A Low-Cost Smart Glove for Hand Functions Evaluation

Izzeldin Ibrahim Mohamed Abdelaziz
Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang

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ABSTRACT

This paper focuses on the development of a reliable, low cost, average size, light weight, simple, rugged, and compact design five fingers real time smart glove and a measurement hand gripper that emulate the human hand functions that can be used as a prototype model for hand rehabilitation systems for patients suffering from paralyze or contracture. The hand gripper device will move based on a human operator's finger movement using the smart glove. Index, Middle, ring, and little fingers of the hand have a three degree of freedom, while the thumb finger has a two degree of freedom. All fingers are equipped with sensors for a smooth precise movement on a small scale with a perfect incision and without any vibration. This gripper is ideal for light objects. All the fingers have high speed motion and can be controlled individually and this gives the gripper ability to grasp complex shaped objects this work contains two PIC 18F452 microcontrollers for the instrumentation, communication and controlling applications. A series of flex sensors are built-in a master glove to get readings from the movement of human fingers. Microcontrollers will further use this information to control multiple servos that controls the movement of the slave hand.

Corresponding Author:

Izzeldin Ibrahim Mohamed,
Faculty of Electrical and Electronics Engineering,
Universiti Malaysia Pahang,
26600 Pekan, Pahang Darul Makmur, Malaysia
Email: izzeldin@ump.edu.my

1. INTRODUCTION

Human hand symbolizes a mechanism of great complexity and utility as it is firmly interconnected with the brain, in the evolution of the species and in the development of the individual. Hence, to a degree we "think" and "feel" with our hands, and, in turn, our hands contribute to the mental processes of thought and feeling. The functional capabilities of any mechanism depend on the characteristics and to the nature of the control system used for managing these functions. Just so with human hand, it is characteristics analysis required a fully understanding of it is sensory and mechanical anatomy features. The human hand has a twenty-four muscle groups, controlled by the different motor and sensory nerve pathways, with their rich capabilities for central connection, and acting upon a bone and joint system of great mechanical possibilities, give to the hand its capacity for innumerable shapes of action [1], [2].

Malaysia is a multi-racial country with a population of 26.64 million, comprising of 58.1% Malays, 32.1% Chinese, 8.3% Indians and 1% other ethnic groups (Department of Statistics, 2006) [3], [4]. With the improvement in the standard of living and control of communicable diseases, non-communicable diseases such as cardiovascular, stroke, and road traffic accidents have become leading causes of disability in Malaysia [5, 6]. Road traffic injuries constituted the leading causes of medically certified disabilities between ages of 5 and 39 years [7]. The incidence of road traffic injuries per 100,000 populations has increased from 19.0 in 1973 to 28.4 in 1995. This is probably due to polices of the government which have favoured private transportation and fuelled growth of the automobile manufactures. In Malaysia, the total number private cars and motorcycles increased by 246% which is approximately is twice the growth of the public vehicles [8]. Since the young productive are the mainly injured, the economic loss due to injuries is considerable [9], [10].

People with disabilities in Malaysia can be considered as one of the most vulnerable of the minority group in the Malaysian population. According to World Health Organization (WHO), 10% of any population has some form of disability; one third of which are children younger than 15 years old [7]. Translating this into the Malaysian context, it is estimated that about 900,000 children suffer from various disabilities, and around 2% would need some form of rehabilitation services (Ministry of Education, 2009) [11]. The official number of registered people with disabilities in Malaysia has increased steadily over the last five years, and according to the statistics from the Department of Social Welfare, the registered number of disabled people stood at 331,606 (Department of Social Welfare, 2011) [12].

Upper limb fractures are common and affect all age groups. Younger adults are usually sustained from motor vehicle accidents, whereas in older adults sustained form fall. Due to an aging population, the numbers of the common limb fractures are expected to increase about 10% every five years. Whereas approximately 60% of stroke experience upper extremity dysfunction such as distal limb impairment [8]. This distal limb impairment is problematic, because proper hand function is crucial to manual exploration and manipulation of the environment. Indeed, loss of hand function is a major source of impairment in neuromuscular disorders, frequently preventing effective occupational performance and independent participation in daily life. Following an upper limb fracture and upper extremity dysfunction, patients are often referred to physiotherapy for rehabilitation for exercise to improve range of movement strength, and to regain function [9].

The growing number of disable group among Malaysia‘s citizens indicates the importance towards full protection and safeguarding the interest by this special underserved group. Basically, when the patient needed to perform exercises they must get an appointment with a doctor. Normally this will take few weeks or months. This is because the rehabilitation devices at Physiotherapy Department in Malaysia hospital are very limited. From this problem, this work is aims to develop a reasonably cheap home-based rehabilitation measurement device which can perform the task of assisting paralyze patient at home.

2. KINEMATIC AND JACOBIAN OF HUMANOID FINGER

One of the inspirational successes of biological motor control systems is their ability to calibrate themselves and improve their performance with experience. Man-made machines are typically calibrated using external measuring devices and references, and often execute the same errors repeatedly. Robotics is an important source of ideas for biologists. The study of robot control and learning contributes to the understanding of biological motor control and learning. Motor control may be viewed as a series of transformations from a specified behavioral objective to a plan specifying the desired mechanical output of the motor [13]. In this section the transformations that involved in executing a movement are discussed. Two types of transformations, kinematic and Jacobian, are explored [14], [15].

2.1. Kinematics

Kinematics is the study of motion regardless to the forces that generate it [16]-[18]. The representation of the fingers position and orientation are called direct kinematics. In this work, the mathematical model is developed to compute the position and orientation of each finger of our five fingers hand based on the given human joint position. Each human joint is considered as revolute joint. At the beginning of the direct kinematic analysis, coordinate axes and origin of the system is determined.

Since the fingers are fixed at the gripper’s palm, center of the joint 1 is defined as coordinate axis origin and axis is placed as shown on Figure 1. The homogenous transformation of the index, middle, ring, and little fingers related to the base frame is expressed using Denavit Hartenberg (DH) method [19]-[21].

A three link planar for the index, middle, ring, and little arm fingers shown in Figure 2. The coordinate frames to define the DH parameters are shown in the figure, and their DH parameters are tabulated in Table 1, where θ_1, θ_2, and θ_3 represents the angles of the links and l_1, l_2, and l_3 represent the length of each link. Whereas the two link planar for the thumb and its DH parameters are shown in Figure 3 and Table 2 respectively.

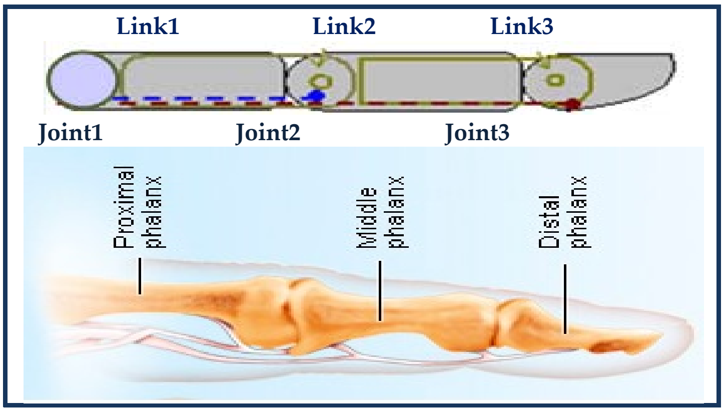


Figure 1. Schematic view of the finger

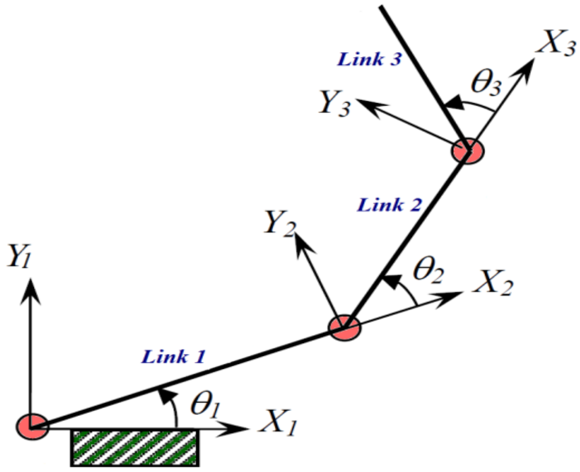


Figure 2. A three link planar finger

Table 1. The DH Parameters of the three link Fingers

link	θ	*d*	*l*	α
1	θ_1	0	l_1	0
2	θ_2	0	l_2	0
3	θ_3	0	l_3	0

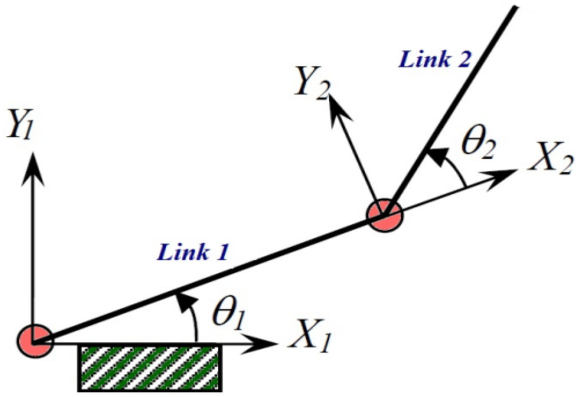


Figure 3. A two link planar finger (Thumb)

Table 2. The DH Parameters of the two links Finger (Thumb)

link	θ	*d*	*l*	α
1	θ_1	0	l_1	0
2	θ_2	0	l_2	0

The transformation of the index, middle, ring, and little fingers matrix are expressed by:

$$T_0^1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & l_1 * \cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & l_1 * \sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$T_1^2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & l_2 * \cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_2 * \sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$T_2^3 = \begin{bmatrix} \cos\theta_3 & -\sin\theta_3 & 0 & l_3 * \cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & l_3 * \sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$T_0^2 = T_0^1 \times T_1^2 = \begin{bmatrix} C_{12} & -S_{12} & 0 & l_1C_1 + l_2C_{12} \\ S_{12} & C_{12} & 0 & l_1S_1 + l_2S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

Hence the forward kinematic for the fingers expressed as:

$$T_0^3 = T_0^1 \times T_1^2 \times T_2^3 \quad (5)$$

$$T_0^3 = \begin{bmatrix} C_{123} & -S_{123} & 0 & l_1C_1 + l_2C_{12} + l_3C_{123} \\ S_{123} & C_{123} & 0 & l_1S_1 + l_2S_{12} + l_3S_{123} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where,

$$\cos\theta_1 = C_1 \quad (7)$$

$$\sin\theta_1 = S_1 \quad (8)$$

$$\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2 = \cos(\theta_1 + \theta_2) = C_{12} \quad (9)$$

$$\sin\theta_1\cos\theta_2 + \cos\theta_1\sin\theta_2 = \sin(\theta_1 + \theta_2) = S_{12} \quad (10)$$

$$\begin{aligned} &\cos\theta_1\cos\theta_2\cos\theta_3 - \sin\theta_1\sin\theta_2\sin\theta_3 \\ &= (\cos\theta_1\cos\theta_2)\cos\theta_3 - (\sin\theta_1\sin\theta_2)\sin\theta_3 \\ &= \cos\theta_{12}\cos\theta_3 - \sin\theta_{12}\sin\theta_3 = \cos(\theta_1 + \theta_2 + \theta_3) = C_{123} \end{aligned} \quad (11)$$

$$\begin{aligned} &\sin\theta_1\sin\theta_2\cos\theta_3 + \cos\theta_1\cos\theta_2\sin\theta_3 \\ &= (\sin\theta_1\sin\theta_2)\cos\theta_3 + (\cos\theta_1\cos\theta_2)\sin\theta_3 \\ &= \sin\theta_{12}\cos\theta_3 + \cos\theta_{12}\sin\theta_3 = \sin(\theta_1 + \theta_2 + \theta_3) = S_{123} \end{aligned} \quad (12)$$

2.1. Jacobian

The Jacobian matrix is an extension of the derivative for a scalar function of a scalar variable to the case of vectors [22[, [23]. Jacobian matrix expresses the relation between the finger velocity and the joint velocity of a humanoid arm in a compact form. The index, middle, ring, and little fingers positions and orientations are specified as:

$$r = \begin{bmatrix} x & y & \phi \end{bmatrix}^T \tag{13}$$

Where and represent the fingers position coordinates and represents their orientations. The joint angles are:

$$q = \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 \end{bmatrix}^T \tag{14}$$

The Jacobian matrix is given as:

$$J = \begin{bmatrix} \frac{\partial x}{\partial \theta_1} & \frac{\partial x}{\partial \theta_2} & \frac{\partial x}{\partial \theta_3} \\ \frac{\partial y}{\partial \theta_1} & \frac{\partial y}{\partial \theta_2} & \frac{\partial y}{\partial \theta_3} \\ \frac{\partial \phi}{\partial \theta_1} & \frac{\partial \phi}{\partial \theta_2} & \frac{\partial \phi}{\partial \theta_3} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} \tag{15}$$

Where,

$$\begin{aligned} x &= l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \cos\theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \\ &= l_1 C_1 + l_2 C_{12} + l_3 C_{123} \end{aligned} \tag{16}$$

$$\begin{aligned} y &= l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) \\ &= l_1 S_1 + l_2 S_{12} + l_3 S_{123} \end{aligned} \tag{17}$$

$$\phi = \theta_1 + \theta_2 + \theta_3 \tag{18}$$

Therefore, by taking the first derivative we get that:

$$\frac{\partial x}{\partial \theta_1} = -l_1 S_1 - l_2 S_{12} - l_3 S_{123} \tag{19}$$

$$\frac{\partial x}{\partial \theta_2} = -l_2 S_{12} - l_3 S_{123} \tag{20}$$

$$\frac{\partial x}{\partial \theta 3} = -l_3 S_{123} \tag{21}$$

$$\frac{\partial y}{\partial \theta_1} = l_1 C_1 + l_2 C_{12} + l_3 C_{123} \tag{22}$$

$$\frac{\partial y}{\partial \theta_2} = l_2 C_{12} + l_3 C_{123} \tag{23}$$

$$\frac{\partial y}{\partial \theta_3} = l_3 C_{123} \tag{24}$$

$$\frac{\partial \phi}{\partial \theta_1} = 1, \quad \frac{\partial \phi}{\partial \theta_2} = 1, \quad and \quad \frac{\partial \phi}{\partial \theta_3} = 1 \tag{25}$$

Hence by substituting of equations (19-25) into equation 15, the Jacobian matrix is given as:

$$J = \begin{bmatrix} -l_1 S_1 - l_2 S_{12} - l_3 S_{123} & -l_2 S_{12} - l_3 S_{123} & -l_3 S_{123} \\ l_1 C_1 + l_2 C_{12} + l_3 C_{123} & l_2 C_{12} + l_3 C_{123} & l_3 C_{123} \\ 1 & 1 & 1 \end{bmatrix} \quad (26)$$

The kinematic analysis where derived manually to determine the position, velocity, acceleration and torque with respect to time. Kinematic simulation was carried out using ROBOT MATLAB toolbox which gave us the simulation regarding various grasp positions regarding different size and objects. The Index finger variation of the angles and acceleration with respect to the time is shown in Figure 4.

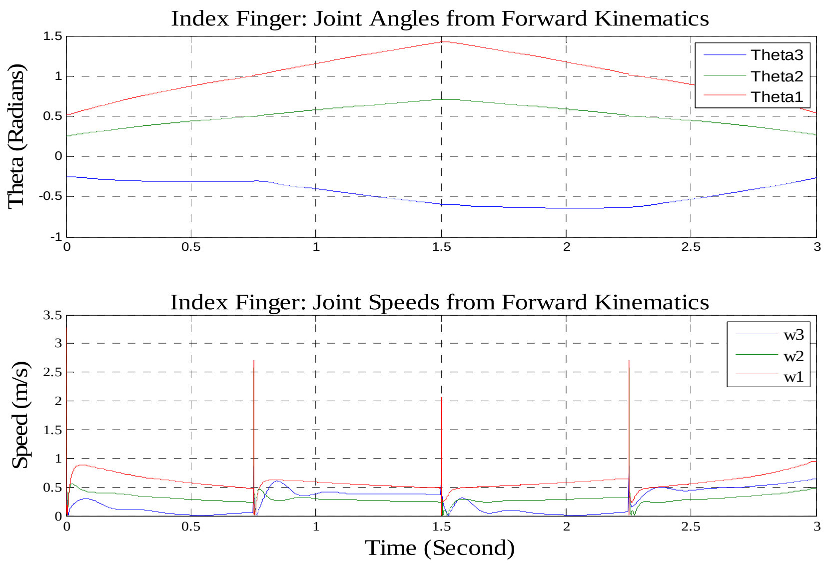


Figure 4. Index Finger angles and acceleration

3. IMPLEMENTATION OF THE HUMANOID FINGER

Based on the discussion given in the previous sections a master glove controller and a humanoid hand of four fingers and an opposable thumb were designed. The master glove used to control the fingers movement. Each of the fingers in our design has three joints and a three degree of freedom and the thumb has two joints and two degree of freedom allowing flexion motion, equivalent to the joints of the human finger. The overall system design is shown in Figure 5

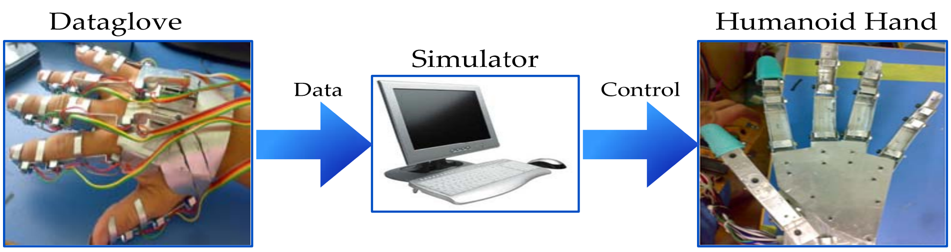


Figure 5. Control of humanoid hand using dataglove

3.1. Control System Design

The open loop control systems block diagram which is consist of 8 blocks is shown in Figure 6. The inputs to this system are reset button, button1, slide switch and 16 analog signals from the potentiometers of the master glove. The slide switch is use to activate the manual control mode while button1 is use to activate the autonomous mode of the robot hand. The outputs generated by the microcontroller are the PWMs that used to control the servomotors.

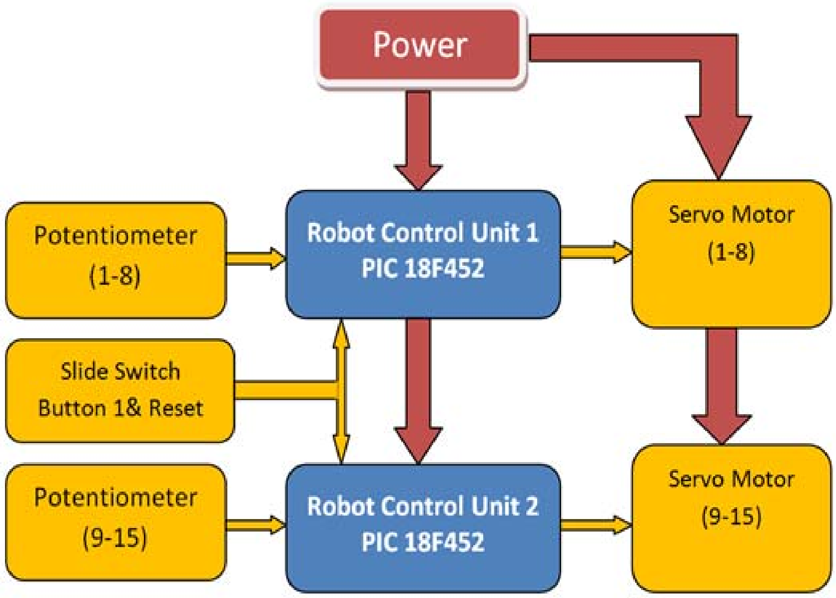


Figure 6. Control System Block Diagram

3.2. Hardware Development

This section presents the hardware development of our 5 fingers hand gripper and the smart glove. The hardware divided into mechanical and software design. All the aspects and techniques applied in the hardware development are presented in this section

3.2.1 Hardware Development

The skeleton of the hand gripper is designed to provide a place to mount the electronics component such as sensor, and servo motor for the gripper fingers. The fingers movement is controlled by these servomotors using strings tied at the servomotors shaft as shown in Figure 7.

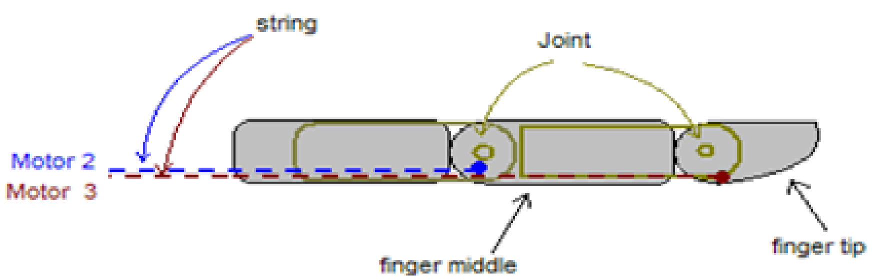


Figure 7. Finger Design

3.2.1.1 Gripper Framework

The hand gripper was designed to emulate the human hand. Sixteen servo motors were placed at the forearm which acted as the muscle of the hand. Strings were tied from the shaft of servomotor to each sector of finger to mimic the tendon and muscle of the fingers as shown in Figure 8. The upper string was tied on the left side of shaft and the lower string was tied on the right side of the servomotor’s shaft. The gripper framework specifications were summarized in Table 3 while the dimensions and orientations for the chassis were shown in Figure 9.

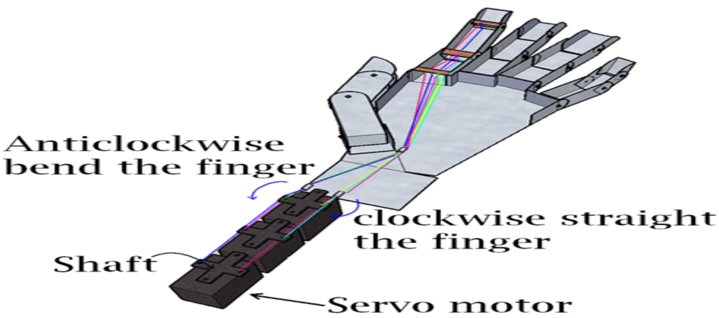


Figure 8. Servomotors and Fingers connection

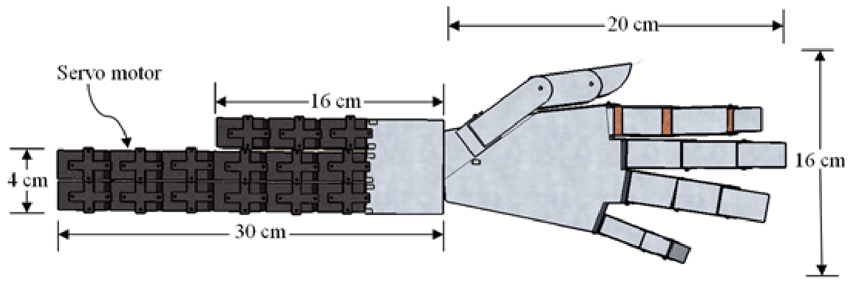


Figure 9. Gripper Dimension and Orientation

Table 3. Gripper Framework Specifications

Design Factor	Specification	Description
Weight	1.2 kg	The weight includes the forearm and all the servomotors. As long as the overall robot hand weight is not heavier than an average human hand weight, this project is acceptable.
Size	300mm x 245mm x 150mm (length x width x high)	The size of the framework is according to the size of an average human hand.
Material	Aluminum plate	This material is relatively inexpensive, light and available everywhere.

The gripper fingers can be bends 90º upwards by turning the servomotors shaft 90º anticlockwise, and return them back to their initial position by turning the servomotors shaft 90º clockwise as shown in Figure 10.

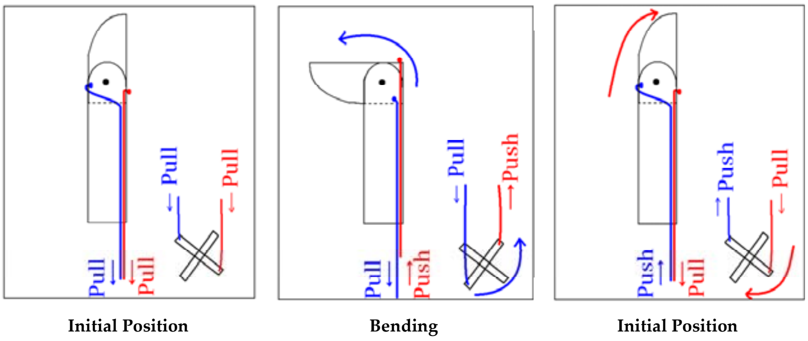


Figure 10. Finger Movement

3.2.1.2 Glove Design

The Glove was fabricated for the right hand as shown in Figure 11; it was in medium size and equipped with laminated potentiometer resistive sensors. Three sensors were used to cover each finger joints as shown in Figure 12. We decided to limit finger flexion and extension monitoring to these finger joints given that we observed that they displayed the greatest changes in bending angles during the performance of the main grasp forms. Nevertheless, we do not exclude the additional capturing of movements of the index, middle, ring and little fingers as well as of joint of the thumb in the development step of the glove. Moreover, two sensors covered the wrist joint to determine the wrist movements. However, this work was focus on the analysis of finger joint bending rather than on wrist bending. Each sensor cable was connected to its physically separated signal conditioning unit. The conditioning unit was an 8-channel; 10-bits analog digital converter (ADC) built in the PIC18F542 microcontroller. The 10-bits conversion result was stored into the ADC result registers ADRESH (A/D Result Higher byte) and ADRESL (A/D Result Lower byte). The supply voltage (+5V) was chosen as reference voltage for A/D conversion. Therefore, the 10-bits ADC will convert any analog voltage between 0-5V to a digital number ranging from 0-1023.

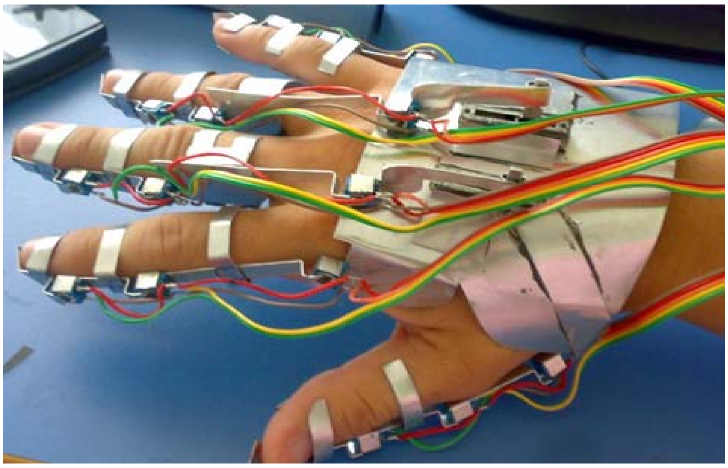


Figure 11. Top view of the Glove

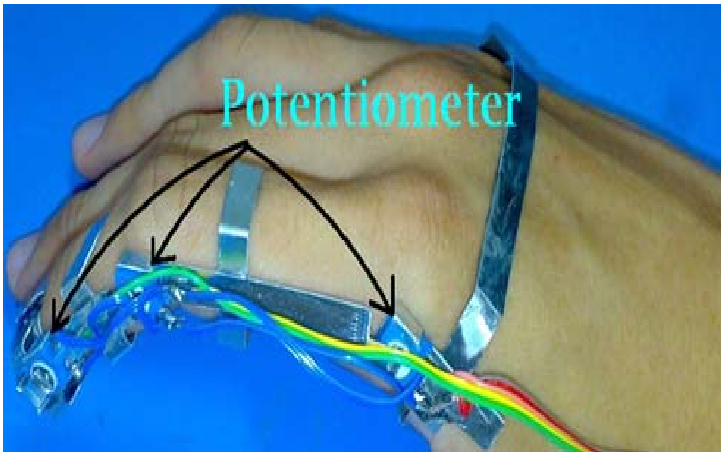


Figure 12. Sensors Position at each Finger joints

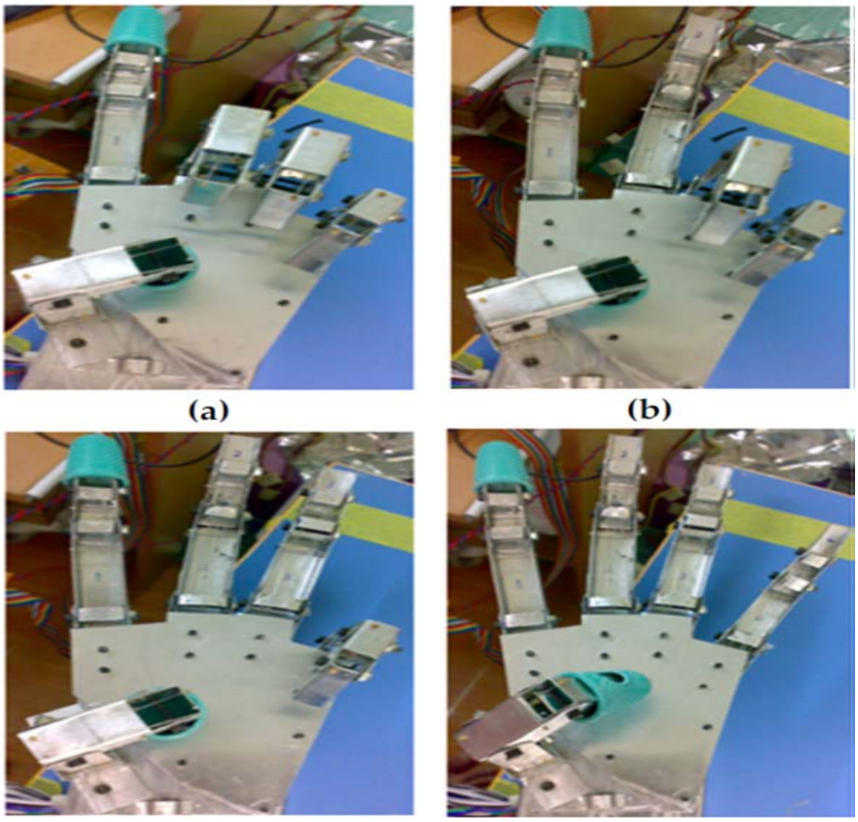
3.2.2 Software Design

PIC18F542 microcontroller is programmed in C language. There are two parts of the program, which are main program and interrupt program. The microcontroller will always run the main program until there is an interrupt occurred. When microcontroller receives an interrupt flag, then it will jump to interrupt process, where the responses of the sensor were measured and PWM pulses were generated to control the servomotors bending angles.

The firmware for PIC18F542 was written in C18 compiler for PIC. The Timer0 module is operated as timer with prescaler to generate an approximate 20 ms gap between the two successive PWM pulses. The second Timer, Timer1 was used to generate the pulse width values which determine the angular position of the servomotors. As the servomotors speeds depend on the analog input from sensor of the master glove, the speed was directly proportional to the voltage change of the potentiometers. Since the servomotors operate at 5.0 V power supply, we determined that the fingers maximum speed was 0.14 s/60°.

4. RESULTS AND DISCUSSION

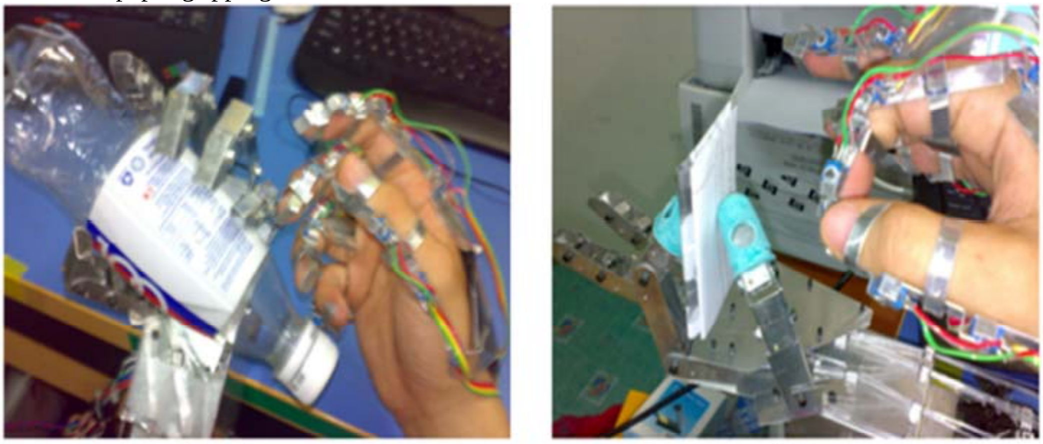
The smart glove performance is evaluated by number of experiments carried out to generate finger characters by sign language using this humanoid hand to be used as examples of information transmission by finger movement. Four concrete examples were generated. Numeral 1 was expressed by stretched the index finger and thumb, middle, ring, and little finger raised and then bent, numeral 2 was expressed by scissors gesture (paper-rock-scissors), numeral 3 was expressed by stretched index, middle, and ring fingers while the thumb and little fingers were raised and then bent, and finally the numeral 4 was expressed by stretched the index, middle, ring, and little fingers while the thumb finer was raised and then bent. Figure 13 (a, b, c, and d) shows snapshot of those numeral generated patterns. As for the four examples generated by our proposed system, movements were carried out promptly while maintaining appropriate accuracy to allow reasonable judgment of numerals created by sign language; it took a little over one second for each of those numerals.



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

Figure 13. Numeral generated Patterns

Finally, control experiments of humanoid gripper using the smart glove were carried out to perform number of tasks. We have tested the gripper with everyday objects of various shapes, sizes, and low mechanical resistance (plastic bottles, pieces of fruit, glasses, paper, and so forth).The grip is such that these objects are not damaged. The gripper was effectively emulated human hand in gripping and capable of handling complex shaped objects as well as objects having thickness of paper as verified in Figure 14 (a and b) for bottle and paper gripping test.



(a) (b)

Figure 14. Gripping Water Bottle and Paper

5. CONCLUSION

The two most notable features between humans and animals are hand and mind. Since the next generation of robots will interact with people directly, the interest on the implementation of systems to imitate the manipulating ability of the human hand is growing among researchers. The three most significant functions of the human hand are to explore, move, and to grip objects. This work tried to understand and to emulate the last function and develop a prototype model that can be used as hand rehabilitation systems for patients suffering from paralyze or contracture. The contributions presented in this work is aimed at modeling and controlling of a five-fingered humanoid hand with smart glove for manipulation tasks, essentially for gripping tasks. A five fingers real-time humanoid gripper has been presented, whereby a human demonstrator controls the system using n smart glove. With number of experiments performed, we provided a proof that our system showed a good and promising performance, and capable of handling complex shaped objects as well as objects having thickness of paper.

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BIOGRAPHY OF AUTHOR

Izzeldin Ibrahim Mohamed received a B.Tech. degree in Control Systems from Sudan University of Science and Technology, Khartoum, in 1995, and M.Eng. degree in Mechatronics and Robotics Engineering from Universiti Teknologi Malaysia, Johor, in 1999. He received a PhD. degree in Microelectronics and Computer Engineering from Universiti Teknologi Malaysia, Johor, in 2006. From July 1999 to May 2001, he was a Lecturer with TATI Universiti College, Malaysia and from February 2006 to January 2008 he was a Lecturer with Multimedia University, Malaysia. Since February 2008, he has a Senior Lecturer with Department of Electronic and Computer Engineering, Universiti Teknologi Malaysia. His research interests include Rehabilitation Robotics, Bio-Signal Control Systems, and Human-Machine Interaction. His other research interests are in the areas of performance Analysis, Simulation and Modeling, and Network Security.