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Research Article

Robust Feedback Control Design of Underactuated Robotic Hands with Selectively Lockable Switches for Amputees

Bilal M. Yousuf[1], **Asim Mehdi**[2], **Abdul Saboor Khan**[2], **Aqib Noor**[2], **and Arslan Ali**[2]

[1]*Electronics & Power Engineering, PN Engineering College, National University of Sciences and Technology, Karachi, Pakistan*
[2]*Electrical Department, Fast-National University of Computing and Emerging Sciences, Karachi, Pakistan*

Correspondence should be addressed to Bilal M. Yousuf; bilalmyousuf4@gmail.com

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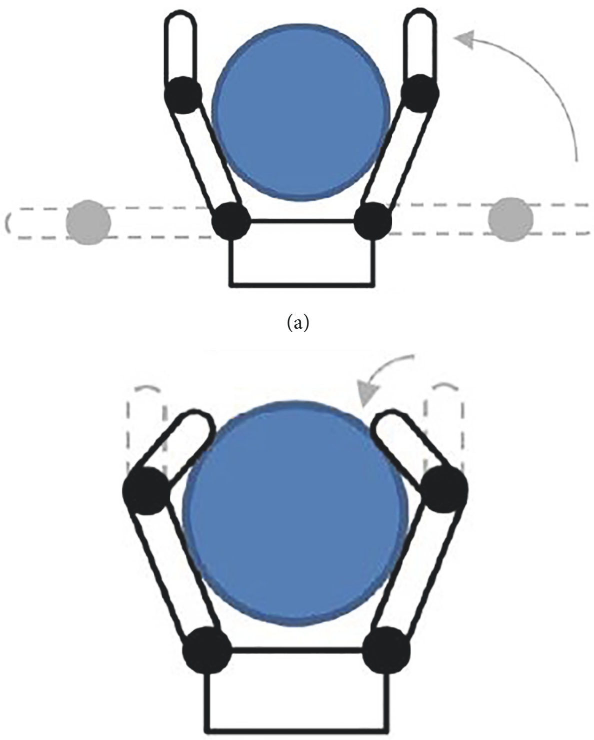
In recent years, reproduction of human mechanical hand with upgraded abilities is one of the major concerns. This paper addresses the problems of underactuated robotic hand with low cost design as it avoids electromyogram (EMG) sensors. The main goal is to balance the hand in the way, like grabbing, speed, and power, and provide a more robust and cost effective solution. All fingers have some mechanical consistency for picking up objects in a better way. A Flex sensor is attached to all fingers and it is interfaced with a computer using Arduino UNO microcontroller. The sensor aids the arm in three different directions: at first it senses whether an object is grasped or not. In the second step, it determines the coefficient of friction between the objects. Finally it grasps the object and stops. One of the primary issues of prosthetic hand is to have the capacity to satisfy every detail of torque, speed, and latency. In this research, we have developed a model of robotic hand with some modifications. The adaptability of grasping is compared with the degree of freedom (DOF) along with the quantity of fingers. We are controlling our hands via sensors based signal controlling system. The idea is to design a robotic hand, which has low cost, is easy to use, and is light in weight, which helps the amputees to use it with ease in their daily lives. The efficacy of the proposed control is verified and validated using simulations.

1. Introduction

The field of robotics has always been an inspiration for researchers, due to its stability problem [1]. The robotic arm has many applications in the field of automation in industries, medical fields, etc.

The main problem which has influenced the advancement of this field is the stability and accuracy. Many researchers came across with different solutions for this problem. The main problems which are under consideration in this paper are the high cost, complex structure, control frameworks, and their synchronization. The quantity of the physical amputees has been expanded due to the accidents in traffic, workshop mishaps, and sickness. Our end goal is to enhance the quality of life for numerous amputees and tend to utilize their energy in their daily life [1, 2]. The hand is a unique part of the body that can perform different control undertakings with five fingers and with more than 20 DOF [3]. Despite the fact that a genuine human hand is more capable compared to some other manufactured control instruments, it still experiences a few challenges in certain condition. The outline of an automated prosthetic hand is an extremely dynamic field of research.

Over the years, it was simple two degrees of freedom with the limiting capacity of grasping and pulling mentioned in Figure 1. Nowadays, the researchers were working on improving the degree of freedom for the multifingered framework. The robotic hand is equipped with different sensors, which gives a feedback signal to the controller. The controller will control the speed and angle of the motor for better transient response [4, 5]. The hand needs a complicated controller, which stabilized the performance of the system. The proper usage of electrically powered prosthetic hand designs has been started from the twentieth century. The research found its ways for the electromyogram sensors to control the hand [5]. In recent days, the proposed design of robotic hand is becoming more simple, flexible, and generous without compromising the postures. Recently a researcher, Dollar et al. in [5], presented a new solution through elastomer material, which gained so much attention due to its low cost.



(a)

(b)

Figure 1: Grasping model of robot [2].

Robotic literature always discussed the major problems, which occur in the system over the time period. This may cause a certain fear for amputees. Therefore, they are avoiding using a prosthetic hand. As per survey the fact which comes in our mind is that they need a low cost, light weight, and easily repairable device. With these objectives in consideration, we focus on the development of the prototype in order to improve the following critical aspects of a biomedical device [6].

In this paper, the approach permits the most extreme design of control with an immense plan which required complex control calculations. It is an under demand system, which require less actuators. This approach improves the control calculations by reformulated hand capacity and quality according to the client. The level of flexibility of the human hand is routinely characterized. The primary objective of the prosthetic hand is to mimic the human hand in all viewpoints. As compared to this work, many researchers presented unique ideas about the robotic hand using EMG sensors to enhance their quality of living. But this paper is totally based on ex sensors, which can achieve seven different types of movements; the list of these movements is given below:

(1) **Hook grip**: secure and adaptable hook grip can hold everything from folder cases to purses for substantial shopping material.

(2) **Mouse grip**: someone is working in the office or browsing the Internet.

(3) **Open palm grip**: open palm grip gives a compelling method for conveying bowls or plates securely. Our projects palm is a bit larger than the natural human hand, which proves its uniqueness and allows a person to easily handle large things by carrying them on its palm [7].

(4) **Pinch grip**: with the pinch grip, the thumb and index finger meet up to give an adaptable, helpful approach to get and move an extensive variety of little objects, including auto keys, coins, tops, and pens.

(5) **Power grip**: it allows a person to shake someone's hand or to throw a ball while playing. It also helps while working with garden utensils or sometimes eating a piece of fruit [7].

(6) **Relax hand position**: when someone is not actively using the hand, the relaxed hand position helps to give our project a natural and gap appearance.

(7) **Key grip**: when someone desires to keep making a grip on small thing likes plate card, etc.

Simulations are provided to show the efficacy of the proposed idea of using the ex-sensor and validate the performance of the control algorithm

The rest of the paper is structured in this following manner. Section 2 discusses the literature review. Section 3 shows the problem formulation. Section 4 contains the hardware design of robotic hand. Section 5 contains the results that are shown based on simulation. Finally, Section 6 discusses the concluding remarks with future advancement.

2. Literature Review

Over the years, a number of researchers have proposed various modeling and control schemes for robotic hand starting from simple robotic platform to complex robotic hand. In the course of recent decades, a survey on automated hands has been led into the development of robotic hand, which roughly looks like the human hand [9].

A robotic hand can be viewed as a human hand, if all the definite properties and attributes are satisfied. These properties incorporate momentum, size, and the execution of operations, unwavering quality together with the common perspective. An anthropomorphic hand comprises fingers and a thumb. The arrangement of each of the four fingers is one next to the other opposite to the palm surface. In [10], the author presented a robotic hand with complete four fingers and a thumb. The palm is the medium which joins the fingers together with its corresponding positions. Another work of importance is the robotic hand motion which is shown in Figure 2 outlined by iRobot. Each finger controlled proximal and distal connections, which associated a finger to the base till the fingertip [2]. To prompt adaptability and solidness, overwhelming obligation and flexible joints were utilized which gave an enhanced grip around the items. The grip control is the utilizing link ligaments that provide solid grasping.

Chang in [8] presented the model, which manages to outline an automated hand that imitates a human hand. It

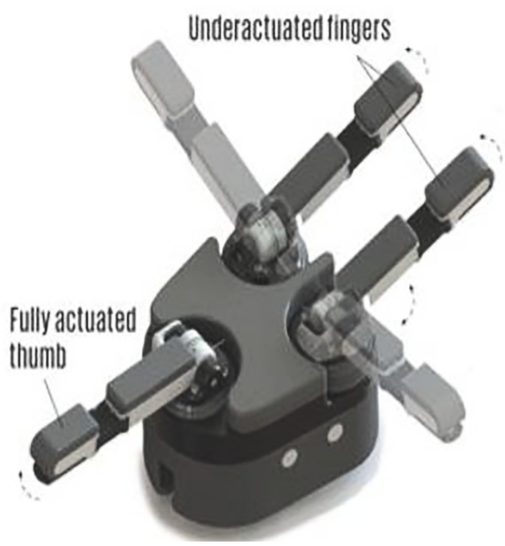


Figure 2: iHY hand design [4].

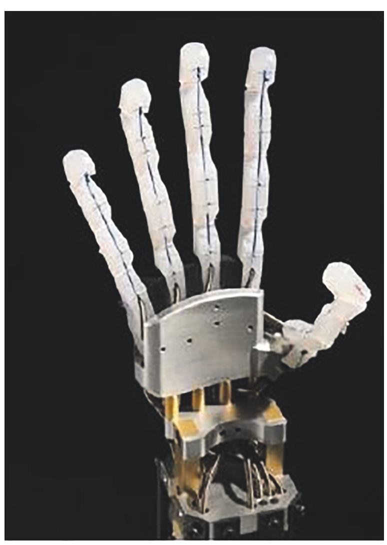


Figure 3: Hand gesture robot [4].

is made out of sensors and actuators. The automated glove controller is mainly based on the sensors, which tracked the development of the human hand. Five exion sensors are attached to the system; one for each finger which can be seen in Figure 3. Finally, in [11–13], the authors presented a unique design of robotic hand; one of them discussed the simple linear control based force feedback for the grasping. A force sensor is attached to one of the claws of the gripper, which sends a signal to the control for further processing. The other author presented a walking microrobot by piezoelectric materials. The last author presented the attitude control of a rigid body. This approach is based on two parallel PD controllers. The results are also compared with a classical PD controller and with an adaptive controller.

3. Problem Formulation

This section discusses the study of underactuated system and about prosthetic hand. The main problem is to design a low cost robotic hand. To come to a unique solution, we need to understand about what kind of sensors is required and their level of compatibility with the controllers.

3.1. Underactuated Design Hand Structure. The proposed design of the robotics hand is fully functional, same like human hands. The paper discusses the design of underactuated five-finger robots, with most complicated flexible joint incorporated by a single actuator and linking with a single sensor. Underactuated system is more reliable in terms of grasping items of different sizes and shapes robustly. The work can be described in two phases:

(i) Every finger is linked with an object and the other one is in free space where the distal link makes contact to fully encompass the object [7].

(ii) Every sensor sends an input signal to the control to operate the speed of the motor accordingly.

To achieve the desire purpose, it needs one single actuator which lies between the finger and the palm. The actuator can add force for grasping an object harder. The underactuated hand is found in different irregular shapes.

3.2. Prosthetic Hand. The prosthetic hand is an artificial device which is used to make an approximation to the appearance and function of a natural human hand [7]. Modernization in technology makes it possible to develop a prosthetic hand. The hand has the tendency of grasping objects, holding pens, and also moving like a natural hand. The process used in this research to make a prosthetic low cost robotic hand for amputees is present in Figure 4.

In this paper, the design of the robotic hand includes the ex-sensors to control the hand movements as shown in Figure 5. The involvement of ex-sensors makes it cost effective and easy to use. Flex sensors are attached to the analog pins of the Arduino UNO microcontroller, which processes and generates an output corresponding voltage. This signal is later used significantly to actuate the servo motors which respond to produce motion in the fingers.

The block structure of the entire system plays an important role in explaining the complete placement of components in system; it defines that every ex-sensor is working individually in every finger.

4. Problem

This section discusses the complete methodology based on computational geometry and graph theory. A method which is used to link multiagent or objects needs a set theory for quantifying the anthropomorphism of hand. The adopted scheme exploits a simple model based on graph theory for the simplification of the design and assumes a perfect communication link between the motors and the controller. The main problem is to maintain the stability of the system, which insures that it grasps the objects which are used in daily

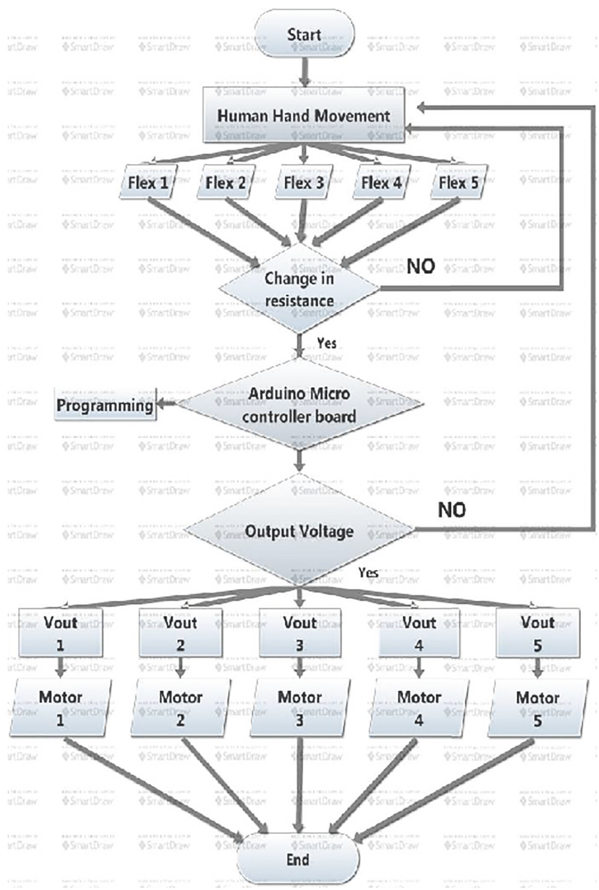


Figure 4: Process flowchart of prosthetic hand.

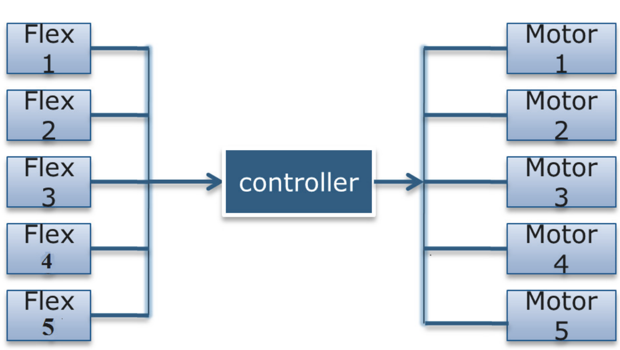


Figure 5: Block diagram of prosthetic hand.

routine. The main contribution of this paper mainly depends on the relationship of the ex-sensor and the motor.

4.1. Graph Theory. The basic idea of using a graph theory is described as the limitation in communication network, which does not allow each robot to communicate. For these limitations, the proposed scheme exploits a simple mathematical model based on graph theory to design such state feedback control. G (V, E), the digraph (directed graph) consists of node V= (1.....N) and edges E. In the diagraph, there are three protocols. The unidirectional symmetry protocol is utilized in this paper. As for this paper we are using directed graph. There will be a nonnegative adjacency matrix. The adjacency matrix basically describes the flow of the instruction of communication and maps the graph into the matrix, for the mathematical formulation. There is a Laplacian matrix Lij, which is sometime called admittance matrix, which gives us some special information like spanning tree. Spanning tree gives the details about undirected link. In this paper, only directed links are being used as the only controller sends the information to the motors, which means spanning tree should be eliminated. For this, Laplacian matrix is being utilized $A = [a_{ij}]\epsilon\mathfrak{R}^{N*N}$ and there will be a Laplacian matrix given as follows.

$L = [L_{ij}]\epsilon\mathfrak{R}^{N*N}$ of a diagraph corresponding to matrix contain elements such that

$$L_{ij} = \sum_{j=1}^{N} a_{ij} \tag{1}$$

if$i \neq j$ $L_{ij} = degout(A) - adj(A)$, where $degout(A)$ matrix shows each node connection with the fellow node and $adj(A)$ shows each node connection with the fellow node with the edges. After the subtraction we get the Laplacian matrix.

5. Design

The design of the robotic hand is presented in the following manner.

5.1. Hand Structure. The desired design incorporates four fingers and a thumb, joint to a settled palm. General joints are utilized in this approach, like Metacarpophalangeal (MCP) and the CMC (Carpometacarpal) joints. These joints make up the other 12 degrees of flexibility in this desired purpose plan. To accomplish the coveted movement with a lightweight, it needs quality pairs of thin gage stainless steel. Singular connections of each finger and the thumb are made up of twisting gage sheet metal that allows the finger, pulleys, and link channel to be tactfully covered up inside. The palm of the hand is built in a comparative form utilizing folded sheet metal. Back to back connections are associated with 3 mm pivot shafts that go through the metal balls.

5.2. Finger Designing. In this paper, we developed a multifingered robotic hand. The robotic hand has four fingers with a thumb [1]. All these flexible joints are implemented and the mechanical structure is developed. For the structure, we need the length and its particular angle. For this we used the aforementioned parametric model.

In this paper, a unique design that reproduces the flexibility and the extensile motion of the finger is presented. An extended mechanical structure was developed through the use of appropriate elastomer material. While flexibility is implemented through cable between the controller and the

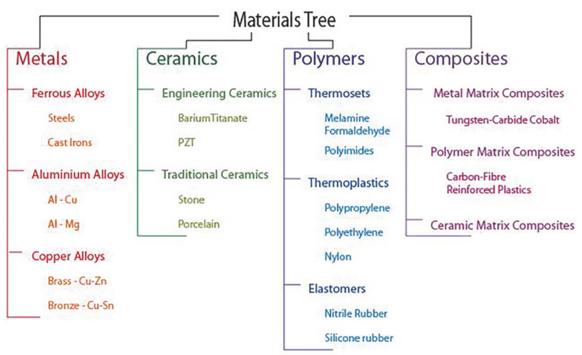


FIGURE 6: Material classification [5].

motor, the joints were made of the lightest material, but also stiff enough to produce a force range that corresponds to everyday life task.

The proposed design is completely stiff in contrast to friction based mechanisms, which is affected due to some external forces (these forces can create unstability). A completely different routing system is used for the design of thumb. The thumb is made with two different servo pulleys, which allows servo motors to make contact with the other fingers

After all the survey, we need to collect the desired parts of our project, which ensures the accuracy in making of robotic hand with low cost. The design should be easy to use for the amputees. Firstly, it needs a microcomputer which handles all the motor and sensor and makes them synchronize. The main working of the controller is mainly based on signals, which are coming from the sensor and it is making an output to the motors.

For the making of the prosthetic robotic hand, the material which was firstly implemented was Telon. The results are not as accurate as expected and also not fulfilling our requirements. For the better results, the design of the robotic hand is made up of acrylonitrile butadiene styrene (ABS) material. ABS is a polymer which consists of 3 monomers: acrylonitrile, butadiene, and styrene. ABS types can be manufactured offering a wide spectrum of different properties by means of branching or copolymerization [6]. It can often be quite straightforward to tell materials classes apart by look or feel. The class of material is shown in Figure 6. Metals are usually more reactive or metallic looking.

The motor selection was also really important for this project. Due to accuracy, a proper grip of the hand is entirely depending on the type of motor. For this research servo motor is selected, which was perfectly suitable. Typically, a servo motor is utilized to control a precise movement of somewhere around 0 and 180 degrees.

Flex sensors are the analog sensors which change the electrical resistance as they bend. The value of the resistance increases as the angle of curvature decreases. The design utilizes 5 ex-sensors. For this ex-sensor, it requires a microcontroller which has at least 5 analog pins. These pins work as analog voltage dividers.

6. Simulation Analysis

6.1. Momentum Analysis. This section discusses the graphical representation and the momentum analysis of the voltage of ex-sensor and the output of the controller. Let L1, L2, and L3 be the lengths of the phalanges and φ_1 to φ_4 be the joint edges of the 4 finger joints. The stance of fingertip (point Y) along with the values at point X can be communicated as a change, where the introduction of the fingertip is given by the quaternion:

$$T = \begin{bmatrix} \sin\left(\frac{\phi_1}{2}\right)\sin\left(\frac{\phi_2+\phi_3+\phi_4}{2}\right) \\ \sin\left(\frac{\phi_1}{2}\right)\cos\left(\frac{\phi_2+\phi_3+\phi_4}{2}\right) \\ \cos\left(\frac{\phi_1}{2}\right)\sin\left(\frac{\phi_2+\phi_3+\phi_4}{2}\right) \\ \cos\left(\frac{\phi_1}{2}\right)\cos\left(\frac{\phi_2+\phi_3+\phi_4}{2}\right) \end{bmatrix} \tag{2}$$

The area of point Y referenced from point X is given by the vector

$$Q_Y = \begin{bmatrix} \cos(\phi_1) L_1 \cos(\phi_2) + L_2 \cos(\phi_2+\phi_3) \\ -(2(L_1+L_2)+L_3)\cos(\phi_2+\phi_3+\phi_4) \\ L_1 \sin(\phi_2) + L_2 \sin(\phi_2+\phi_3) \\ -(2(L_1+L_2)+L_3)\sin(\phi_2+\phi_3+\phi_4) \\ \sin(\phi_1)(-L_1\cos(\phi_2)) - L_2\cos(\phi_2+\phi_3) \\ +(2(L_1+L_2)+L_3)\cos(\phi_2+\phi_3+\phi_4) \end{bmatrix} \tag{3}$$

ϕ_1, ϕ_2, and ϕ_3 joints are controlled by their own free actuator.

6.2. Simulation. As per proof of the theoretical concept, these simulations have been performed in order to validate the performance of the control scheme. The results are shown in terms of voltages between the controller and sensors, also with the controller and motors. These results show the behaviour of voltages according to the motion.

As shown in Figure 7, the curve is mainly based on the measured parameters, i.e., the curvature of a human hand on x-axis with the corresponding varying values of resistances of ex-sensors on the y-axis. This graph is proving that the theoretical concept between the changes occurs in resistance of the ex-sensor over the time. The mathematical equation gives us the following result:

$$y = 44x^2 + 32x + 15 \tag{4}$$

As shown in Figure 8, the graph is plotted between the resistances of ex-sensors on x-axis and input values of the voltages on the y-axis. This shows that the resistance is inversely proportional towards the input voltage. As the resistance of the ex-sensor increases, by the effect of resistance the input voltage at microcontroller terminal decreases. The mathematical model for this is defined as

$$y = 0.0071x^2 - 0.3x + 5.6 \tag{5}$$

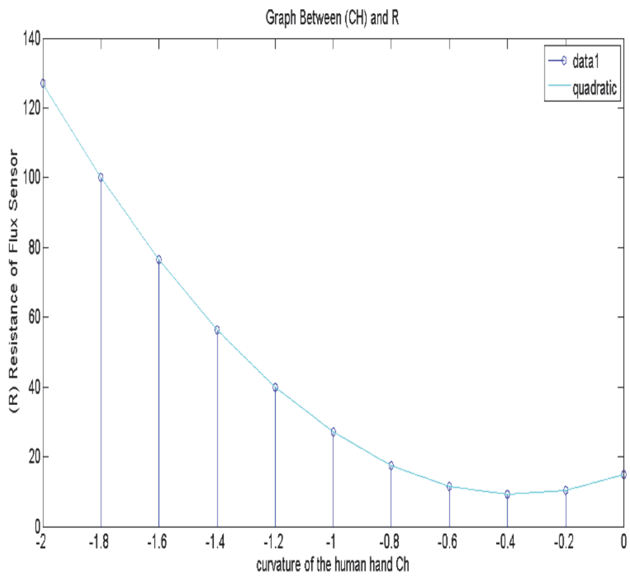


Figure 7: Curvature of human hand.

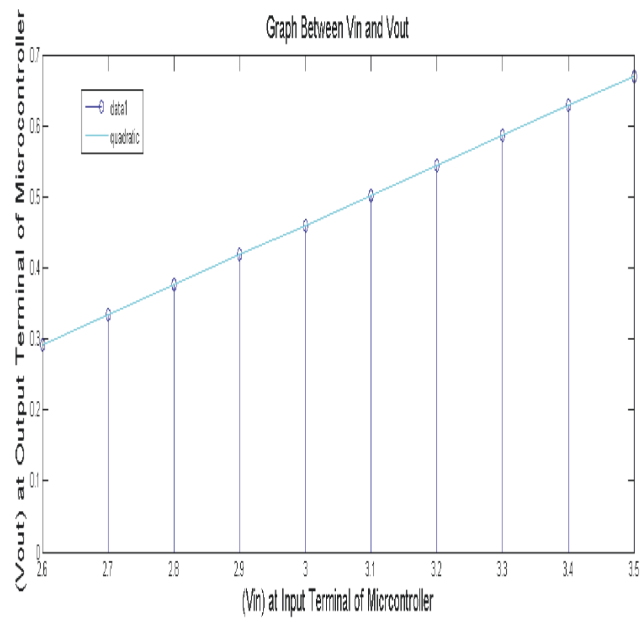


Figure 9: Input and output voltage of the controller.

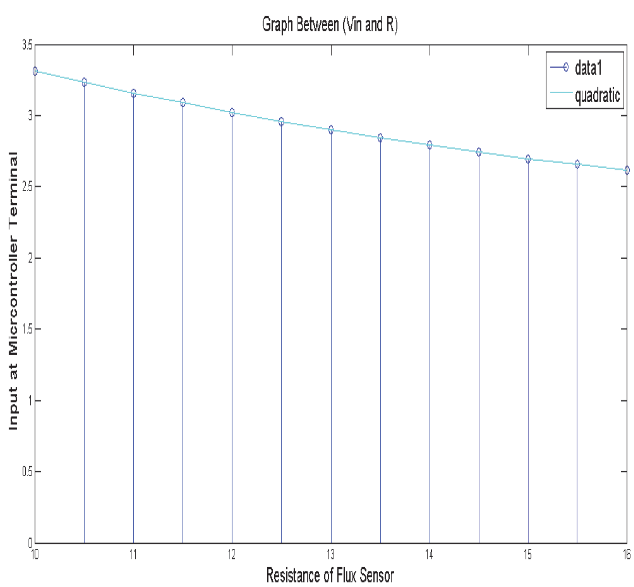


Figure 8: Resistance of flex sensor versus input voltage.

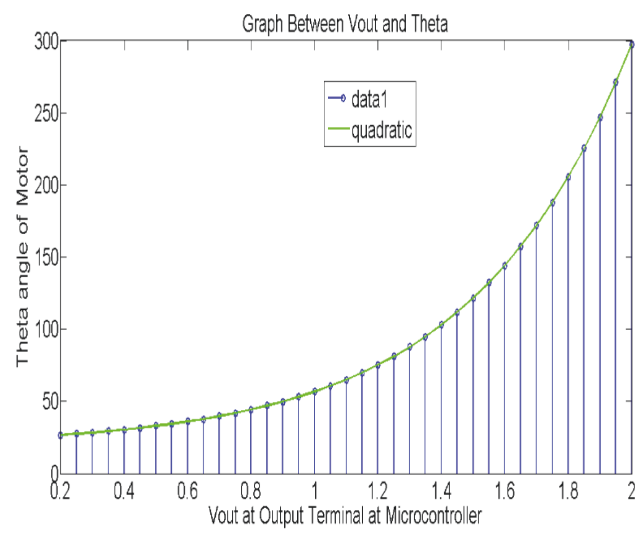


Figure 10: V(out) versus speed of the motor.

As shown in Figure 9, this curve is based on the following above equation, i.e., varying input values of the voltage on the x-axis and its corresponding output voltages of the micro-controller on the y-axis. This shows the linear relationship between the input and output voltages of the controller. The mathematical equation of this graph will be

$$y = 0.42x - 0.8 \tag{6}$$

Finally, Figure 10 shows us the curve, which is mainly based on the output voltages from the microcontroller on x-axis and the theta angle of the motor on the y-axis. This proves the concept that increase in voltage will also increase the rpm of the motor in nonlinear term which can be seen from this curve. This plot is defined by this mathematical equation:

$$y = 5.1 * e^{0.02x} - 1.8 * e^{0.02x} + 19 \tag{7}$$

In Figures 11-12, the relationship between the tendon and the finger motion has been shown, to evaluate how much the finger forces for different grasping positions. This shows the movement of one particular finger at a time.

7. Results

In this section, we validate the efficacy of the proposed design through extensive experimental paradigms that is included in the table. The table shows how the voltages have

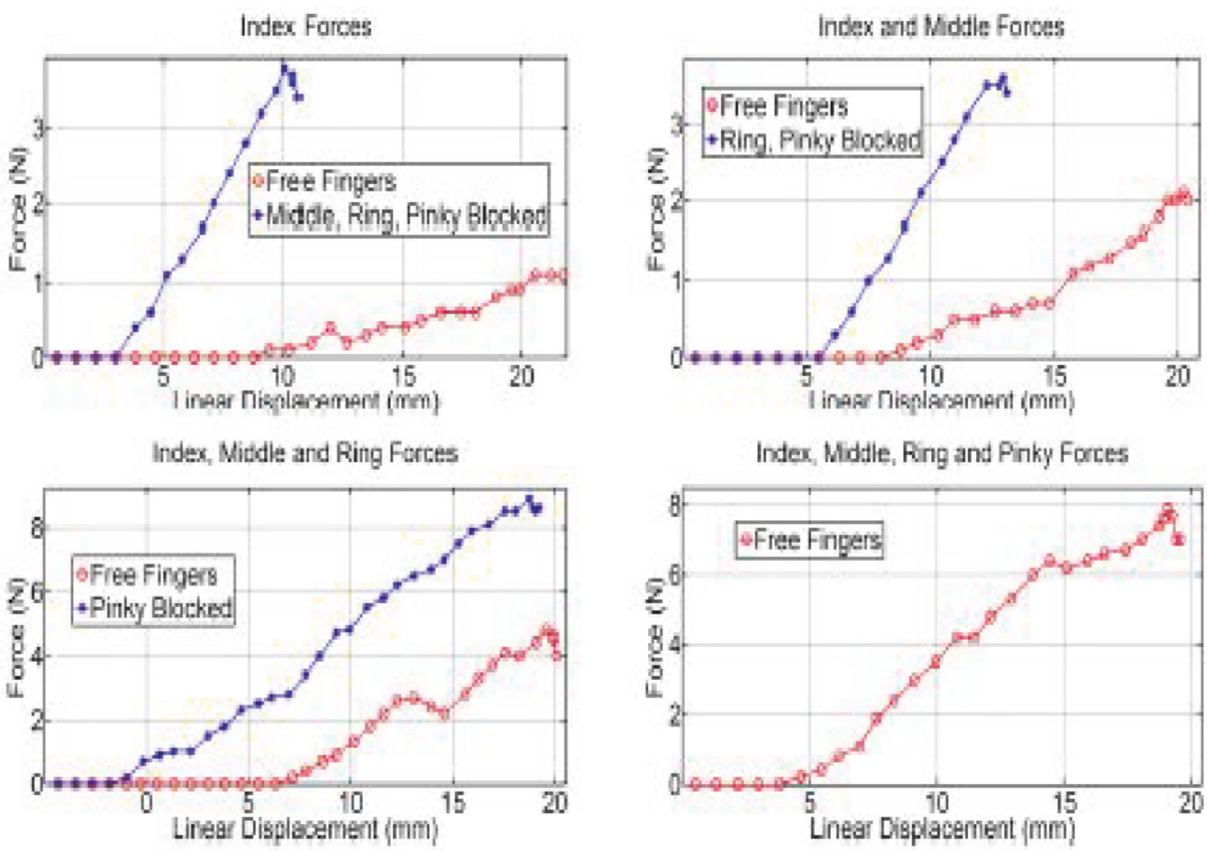


Figure 11: Linear displacement of fingers.

Table 1: Different voltage reading for different resistances of the Flux sensor.

S NO:	R(K ohm)	C(H)	Vin (V)	Vout (V)	Theta
1	15.2	0	2.65	0.295	0
2	14.88	-0.009612	2.676	0.3085	17.5
3	15.2	-0.019225	2.697	0.322	20
4	13.925	-0.03847	2.725	0.346	22.5
5	12.67	-0.0769	2.8	0.37	25
6	12.4	-0.0826	2.85	0.3955	27.5
7	12.21	-0.0884	2.913	0.42	30
8	12.055	-0.0826	3.006	0.4	32.5
9	11.9777	-01392	3.0532	0.469	42.2
10	11.8	-0.156	3.1	0.481	52
11	11.527	-0.1643	3.123	0.487	56.8
12	10.955	-0.1724	3.1468	0.493	61.7
13	10.588	-0.1805	3.1834	0.5315	71.3
14	10.01	-0.1866	3.22	0.57	81

been fluctuating which is measured in real time through the sensors. This signal is then fed to the controller by varying the control input parameter in real time, to produce such a control input which tackles the disturbances created due to the presence of uncertainties in the environment as shown in Table 1.

In order to verify our theoretical concept, different experiments are being conducted on the desired model. The main arrangement of tests concentrates on approving the viability of the proposed lockable differential component especially. The user can access different posture using a different switch which is placed on the fingers. Such functionality is not only

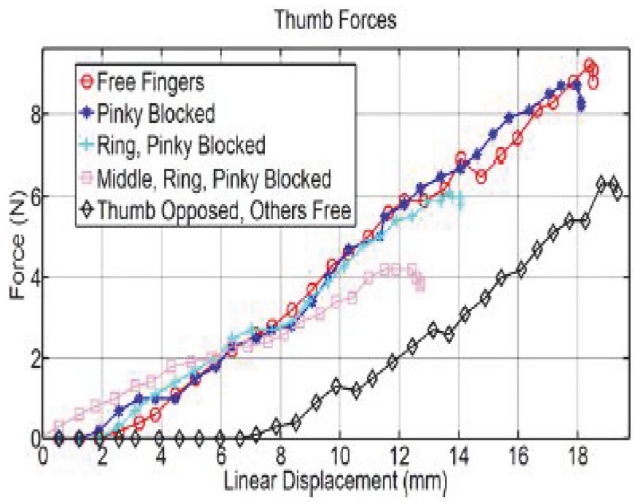


Figure 12: Thumbs displacement.

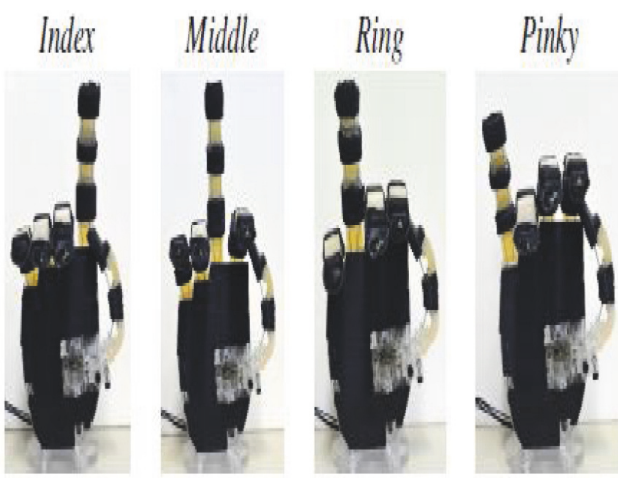


Figure 13: Movement of the fingers [8].

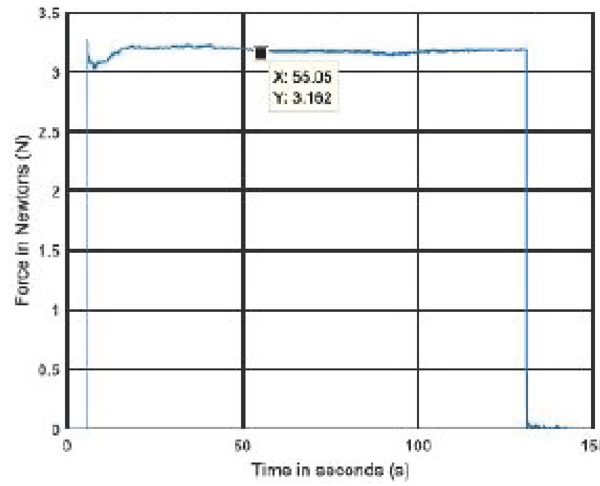


Figure 14: Object grasping at 200g.

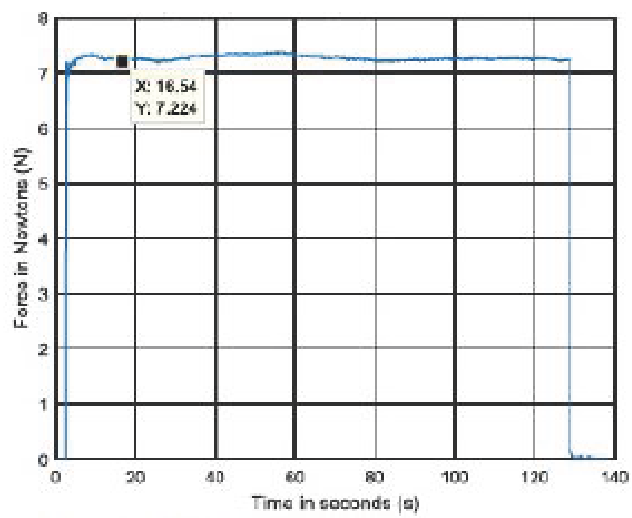


Figure 15: Object grasping at 400g.

important for grasping (where the user is able to choose the preferred grasping posture).

In Figure 13, different postures are depicted. The motion of each locked finger is constrained through the corresponding gesture which is changing according to user defined switches. The second set of examinations concentrates on getting a handle on the extensive variety of regular day to day objects, so as to execute everyday living exercises. Figures 14-15 show a real time graph, while grabbing weight of 200g and 400g, respectively. This figure shows the gripper successfully grasped objects. After a steady response of the system until 140 seconds, the force abruptly reaches toward zero as shown, indicating that the gripper released the object. In Figure 15, the weight is now being doubled as the mass, subsequent simulation result is shown. The result discusses that the increase in mass decreases the gripper power, as it converges to zero in 130 seconds.

8. Conclusion

In this paper, the design of an underactuated robotic hand is discussed using linear control and implemented as a prototype. According to the calculations and simulations readings during this research, it can be easily said that this mathematical model is now perfect. An ex-sensor is attached to every single finger for accurate measurement of the movement and grasping power of the robotic hand. Using the developed linear force, an object is handled by applying adequate force through the controller without damaging the object. The major advantage of this model can be seen as it easily allows all the fingers to move easily and independently using servo motors. A user can also change to different grasping postures by changing the programming of the controller. The thumb configuration can be easily adjusted by the user, using the lockable, stiff opposition mechanism. In conclusion, this robotic hand is a better device for helping amputees in their daily routine activities. This research shows how a prosthetic robotic hand can be developed with low cost. Flex sensor based hand gives proper hand control in grasping picking and holding things. The efficiency of the proposed robotic hands has been experimentally validated and the results were shown in the earlier sections. Hence, for future research investigation, it is recommended to use the output feedback controller for estimation of the states for better accuracy and low cost, as we eliminate the sensors from the system. Another recommendation is to include optimizing and building more intelligent control for such a robotic hand.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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