Design and Development of Bio-Sensitive Robotic Arm using Gesture Control

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Abstract. In this paper, a model of a robotic arm is designed and manufactured using a 3D printer, which is to be operated via human gesture by using the Accelerometer and Gyroscope Module. This arm is proposed to help in the medical field, in military operations, in hazardous conditions and in industries to maximize human safety. The robot arm is designed such that, it has 5 degrees of freedom controlled by the 3-axis accelerometer mounted on the IC placed on the glove of the user. The module will replicate the movement of the user’s hand to extend, retract, and rotate accordingly to accurately position as required for the application. The user’s finger action is used to manipulate the working of the gripper. Therefore, gesture control in a broad sense is a computerized interface that allows computers to record and interpret those gestures into commands to adhere to actions.

1. Introduction
Robots are electromechanical machines which are programmed to carry out a series of operations with or without human supervision. This scope of being fully autonomous makes them suitable usage in various fields such as medical, military, industries and research etc [1]. A robotic arm is an assemblage of mechanical linkages which are usually programmable, with capabilities to function similar to a human arm. Such robotic arms are then used to perform the task with unmatchable consistency and accuracy. Gesture recognition and control is one of the methods which is used to interface human commands in the form of gesture into executable operations of the arm [2]. In this paper, hand gestures are focused upon as they can be extensively mapped and used for controlling robotic hand actions.

The following are the objectives of this work:
- To build a 5-axis robotic arm.
- To implement gesture assisted control on the robotic arm.
- To incorporate and familiarize with working of flex sensor.

The working concept of this arm is that it uses Arduino Uno as the micro-controller platform for the prototype arm and is programmed for the processing the input signals by the user against the standard library code [3]. The designed robotic arm prototype can mimic the certain hand actions of the user in real-time. Characteristics such as surviving repeated usability and having a realistic extent in its work area all while keeping the entire model simple in construction, light in weight, economical and durable in nature is desired [4].
2. Methodology
Using flex sensors, the finer movement of the user’s human hand fingers such as pinch is mapped and the gestures made by the user is translated into the corresponding electrical signal. This signal is fed to the microcontroller (Arduino Nano) which has the accelerometer & gyroscope module (MPU 6050) which helps to track the other movements of the hand such as pitch, roll etc [5]. The Bluetooth module (HC-05) is used to interface the processed data to the microcontroller on the robotic arm side [6]. The servos of the arm assembly are connected to the Arduino Uno and have been programmed to execute the received signals accordingly [7]. Figure 1 below is a schematic representation of the involved work flow.

![Figure 1. Methodology of work flow.](image)

3. Design of Robotic Arm
The robotic arm assembly shown in figure 2 was designed in CAD software Solidworks. The model can be divided into 2 main assemblies – the arm and the gripper. The arm assembly consists of five components – Base, Waist, Arm, Shoulder and Elbow and is shown below as figure 3. The assemblage has 4 Degrees of Freedom. Each model component was designed in Solidworks with extrudses and holes to connect them with one another and to facilitate the installation of the servo motors and wirings. Similarly, the gripper assembly consists of five components – Gripper Base, Gear, Gripper Link, Support Rings and Gripper Finger and is shown below in figure 4. The Gripper assembly uses a single servo to produce the action among the linkages. Certain extrudses and screw threads are designed int the parts to facilitate during the assembling of the prototype model. The entire model is made up of 16 subparts and can demonstrate up to 5 Degrees of Freedom. The model is a stationary in nature as it can be mounted on a tabletop or flat surfaces with the possibility of attaching to a movable base as
when required. The entire model has a maximum vertical reach of about 0.46m from the base and has a maximum horizontal reach of 0.36m.

![Figure 2. Assembly Model of Robotic Arm.](image)

![Figure 3. Parts in the Arm Assembly.](image)

![Figure 4. Parts in the Gripper Assembly.](image)
4. Direct Forward Kinematics Study

Forward kinematics establishes the orientation and location of the robot’s manipulator hand in the cartesian coordinate space if every joint variable is declared and inverse kinematics will determine how every joint variable has to be if it is to achieve the known position and orientation of end effector. Therefore, Forward kinematics is the conversion of Joint space to Cartesian space whereas Inverse kinematics is the conversion from Cartesian space to Joint space [15]. The study was performed to determine the direct forward kinematics of the fabricated prototype model. The Denavit Hartenberg principle matrix representation of forward kinematics is made following which an analytic configuration result is found out. Denavit Hartenberg representation is a standard methodology to represent the kinematics of the manipulators [16]. Due to its wide acceptability and popularity of being used in various industries, the following methodology will be used in the study. The software used for this purpose is MATLAB which aids in solving the complex matrix formed. MATLAB is a highly intuitive and user-friendly yet powerful high – performance software and language package which offers programming in an easy to use environment and is known for its acceptability among the academia.

Figure 5. Process Schematic of Direct Kinematics.

A simple block diagram in figure 5 is provided to illustrate the key skeletal operation under forward kinematics. At first, a central model is developed into which input variables such as Joints and Angles are fed along with known restrictions in link movements. The central system then performs a computation at the mathematical model to provide a solution in the orientation and position of the end effectors. The Coordinate Frame Assignment for the prototype has been made in figure 6 which consists of a reference Ground Origin and the other joints which represent the different Degree of Freedoms. The final joint is also the End Effector which is the gripper base that is considered as changeable tool post.

Figure 6. Coordinate Frame Assignment for the Prototype.
Following the Coordinate Frame Assignment, a detailed tabulation was formed to facilitate the application of the Denavit-Hartenberg (DH) Methodology. The table has 4 parameters and 20 variables. They are as follows:

Table 1. Link Parameters Setup.

| Joint | Type      | $\alpha_i$ (deg) | $\theta_i$ (deg) | $a_i$ (mm) | $d_i$ (mm) |
|-------|-----------|-------------------|------------------|------------|------------|
| 1     | Base      | 0°                | $\theta_1$       | 0          | 56         |
| 2     | Shoulder  | 90°               | 02               | 0          | 42         |
| 3     | Elbow     | 0°                | 03               | 120        | 0          |
| 4     | Wrist     | 90°               | 04               | 74         | 0          |
| 5     | Gripper Base | 90°            | 05               | 30         | 13         |

The transformation matrix set up from $i$-1st Joint to $i$th Joint according to DH convention is:

$$T_{i-1}^i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Where, $S\theta_i = \sin \theta_i$, $C\theta_i = \cos \theta_i$, $S\alpha_i = \sin \alpha_i$, $C\alpha_i = \cos \alpha_i$

Now according to the design of the prototype, the transformation matrix is set up for each joint using the parameters earlier established and noted in the table.

For 1st Joint:

$$T_{01} = \begin{bmatrix} c_1 & -s_1 & 0 & 0 \\ s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For 2nd Joint:

$$T_{12} = \begin{bmatrix} c_2 & 0 & s_2 & 0 \\ s_2 & 0 & -c_2 & 0 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For 3rd Joint:

$$T_{23} = \begin{bmatrix} c_3 & -s_3 & 0 & a_3 \cdot c_3 \\ s_3 & c_3 & 0 & a_3 \cdot s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For 4th Joint:

$$T_{34} = \begin{bmatrix} c_4 & 0 & s_4 & a_4 \cdot c_4 \\ s_4 & 0 & -c_4 & a_4 \cdot s_4 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
For 5th Joint:

\[ T_{45} = \begin{bmatrix}
  c5 & 0 & s5 & a5 \cdot c5 \\
  s5 & 0 & -c5 & a5 \cdot s5 \\
  0 & 1 & 0 & d5 \\
  0 & 0 & 0 & 1
\end{bmatrix} \]

Using the above-formulated matrices, we find the effective end effector matrix as follows:

\[ T_E = T_01 \cdot T_{12} \cdot T_{23} \cdot T_{34} \cdot T_{45} \]

i.e.

\[ T_E = \begin{bmatrix}
  NX & OX & AX & PX \\
  NY & OY & AY & PY \\
  NZ & OZ & AZ & PZ \\
  0 & 0 & 0 & 1
\end{bmatrix} \]

Where,

- \( NX = s5 \cdot (c1 \cdot s2 + c2 \cdot s1) - c5 \cdot (s3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) - c3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2)) \)
- \( NY = -c5 \cdot (s3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) - c3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1)) - s5 \cdot (c1 \cdot c2 - s1 \cdot s2) \)
- \( NZ = c5 \cdot (c3 \cdot s4 + c4 \cdot s3) \)
- \( OX = c3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) + c4 \cdot s3 \cdot (c1 \cdot c2 - s1 \cdot s2) \)
- \( OY = c3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) + c4 \cdot s3 \cdot (c1 \cdot s2 + c2 \cdot s1) \)
- \( OZ = s3 \cdot s4 - c3 \cdot c4 \)
- \( AX = -s5 \cdot (s3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) - c3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2)) - c5 \cdot (c1 \cdot s2 + c2 \cdot s1) \)
- \( AY = c5 \cdot (c1 \cdot c2 - s1 \cdot s2) - s5 \cdot (s3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) - c3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1)) \)
- \( AZ = s5 \cdot (c3 \cdot s4 + c4 \cdot s3) \)
- \( PX = d5 \cdot (c3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) + c4 \cdot s3 \cdot (c1 \cdot c2 - s1 \cdot s2)) - a5 \cdot c5 \cdot (s3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) - c3 \cdot c4 \cdot (c1 \cdot c2 - s1 \cdot s2)) + a3 \cdot c3 \cdot (c1 \cdot c2 - s1 \cdot s2) + a5 \cdot s5 \cdot (c1 \cdot s2 + c2 \cdot s1) + a4 \cdot c3 \cdot c4 \cdot (c1 \cdot c2 - s1 \cdot s2) - a4 \cdot s3 \cdot s4 \cdot (c1 \cdot c2 - s1 \cdot s2) \)
- \( PY = d5 \cdot (c3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) + c4 \cdot s3 \cdot (c1 \cdot s2 + c2 \cdot s1)) - a5 \cdot c5 \cdot (s3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) - c3 \cdot c4 \cdot (c1 \cdot s2 + c2 \cdot s1)) + a3 \cdot c3 \cdot (c1 \cdot s2 + c2 \cdot s1) - a5 \cdot s5 \cdot (c1 \cdot c2 - s1 \cdot s2) + a4 \cdot c3 \cdot c4 \cdot (c1 \cdot s2 + c2 \cdot s1) - a4 \cdot s3 \cdot s4 \cdot (c1 \cdot s2 + c2 \cdot s1) \)
- \( PZ = d1 + d2 + a3 \cdot s3 - d5 \cdot (c3 \cdot c4 - s3 \cdot s4) + a4 \cdot c3 \cdot s4 + a4 \cdot c4 \cdot s3 + a5 \cdot c5 \cdot (c3 \cdot s4 + c4 \cdot s3) \)

Thus, the above set matrix is the generalised end effective transformation matrix for the prototype model and for a set of angles i.e. \( \theta \) and \( \alpha \), the position and of the end effector can be found out in relation to reference origin following the constrains of the design.

For example:

For the Test Case Arbitrary Values of \( \theta_1 = 56^\circ \), \( \theta_2 = 89^\circ \), \( \theta_3 = 35^\circ \), \( \theta_4 = 15^\circ \) and \( \theta_5 = 50^\circ \)

The Final Effective Matrix \( T_E \) obtained in MATLAB program was as follows:

\[
\begin{bmatrix}
0.1009 & -0.6275 & -0.7720 & 124.5513 \\
0.8645 & 0.4394 & -0.2441 & 115.8559 \\
0.4924 & -0.6428 & 0.5868 & 229.2426 \\
0.0000 & 0.0000 & 0.0000 & 1.0000
\end{bmatrix}
\]

The final end-effector position with the reference ground origin is:

- \( P_x = 125 \text{ mm} \)
- \( P_y = 116 \text{ mm} \)
- \( P_z = 229 \text{ mm Approximately} \)
5. Finite Element Analysis of Components

Structural analysis is studied to understand the effects of the application of loading on physical structures and their sub-components. Finite element analysis is one of the key elements in the fields of application of mechanics, materials science and even in mathematics to process the structure deformations, internal acting forces, induced stresses, support reactions, accelerations, and stability [17]. The results obtained from this analysis are often helpful in modifying as well as used to establish a structure's stability for appropriate use and hugely eliminating time and resources required to build a costly prototype and conduct physical testing. This study was performed to verify the structural soundness of the components before fabricating the 3D printed prototype model under one of the ideal conditions [18]. The condition chosen for this testing is the one where the servo motors so used exert their maximum capabilities. This is taken under consideration because for a given set of standard servos available in the market, the prototype should be able to withstand the max applied torque.

5.1. Meshing

Meshing is defined as the process of dividing the entire CAD model into a number of elements such that whenever the load is applied, the load is distributed uniformly. It is the process of discretization. The entire continuum is required to be discretized into a finite number of elements [19]. The meshing of component parts is shown in figure 7.

![Meshing of the component parts](image)

**Figure 7.** Meshing of the component parts.

5.2. Material

Assignment of Material Properties was done from the standard inbuilt material library. Polylactic acid was assigned as the material for analysis. The properties of Polylactic acid assigned is as shown in Table 2:

| S. No | Property                  | Value        | Unit     |
|-------|---------------------------|--------------|----------|
| 1     | Density                   | 1250         | kg m⁻³   |
| 2     | Coefficient of thermal expansion | 0.000135   | C⁻¹      |
| 3     | Young’s Modulus           | 3.45E+09     | Pa       |
| 4     | Poisson’s Ratio           | 0.39         | Pa       |
| 5     | Bulk Modulus              | 5.2273E+09   | Pa       |
| 6     | Shear Modulus             | 1.241E+09    | Pa       |
| 7     | Tensile Yield Strength    | 5.41E+07     | Pa       |
| 8     | Tensile Ultimate Strength | 5.92E+07     | Pa       |

Table 2. Properties of PLA in assigned in Ansys Workbench.
5.3. **Structural Analysis**

The loaded geometry of the prototype components was applied boundary and loading conditions. The direction and location of load input is defined and the component behaviour and material properties are assigned to be linearly elastic. The Total Deformation and Equivalent Stress on each of the components was determined and shown in figure 8 and figure 9 and it was found out that the total deformation for each of the components was within the acceptability and the design was considered suitable for being manufactured [20].

![Figure 8. Total Deformation of component parts.](image1)

![Figure 9. Equivalent Stress of component parts.](image2)

The results of the structural analysis have been tabulated below in the table 3.
Table 3. Results of Static Structural Analysis.

| S. No | Component Name     | Total Load Applied (N) | Total Deformation (mm) | Equivalent (Von-Mises) Stress (MPa) | Equivalent Elastic Strain (mm/mm) |
|-------|--------------------|------------------------|------------------------|-------------------------------------|-----------------------------------|
| 1     | Base               | 7.21                   | 1.6278e-004            | 2.3094e-002                         | 6.7423e-006                      |
| 2     | Waist              | 4                      | 9.7018e-004            | 0.10176                             | 2.9611e-005                      |
| 3     | Shoulder Arm       | 9.167                  | 0.17297                | 3.8659                              | 1.1206e-003                      |
| 4     | Elbow Arm          | 12.222                 | 4.9169e-002            | 2.8052                              | 8.1326e-004                      |
| 5     | Wrist Joint        | 8.928                  | 3.1466e-003            | 0.40555                             | 1.1759e-004                      |
| 6     | Gripper Base       | 5                      | 7.6195e-002            | 5.5534                              | 1.9672e-003                      |

6. Additive Manufacturing – 3D Printing
The prototype was 3D printed by converting the CAD files into stereolithography or STL file format. After this, it was 3D printed using PLA material of about a slice layer thickness of about 0.3mm. PLA or Polylactic Acid is a fully biodegradable thermoplastic that uses corn-starch as its special raw material. PLA is environment-friendly in nature and reduces greenhouse gas emission. Since the PLA is a thermoplastic, it can be easily recycled and makes it a desirable material. The total model was estimated to weigh around 270 gram and took around 15 hours to completely print out. It was made of 30% infill. Figure 10 shows the component parts being 3D printed while Figure 11 is the photographic view of components parts being completely 3D printed.

![Figure 10](image1.jpg)  [Figure 10. Photographic view of model printing - 3D printed.]

![Figure 11](image2.jpg)  [Figure 11. 3D printed components of Robotic Arm.]

7. Electronic Circuitry and Implementation
The workings of the prototype can be thought to be made up of 2 parts – sending or transmission and collecting or receptor side. The Arduino NANO microcontroller is placed the user’s glove and acts as the transmitting station [8]. This unit contains flex sensors for detecting actions of fingers, an accelerometer & gyroscope module for sensing positional movement of the hand and a Bluetooth chip to send the input signal from MCU [9]. The prototyped arm being the receiving station, receives the
signals which are then fed into the microcontroller which accordingly operates the servo motors as per required. Figure 12 illustrates the above discussion.

Figure 12. Schematic Representation of Involved Circuitry.

Arduino Nano. Arduino NANO is the microcontroller that is used in the transmitting side. The Arduino NANO has the advantage of being small and compact which enables it to be used and mounted on a glove [10]. The flex sensor, accelerometer module and Bluetooth transmitter are connected to it. Inertial Measurement Unit. MPU6050 is based on Micro-Mechanical Systems (MEMS) technology. This sensor has a 3-axis accelerometer, a 3-axis gyroscope, and an in-built temperature sensor. It can be used to measure parameters like Acceleration, Velocity, Orientation, Displacement, etc [11]. Flex Sensor. Flex Sensors are nothing but a variable resistor. The flex sensor resistance changes when the sensor is bent [12]. They are usually available in two sizes 2.2 inches and 4.5 inches. In this Gesture controlled Robotic Arm, gripper movement is manipulated by the state of the flex sensor. When the finger which has the flex sensor attached is bent, the servo motor connected to the gripper rotates and the gripper opens. Bluetooth Module. HC-05 module is chosen to work as the Bluetooth transmitter and receiver in the working model. Bluetooth modules can establish a master-slave configuration which results in accurate signal transmission in between them [13]. Arduino UNO. Arduino Uno is the microcontroller board that is attached to the prototype. It is larger compared to the Arduino NANO and hence is suitable for the purpose of controlling several servos used in controlling the arm [14]. It uses a USB cable to enable it to be programmed easily and also serves as the power source [15]. Servo Motors. The servo motors are used to move the assembly of parts in the prototype. The MG996R is the larger servo which delivers stall torque of about 11 kg/cm. The motor can rotate from 0 to 180 degree. The SG90 9g Mini Servo is smaller servo with 180° rotation. It is used in places where finer precise movement is needed.

Figure 13. Electronic Components Used.
8. Result
The model of the robotic arm system is developed which operates according to given hand gesture. It is a novel alternative to manipulate the robotic arm which makes easier to work, cheaper and intuitive. The RF module ensures it works suitable wireless range which makes the system mobile. This robot can be used to mimic and potentially learn the movements of the user using AI technology.

9. Conclusion
The research objectives were reached which involved developing and utilizing hardware and software for controlling the robotic arm based on Microelectromechanical systems (MEMS) sensors. By recording the observations, it was concluded that the movements of the robotic arm were accurate, easy to control, specific, and user-friendly. This method of controlling the arm is an intuitive way to overcome a number of problems such as picking or placing objects that are away from the users, pick and disposal of dangerous objects and hazards in a very fast, secure and convenient way, and to facilitate operating surgeries and other scientific procedures in medical application in the coming future.

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