A Novel Design of a Full Length Prosthetic Robotic Arm for the Disabled

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Abstract This paper shows the design methodology of a humanoid robotic arm with realistic mechanical structure and performance. Realistic and mechanically robust structure for a prosthetic arm was developed in Solid Works. The torque, power requirements and cost estimation were assessed systematically by interfacing the model with SimMechanics software. The robotic arm is equipped with several robot servo motors which perform as links between arms and perform arm movements by interfacing with a robot servo controller and the PIC16F886 microcontroller. The robot servo controller has the capability to drive the servo in controlled position, speed, and acceleration modes. Due to the complexity of the arm kinematics, machine-learning techniques, which rely less on precise mathematical analysis, are implemented. ANFIS is one such machine-learning technique which helps in decision-making and control of robotic arms. This paper implements a MATLAB-derived multilayered ANFIS controller using a PIC16F886 microcontroller as a supervisory control for a 6 DOF robotic arm. This type of robotic arm has many advantages such as simple structure, high flexibility, low energy consumption, quiet operation, and sensory feedback which make it a prosthetic arm with very high resemblance to a normal arm. A good tradeoff between cost and performance is achieved in order to meet the goal of less expensive and useful

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robotic arm for the disabled. The practically built arm is tested with predefined paths and random positional targets with in work space and results are shown to act satisfactorily.

Keywords Robotic arm · Prosthetics · ANFIS · Control system · Servo motor · Fuzzy logic · Clustering · SimMechanics

1 Introduction

Robots are generally used to perform unsafe, hazardous, highly repetitive, and unpleasant tasks. They have many different functions such as material handling, assembly, arc welding, resistance welding, and machine tool load and unload functions, painting, spraying, etc. There are mainly two different kinds of robots: a service robot and an industrial robot. A service robot is a robot that operates semi or fully autonomously to perform services useful to the well being of humans and equipment, excluding manufacturing operations [1, 2].

An industrial robot, on the other hand, is officially defined by ISO (International Standards Organization) as an automatically controlled and multipurpose manipulator programmable in three or more axes [3]. Industrial robots are designed to move material, parts, tools, or specialized devices through variable programmed motions to perform a variety of tasks. An industrial robot system includes not only industrial robots but also any devices or sensors required for the robot to perform its tasks as well as sequencing or monitoring communication interfaces. Robotic manipulators, especially of the SCARA type, have found wide range application from small-scale sectors to high-end industries. They also play a primary role in helping disabled people to do their work in daily life. They are often used in inaccessible places, space, and robotically assisted surgeries. Designing an arm which can mimic human motions with appropriate forces and torques is a challenging task since the design involves the consideration of a large number of conflicting parameters such as battery management, appropriate force, and torque estimation, avoiding singularities, cost, modeling, and control of arm while still maintaining an anthropomorphic nature.

With the increased use of industrial robotic arms, a logical evolutionary step is to imitate detailed human movements. A group of engineers developed an eight degree of freedom (DOF) robot arm, this robot is able to grasp many objects, ranging from a pen to a ball, simulating the hand of human being [4]. Another group of students in Korea made an innovative robotic arm that could perform dancing, weight lifting, writing Chinese calligraphy, and color classification [5]. In space, the Space Shuttle Remote Manipulator System, known as the SSRMS or Canadarm, and its successor, is example of multi-degree of freedom robot arms that have been used to perform a variety of tasks such as inspections of the space shuttle (using a specially deployed boom with cameras and sensors attached at the end effector) and satellite deployment and retrieval maneuvers from the cargo bay of the space shuttle [6].

Another group of people in Mexico has completed a competitive low-cost robot arm with 4 DOF-[7]. One of the most important problems in robot kinematics and control is finding the solution of inverse kinematics. Traditional solution methods such as geometric, iterative, and algebraic are inadequate if the joint structure of the manipulator is complex. Complexity of modeling and control of arm is proportional to the DOF of the manipulator. As the complexity of a robot increases, obtaining the inverse kinematics is difficult and computationally expensive. For a 6-DOF robotic arm, these methods become inaccurate because of increased complexity in mathematical modeling and computation management [8].

Soft computing techniques provide a beneficial approach in the modeling and control of such complex systems. Systems with less mathematical model knowledge could be controlled successfully with neural networks, and systems with incomplete knowledge could be modeled and controlled using Fuzzy systems. Artificial Neural Networks (ANN) have a limitation with complexity and in higher DOF robotic arms, lack of intuition makes fuzzy modeling tough. It is well known that a solution exists in adaptive neuro-fuzzy inference systems (ANFIS), where the learning ability of neural networks to assist the Fuzzy systems to represent the knowledge expressed in the form of linguistic rules [9–12].

It is possible to create an ANFIS control system with a limited mathematical representation of the system [13]. Computer simulations conducted on 2DOF and 3DOF robot manipulators show the effectiveness of the approach [14].

The paper focuses on the design of a low-weight robotic arm with 6-DOF which is to be mechanically stable, economically reliable, and should mimic the natural human arm movements. The humanoid robotic hand is also designed to be cost-effective. Many different approaches exist for minimizing the weight of a robot. These approaches are based on the use of

(1) High-performance actuators
(2) Composite material selection
(3) Efficient mechanical design
(4) Advanced control and sensing techniques

Our work aims at developing a framework to generate arm motions of a humanoid robot in two aspects of human likeness and minimal torque requirements. The robotic arm with 6-DOF delivers fast, accurate, and repeatable movements. It features base rotation, a shoulder, an elbow, wrist motion, wrist rotation, and a functional gripper. This paper also focuses on the application of ANFIS on robotic arms with higher DOFs and larger reachable sets, For a 6 DOF arm, it can reach to 40,000 data points with 1 cm resolution in end-effector positioning. The number of neural networks and the number of membership functions in each ANFIS controller need to be optimized in order to obtain satisfactory control performance and reduce computational cost. The cost estimation and power requirements were assessed systematically by interfacing the model with SimMechanics. This type of robotic arm has many advantages like low cost, simple structure, high flexibility, low energy consumption, quiet operation, and sensory feedback.

2 Mechanical Design

The following aspects of the humanoid robotic arm such as movement and material handling have been handled with respect to design, implementation, and development. Movements inculcated in the design replicate the actual human arm, wherein the cost and complexity of arm are kept under check. A complete mechanical design of a full length prosthetic hand was developed with marginally increased functionality. Table 1 shows the humanoid robotic arm specifications and the Fig. 1 shows the components of the mechanical design of the humanoid robotic arm.

Table 1 Humanoid robotic arm specifications

Design payload	300 g
Degrees of freedom	6
Arm mass	1200 g
Actuator type	Dc servo motor
Average current draw	10 A/h
Max reachable height	60 cm

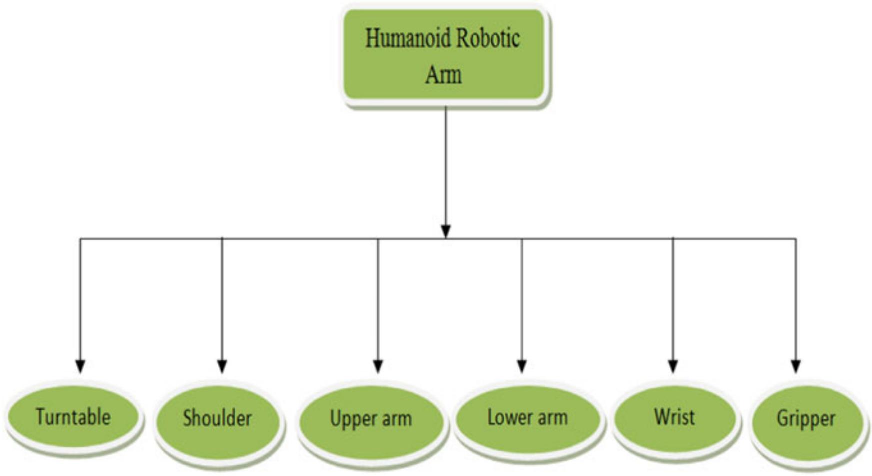

Fig. 1 Components of the mechanical design of the humanoid robotic arm

Table 2 Preliminary weight description

Component description	Weight (g)
First link	92
Second link	157
End effecter/payload	300
First motor assembly	185
Second motor assembly	205
Weight to payload ratio (moving parts only)	3.1:1

2.1 Design Selection-Humanoid Robotic Arm

Table 2 shows the preliminary weight description of the humanoid robotic arm. In choosing materials and the shape for the fabrication of the humanoid robotic arm, the following were taken into consideration:

(1) Weight of the robotic arm
(2) The mode of manufacturing
(3) The ease of manufacturing the parts
(4) Ease of assembly
(5) Cost
(6) Strength and durability of the parts

2.2 Material Selection

The appropriate materials considered for developing the model are plastic polymer, carbon fiber, and aluminum. Thus among them, Billet 6061 aluminum was selected based on the factors that include its work envelop, dimensional accuracy, workability, maintainability, machinability, high strength, lower cost, strength, thickness, weldability, good strength-to-weight ratio, and availability. Table 3 below shows the mechanical properties of Billet 6061 aluminum.

Table 3 Mechanical properties of Billet 6061 Aluminum

	Ultimate tensile strength (MPa)	0.2 % Proof stress (MPa)	Brinell hardness (500 kg load, 10 mm ball)	Elongation 50 mm diameter (%)
0	110–152	65–110	30–33	14–16
T1	180	95–96		16
T4	179 min	110 min		
T6	260–310	240–276	95–97	9–13

2.3 Force Analysis

Figure 2 shows the force diagram used for load calculations. The calculations were carried out only for the joints that have the largest loads, since the other joints would have the same motor, i.e., the motor can move the links without problems.

These force representation values are also used for torque calculations

W_d 0.065 kg (weight of link *DE*)
W_c 0.115 kg (weight of link *CD*)
W_b 0.126 kg (weight of link *CB*)
L 0.3 kg (payload)
C_m 0.045 kg; D_m 0.105 kg (weight of motor)
L_{BC} 0.26 m (length of link *BC*)
L_{CD} 0.22 m (length of link *CD*)
L_{DE} 0.088 m (length of link *DE*)

Calculating the sum of forces in the Y-axis using the loads is shown in Fig. 3 and solving for C_y and $C_{b,}$ is shown in the Eqs. (1)–(4).

$$\sum Fy = (L + W_d + D_m + W_c + C_m) * g - Cy = 0 \tag{1}$$

$$C_y = (0.630) * 9.8\,\mathrm{m/s^2} = 6.174\,\mathrm{N} \tag{2}$$

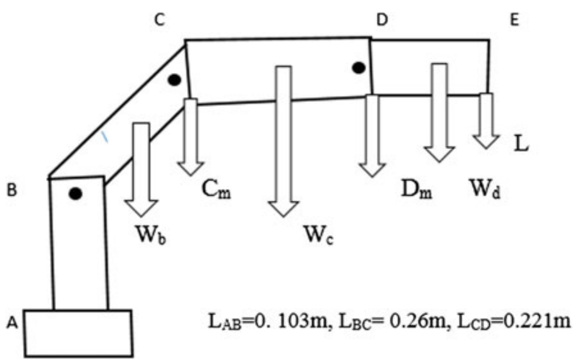

Fig. 2 Force representation of robotic arm

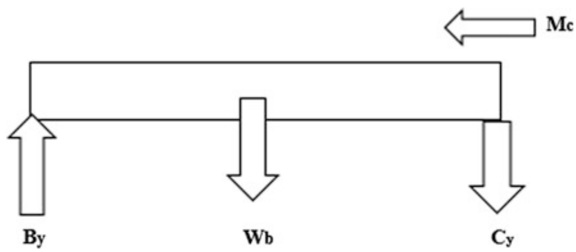

Fig. 3 Force diagram of link CB

$$\sum Fy = (L + W_d + D_m + W_c + C_m + W_b)*g - Cb = 0 \tag{3}$$

$$C_b = (0.756)*9.8\,\mathrm{m/s^2} = 7.408\,\mathrm{N} \tag{4}$$

Similarly, sum of moments around point C is obtained by Eq. (5), and point B is obtained by Eq. (6), torque at C and B is obtained by Eqs. (7) and (8).

$$\begin{aligned} \sum M_c = &- \left(\frac{W_c*L_{cd}}{2}\right) - W_d*\left(L_{cd} + \left(\frac{L_{de}}{2}\right)\right) \\ &- (L_{cd} + L_{de}) - D_m*(L_{cd}) + M_c = 0 \end{aligned} \tag{5}$$

$$\begin{aligned} \sum M_b = &- L(L_{bc} + L_{cd} + L_{de}) - W_d\left(L_{bc} + L_{cd} + \left(\frac{L_{de}}{2}\right)\right) \\ &- D_m*(L_{bc} + L_{cd}) - W_c*\left(L_{bc} + \left(\frac{L_{cd}}{2}\right)\right) - C_m*(L_{bc}) \\ &- W_b*(L_{bc}/2) + M_b = 0 \end{aligned} \tag{6}$$

$$M_c = 0.1397 \quad N - m \tag{7}$$

$$M_b = 0.2362 \quad N - m \tag{8}$$

From the above calculations, all these parameters are obtained for servo motor selection.

3 Solid Work Design-Humanoid Robotic Arm

The mechanical design of a humanoid robotic arm is based on a robotic manipulator which mimics the natural functions of a human arm. The links of such a robotic arm are connected by joints allowing rotational motion and those links are considered to form a kinematic chain. The other end of the kinematic chain of the manipulator is called the end effector and it is analogous to the human hand. Figure 4 shows the solid works layout of a humanoid robotic arm. As shown, the end effector is not included in the design because a commercially available gripper is used. This is because that the end effector of a robotic arm structure increases the degrees of freedom, which directly affects the complexity level of model and control of arm. It is much easier and economical to use a commercial one than to build it.

The humanoid robotic arm joints are actuated by electrical motors. Dynamixel servo motors were chosen, since they include positional feedback in real time to the motors and adjust the position according to the requirements. These servo motors were selected also based on the maximum torque required by the structure and the maximum allowable load that can be withstood by each joints of the designed

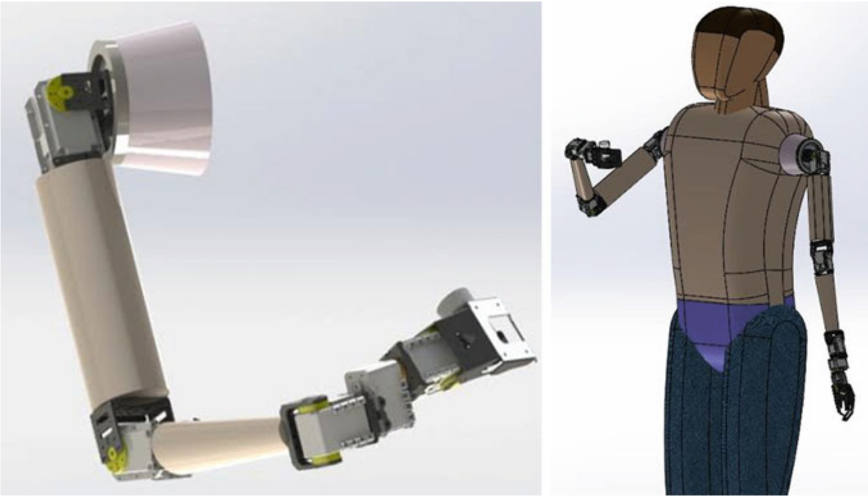

Fig. 4 Solid works layout of humanoid robotic arm

robotic arm. The mass properties of the designed solid works humanoid robotic arm are shown below.

Mass = 931.49 g
Volume = 768467.77 mm^3
Surface area = 331957.92 mm^2
Center of mass: (mm)
X = 338.97, Y = 210.63, Z = 853.52

Principal axes of inertia and principal moments of inertia (grams * square millimeters):

Taken at the center of mass

$$I_x = (0.23, 0.19, 0.95) \quad P_x = 1164786.73$$
$$I_y = (0.58, -0.81, -0.02) \quad P_y = 44982080.21$$
$$I_z = (0.78, 0.55, -.030) \quad P_z = 45345554.06$$

Moments of inertia: (grams * square millimeters)

Taken at the center of mass and aligned with the output coordinated system

$$L_{xx} = 42908809.21 \; L_{xy} = 1753414.06 \quad L_{xz} = 9657538.43$$
$$L_{yx} = 1753414.06 \; L_{yy} = 43503229.04 \quad L_{yz} = 8024069.70$$
$$L_{zx} = 9657538.43 \; L_{zy} = 8024069.70 \quad L_{zz} = 5080382.75$$

Moments of inertia: (grams * square millimeters)

Taken at the output coordinate system.

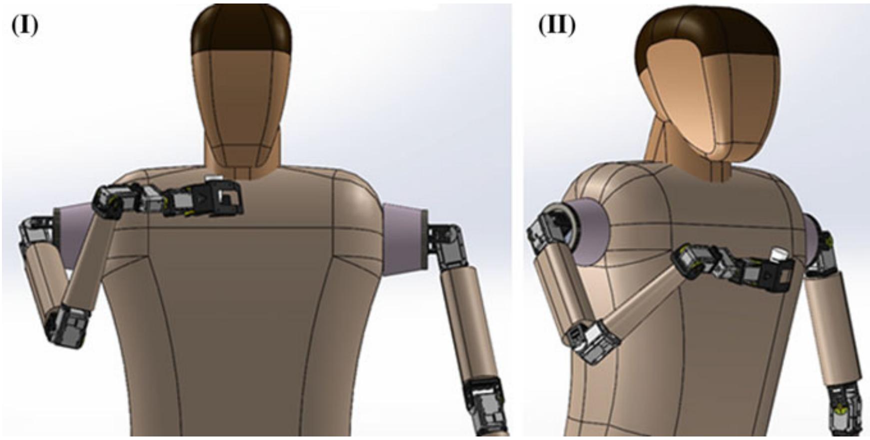

Fig. 5 Robotic arm 3D model 7(I) Front view 7(II) Side view

$$
\begin{aligned}
&I_{xx} = 762828393.57 \; I_{xy} = 68259101.39 \quad I_{xz} = 279154134.6\\
&I_{yx} = 68259101.39 \; I_{yy} = 829124865.68 \quad I_{yz} = 175485733.3\\
&I_{zx} = 279154134.68 \; I_{zy} = 175485733.3 \quad I_{zz} = 153433965.3
\end{aligned}
$$

Figure 4 shows the 3D model of the humanoid robotic arm. Figure 5(I), (II) show the front and side view of the robotic arm.

4 Design Challenges

Structural parameters like mobility, connectivity, and redundancy are to set up a mechanical structure which corresponds to a human arm, these parameters defines a number of actuators and the degrees of freedom required for the required movement of the platform. However this approach has disadvantages in adding more features.

The number of actuators implemented directly escalates the cost of the device and also reduces the stability due to weight. As the number of actuators increases, the time span of the process also increases. A large amount of humanoid arms have low quality and fewer than 6-DOF with a backlash and less payload. Thereby, it is seen that the robotic arm is affected by many parameters. We can say that the payload of an arm is the sum total effect of the axis and the workspace extensive care has to be undertaken in order to develop a humanoid robotic arm successfully.

Any humanoid robotic arm is devised with an aim of providing services to people in a selected work area. It is so designed that it has the size and dimensions of an average human arm while being as light as possible. This robotic arm should have 2DOF in a shoulder joint, 1DOF at an elbow joint and 3DOF at the wrist joint. The advantage of electrical motors is being environment friendly and noise less unlike usual hydraulic cylinders. The function of linear actuators is the same as that of the muscles operating with the principle of change of length.

5 SimMechanics

In order to capture the static and the dynamic properties of the humanoid robotic arm, both the mechanical properties of all its components, such as the moment of inertia, as well as its servos' dynamic responses, must be known to a certain degree of accuracy. These dynamic properties will be used in Simulink and SimMechanics in order to get an accurate simulator for the real humanoid robotic arm aiming at a good strategy. Figure 6 shows the modeling of robotic arm using SimMechanics.

Using the same design parameters which were implemented in solidworks, the model was built using SimMechanics software for force analysis. We have modeled this arm by considering gravity effect, constraints, and singularities. This figure represents the eating posture of a humanoid robotic arm. The designed arm should mimic the natural movements of a human arm. This eating posture of a humanoid robotic arm ensures the basic needs of a human arm. The torque required at each of the actuators of the modeled arm was simulated to analyze how much force is required to get this eating posture movement of the modeled arm.

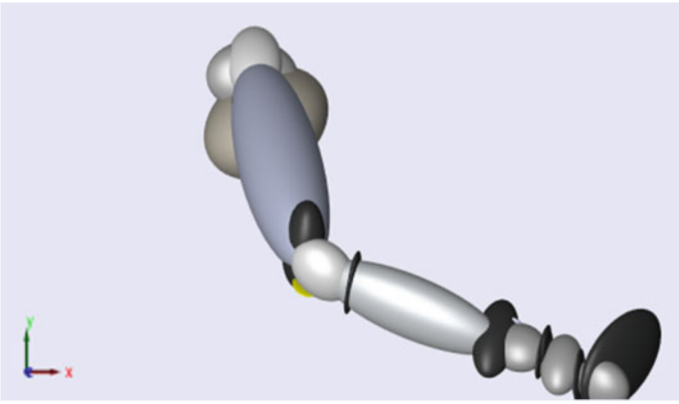

Fig. 6 Modeling of robotic arm using SimMechanics

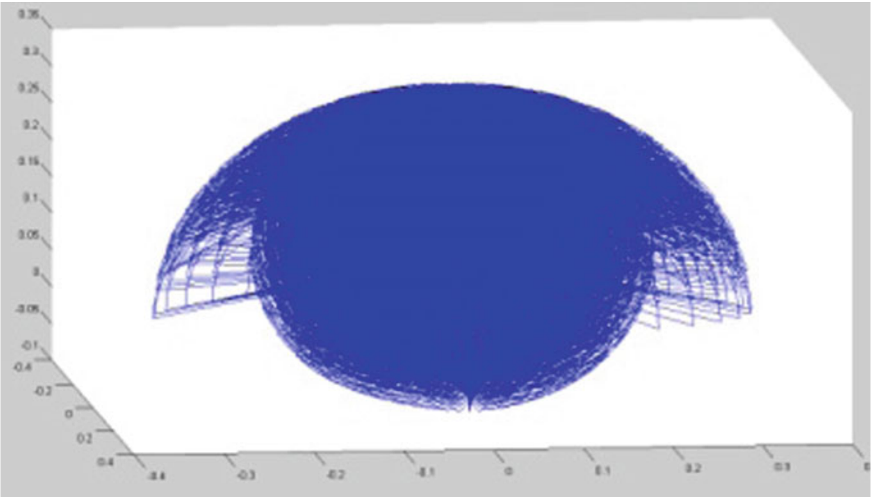

Fig. 7 Workspace region of the robotic arm

6 Data Generation

SimMechanics model developed based on the solid works layout of arm, includes the properties of mass, inertia, motor dynamics, etc. This model acts as a practical arm under gravity and generates dynamic data without any sensor interface. This model obtains data by behaving as real arm avoiding the link singularities and mimicking the practical motion of real human arm. A plot of 40,000 end-effector positions with 1 cm resolution is shown in Fig. 7. Obtained link angles and their corresponding end effector positions are used in training data to create ANFIS controller [9].

7 Control System-ANFIS in PIC16F886

ANFIS is a neural network with hybrid learning rules based on sugeno fuzzy interface system, which maps the input and output data. ANFIS architecture is developed to control each link of arm. Data obtained from SimMechanics model of arm is clustered to divide data into several statistical criteria. This procedure reduces the complexity on ANFIS training to find out the appropriate membership functions. Developed ANFIS in MATLAB is used for training the clustered data [9].

In order to make portable arm, the ANFIS network shown above has been programmed in microcontroller. This section explains the techniques and modifications followed in implementing MATLAB-generated ANFIS into an 8-bit microcontroller. To implement ANFIS in microcontroller, generated FIS is

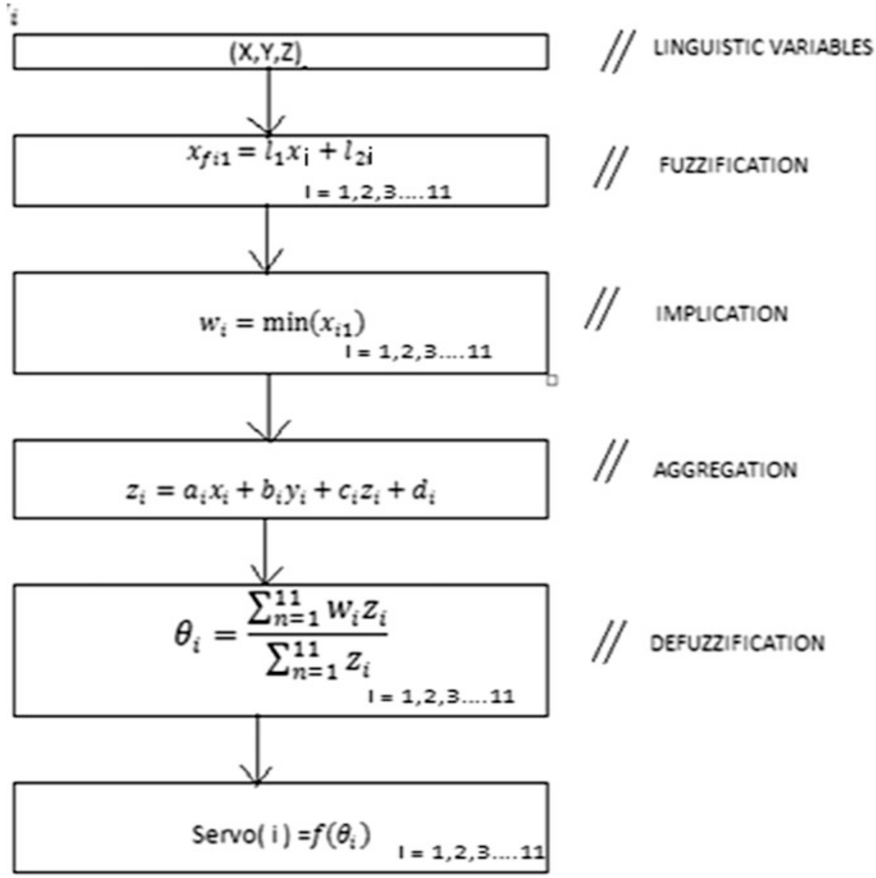

Fig. 8 MicroController implementation of ANFIS flow chart

modified to triangular membership functions [15–17]. Weights of rules can be obtained from the trained data obtained from the SimMechanics simulation. Output equations are de-fuzzified using Sugeno fuzzy inference method and finally the output angles are obtained using the weighted average method [13]. The flow chart for microcontroller implementation of ANFIS is shown in Fig. 8.

8 Simulations and Results

8.1 Simulink Simulation

The glass to mouth posture of a robotic arm has its own features in terms of distances in 3D space environment such as delta X, delta Y, and delta Z,

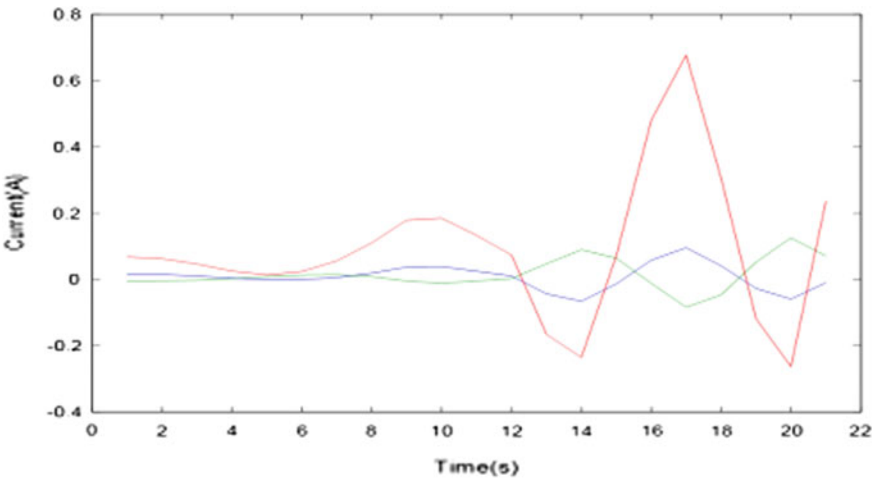

Fig. 9 Current versus time plot obtained at shoulder actuator

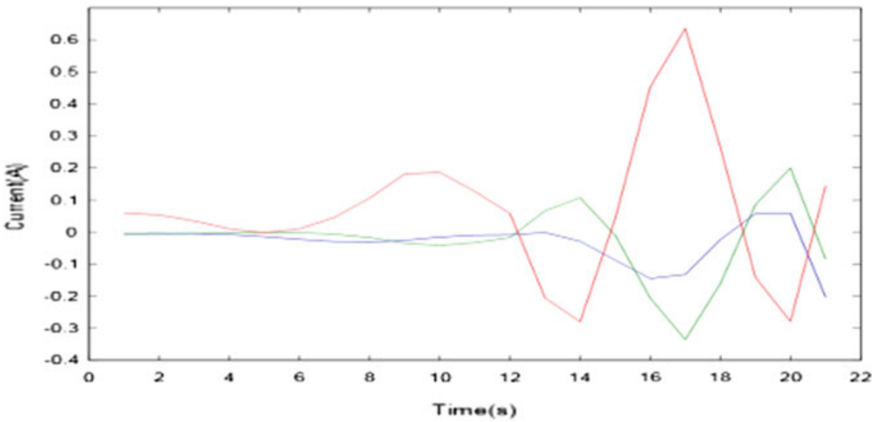

Fig. 10 Current versus time plot obtained at elbow actuator

correspondingly. With Simulink as an interface, the corresponding current vs. time plots were obtained and the power consumption of the arm can be found through these plots. The below-mentioned graphs from Figs. 9, 10, 11 and 12 are the current versus time plots obtained corresponding to the torque sensed by each of the actuators of a robotic arm.

Shoulder Actuator
From shoulder motor to base rotation length
Distance: 10.35 cm
Delta X: 4.76 cm, Delta Y: 8.61 cm, Delta Z: 3.19 cm
Total Length: 36.43 cm

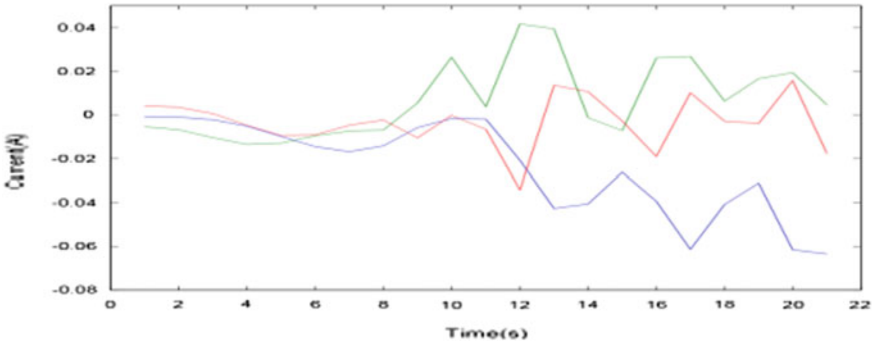

Fig. 11 Current versus time plot obtained at wrist-up actuator

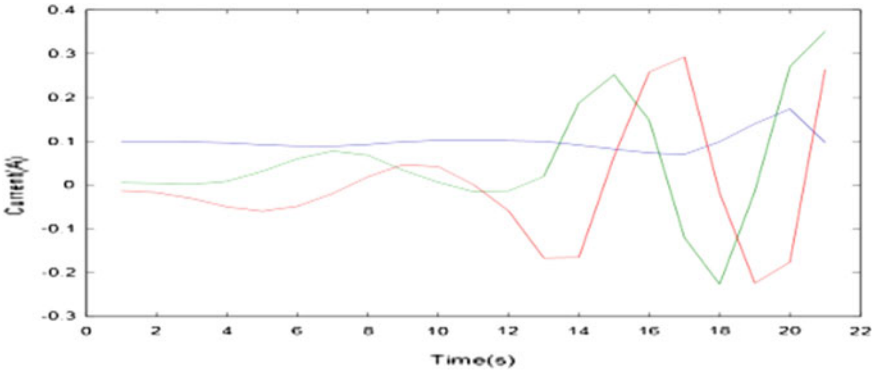

Fig. 12 Current versus time plot obtained at Gripper actuator

Elbow Actuator
From wrist to elbow length
Arc/Circle Measurements Distance: 22.51 cm
Delta *X*: 5.48 cm, Delta *Y*: 2.32 cm, Delta *Z*: 21.7 cm

Wrist-up Actuator
From gripper to wrist length
Arc/Circle Measurements Distance: 12.49 cm Delta *X*: 0.709 cm Delta *Y*: 1.171 cm Delta *Z*: 1.418 cm

Gripper Actuator
Distance: 8.80 cm
Delta *X*: 3.75 cm Delta *Y*: 0.56 cm Delta *Z*: 7.94 cm

8.2 Energy Requirement Durability

With any battery-operated device, energy use is very important. Table 4 shows the power consumption of humanoid robotic arm.

From this power usage table, the total current required for the sample movements posture of a humanoid robotic arm is 9.738 A. While more testing will be instructive, a reasonable estimate is that typical household and office tasks will lead to an average current of 10 Amperes. Therefore, six continuous hours of arm use would consume 12 Ah. This should be acceptable for most users, and daytime charging can help restore range. Overall cost analysis and estimation has been done as show in Table 5.

Table 4 Power consumption

S no	Type of actuator	Maximum current (Ampere)	Total current for each actuator (Ampere)
1	Gripper	0.351	2.0871
2	Wrist rotation	0.1034	0.6067
3	Wrist up	0.0417	0.5019
4	Elbow	0.6374	3.3187
5	Shoulder-A	0.677	1.9641
6	Shoulder-B	0.6	1.2629

Table 5 Cost estimation

S. no	Description	Quantity	Unit cost	Total cost
1	Big gripper (Ax-12 a)	1	9242.34	9242.34
2	Wrist servo motor (Ax-12 a)	2	2807.87	5615.74
3	Elbow servo motor (Mx-6 4 T)	1	13640.21	13640.21
4	Shoulder servo motor (Mx106 T)	1	30076.04	30076.04
5	Turntable (Mx-106 T)	1	38302.96	38302.96
6	FR05-H101k (bracket)	1	1823.9 5	1823.95
7	FR08-H101k brackets	1	1817.17	1817.17
8	Wiring extensions(24 in., 3 pinwire)	1	609.75	609.75
9	Power supply (12 V, 10 amps)	1	1212.46	1212.46
10	Miscellaneous		10000	10000
		Total cost		112340.62

9 Conclusion and Future Works

To sum up, design methodology and implementation of a humanoid robotic arm of 6 DOF with realistic mechanical structure and performance have been obtained. Modeled an arm in solid works based on requirements and corresponding mechanical analysis is done in SimMechanics to obtain the stability. Data required for ANFIS training is obtained by giving all the possible theta to modeled arm kinematics. Practical implementation of moving the robot to the desired position is done using trained ANFIS simulations. A simpler and more attractive way to turn the hand prosthesis into a product is to release it as a mechanical testing and research platform for universities. This type of robotic arm has many advantages such as simple structure, high flexibility, low energy consumption, quiet operation, and sensory feedback which make it a prosthetic arm with very high resemblance to a normal arm. As future works, the following has been taken into consideration.

- The designed robotic arm should be manufactured using 3D printer.
- Remodeling the design by adding 1dof between the shoulder and elbow which is analogous to the human arm.
- Show the device to prosthetics and amputees and get their feedback on the current system.
- Redesign mechanical packaging to further reduce the size and weight of the system
- Orientation-based control algorithms can be developed.

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