Design and Control of a Multifingered Anthropomorphic Robotic Hand

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Abstract — **This work describes a multifingered anthropomorphic robotic hand with fourteen Degrees of Freedom (DOF) which is able to mimic the functional motions of a biological hand especially in handling complex objects. The actuation mechanisms consisting of micro servo-motors, pulleys and belts are connected to the finger joints and thus promote bending and extending of the fingers. Two kinds of sensors, i.e. force sensor and light dependent resistor, are integrated into the system. The robotic hand can be controlled via a graphical user interface embedded with control codes or a joy stick integrated to a control board. Furthermore, the robotic hand is able to operate autonomously with the aid of sensory elements and embedded control software. Workability tests showed the capability of the system to move every finger individually and to perform grasping tasks on objects with varying sizes and geometries such as a tennis ball and a screw driver.**

***Index Term*-- robotic hand, degree of freedom, mechanism**

I. INTRODUCTION

Among the vast applications of robotics, robotic assistance in human daily life and has been the major factor that contributes to its development. The focus on the anthropomorphism robotic limbs is currently undergoing a very rapid development. The creation of a multifingered anthropomorphic robotic hand is a challenge that demands innovative integration of mechanical, electronics, control and embedded software designs.

II. LITERATURE REVIEW

The normal human hand has a set of hand which includes palm and fingers. There are five fingers in each hand, where each finger has three different phalanxes: Proximal, Middle and Distal Phalanxes. These three phalanxes are separated by two joints, called the Interphalangeal joints (IP joints). The IP joints function like hinges for bending and straightening the fingers and the thumb. The IP joint closest to the palm is called the Metacarpals joint (MCP). Next to the MCP joint is the Proximal IP joint (PIP) which is in between the Proximal and Middle Phalanx of a finger. The joint at the end of the finger is called the Distal IP joint (DIP). Both PIP and DIP joints have one Degree of Freedom (DOF) owing to rotational movement [2].

The thumb is a complex physical structure among the fingers and only has one IP joint between the two thumb phalanxes. Except for the thumb, the other four fingers (index, middle, ring and pinky) have similar structures in terms of kinematics and dynamics features. Average range of motion among the four fingers for flexion-extension movement is 65^0 at the DIP joint, 100^0 at the PIP joint and 80^0 at the MCP joint while the abduction-adduction angles for the index finger has been measured as 20^0 at the MCP joint[2,3]. Figure 1 illustrates the structure of a human finger.

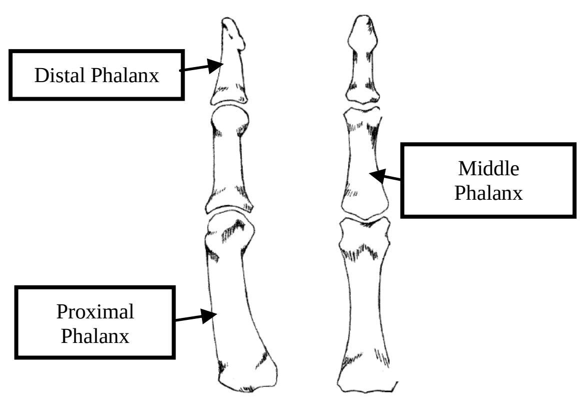

Fig. 1. Structure of Human Finger. [1]

Tendons allow each finger joint to be straightened. Pulley system in a human finger keeps the flexor tendons close to the bone, thus optimizing the biomechanical functioning of the flexor tendons. The pulleys control the moment arm, excursion, and joint rotation produced by the flexor tendons [1]. This will result in flexion-extension movement in a finger. Figure 2 ilustrates the arrangement of flexor tendons and pulleys in a finger.

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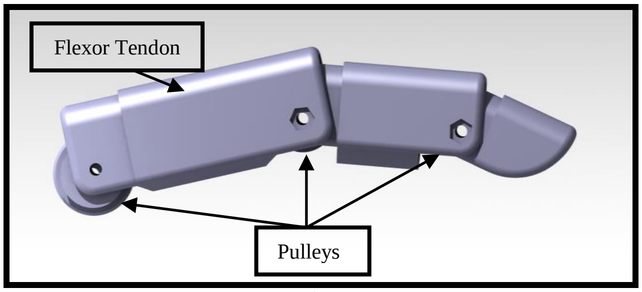


Fig. 2. Arrangement of Flexor Tendons and Pulleys.

Other than tendons and pulleys, the nerve is another important system in a human hand. The nerve system is a natural sensing system in human anatomy which carries signals from the brain to the muscles that moves the arm, hand, fingers, and thumb. It also carries signals back to the brain about sensations such as touch, pain, and temperature [4].

III. THE HUMAN HAND

The human hand has been cited as an important limb that developed the ability of the human brain to form the essential activities in life. The nerves trigger the muscle to generate force. Two sets of muscle act on the hand; extrinsic located in the forearm which is less powerful while the intrinsic that is located within the hand itself is much stronger. Most of the dexterity and flexibility of the hand is attributed by the intrinsic muscle. Some of the muscles act directly on the bones while others act through tendons. Flexor is used to close fingers to grip object and the extensors are used to open the hand again [5, 9].

A hand is supported by a lot of bones that provide movement to each parts of the hand from the fingertips to the elbow. The human hand can perform all the necessary type of grasping. A human hand with twenty five degree of freedom is very flexible and versatile [6]. The basic types of hand grasping are cylindrical, tip, hook or snap, palmer, spherical and lateral or key pinch grasp shown in Figure 3.

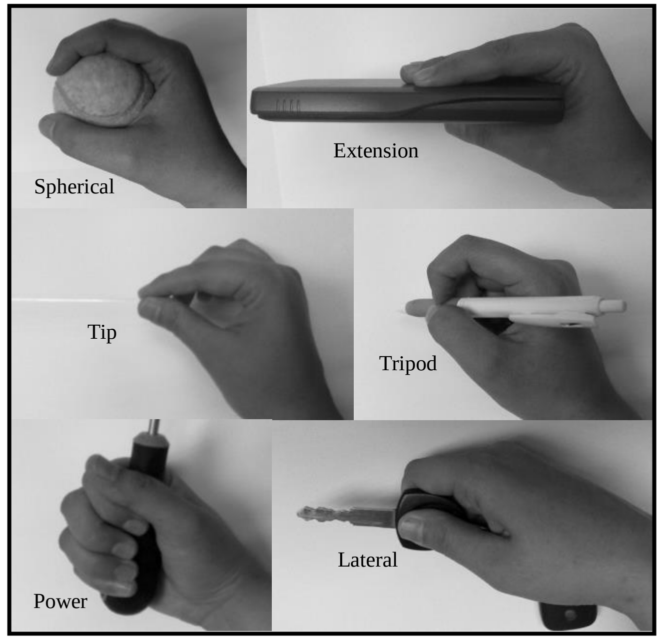
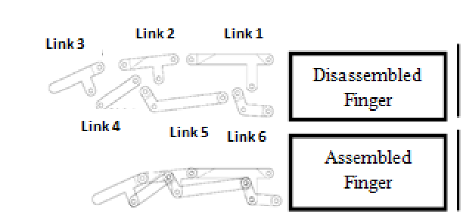
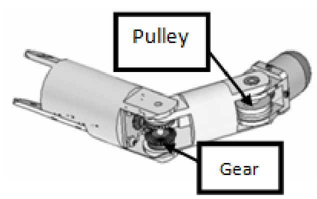
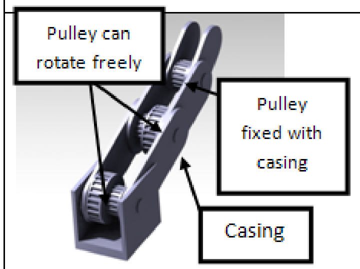


Fig. 3. The Basic Types of Hand Grasping

IV. DESIGN CONCEPT

From the literature review, three concepts of design are established as shown in Table 1 with the study of design analysis for a better design. The selected design is a combination of belt and a pulley system. To generate movement, the servo motor will be replaced by a DC motor for easy control of the finger movement and setting it movement angle. The fingers of a robot hand should preferably be high in coefficient of friction to enable the object to be hold securely. In addition, a large contact area is preferably established between the fingers and the object. Enlargement of the contact area between a finger and the object held requires the finger to be given high flexibility so that it can deform in compliance with the shape or profile of the object.

Table I
Design Concept Selection

Illustration of Design Concept	Mechanism	Actuation	Motion Control Method
	- Combination of linkages. - One finger needs six Links.	- Require one servo motor for each finger. - Movement not smooth - Angle of movement limited.	- Use joystick with five buttons to control motor of each finger - Control using GUI with computer interface - Automatic movement depends on Microchip program.
	- Combination of gear and pulley	- Require two dc motor for one finger - Require two switch to control movement. - Angle of movement similar to human finger.	- Use joystick with 10 buttons to control motor of each finger - Control using GUI with computer interface - Automatic movement depends on Microchip program.
	- Combination of pulley and belt. - Two pulleys can rotate freely. - One pulley is fixed with casing of finger.	- Require one servo motor for one finger - Movement smooth compared to linkage design - Angle of movement similar to human finger.	- Use joystick with five buttons to control motor each finger - Control using GUI with computer interface - Automatic movement depends on Microchip program.

V. ACTUATION MECHANISM DESIGN

The actuation mechanism is designed based on the internal actuation concept in order to simplify the connection between the actuator and the driving mechanism of the finger. The distance between the servomotors and pulleys that are connected together by a timing belt was short as compared to the external actuator type which is normally located outside the palm or fingers. Figure 4 shows the basic concept of an open belt pulley system. The diameter of pulley A is bigger than pulley B for adjusting the angular position and speed between the pulleys A.

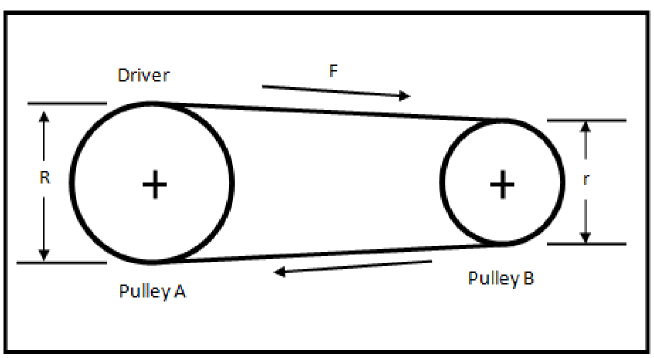


Fig. 4. Open Belt Pulley System Concept

Servo motors have the limitation of rotating 180°. To eliminate this limitation, the pulley system has to be configured as shown in Figure 5. Pulley A acts as a driver will rotate 180° and will increase the rotation of pulley B. Pulley B will then increase the rotation of pulley C and as a result the last pulley will rotate more than 180°.

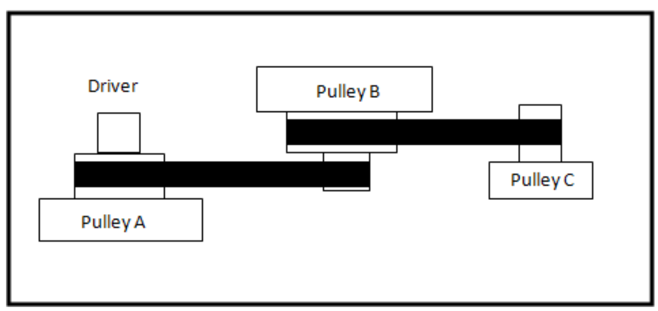


Fig. 5. Variable Speed of Pulley

The basic idea of this finger system is to drive the distal, middle and proximal phalanx mechanically using pulleys and timing belt. A servomotor drives the MCP joint pulleys. As the MCP joint pulleys rotate, it would drive the PIP joint pulleys. The PIP joint pulleys subsequently drive the DIP joint which is fixed at the distal phalanx. The joint pins allow the pulleys to be in position and rotate within its axis. Combination of these components produces a pulley system for the robot finger as shown in Figure 6. Servomotor was used as an actuator in this project as it offers high torque at low rotational speed, compact size and very light in weight.

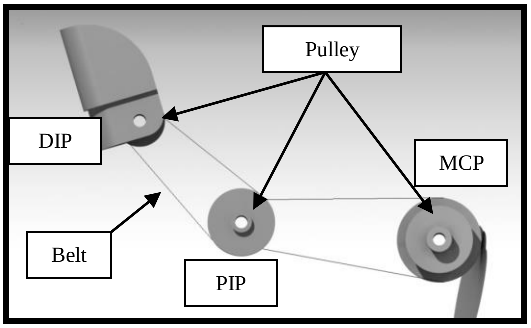


Fig. 6. Combination of Belt and Pulley

The differential pulley concept was adopted in order to get a higher torque over a short distance. Differential pulley is a set of fixed pulley with different radii, *R* and *r* as shown in Figure 7. These different radii will create mechanical advantage (MA) on each rotation of the pulley. MA is a factor by which a mechanism of pulley multiplies the force or torque applied to the system. Neglecting friction, the mechanical advantage is given by the following formula;

$$MA = \frac{2.R}{R-r} \qquad \text{(Eq.1)}$$

For MCP Joint: MA = 2(10)/ (10-7.5)
= 8

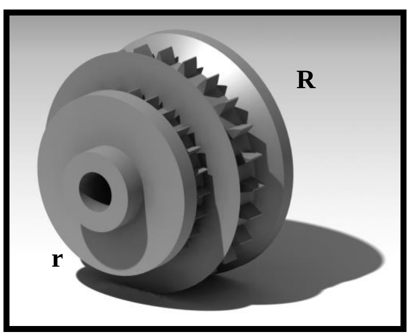


Fig. 7. Differential Pulley Radii

A smaller difference between the radius of the pulleys results in a larger mechanical advantage. For this project, the MA established from the MCP and PIP Joint differential pulleys are 8 and 9 respectively. Table 2 shows the pulley radius for each of the index finger joints.

Table II
Pulley Radius and MA for Each Joint of Index Finger

Pulleys/Joints	Pulleys/Differential Pulleys Radius (mm) R	Pulleys/Differential Pulleys Radius (mm) r	Mechanical Advantage (MA)
Servomotor	24		0
MCP	10	7.5	8
PIP	9	6.5	9
DIP	6		0

VI. Kinematics Analysis

In most of the natural grasping movements, the thumb comes from the opposite direction to the other fingers. This is also considered in the design and opens at all the demanded grasping areas. Each finger is actuated by one servo motor, whereas the rotation will be transferred over by a gear belt mechanism. Thus there are three gears in the finger, one for every limb connected by a belt and with a fixed gear at the last segment as shown in Figure 8. Hence the motor rotation will generate the movement of all limbs in natural motion. An exception is the thumb having only two limbs, but the principle function is still the same. Furthermore, the determination of the correct ratio between the motor rotation and the limb movement was a very difficult part. In this framework, the first prototype model of a multifingered anthropomorphic hand has been developed.

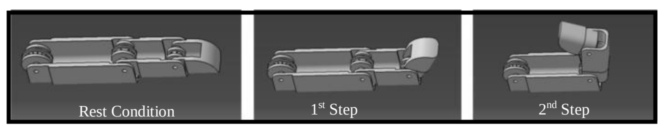


Fig. 8. Sequence Movement

It is important to point out that robotic hand is designed primarily for grasping tasks. The design approach is based on underactuated mechanism reproducing most of the grasping behaviors of the human hand without augmenting the mechanical and the control complexity. In general, an underactuated hand, the correct selected of the elastic elements characteristic and the correct placing of the mechanical stops allows a natural wrapping movement of the finger around the object, In order to achieve a correct finger movement, the object should touch the proximal phalanx first, the middle next and finally the distal phalanx as shown in Figure 9.

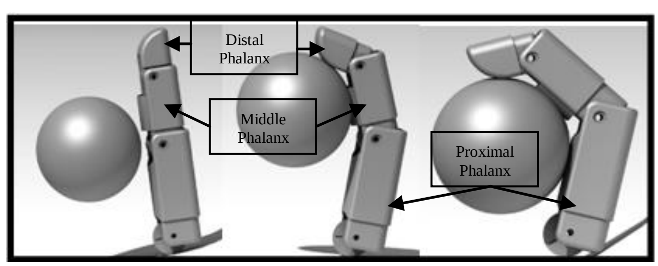


Fig. 9. Finger Movement

The kinematic behavior of the fingers joints is analyzed using the Denavit-Hartenberg method. The direct kinematics of the fingers is solved to determine the relationship between the angular positions of each finger joints with the position and orientation of the finger tip. The schematic diagram the of finger lying on the X-Y plane with the MCP joint fixed to the palm is shown in Figure 10. The parameters of the finger phalanxes are shown in Table 3.

Table III
Parameters of the Finger Phalanxes

Finger Joints	**Range of Angular Displacement (°)**		**Length of Finger Phalanxes (mm)**	
MCP	θ_1	0-80	l_1	40
PIP	θ_2	0-100	l_2	30
DIP	θ_3	0-65	l_3	30

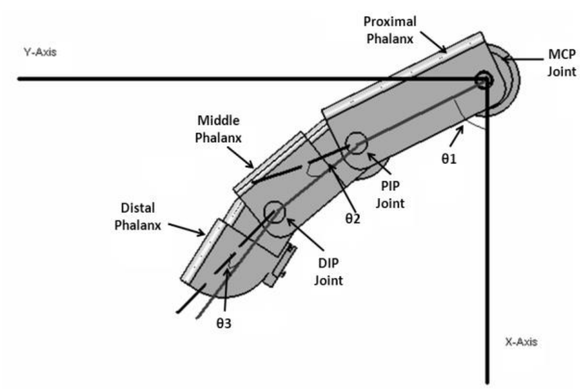


Fig. 10. Coordinate Frames for the Analysis of Finger Kinematics

The Denavit-Hartenberg convention involves the joint angle θ_i , the phalanx offset d_i, the phalanx length l_i and the phalanx twist α_i for the calculation of the position and direction of the finger tip. Since the abduction-adduction of the MCP joint was neglected, the values of the phalanx offset d_i and the phalanx twist α_i become zero. Hence the equation describing the position and orientation of the tip of the finger can be simplified as below:

$$X_{fingertip} = l_1 \cos \grave{e}_1 + l_2 \cos (\grave{e}_1+\grave{e}_2) + l_3 \cos (\grave{e}_1+ \grave{e}_2+ \grave{e}_3) \quad \text{(Eq. 2)}$$

$$Y_{fingertip} = l_1 \sin \theta_1 + l_2 \sin (\theta_1+\theta_2) + l_3 \sin (\theta_1+ \theta_2+ \theta_3) \quad \text{(Eq. 3)}$$

$$\theta_{fingertip} = \theta_1+ \theta_2+ \theta_3 \quad \text{(Eq. 4)}$$

A trajectory profile was obtained by using MATLAB® software to simplify the DH parameter for the forward kinematics problem using the above equations. Figure 11 shows the working envelope generated for the mechanical linked finger. The trajectory profile covers almost the same ranges of movement of a human finger [8], thus enable the functionality of this robot finger to be close to the human finger.

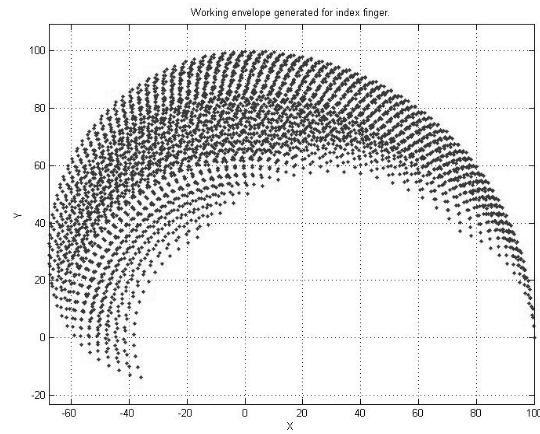


Fig. 11. Trajectory Profile for Mechanical Linked Finger

VII. PROTOTYPE FABRICATION

The prototype was fabricated using Rapid Prototyping (RP) technique. RP is an advanced technique which utilizes automated fabrication of physical model or prototype from computerized data or CAD system for visualization, testing and verification. It works by forming desired shape through adding or removing layers of material. There are several RP techniques that can be used to produce this finger prototype such as Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Modeling, Ballistic Particle Manufacturing and many others. Within this project; the InVision® XT 3-D Modeler machine using the SLA technique was used. Acrylic plastic is used as the material with a tensile modulus and tensile strength are 1772 MPa and 34 MPa respectively.

The advantage of using the SLA technique is within the resolution and accuracy of its final product. It can maintain the dimensional accuracy of the built parts within 0.1mm which close to the physical product being modeled by CATIA®. Figure 12 shows the complete system of the prototype robotic hand and its components.

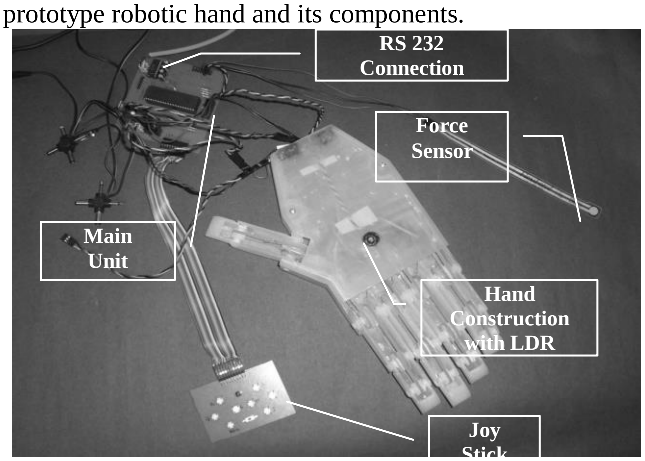


Fig. 12. Prototype Robotic hand system

VIII. FINGER ACTUATOR

This robotic hand deploys five micro servos which provide a rotation in a range of 0° to 180°. An internal circuit has been implemented to measure and regulate the movement. This regulation is done by supplying an appropriate signal to the input. The frequency of this signal has to be 40 Hz. Converting into timescale; a period length of 25ms is needed. Depending on the pulse width of the high gauge in a period the motor will turn. The range of the pulse width has to be between 0.5ms – 2.5ms, whereas a pulse of 0.5ms causes a rotation to 0°. Hence a high time of 2.5ms drives the motor to 180°. By applying a signal with at a high pulse in the requested range and with the required frequency, it is feasible to reach every angle between 0° - 180°. The function of the servomotor is clarified in the following Figure13.

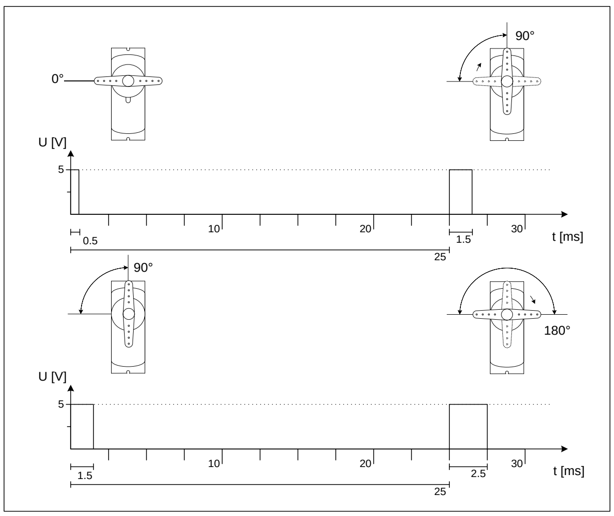


Fig. 13. Servomotor Function

IX. MAIN CONTROLLER

The design and layout of an appropriate circuit board was one of the main aspects in developing the robotic hand. Figure 14 shows the layout of the main printed circuit board. In the following there is an explanation of the main elements of this board with the auxiliary circuits: the microcontroller, the communication module and the voltage regulator. Figure 14 shows the full circuit design of main unit for top and bottom layer.

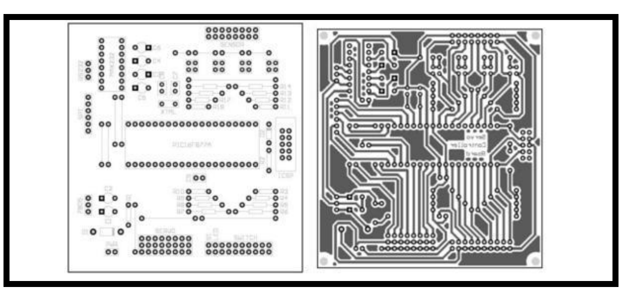


Fig. 14. PCB Layout

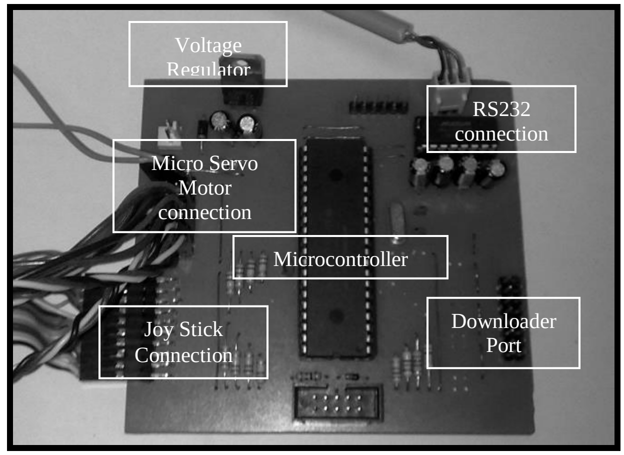


Fig. 15. Main Control Board

It was disclosed that the most suitable microcontroller for this task is the PIC 16F877A. For the demanded operation it is essential to connect it correctly with some additional devices. These are fundamental frequency pulses by an external crystal with 20MHz and two capacitors. Another option for running this device is by using the internal oscillator, but the frequency is not sufficient for this application. In addition, the stability of the frequency is inconsistent and causes the temperature, as one example.

A microcontroller is equipped with several ports indicated by the letter R.A-E. Each port consists of at least three to eight pins each having its own special feature. The ports A and E are connected to an internal analogue-digital converter, which offers the handling of analogue voltage input. This is very useful for getting reading from the sensors.

The complete digital Port B is used for the connection of the controller board to serve as a push-button based control method. The digital port is equipped with a TTL buffer and can only detect determined values. These are high gauge accomplished with +2V to +5V and low with 0V. Therefore the input pins are connected over a 1kΩ resistor with 5V. If a button is pressed, the input will be connected to GND resulting 0V.

Furthermore, the connection of a resistor in combination with a push-button at pin 1 is for resetting the device when a failed or unexpected in-use sticking occurs. The pin input is low active so the button will connect the pin with the ground if the reset is requested. This function is only planned in the first concept. With the final layout, a reset is only possible to interrupt the power supply using a specific switch.

X. CONTROL METHOD FOR FINGER MOVEMENT

These robotic hands have three types of controller to control the movement of each finger described as below:

I. GUI (Graphical User Interface)

Combination of programming and Visual Basic to control the movement of each finger. All the fingers can operate simultaneously and can simulate like human hand by controlling a consol at computer screen shown in Figure 16.

II. *Programming*
Program is downloaded to microcontroller to make each finger acts like human hand and depends on the movement required.

III. *Manually control*
Each finger can be controlled by using push button to simulate the movement.

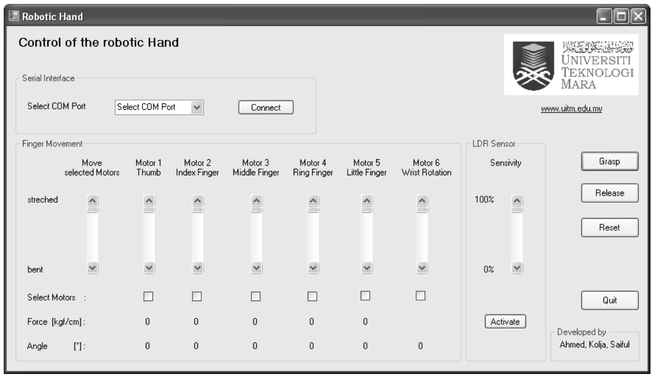


Fig. 16. GUI controller

To add extra feature of this hand, a light dependent resistor (LDR) sensor will be added at the palm. To enhance the automation in this system, the LDR comes into operation with the aim of detecting an approaching object. The light depending resistor changes the value in relation to the incident light. It is placed in the middle of the palm. Thus an approaching object will reduce the incident light and cause a decrease in the resistance value. This changed will be captured by the microcontroller in the form of several voltages provided by the voltage divider. A threshold value must be set to determine the distance from the object to the palm. If the object comes nearer than this limit, the hand will perform the grasping movement. Considering the brightness in different working environments, this threshold could be set by using the GUI.

XI. TEST RESULTS

The test outlines the performances of several grasping motions with different objects. The first attempt was to grasp a ball as an example for round objects. The GUI and controller board were used to simulate this grasping action as shown from Figure 17. The other attempts made include the handling of cylindrical objects such as gripping a screwdriver as shown in Figure 18.

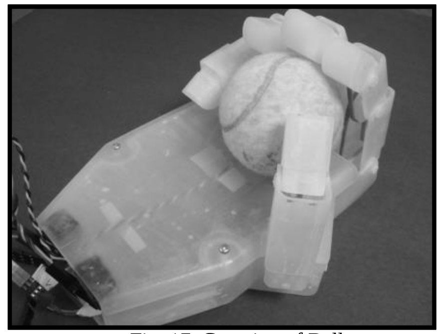


Fig. 17. Grasping of Ball

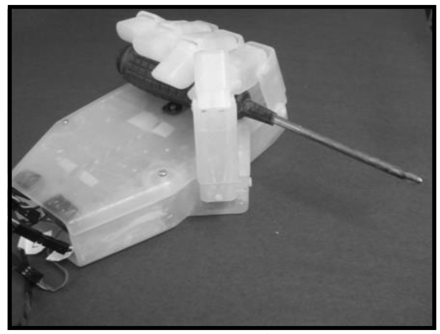


Fig. 18. Grasping of Screwdriver

These final tests have shown that the system is able to perform rough grasping movements on common objects. The next trial was to hold a pencil using the precision grip. However this simulation failed because the force transmission of the motor over the gear-belt mechanism was not strong enough. Therefore future work needs to be done to improve on the current design.

XII. CONCLUSION

A multifingered anthropomorphic robotic hand encompassing innovative interactions of mechanical, electronics, software and control solutions has been successfully designed, fabricated and tested. The integration of sensory and actuation devices was complex and troublesome development phase. All the connections and operations must be programmed precisely. Future research will make use of a shape memory alloy (SMA) wire to replace the servo motors that will enhance the performance of the robotic hand and provide a silent grasping motion.

ACKNOWLEDGEMENT

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