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Developing and Building a 3D-Printed Bionic Arm

Ahmed Abrar Shayor[*], *Mohammad Sultan Mahmud*
Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

ABSTRACT

A 3D printable design and it's analysis for a myoelectric prosthetic arm was explored in this paper. The arm is electronically actuated and controlled by a user flexing and relaxing his/her biceps muscles. The bionic arm presented has the scope of being used by a person with no limbs or not having it from below the elbow. The main objective of this work was to make a cost effective prosthetic which was also sophisticated enough Normally such devices are mechani- cally actuated and therefore not as noticeably complicated as myoelectric devices are. The technology of 3D Printing is something that caused a new era of hope for physically challenged 3D printing does have its limitations but growth and development in the field will only lead to improvements over time. Low cost moderate strength materials for the body and parts available almost everywhere was used for the construction of it's body to make it as affordable as possible. The electronics used were less, hence not so complicated to troubleshoot. The developed design showed promise as it could do many basic things having 5 DOFs.This study topic covers a broad range of engineering disciplines. The root of the system is an innovative mechanical design for a 3D printed prosthetic arm. Modern day electronic actuators, that is servo motors and circuitry using sensors animate the device and allow for sophisticated control schemes. It is hoped that this work will be of value to the future prosthetic manufacturing engineers of this subcontinent. The main objective of the research was fulfilled but due to the problems and shortcomings of availability and support community for the technologies used , seen in relatively underdeveloped countries some features of the arm were not achieved as expected but the project is nonetheless promising.

Keywords: Prosthetic, Bionic Arm, Muscle Sensor, Microprocessor, 3D Printing

1.Introduction

It could be argued that the most valuable possession to any human being is their body. Replacing a missing human limb, especially a hand, is a challenging task which makes one truly appreciate the complexity of the human body. Until modern times the design of prosthetic limbs has progressed relatively slowly. Over time materials improved and designs started incorporating hinges and pulley systems. This led to simple mechanical body powered devices such as metal hooks which can open and close as a user bends their elbow for example. Recent times however have given way to enormous advancements in prosthetic devices. Focus is not only on the physical aspects of a device but also the control and biofeedback systems. Slowly we are approaching an advanced trans-human integration between machine and body. Perhaps sometime in the future prosthetic devices will be faster, stronger and maybe even better than our biological limbs.

Throughout the course of this study we will explore myoelectric prosthetic arm.It is aimed to design a device which mimics the function of the human arm as best as possible and can be controlled to some extent by muscular contractions.The name was fixed with an insight to build a cost-effective yet moderately strong, aesthetic and most important of all a diverse movements-equipped prosthetic using 3D printing technology and low cost myoware sensors.

The human finger in total has 4 degrees of freedom [1]. Three of these are the rotations of each joint, Distal Interphalengeal Joint,Proximal Interphalangeal Joint,Metacarpophalangeal Joint(DIP, PIP, MCP) which combine to control flexion and extension of the finger.The knuckle (MCP joint) also allows for abduction/adduction (wiggling the finger from side to side). The complex motions of this incredible piece of natural,bio machine which still can't be replicated in man-made fingers are precise and perfect and their extensive explanation are beyond the scope of this section.But for a general conception a figure is given below for description and understanding

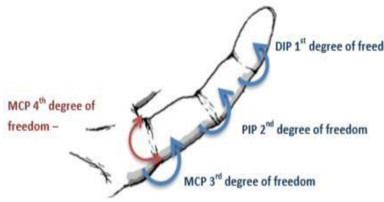


Fig.1: Degrees of freedom of Human Hand [2]

In the thumb the lower CMC joint also allows for abduction/adduction which gives 5 DOFs in the thumb [3]. Fingers, and all joints in the human body are actuated (moved) via contraction of muscles and tendons. Dexterity arises from the numerous degrees of freedom of the human hand. The fine motor control a person has over their individual finger joints allows for a vast array of intricate tasks to be achieved. In contrast, commercial prostheses are limited to simple tasks partially due to the lack of fine control in the fingers.

Several arms such as the Bebionic 3 [4] and iLimb [5] are myoelectric controlled robotic arms commercially available to the public.Numerous more prosthetic arms exist in research labs around the world

shayor1605052@stud.kuet.ac.bd Tel-+8801627285545

which are usually developed as prototypes to test advanced designs and concepts. Research prosthetics are generally more complex in terms of mechanical design ,control and monitoring systems but are inferior to commercial devices in terms of practicality, cost and robustness [6].Other such arms studied were Vanderbilt Hand[7],Intrinsic Hand[8],Shadow Hand[9].

The contribution from our project was to showcase a prosthetic hand made with technologies available locally and with ease and even at low cost if compared to industrial alternatives.

2.Theory

A prosthesis is an artificial limb,an artificial substitute that replaces a missing leg or arm due to disease,accidents or congential defects. Prosthetics is the evaluation, fabrication, and custom fitting of artificial limbs, known as “prostheses.”The prosthesis must be a unique combination of appropriate materials, alignment, design, and construction.There are outside body and inside body prosthetics if broadly classified.

Lower-limb prostheses might address stability in standing and walking, shock absorption, energy storage and return, cosmetic appearance, and even running, jumping, and other athletic activities. Upper-limb prostheses might address reaching and grasping, occupational challenges including hammering, painting, or weight lifting, and activities of daily living like eating, writing, and dressing.

These are what constitutes the outer body prosthesis and is our main concern and topic of attention for the ongoing study and future project.

Prosthetic patients may have been born with limb deficiency or have experienced amputation due to trauma, cancer, infection, or abnormalities in blood vessels or nerves and the aim of prosthetics is to return them to their normal lives.There are notable benefits to 3D-printed prostheses.

Firstly, open-source files for the designs are easy to download and include a wide variety of designs that are challenge to create affordable, customized, easily repaired, well-fitting devices specific for each activity, interest, and size increasing daily.Secondly, the components necessary to create a “helper hand” are available at a fraction of the cost and weight of those used in even the most basic traditional prosthesis.As children grow and develop interests in instruments and sports, 3D printing can meet the challenge to create affordable, customized, easily repaired, well-fitting devices specific for each activity, interest, and size increasing daily.Printing a prosthesis starts by downloading an open-source design file from the Internet and scaling the model to fit the recipient. Many prosthetic models require measurements from the unaffected hand and arm,such as the width across the palm or the circumference of the fore arm, to approximate the best fit. For a patient with bi- lateral upper extremity amputations, the maker may choose to scale the forearm portion—often called the gauntlet—to fit the existing arm, and then scale the remaining components to the same size.

This may require printing several test components to find the correct fit for a recipient. Customization can be done using computer-aided design (CAD) software such as AutoCAD or SOLIDWORKS Scaling and layout of parts is easily done with the programs provided by the printer companies or with independent programs such as Slic3r (slic3r.org).Parts can be printed in a wide spectrum of colored filament feedstocks that can be transparent, opaque, fluorescent, glow in the dark, or metallic.

The filaments used or can be used are of many types almost an infinite combination of color and a very large collection of materials ranging from commonly used plastics to the very hardest of metals. Another critical design point in commercial prosthesis is durability. The average user will wear a myoelectric pro- thetic hand in excess of 8 hours per day [10].

Therefore, prosthetic arms for commercial use must be robust, lightweight and packaged into a closed system that can be attached to an amputee. Mechanical complexity determines the degrees of freedom in the system; however, there is usually a trade-off because increasing complexity can lead to an increase of the size of the device and also reduce robustness and durability [6].

2.Design

The prosthetic arm is to be developed and put forward for mainly study purposes but with the aim of usability in light weight works and situations where a static,motionless prosthesis is just not enough is named “Bionic Arm” because it basically depends on bio-generated electricity in the muscles ,if we summarize it all that is, and hence is an integration of a mechanical shell(arm) ,powered by electrical batteries, and a biological power(electrical signals through neurons in the surface) actuating and basically controlling it.

The design of the project was done by a designer at Thingiverse using Designspark Mechanical. Solidworks(A Computer Aided Design software)has been used extensively in analysing and searching for defects by me,if any in the mechanical components before 3D printing.The STL files from Thingiverse were hence directly used in the project.Below the original files in 3D view have been provided with short descriptions on their design inspired by Gael Langevin[11]:

3.1 Fingers:

The fingers were designed inspired by the Inmoov project,an open source 3D printable life sized robots with all parts 3D printed Inmoov being a website created by Gael Langevin a French sculptor,designer,and done as shown below by a designer at Thingiverse.

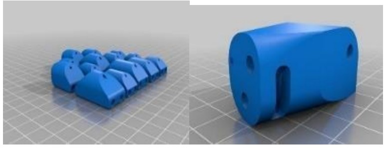


Fig.2:CAD model of fingers(Four Fingers and Thumb as standalone)

3.1 Palms**:**

The palm was developed so as to withstand force and show great flexibility and allow great mobility for the thumb(a very important issue).The design is as follows:

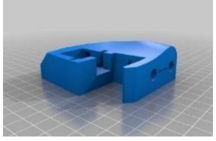


Fig.3:CAD model of palm design

3.2 Wrist:

The wrist is part of the forearm and strong enough to bear the weight or load on it when raising itself and some load, the construction of prosthesis may be done following the rough sketch below:

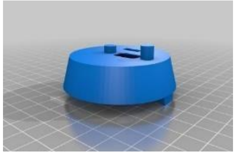


Fig.4:CAD Model Of Wrist Part

Inspite of having no moving parts the forearm design was done exactly similar to the figure below(following it) and demanded just as attention as any other part due to the necessity of housing the five servos,lithium polymer,myoware muscle sensor in it and allowing assembly as well.The forearm was designed also taking into account that 3D printers available at our lab will take huge time to print and will not be able to hold the other parts of the model in it(due to size of the printer) since these parts might need to be re-placed or repaired,etc after testing,hence it consists of more than one parts instead of a single parts which was screwed together when printed.3D printed PLA plastic is relatively weak and can easily be split by the turing of screws(excessive tightening).To minimize the chances of cracks guide holes for the screws have been incorporated into the design and care has been taken to ensure there is enough material to firmly support the screws.

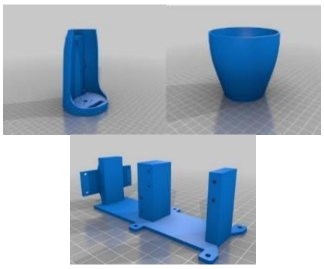


Fig.5:CAD model of forearm & supports for servos

4.Mechanical Calculations:

The mechanical calculations involving dynamics and statics for each part is presented below.

4.1 Force in Fingers

In order to calculate the theoretical force in fingers neglecting any frictional losses and deformity in shape (elongation, contraction) we must first find the force generated by the servo which will later be used for failure analysis of other components.

If the tensile force on the artificial tendon for the bionic arm is to be calculated then the stall torque (maximum turning force) of MG996R Digi Hi Torque (Hwayeh) of 12kg-cm at 5.5 V approximately can be used.

$$\tau_{serv} * r = F_2 \qquad (1)$$

$$F_2 = 1.177 * 7 = 8.239 \text{ N}$$

As the span of the smallest finger of the palm is only about 55cm,hence it will have minimum effective moment when raising an object .Thus an overall correct evaluation for the fingers can be done,Otherwise it may lose support and fall down.So to know the maximum theoretical force if we assume the polystyrene cord to act exactly like a pivot then we get-

$$F_1 l_1 = F_2 l_2 \qquad (2)$$

$$F_1 = \frac{8.239 * 5}{55} = 0.749\ N$$

$$\text{Mass} \times \text{g} = 0.749 \qquad (3)$$

$$\text{or Mass} \cong 76\ gm$$

4.1.1 Gripping Force:

As the finger curls the perpendicular distance be- tween the knuckle joint and the applied load decreases- which results in a lesser moment about the knuckle joint. This means that the finger tips apply more force as they close further. Suppose the hand is curled around an object then the applied force to the index finger would be acting in a different orientation.Resembling a clenched fist.

Since the perpendicular distance from the applied force point to the knuckle joint is now smaller, fingertip can apply a greater force. In this case each finger can support a mass roughly 140 g(using the same calculation as above) which would give the hand a lifting/holding capacity of about 560 gm.

Max fingertip gripping $\cong 140\ gm$

4.1.2 Finger Actuation Speed**:**

The Digi High Torque MG996R used has an actuation speed 0.15s/60° at 5.5 V so a full wrist rotation from a palm up position to palm down position, i.e 0° to 180°, therefore takes-

$$\frac{0.15s}{60}.180 = 0.45s$$

It has been measured that a tendon must move about 2 cm to move the finger from fully extended to fully flexed.Using the arc length formula-

$$length = \frac{x^{\circ}}{360} \times 2\pi r \qquad (5)$$

$$x = 160^{\circ}$$

Here length is 2cm, r is the radius of the custom servo horns is 7 mm.

We find that the servo must rotate 160° to completely open/close each finger through clockwise/anti-clockwise rotation and the time taken is

$$\frac{0.15\ s}{60^{\circ}} \times 160^{\circ} = 0.45s$$

The time taken hence for any loss of energy in the process due to friction or such phenomena will not cause it to exceed 0.5s.The force on the polystyrene fiber had the greatest stress after that on the nylon fishing line wires.The force on the fiber can be calculated as follows-

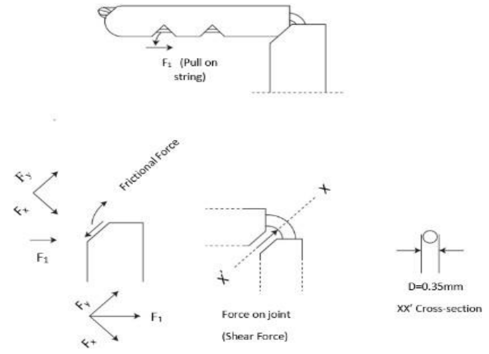


Fig.6: Free Body Diagram

Frictional Force,$s = \mu_s F_x$ (6)

$=0.4\times F_2 \cos 45 \ =2.3303\,\mathrm{N}$($F_2$ is the force on the contact surface due to pull on the string,F_1)

Shearing stress,$_s= \frac{8.239\sin 45^{\circ}-2.303}{\frac{\pi}{4}D^2}$ (7)

$=363.351$ KPa(where dia is only 3.5 mm and F_y is the shear force)

Shear strength of polystyrene ropes of this size are over 700 KPa. So it won't tear. If we now consider the nylon wire then it would have almost same calculation with force being 5.836 N(no friction).This means that a force of 4.45 MPa will be generated but the nylon wire has strength of about 5.5 MPa. Hence it will not fail as it strong enough for F_y

5.Materials and Machines Used

Every part constituting the Bionics Arm was manufactured using the Ultimaker 3D printer available in our University's Fabrication Lab. It is a fused deposition modelling 3D printer. This type of 3D printer produces what is known as support material which provides support to horizontal planes during printing. Care has to be taken when removing this support material so as to not damage the component.The parts of fingers were joined using heavy duty polyster fibers of dia about 3.5 mm which passed through the holes on the fingers and were knotted and soldered to make it permanent.

The Ultimaker provides its own development environment which allows for fine tuning of the printer options. Several features have been experimented with such as print speed, layer resolution and extrusion temperature to produces high quality printed components.Nylon wires were used as artificial tendons connecting the servos "representing" the muscles of the Bionic arm and the fingers.

6.Electrical and Electronics Setup

The electrical parts that were used consisted of voltmeters for checking proper battery voltages,the batteries themselves,the soldering iron and it's accessories.The electronics mainly were the Muscle Sensor V3 sensor ,self- adhesive disposable electrodes and voltage regulator Buck Module also known as Buck Converter for controlling voltage supply to the servos.As microcontroller Arduino Nano was used coding was done in Arduino IDE 1.8.9 platform. The batteries used were 9V 6F22 NEW LEADER battery and Red 2600 mAh Li- Po battery of 7.4 V rated voltage output.The 9V batteries were used for powering the sensors and the 7.4 V for the servos as they are rechargeable. The setup can be understood easily through the following schematic diagram and flow chart using real picture to show how the control system works.

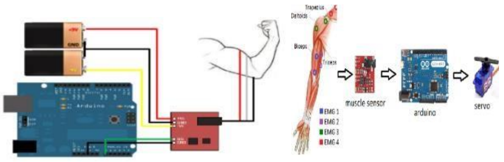


Fig.7: Flow Chart for Control System

6.1Microprocessor

As the microcontroller or microprocessor the Arduino Nano has been used .The Arduino Nano is a small,complete,and breadboard-friendly board based on ATmega 328P(Arduino Nano 3).It lacks only a DC power jack, and works with a Mini-B USB cable instead of a standard one.It was used to store the program and run it to control the servos after reading the signals from the EMG sensor.

6.2 Voltage Regulators

The voltage regulator used was the buck converter.A buck converter is a DC-to-DC power converter which steps down volt- age from its input to its output. It is a class of switched-mode power supply,a capacitor, inductor, or the two in combination.It was used to drop the voltage down to 5.8 V (approx) ,the output from the Li-Po battery, from the 8.2 V it could supply after full charge.This is because the maximum voltage the servos could handle was 6V as given in the specifications.

6.3 Electromyography Signal Extraction

Easy to use single channel EMG sensor boards had been used to sense and measure muscle activity. This kit contains a small PCB and three surface electrodes. Two of these electrodes measure the voltage potential across a muscle and the third is a ground reference point placed on a boney feature. The muscle sensor kit is designed to be used directly with a microcontroller. As a user flexes, an internal amplification system converts minute electrical pulses into a rectified and smoothed signal that can be used as an input to a microcontroller's analogue to digital converter.The basic working principle of the Muscle Sensor V3 for the signal extraction and filtering can be made clear through these following figures

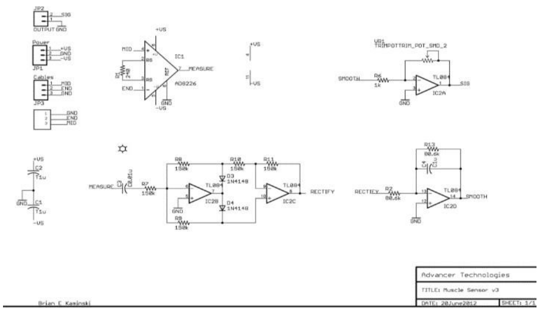


Fig.8: Working principle of EMG Sensor

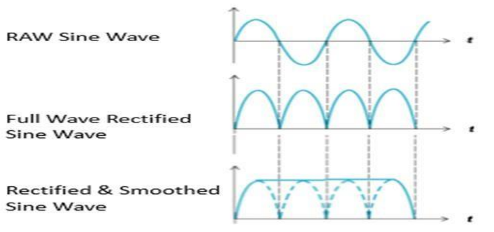


Fig 9:Sine wave of electric signal

6.4 Power Supply

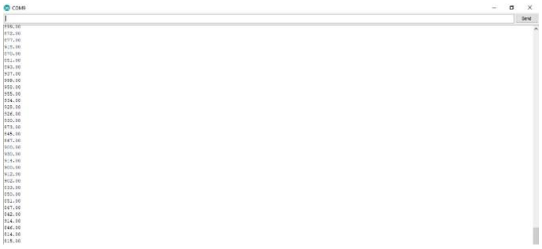
It is important that this system is portable and completely powered by internal sources. Using a wall power supply is fine for testing and debugging but a prosthetic arm needs to be powered by a source an amputee can easily carry around. Servo motors use a significant amount of current during operation. Disposable batteries would not be a good solution since the servos would drain power too fast meaning they would have to be replaced quite frequently. Lithium Polymer (Li-Po) batteries offer a high energy density and are rechargeable. There is a trade-off between battery life and battery size. Ideally we would like the arm to be able to run for several hours without needing to be recharged. However, to achieve this, the size of the battery may become too large to be housed within the device.

6.5 Different EMG sensors

Many different EMG sensors were studied and performance investigated by viewing online authentic reviews as well as the features provided in those EMG Sensors at their websites.These sensors were- Gravity: Analog EMG Sensor by OYMotion-DFRobot,EMG-EKG Olimex Shields.

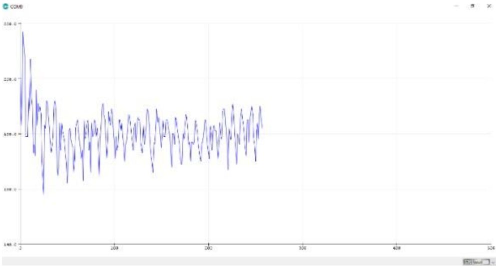
7.Programming.

The program used to control the Bionic Arm was not very complex and took up about 100 bytes of memory of the Arduino Nano part of it is given as sample below.The program was made as simple as possible to reduce time required to process and carry out the instructions of the code by the Arduino Nano board.Other programs were also written to carry out more functions that are in the process of development and debugging due to complexity arising when in motion ,that is during different motions of the Bionic Arm.The arm was actually programmed for 10 different motions in one program as previously mentioned and another for just grasping objects but the power of grasp controlled by flexion of muscles and relaxation also controlled by muscles not included here.It depended on the level of mili-volts generated from biceps.

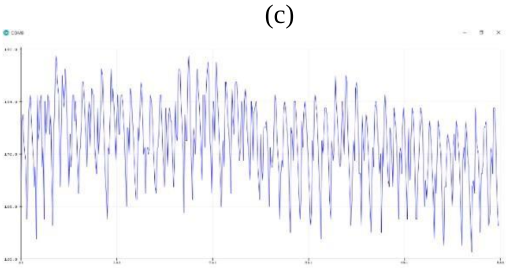


(a)

(b)



(c)

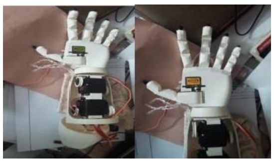


(d)

Fig.10:(a)Serial Monitor output for biceps contraction(b)for thumbs-up gesture(c)Serial Plotter output at beginning of motion of arm(d)for continuous state of biceps contraction.All the Y axis values are 100XVolts(generated by arm) & X gives time “t” in miliseconds.

7.Test Result and Discussion

The grips obtained at this time properly was just the following two(number 1 in slightly more details explained in ‘Programming section’),other types of gestures could also be achieved but not steadily and often resulted in getting mixed.By using the word mixed the point being referred to, is that the microprocessor could not distinguish the results from the sensor as the readings obtained were incorrect was mentioned The arm could lift about 500 gms on its palm.The load that could be lifted by the finger was 300 gms upto which it was tested ,further load was not given and tested because of time constraints.



(a)

(b)

Fig.11:(a)Figure of construction(b)Grip Finger Motion and three finger motion of the Bionic Arm

This work was only experimented with PLA plastic for 3D printing.Nylon can be used for 3D printing as well and offers significantly more strength than PLA.Reviews from 3D printing specialists show clear advantages in strength Nylon has over PLA and ABS.The joint-linked finger actuation design dis- cussed in the literature review would offer greater strength and reliability compared to an artificial tendon network.However,designing the small intricate gears would be challenging and problematic to print.The design of a wrist joint which allowed for two or three degrees of rotational freedom would be a design of significant value.

One of the biggest limitations of this device is its lack of feedback. Pressure sensors could be used to provide fingertip pressure feedback, which would allow the fingers to automatically conform to specific object shapes. Feedback would also facilitate even and controlled fingertip pressure and would reduce the strain on the servos when trying to grasp an object.Future academics are encouraged to develop more advanced EMG control algorithms which facilitate the control of various movements of the arm simultaneously. Such a control system would have to offer some kind of calibration routine to allow the system to adjust to the myoelectric signals of each individual user.Hence this upgrades would make this project a high-performance and durable prosthetic for all people of all ages.However just continuing development of the current project would still give good results.

8.Conclusion

Some conclusion can be drawn from the overall discussion made specially about the feasibility and real world use of the prosthesis and why,where,etc questions regarding possible developments of this project.

The nature of 3D printing leads to components of minimal quality.Unfortunately the bionic arm prototype is not of high enough quality to be used as a prothesis or benefit amputees at this point in time,atleast not as it would be expected to.As the initial aim was to develop a low cost 3D printed myoelectric prosthetic arm.The goals and expectations for this ‘study based project development’ was more or less achieved.Further analysis and research will still be done.With the ongoing rapid growth of the 3D printing industry advanced materials will allow students to develop more commercial like prosthetic devices,robust and durable systems,those that will benefit a wide range of people with missing people.The current research improvement on a personal or different organizational scale will hopefully gradually lead to systems better in all aspects and offers,improved dexterity and control.Perhaps these prostheses will improve quality of the lives of amputees.

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