor is bent. Left flat, this sensor acts as a 30kΩ resistor and as it bends, the resistance between the two terminals will increase to as much as 70kΩ at a 90° angle. By combining the flex sensor with a static resistor to create a voltage divider, a variable voltage that can be read by the Arduino’s analog-to-digital converter is produced. This sensor is used to sense and measure the changes in the linearity of the fingers in order to allow precise control of their motion.

Figure 13. Flex sensor. (Source: https://components101.com/sensors/flex-sensor-working-circuit-datasheet).

iii. Infrared Sensor MLX90614:

An infrared temperature sensor acts by focusing the infrared energy emitted by an object onto photodetectors in order to convert it into an electrical signal. Since the emitted infrared energy of any object is proportional to its temperature, the electrical signal provides an accurate reading of the temperature of the object that it is pointed at. An IR sensor allows greater detail during a measurement than contact devices as well as the ability of measuring the temperature of moving objects.

iv. Negative Temperature Coefficient thermistor (NTC):

An NTC thermistor (Figure 14) is a variable resistor whose resistance varies with an increase in temperature. It is made of sintered metal oxide. Thus, it displays a large decrease in resistance in proportion to small increases in temperature. It operates in the range between -50°C and 250°C. It offers excellent immunity to electrical noise and lead resistance.

Figure 14. Thermistors. (Source: https://www.ametherm.com/thermistor/what-is-an-ntc-thermistor).

v. Force Sensitive Resistor (FSR):

An FSR (Figure 15) is a variable resistor whose resistance changes when a force, pressure or mechanical stress is applied. The FSR is made of two layers separated by a spacer. The more one presses, the more of those Active Element dots touch the semiconductor and that makes the resistance go down. When there is no pressure, the sensor looks like an infinite resistor, as the pressure increases, the resistance goes down. It operates in the range between 0.1 and 100 Newtons.

Figure 15. Force Sensitive Resistor. (Source: https://www.google.com.lb/search?q=fsr&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjVvurawczbAhXQt1kKHRfBC1MQ_AUICigB&biw=1366&bih=635#imgrc=-0_nwxsTADkGpM:).

vi. Servo Motor:

A servo motor is a rotary actuator that allows precise control of angular position. It is controlled by sending an electrical pulse of variable width, or pulse width modulation (PWM), through the control wire. The PWM sent to the motor determines position of the shaft, and based on the duration of the pulse sent via the control wire, the rotor will turn to the desired position.

vii. NiCd battery:

The nickel–cadmium battery is a type of rechargeable battery using metallic cadmium as electrodes and nickel oxide hydroxide. This battery has a nominal potential of 1.2 volts (V). Compared to other types of batteries, the NiCd batteries are more difficult to damage than other batteries. It is perfect for use in the portable tools. NiCd batteries typically last longer, in terms of number of charge/discharge cycles, than other rechargeable batteries such as lead/acid batteries.

F. Methods

The following flowchart (Figure 16) describes how the team members wish their project to work.

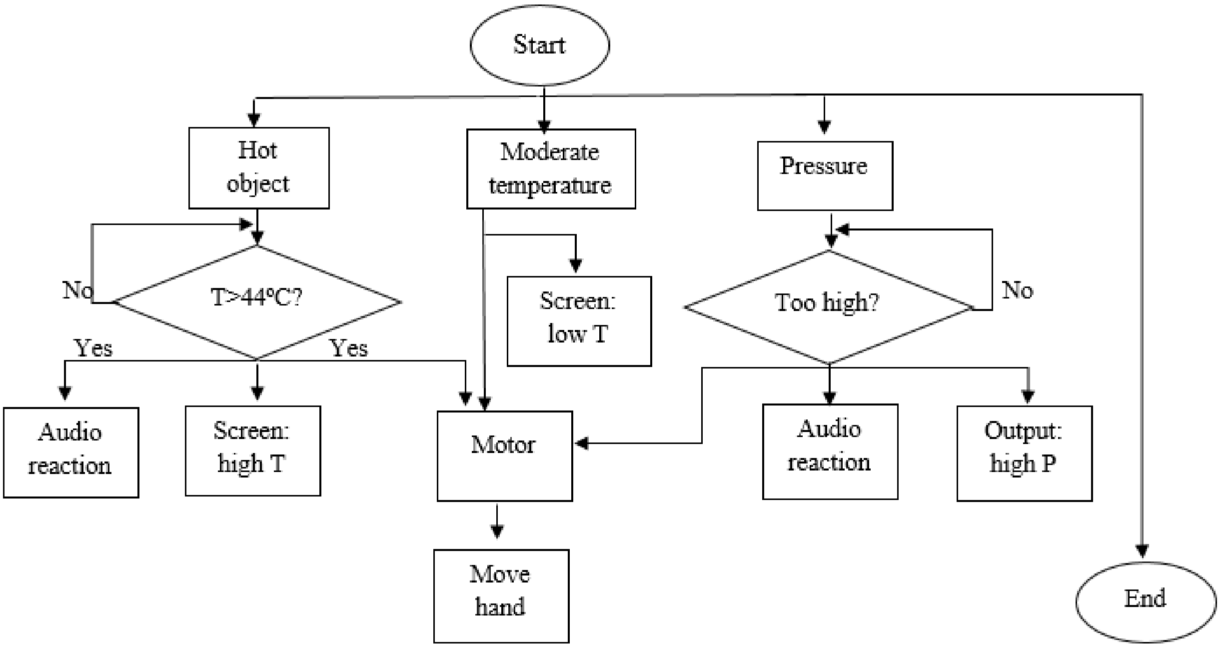

Figure 16. Design Flowchart.

Figure 11 shows a 3-D design of the project which consists of a robotic arm with five temperature sensors (thermistors) implemented on the inner side of the fingers along with five pressure sensors (FSR); additionally, five flex sensors for measuring the bending angle of the arm are implemented on the outer sides of the fingers. The movement of the whole arm is controlled by servo motors implemented on the elbow and inside each finger. All of these sensors are connected to an Arduino that controls the whole project. A tablet is connected in order to display the temperature and pressure levels measured by the FSR's and thermistors every time the hand touches any object; the tablet also provides a voice signal and a face representing the sensation felt by the arm. The whole project is powered by three NICD batteries.

According to the flowchart, the arm is exposed to three different objects: one with moderate temperature, the other with a high temperature and the last one with low temperature. The hand senses the object, if it has a moderate temperature, it holds and then releases it; if it is too hot, it will perform a withdrawal reflex; if it is not too hot, it touches but then releases it after a short time; finally, if it is cold, the arm holds the object and then releases it. In addition, if anyone presses on the hand, it will declare that it is in pain. It is important to note that the hand is continuously sensing the temperature and pressure and displaying their levels on the screen next to the face. This way, it is being assured that the hand is protecting itself the whole time.

G. Cost Analysis

The following table provides the total cost of the whole project. The cost depends on the item's quality, quantity, shipping, and price. In this table, the quantities of some components are raised since errors and accidents are taken into consideration.

Table 4. Cost Analysis

Item No.	Description	Quantity	Unit price ($)	Total Cost ($)
1	Robotic Hand (including taxes + shipping from US.)	1	180.00	180.00
2	7 inch. Windows tablet	1	320.00	320.00
3	IR Thermometer	1	16.00	16.00
4	Flex sensor	5	15.00	75.00
5	FSR sensor	6	10.00	60.00
6	Thermistor sensor	5	5.00	25.00
7	Servo motor (13-15 KG)	3	15.00	45.00
8	Servo motor (0.5-1 KG)	5	9.00	45.00
9	Servo mount + bracket(aluminum)	5	10.00	50.00
10	Straight bracket	1	10.00	10.00
11	NICD Battery	6	6.00	36.00
12	NICD Battery charger	1	7.00	7.00
13	Plexi + laser cut	1	70.00	70.00
14	Robot arm disc base	1	45.00	45.00
15	M/F and M/M wires + Electrical tape	~	30.00	30.00

Item No.	Description	Quantity	Unit Price ($)	Total Cost ($)
16	Handling	~	30.00	30.00
			Total	1,044

Chapter 5

SOCIETAL ISSUES

A. ETHICAL

This technological innovation will allow the less fortunate who lost their arm to regain the privilege of not only grasping objects, but also their sense of touch.

B. SOCIAL

There are countless people living with limb loss, who, with no doubt, wish to return to their pre-amputation life. Having their biological arm replaced by a robotic one that senses in a similar way, these individuals will get back their sense of belonging in this world and will have the opportunity to feel again.

C. ECONOMIC

One of the major purposes of designing this project is to later develop it into a prosthetic arm that can be implemented on the amputee with the lowest possible price. Hence, economic considerations motivated the team in designing this machine in a simple, effective, and efficient way.

D. HEALTH AND SAFETY

Safety is a concern when designing a mechanical part that is meant to replace biological limbs. However, in this machine, which is an initial step towards reaching this goal, health and safety issues are not a concern. The only precaution one has to take is holding the high level iron while testing the machine.

E. MANUFACTURABILITY

Before proceeding with the project's design, the different ways in which it could be implemented were studied. It was decided to work on an already built robotic arm with a motor by adding the required sensors.

F. USABILITY

This project is ultimately usable by anyone since the user will only have to expose it to a high temperature, give it an object to hold, or introduce a painful stimulus on it. The robotic arm will then perform a reflex and display a message on the screen.

G. LIFELONG LEARNING

Lifelong learning is one of the most important factors in developing such projects. New concepts and techniques were gained to help enhance some skills. Moreover, new components, materials, and software were learned.

Chapter 6

RESULTS AND DISCUSSION

A. Testing and Validation

When building and programming are complete, the entire project must be tested to see if it does the job for which it was designed.

For the hardware part, the servo motors must be tested to achieve the right angle of freedom of the arm; the calibration of the sensors must also be ensured. Moreover, the functionality of the screen must be checked to ensure that it is delivering a response. As for the software parts, the arm must be controlled using Arduino.

After testing, an evaluation needs to be written; this should be a statement outlining the strengths and weaknesses in the design in order to fix the problems and achieve the goal of the project.

The following block diagram describes the testing procedure.

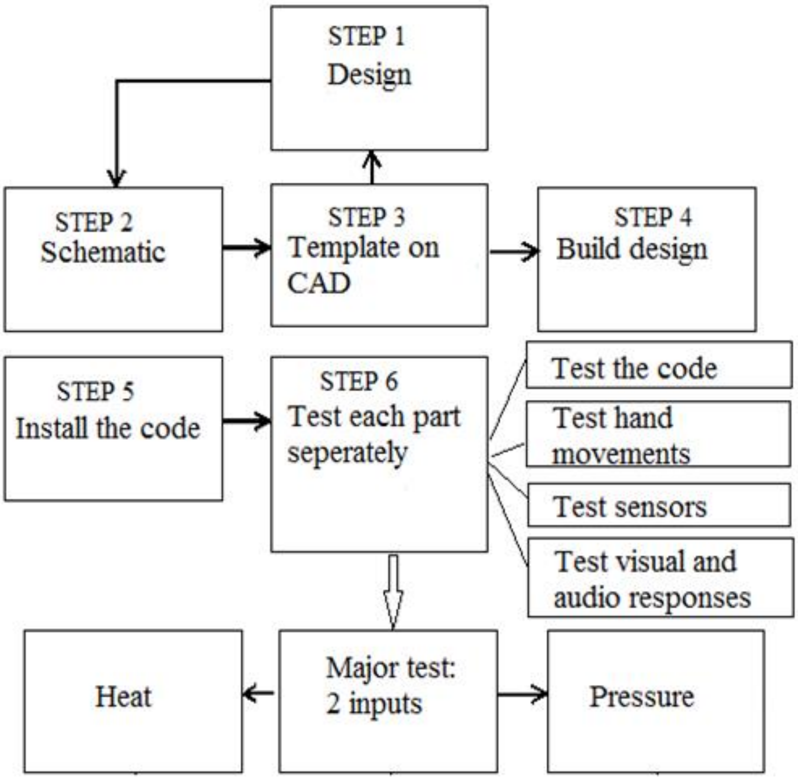

Figure 17. Testing block diagram.

As in any project, the first step is always to decide on the design and its specifications, then a schematic including the detailed circuitry and functioning of the system should be drawn. The next step is to design a project template using 3D programs such as CAD. As the schematic and the design are finished, the project begins to be built accordingly for both the hardware and software parts. After finishing the whole design with the connections and the program, testing takes place. It is important that each part should be tested separately in order to know the errors without losing track of the project functioning. In this design, the code is tested by applying low, moderate, and high temperature and pressure levels to the hand each alone, and observing the response of the hand to these levels; if the hand responds fast and accurately enough, then the code is written as desired, and if not, the code will be changed until the desired output is obtained. While testing the code, the whole system is being tested - that is the sensors, hand movements, visual, and audio responses since the output is obtained using all of these components. Any unwanted results should be eliminated and changed in order to obtain an error-free design.

Testing is the most important part in any design since it validates the functioning of the project, as well as the environmental changes around it, and specifically the temperature in the case of the robotic arm.

B. Results

As a result, the robotic hand was able to sense the temperature and the pressure applied on it. Consequently, the hand secures itself from dangerous ranges of these two sensations by exerting a withdrawal reflex in order to escape from the source of danger. In addition, a Windows application is controlled by the hand and displays the values of temperature and pressure as well as a graphical face that describes the feeling of the hand whether it is normal, hot, or in pain. For example, if high temperature and pressure are applied on the hand, the hand will move in the opposite direction of these sensations' source, and the application will display a face describing that it is in pain along with the values of the temperature and pressure. Figures 18, 19 and 20 show the resulting designed robotic arm.

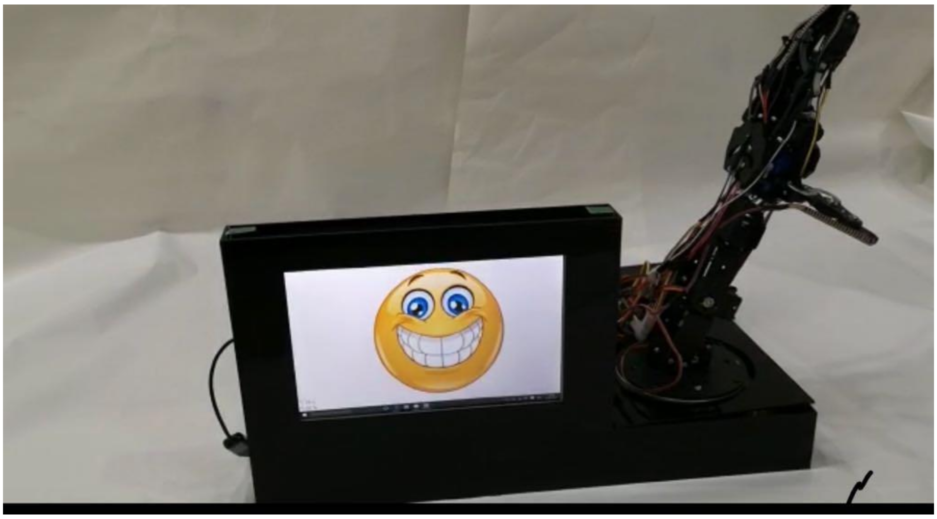

Figure 18. Results while the arm is resting.

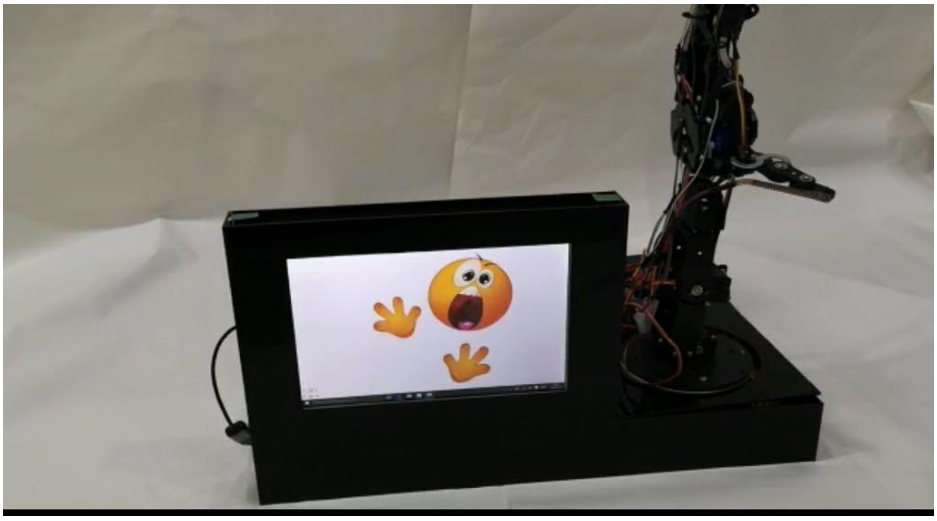

Figure 19. Results while the arm is in pain.

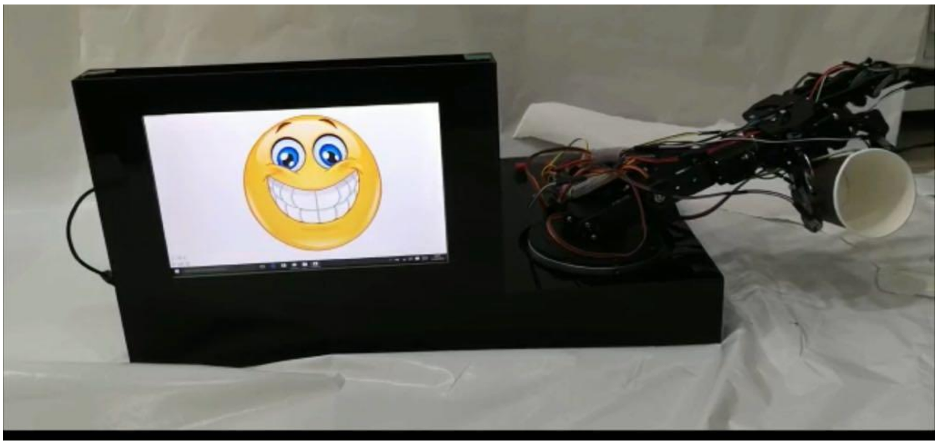

Figure 20. Results while the hand is holding a cold object.

C. Discussion

In order to design the sensing robotic hand, the opportunity to relate between theory and practice was grasped along with getting involved in real life applications of theories, programming, circuit making, and analytical studies. For instance, a long way of testing and validation led to the choice of the sensors according to their accuracy, response time and size. Moreover, the performance analysis of this hand is done by varying temperatures and pressures near the hand. Although the prototype of the sensing robotic hand does not show the full benefit of its usage, however once implemented on a robot it will be a revolution to the robotics' world. The designed hand is a step towards humanizing the robots working in workplaces in order to protect their hardware from being harmed and alerting other people of any potential danger.

Chapter 7

CONCLUSIONS AND FUTURE WORK

The main goal of this project was to develop a robotic arm that senses temperature, pain and pressure altogether. The purpose was to make robots close to being like humans by protecting themselves from any potential damage, in addition to improving the arm in the future to a prosthetic one for amputees. This design is of great importance not only for robots, but also for amputees who dream to feel normal again.

The objectives were to make the arm able to detect and sense temperature and pressure, and respond accordingly through a withdrawal reflex and a screen displaying facial expressions, temperature and pressure levels and a sound output. Also, the sensations' measurements were desired to be accurate and the arm's response was aimed to be fast. Accordingly, as seen in the results, the purpose and objectives of the project were obtained after a long process of research, implementation, testing and validation.

Many alternative designs were taken into consideration at first, but only one was chosen for reasons such as being available in the market and having the required specifications for the project. At first, thermocouple and piezoelectric sensors were used to sense temperature and pressure, respectively; however, their measurements were not accurate nor fast enough, so they were replaced by thermistors, FSRs, and flex sensors which provided the needed specifications. Every part of the project was tested alone i.e. the part of the Arduino program concerning temperature measurements was tested alone along with the temperature sensors, and the same process was done for pressure. The output was also tested alone by sending to it random values and observing the changes happening on the screen. Finally, all of these components were implemented and assembled together, and the whole arm was tested using objects with moderate, low, high temperature and high pressure levels.

Many problems were faced before getting the arm to be fully functioning. One of the problems was the power consumption because the batteries needed to be continuously charged and the screen needed a special type of charger that was not found in the market. Another problem was with the servo motors since they were very delicate and some of them were replaced more than once. Additionally, the calibration was a little hard to accomplish. The most important problem was concerning the code that was being continuously changed because of issues with the coordination between the input and output.

A. Conclusions

In conclusion, the resulting arm is a fully functioning one but with some problems. The arm is able to detect and sense temperature and pressure values; it is also capable of declaring when it is in pain while high temperature or pressure levels are applied to it. However, its movements are limited because the purchased hand is of low quality.

Even though the arm requires some improvements, it is considered an innovation in the world of robotics because it is the first to have the three sensations combined.

B. Future Work

For future work, the first step to be done is to get rid of the push buttons and make the arm fully automated; this would make the project more practical and professional. The next step is to improve the arm's movements by enhancing the code and adding some components. Most importantly, this arm can be further developed into a human-like prosthetic arm.

References

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[2] Menche N. (ed.) Biologie Anatomie Physiologie. Munich: Urban & Fischer/ Elsevier; 2012. [3] Phillip L Rice, Jr.; Dennis P Orgill. "Emergency care of moderate and severe thermal burns in adults".

[4] Abe S, Lan M.A method for fuzzy rule extraction directly from numerical data and its application to pattern classification. IEEE trans Fuzzy Syst 1995; 3:18-28.

[5] Berger CC, Ehrsson HH (2014) The fusion of mental imagery and sensation in the temporal association cortex. J Neurosci 34(41):13684–13692.

[6] C.Cipriani, F.Zaccone, S.Micera, M. Carrozza, “On the Shared Control of an EMG-Controlled Prosthetic Hand: Analysis of User-Prosthesis Interaction”, IEEE Trans. On Robotics, vol. no. 24, pp. 177-184, February 2008.

Datasheets

1. FSR
2. Thermistor
3. IR
4. Flex Sensor
5. Arduino Mega.

Appendix A

Robotic Arm Code

```
//Including libraries
#include <Servo.h>
#include <Wire.h>
#include <Adafruit_MLX90614.h>



//Defining temp sensor
Adafruit_MLX90614 mlx = Adafruit_MLX90614();

// Defining Thermistor pins (direct temperature sensing)
#define Therm1 A1 //index thermistor
#define Therm2 A2 //middle thermistor
#define Therm3 A3 //ring thermistor
#define BackTherm A4 //back thermistor

//defining force sensitive resistor pins (pressure sensing)
#define ThumbFSR A5
#define IndexFSR A6
#define MiddleFSR A7
#define RingFSR A8 //IndexFSR
#define PinkyFSR A9 //RingFSR

//defining flex sensor pins (finger bend angle sensing)
#define ThumbFlex A10 //pinky flex
#define IndexFlex A11 //index flex
#define MiddleFlex A12 //middle flex
```

```
#define RingFlex A13 //ring flex
#define PinkyFlex A14 //thumb flex

//defining large force sensitive resistor (pain sensing)
#define PainFSR A15

//defining Servo pins (arm)
#define WristPin 2
#define ShoulderPin 3
#define ElbowPin 12
#define BasePin 5

//defining Servo pins (hand)
#define ThumbPin 8
#define IndexPin 10
#define MiddlePin 9
#define RingPin 7
#define PinkyPin 6

//Defining Servo Initial Positions (arm)
#define WristInitPos 90
#define ShoulderInitPos 120
#define ElbowInitPos 50
#define BaseInitPos 130

//Defining Servo Initial Positions (hand)
#define ThumbInitPos 0
#define IndexInitPos 0
#define MiddleInitPos 0
#define RingInitPos 120
```

```
#define PinkyInitPos 0

//Defining Servo Close Positions (close hand)
#define ThumbClosePos 180
#define IndexClosePos 150
#define MiddleClosePos 180
#define RingClosePos 0
#define PinkyClosePos 150

//Defining Catch Positions
#define ShoulderCatchPos 60
#define ElbowCatchPos 55
#define WristCatchPos 20
#define BaseCatchMiddlePos 130
#define BaseCatchRightPos 135
#define BaseCatchLeftPos 45

//Defining Threshold Values
#define MaxTemp 40
#define MaxTempTherm 600
#define PainThreshold 650

//Defining Fire Escape Angles
#define ShoulderEscapeAngle 15
#define ElbowEscapeAngle 15


//Defining Heat Detection Booleans
boolean IRHeatDetected;
boolean FingerHeatDetected;
```

```
boolean BackHeatDetected;
boolean HeatDetected;
boolean PainDetected;

//Defining Max Pressure Detection Booleans
boolean MaxPinkyPressure;
boolean MaxRingPressure;
boolean MaxMiddlePressure;
boolean MaxIndexPressure;
boolean MaxThumbPressure;
boolean MaxPressureReached;

//Defining Max Angle Detection Booleans
boolean MaxThumbAngleReached;
boolean MaxIndexAngleReached;
boolean MaxMiddleAngleReached;
boolean MaxRingAngleReached;
boolean MaxPinkyAngleReached;
boolean MaxAngleReached;

//Flex Sensor Calibration
const float VCC = 4.93; // Measured voltage of Arduino 5V line
const float R_DIV = 46800.0; // Measured resistance of 47k resistor
const float STRAIGHT_RESISTANCE = 30600.0; // resistance when straight
const float BEND_RESISTANCE = 90000.0; // resistance at 90 deg

//Creating Servo Objects (arm)
Servo Wrist;Servo Elbow;Servo Shoulder;Servo Base;
//Creating Servo Objects (arm)
Servo Thumb;Servo Index;Servo Middle;Servo Ring;Servo Pinky;
```

```
#define InitialPin 22 //Press Button to go to initial value
#define Pin1 23
#define Pin2 24
#define Pin3 25

String S, T, P, M;
int Tint; int Pint;
unsigned long int prevTime;
boolean Open;
bool prevHO;
void setup() {
pinMode(13,OUTPUT);
digitalWrite(13,HIGH);
mlx.begin();
//Attaching Servos to Pins (arm)
Base.attach(BasePin);
Elbow.attach(ElbowPin);
Shoulder.attach(ShoulderPin);
Wrist.attach(WristPin);

//Attaching Servos to Pins (hand)
Thumb.attach(ThumbPin);
Index.attach(IndexPin);
Middle.attach(MiddlePin);
Ring.attach(RingPin);
Pinky.attach(PinkyPin);

//Heat detected set to false as default
boolean IRHeatDetected = false;
```

```
boolean FingerHeatDetected = false;
boolean BackHeatDetected = false;
boolean HeatDetected = false;
boolean PainDetected = false;

//Max pressure reached set to false as default
boolean PinkyMaxPressure = false;
boolean RingMaxPressure = false;
boolean MiddleMaxPressure = false;
boolean IndexMaxPressure = false;
boolean ThumbMaxPressure = false;
boolean MaxPressureReached = false;

//Max angle reached set to false as default
boolean ThumbMaxAngleReached = false;
boolean IndexMaxAngleReached = false;
boolean MiddleMaxAngleReached = false;
boolean RingMaxAngleReached = false;
boolean PinkyMaxAngleReached = false;
boolean MaxAngleReached = false;

Serial.begin(115200);
//Serial3.begin(9600);
OpenHand();

delay(100);
Initial();

S="n";
prevHO = true;
```

```
}


void loop() {

if(digitalRead(InitialPin) == HIGH){ Initial();}
if(digitalRead(Pin1) == HIGH){IRtempDown(); }

if(digitalRead(Pin2) == HIGH){  if(Open) {CloseHand(); Open = false;} else
{OpenHand(); Open = true;}  delay(500); }
if(digitalRead(Pin3) == HIGH){   Catch();  }
printMessage();
delay(10);
}



void Initial()
{
//Move arm to initial Position
Base.write(BaseInitPos);
Elbow.write(ElbowInitPos);
Shoulder.write(ShoulderInitPos);
Wrist.write(WristInitPos);
delay(100);
}

int count = 0;
void IRtempDown() {
  prevTime = millis();
```

```
  for(int
ShoulderAngle=ShoulderInitPos;ShoulderAngle>=ShoulderCatchPos;ShoulderAngle
--) { Shoulder.write(ShoulderAngle);  delay(100); printMessage();
  if(   IRHeatDetected || FingerHeatDetected   ) {   Initial(); break;  }
  if(  BackHeatDetected  ) {ShoulderAngle -= 10;
Shoulder.write(ShoulderAngle); }  }}

//Open finger servos
void OpenHand ()
{
Thumb.write(180-ThumbInitPos);
Index.write(IndexInitPos);
Middle.write(MiddleInitPos);
Ring.write(90-RingInitPos);
Pinky.write(120-PinkyInitPos);
delay(10);
Open = true;
printMessage();
}

void CloseHand()
{
 Thumb.write(ThumbInitPos);
Index.write(180-IndexInitPos);
Middle.write(90-MiddleInitPos);
Ring.write(RingInitPos);
Pinky.write(180-PinkyInitPos);
delay(10);
Open = false;
printMessage();
for(int i=0; i<500; i++)
```

```
{
  printMessage();
if(FingerHeatDetected)
{ OpenHand(); S="h"; break;}

delay(10);
}
}



void Catch()
{
  for(int
BaseAngle=BaseInitPos;BaseAngle<=BaseCatchMiddlePos+25;BaseAngle++)
  {  Base.write(BaseAngle); delay(50);printMessage(); }

for(int ElbowAngle=ElbowInitPos;ElbowAngle<=ElbowCatchPos+25;ElbowAngle++)
  {  Elbow.write(ElbowAngle); delay(50); printMessage(); }

for(int ShoulderAngle=ShoulderInitPos;ShoulderAngle>=ShoulderCatchPos-
20;ShoulderAngle--)
  {  Shoulder.write(ShoulderAngle); delay(50);printMessage();  }

  for(int WristAngle=WristInitPos;WristAngle>=WristCatchPos-10;WristAngle--
)
  {  Wrist.write(WristAngle); delay(50);printMessage();}

  for(int BaseAngle=BaseCatchMiddlePos+25;BaseAngle>=BaseInitPos;BaseAngle-
-)
  {  Base.write(BaseAngle); delay(100); printMessage();}
```

```
  CloseHand();   delay(1000);
  Initial(); delay(2000);

    for(int
BaseAngle=BaseInitPos;BaseAngle<=BaseCatchMiddlePos;BaseAngle++)
  {  Base.write(BaseAngle); delay(50); printMessage();}

for(int ShoulderAngle=ShoulderInitPos;ShoulderAngle>=ShoulderCatchPos-
20;ShoulderAngle--)
  {  Shoulder.write(ShoulderAngle); delay(50); printMessage();}

  for(int
ElbowAngle=ElbowInitPos;ElbowAngle<=ElbowCatchPos+25;ElbowAngle++)
  {  Elbow.write(ElbowAngle); delay(50); printMessage();}

  for(int WristAngle=WristInitPos;WristAngle>=WristCatchPos-10;WristAngle--
)
  {  Wrist.write(WristAngle); delay(50); printMessage();}

  OpenHand();   delay(1000);
  Initial();

}


void ReadFlex()
{ // Read the ADC, and calculate voltage and resistance from it
  if ( FlexToAngle(ThumbFlex) > 90) MaxThumbAngleReached = true;
  if ( FlexToAngle(IndexFlex) > 90) MaxIndexAngleReached = true;
  if ( FlexToAngle(MiddleFlex) > 90) MaxMiddleAngleReached = true;
  if ( FlexToAngle(RingFlex) > 90) MaxRingAngleReached = true;
```

```
   if ( FlexToAngle(PinkyFlex) > 90) MaxPinkyAngleReached = true;
 if( MaxThumbAngleReached && MaxIndexAngleReached && MaxMiddleAngleReached
      && MaxRingAngleReached && MaxPinkyAngleReached ) MaxAngleReached =
true;}


float FlexToAngle(int flexPin)
{
  int flexVal = analogRead(flexPin);
  float flexV = flexVal * VCC / 1023.0;
  float flexR = R_DIV * (VCC / flexV - 1.0);
  float angle = map(flexR, STRAIGHT_RESISTANCE, BEND_RESISTANCE,0, 90.0);
return angle;
}



void ReadFSR()
{
  if ( analogRead(ThumbFSR) > 100) MaxThumbPressure = true;
  if ( analogRead(IndexFSR) > 100)   MaxIndexPressure = true;
  if ( analogRead(MiddleFSR) > 100)  MaxMiddlePressure = true;
  if ( analogRead(RingFSR) > 100)   MaxRingPressure = true;
  if ( analogRead(PinkyFSR) > 100) MaxPinkyPressure = true;
  if(MaxPinkyPressure && MaxRingPressure && MaxMiddlePressure &&
MaxIndexPressure && MaxThumbPressure)
  MaxPressureReached = true; }



//Read temperature on fingers (Thermistors)
void ReadFingerTemp()
```

```
{ if(   (analogRead(Therm1) > MaxTempTherm) || (analogRead(Therm2) >
MaxTempTherm) || (analogRead(Therm3) > MaxTempTherm)   ) FingerHeatDetected
= true;
    else FingerHeatDetected = false;}

//Function to read from the temp sensor
void ReadIRtemp(){ Tint=mlx.readObjectTempC(); T = String(Tint);
  if(Tint >MaxTemp && Tint <100) {IRHeatDetected = true; S="h"; }
  else {IRHeatDetected = false;  if(Tint >= 100) T = "26";}}

//Read Back Temperature (Thermistor)
void ReadBackTemp()
{ if (analogRead(BackTherm) > MaxTempTherm){ BackHeatDetected =
true;S="h"; }
  else{ BackHeatDetected = false; }}

//Read Pain Level from Pain FSR
void DetectPain(){ Pint=analogRead(PainFSR); P = String(Pint/10);
  if( Pint > PainThreshold) { PainDetected = true; S="o";} else
PainDetected = false;
  if (P.length()<2){P="0"+P;}}

void ShoulderEscape (int ShoulderReflex){ ShoulderReflex +=
ShoulderEscapeAngle; Shoulder.write(ShoulderReflex);}

void ShoulderEscapeForward (int ShoulderReflex){  ShoulderReflex -=
ShoulderEscapeAngle; Shoulder.write(ShoulderReflex);}

void printMessage(){
  ReadFingerTemp();ReadIRtemp();ReadBackTemp();DetectPain();
  if((S!="h")&&(S!="o")){S="n"; if(millis()- prevTime > 1000){M = "\n";
M=T+P+S; Serial.println(M); S="n"; prevTime = millis();} }
```

```
  else
  { if(millis()- prevTime > 1000){M = "\n"; M=T+P+S; Serial.println(M);
S="n"; prevTime = millis();}}
  //if(M.length()>=4) }

}
```