

Conceptual Design and Kinematic Analysis of Humanoid Robot

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Abstract

The humanoid robots are necessarily to be developed because of its ability to perform variety of tasks in flexible environment. This paper presents the conceptual design, kinematic analysis and development of voice control system of the proposed 14 Degree of Freedom (DOF) humanoid robot (AKSHAR). The forward kinematics of the humanoid arm is done by (DH) method. Generally, the inverse kinematics of humanoid robot is mostly non-linear and difficult to solve. To overcome this issue, the elbow and wrist are considered as coupled link because of their relative motion which leads to solve the problem with less complexity. A comparative study is carried out between geometry and Adaptive Neuro-Fuzzy Inference system (ANFIS) methods to find a suitable approach to solve inverse kinematics of the robot. Further, in order to improve the humanoid design, the voice control system using Bluetooth is developed to interact with human. The main focus of the research is to carry out accurate solutions for inverse kinematics by using an advance approach so that the results data will be implemented and trained to the robot to grasp the object successively. Based on the inverse kinematics solutions, the developed ANFIS solution using MATLAB shows better results than geometry method. The developed voice controlled system found to be satisfactory with the given inputs.

Keywords: ANFIS, DH Parameters, Forward Kinematics, Humanoid Robot, Inverse Kinematics, Voice Controlled System

1. Introduction

The robotics technology has various applications in many domains like telesurgery, manufacturing automation, UAV, underwater robots, humanoid robots etc. The research of the humanoid robot started in nearly¹. Many humanoid robots were designed and fabricated for research purpose like ASIMO by HONDA², ARMAR 4 in 2013 by Karlsruhe Institute of Technology³, HADALY2⁴ and HRP II⁵. Now a days, very high intelligence based humanoid robots are developing that can behave like human⁶. Based on the above survey, it is found that the design, analysis, and simulation of humanoid robot are very difficult. Generally the analysis is divided into two parts; kinematic analysis and dynamic analysis. The kinematic analysis is related to displacement and derivative equations with respect to velocity and acceleration⁷ but without considering the forces⁸. The kinematics results and its behaviour are used to describe the motion of the robot, to generate dynamic, and its control

equations. There are so many humanoid robots which have higher DOF like ALBERT HUBO with 66 DOF⁹, and KHR II with 41 DOF¹⁰. Generally, the forward kinematics is used to compute the position and orientation of the arm of the robot for specific set of joints variables. The inverse kinematics is more complex than the forward kinematics because of its non-linearity and it may have multiple solutions¹¹. The inverse kinematics helps to determine joints variables from wrist orientation and position. The advance approaches are taken for inverse kinematics like fuzzy logic based approach, Neuro controller learning approach¹² and ANFIS¹³. These approaches reduce the non-convexity, and simplify with effective solution to overcome redundancy¹⁴. The ANFIS approach is having good result and less error compare to only fuzzy logic approach¹⁵. There are several methods to control the entire humanoid robot. HUBO robot and KHR-II are controlled using Wireless LAN and CAN (Controller Area Network). Now days, HMI

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(Human Machine Interface) technology is implemented in machines for increasing productivity, better interaction without any physical touch¹⁶. In this research, a 14 DOF humanoid robot conceptual design is developed. The DH matrix is applied for the numeric calculation for getting final transformation matrix. This final matrix with varying joints variables are taken for MATLAB for solving forward kinematics. Similarly, the geometry method is implemented for inverse kinematic analysis and its results are obtained through MATLAB. The ANFIS is used to verify the geometry method and to compute the error. The solution employed by ANFIS is verified with actual values. In order to achieve HMI (Human Machine Interface), voice controlled commands via Bluetooth Module (HC-05) is implemented. This paper is organized as follows; the section II describes the architecture of the AKSHAR and robot arm with motion of joints, DOF and joints position in body. In section III, the DH convention and the frame assignments for joints are detailed. The kinematic equations and matrices are derived in section IV and its solution using MATLAB is carried out in section V. The voice control system for the robot is detailed in section VI. Similarly sections VII explain the results and finally we concluded with few remarks of the developed humanoid robot.

2. Architecture of Akshar

The proposed humanoid robot has totally 6 DOF in arms and 4 DOF in legs. The torso joint 7 is configured such a way that whole body of the robot moves turn around and such mechanism leads to reduce DOF and also cost. Hence, the robot has 14 DOF as mentioned in the Table 1.

Figure 1 shows the conceptual design of the proposed humanoid with joints and links configuration.

2.1 Architecture of Humanoid Arm

Figure 2 shows the various joints, rotational directions with link length for right arm. The arm model has the

Table 1. DOFs of robot

	DOF
Head	1
Arm	6
Hand	2
Leg	4
Body	1
Total	14

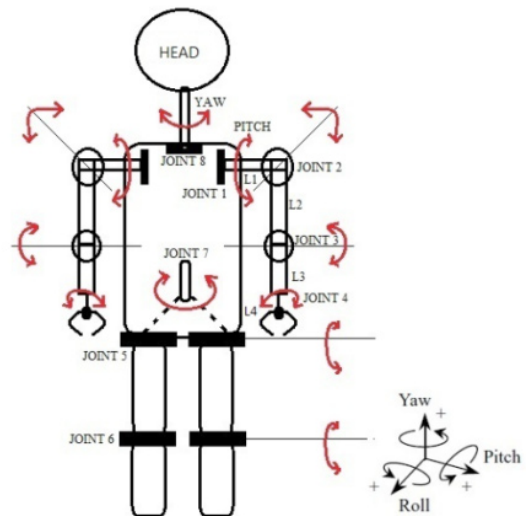


Figure 1. Joints and Links configuration of AKSHAR.

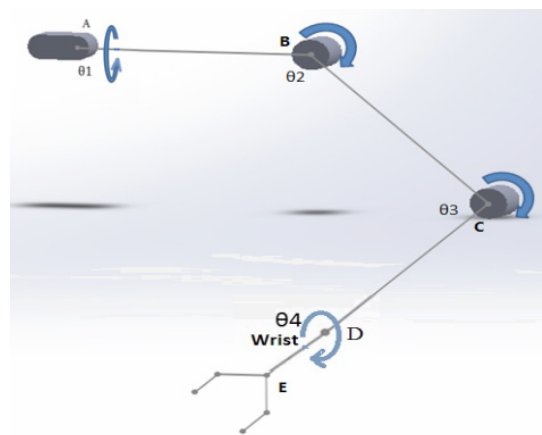


Figure 2. Schematic representation of Right arm.

following joints notation Twisting – Revolute –Revolute – Twisting (TRR: R).

3. Kinematics

3.1 DH Representation

In introduced a method to represent the joints and links parameters¹⁷. The parameters are known as DH parameter and can be represented by DH matrix or Homogeneous transformation of two jointed links as given.

$${}^{i-1}T_i = \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & a_i \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Here the C= cosine (□) and S= sine (□). The matrix represents for homogeneous transformation of frame (i) to (i-1).

3.2 Kinematic Model of the Arm

The frame representation is most important to get the position and orientation of the wrist. The kinematic model of the robot arm and the frames that are assigned for DH convention are expressed in Figure 3. The frame structure represents the link length ($L_i, i=0$ to 4) and joint rotation ($\theta_i, i=0$ to 4).

Table 2 shows the DH parameters which are calculated according to the arm rotation and position of the axes. The rotational limits for the robot arm joints are mention under the variable range.

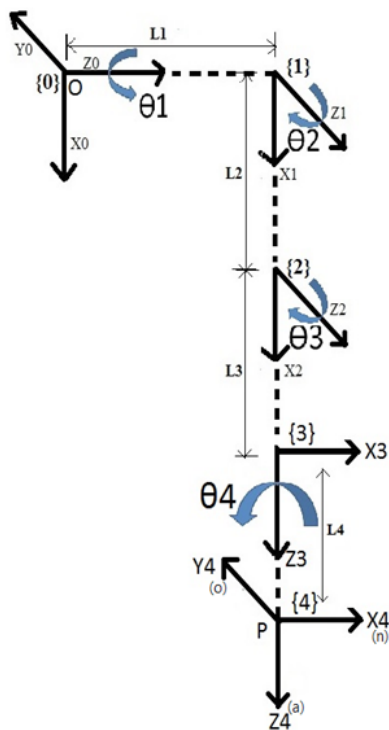


Figure 3. Frames assignment for right arm.

Table 2. The DH Parameters

Link (i)	Frames	a_i	α_i	d_i	θ_i	Variables Range in °
1	{0}-{1}	0	-90	L_1	θ_1	- 90~ 90
2	{1}-{2}	L_2	0	0	θ_2	90~0
3	{2}-{3}	L_3	-90	0	θ_3-90	- 45~45
4	{3}-{4}	0	0	L_4	θ_4	- 90~0

4. Computation of Kinematic Arm Model

The mathematical approach for kinematic equations are considered as standard DH method which is based on numbering system of frames and its parameters. The kinematic solution of the humanoid arm divides in two parts; forward kinematics and inverse kinematics.

4.1 Forward Kinematics

The forward kinematics is useful to determine the final position or orientation of the humanoid wrist. The angle of rotation of the links are required, based on that, the final position of end effector is determined. The total transformation of the robot arm is calculated as per the Equation 1,

$${}^0T_4 = {}^0T_1 {}^1T_2 {}^2T_3 {}^3T_4 \tag{1}$$

The transformation matrix of the humanoid robot arm is detailed as per DH convention. The individual transformation matrices are expressed as follows,

$${}^0T_1 = \begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^1T_2 = \begin{bmatrix} C_2 & -S_2 & 0 & L_2 C_2 \\ S_2 & C_2 & 0 & L_2 S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^2T_3 = \begin{bmatrix} S_3 & 0 & C_3 & L_3 S_3 \\ -C_3 & 0 & S_3 & -L_3 C_3 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^3T_4 = \begin{bmatrix} C_4 & -S_4 & 0 & 0 \\ S_4 & C_4 & 0 & 0 \\ 0 & 0 & 1 & L_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

By applying the above matrices in the Equation 1, the final transformation matrix is obtained and shown in Equation 2,

$${}^0T_4 = \begin{bmatrix} n_x & o_x & a_x & d_x \\ n_y & o_y & a_y & d_y \\ n_z & o_z & a_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Where,

$$n_x = s_1 s_4 + c_4 [c_1 c_2 s_3 + c_1 c_3 s_2]$$

$$n_y = c_4 [c_2 s_1 s_3 + c_3 s_1 s_2] - c_1 s_4$$

$$n_z = c_4 [c_2 c_3 - s_2 s_3]$$

$$o_x = c_4 s_1 - s_4 [c_1 c_2 s_3 + c_1 c_3 s_2]$$

$$\begin{aligned}
 o_y &= -c_1 c_4 - s_4 [c_2 s_1 s_3 + c_3 s_1 s_2] \\
 o_z &= -s_4 [c_2 c_3 - s_2 s_3] \\
 a_x &= c_1 c_2 c_3 - c_1 s_2 s_3 \\
 a_y &= c_2 c_3 s_1 - s_1 s_2 s_3 \\
 a_z &= -c_2 s_3 - c_3 s_2 \\
 d_x &= L_2 c_1 c_2 - L_4 [c_1 s_2 s_3 - c_1 c_2 c_3] + L_3 c_1 c_2 s_3 + L_3 c_1 c_3 s_2 \\
 d_y &= L_2 c_2 s_1 - L_4 [s_1 s_2 s_3 - c_2 c_3 s_1] + L_3 c_2 s_1 s_3 + L_3 c_3 s_1 s_2 \\
 d_z &= L_1 - L_4 [c_2 s_3 + c_3 s_2] - L_2 s_2 + L_3 c_2 c_3 - L_3 s_2 s_3
 \end{aligned}$$

Here c_1 and s_1 stands for $\cos(\theta_1)$ and $\sin(\theta_1)$ respectively.

4.2 Inverse Kinematics

The inverse kinematics is used to determine the joints parameters¹⁸. The joint angle (rotation angle) can be found out if the postion and orientation matrix is available however the inverse kinematics is much difficult compare to direct kinematics. Kinematic decoupling is a major problem for separation of orientation and position¹⁹. To solve that issue, the L_3 and L_4 are considered as coupled link because there is only twisting motion (θ_4) between them and that does not create any offset coordinate frames. In order to solve the kinematic equation easier, we assumed that the shoulder joint is fixed at initial condition ie $\theta_1=0$.

4.2.1 Geometry Method

Figure 4 represents the arm geometry of the humanoid robot with 2 DOF, the inverse kinematic analysis is carried out by geometry transformation.

The following inverse kinematic solutions are obtained from trigonometry relations,

$$C_3 = \frac{N_x^2 + N_y^2 - L_2^2 - L_3^2}{2L_2 L_3} \tag{3}$$

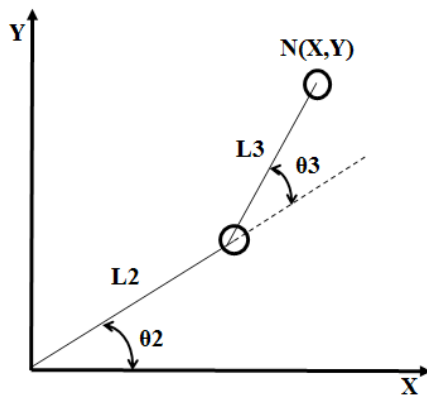


Figure 4. Inverse kinematic model of the humanoid arm.

$$S_3 = \sqrt{(1 - C_3^2)} \tag{4}$$

$$C_2 = \frac{N_x (L_2 + L_3 C_3) + [(N_y) L_3 S_3]}{N_x^2 + N_y^2} \tag{5}$$

$$S_2 = \sqrt{(1 - C_2^2)} \tag{6}$$

The values of θ_1 and θ_2 can be obtained by the above equations,

$$\theta_2 = \text{Atan2}(S_2, C_2) \tag{7}$$

$$\theta_3 = \text{Atan2}(S_3, C_3) \tag{8}$$

4.2.2 ANFIS

ANFIS is introduced to reduce the error in any system and to increase the performance index²⁰. ANFIS is a effective method which combines neuro and fuzzy approach²¹. The ANFIS solution is based on hybrid learning algorithm. In this work, Sugeno type system is used to train the kinematics data. To train the system, the X and Y coordinates are taken as input data. The ANFIS is trained with 5 membership function and 200 epochs for θ_2 and 180 epochs for θ_3 to obtain better results. MATLAB is used to solve the inverse kinematics solution of ANFIS.

5. Simulation

The mathematical simulation of the arm kinematic analysis is done in MATLAB. The particular joints variables are taken in account from Table 2 for the simulation.

5.1 Forward Kinematics Solution for Home Position

From the variable range in Table 2, considering that the home posion of the right arm is $[\theta_i]=[0^\circ 45^\circ 0^\circ 45^\circ]$, where $i=0$ to 4. Hence applying these values as input of angles and other values from DH parameters in Equation 2, the forward kinematic solution is obtained and is shown in Table 3. From the transformation result mentioned in Table 3, the (n, o, a) matrix refers to the orientation of the end effector and vector (d) refers to the position of wrist for the home position.

5.2 Forward Kinematics Solutions for Multiple Positions of Arm

For obtaining forward kinematic solutions, L_3 and L_4 are considered as coupled link. Hence L_3 is assumed to be 250

mm and $\theta_1=0^\circ$, the different solutions for θ_2 and θ_3 is obtained through MATLAB program. From the simulation, 256 different values of X-Y coordinates for all the possible values of θ_2 and θ_3 are obtained as shown in Figure 5.

5.3 Inverse Kinematics

5.3.1 Geometry Method

The inverse kinematic simulation for finding θ_2 and θ_3 values are computed by considering X coordinates range from 176.4 to 449.9 and Y coordinates range from - 449.9 to 135. These coordinates' values are taken from the forward kinematics simulation. These values are implemented in Equations 3 to 8 to obtain the inverse kinematic solutions by Geometry method. The results are shown in Figure 6.

5.3.2 ANFIS Solution

The ANFIS solution is done by MATLAB for inverse kinematics. Figure 7 describes the difference between geometry method and ANFIS solution.

Table 3. Home Position for Arm

n	o	a	d
0.5	-0.5	0.7071	318.1981
-0.7071	-0.7071	0	0
0.5	-0.5	-0.7071	144.6447
0	0	0	1

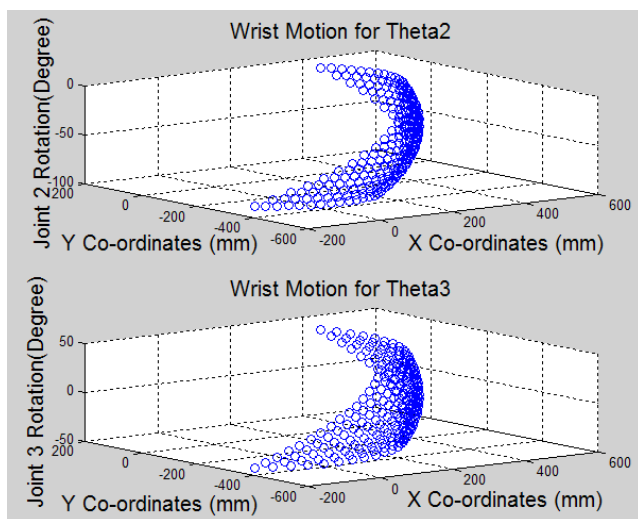


Figure 5. Multiple positions of the arm using forward kinematics.

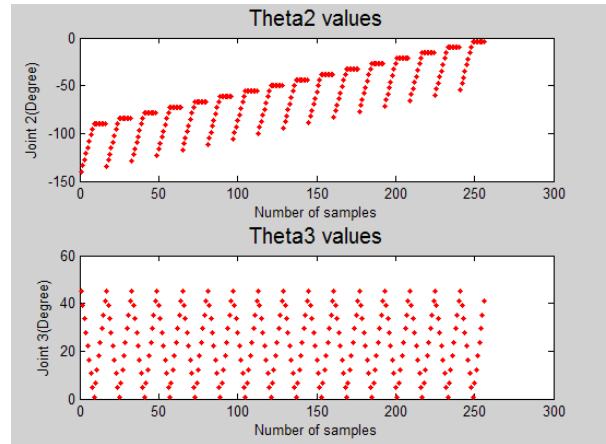


Figure 6. Inverse kinematic solutions by geometry method.

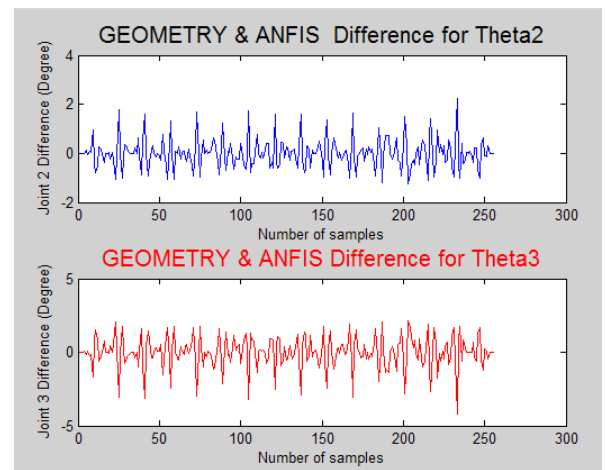


Figure 7. Difference between ANFIS and Geometry result.

6. Voice Control System for Akshar

Figure 8 describes the flowchart of an entire voice control system for the humanoid robot. In the proposed voice control system, the off line switch should be set 'on' when the human wants to interact with the robot. The HMI using Bluetooth module (HC-05) is activated when PIR (Passive Infrared Sensor) detects human inside the room. The Bluetooth module is connected with Arduino Uno which enabled with ATmega328 microcontroller to communicate with android app (ARM_VOICE). The ARM_VOICE application in android phone is help to convert the voice command to text. Figure 9 shows the hardware implementation of Voice control system.

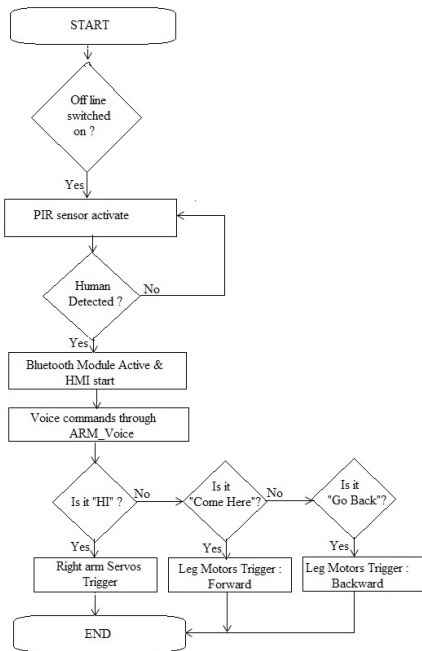


Figure 8. Flowchart of control system.

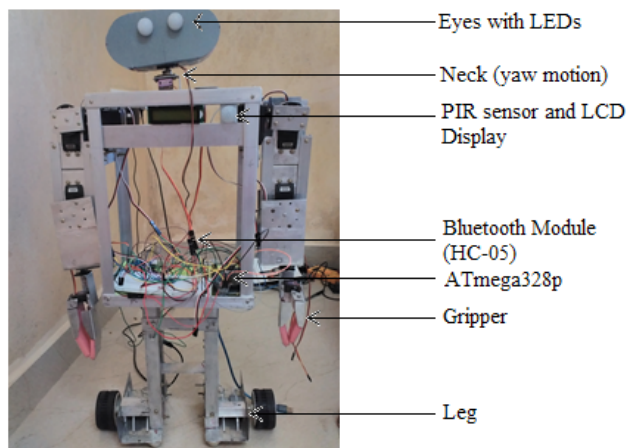


Figure 9. Voice Control System Test.

7. Results and Discussion

The 14 DOF voice controlled humanoid robot is developed and the kinematic analyses were carried out for the TRR: T humanoid arm and the results are discussed as follows,

7.1 Comparison of Forward and Geometry Method

The humanoid arm joints angles (θ_2 and θ_3) are given as input values to the forward kinematics which are considered as actual values. Figure 10 indicates the variation in actual and the geometry method theta values.

Based on the MATLAB solution, the average differences of each 256 values of θ_2 and θ_3 values between the forward kinematic (actual) and geometry solutions for the given joint angles are found to be 13.09° for θ_2 and 24.96° for θ_3 . Similarly, from the results it is found that out of 256 input values 128 exact solutions are obtained with respect to the actual values, remaining 128 solutions are having the minimum and maximum deviation of $7.6 e^{-13^\circ}$ and 50.28° than the actual values of θ_2 . Similarly, the minimum and maximum deviation of θ_3 is found to be $1.36e^{-12^\circ}$ and 90° than the actual values.

7.2 Comparison of Forward and ANFIS Method

The Figure 11 shows the difference between actual joints values and ANFIS predicted joints values. Based on the

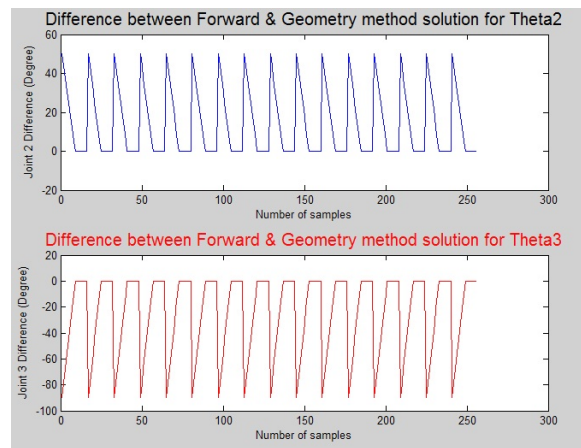


Figure 10. Comparison of Actual and Geometry method solution.

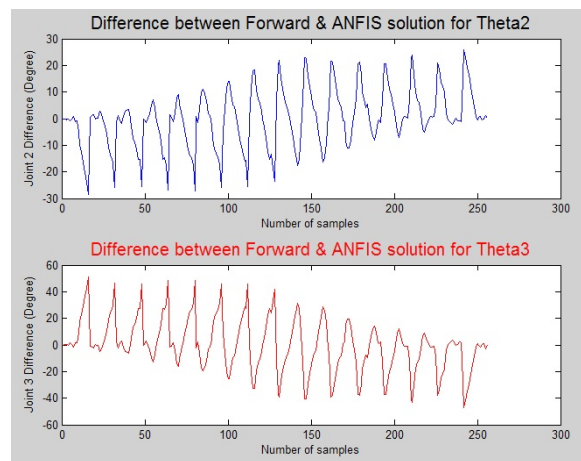


Figure 11. Comparison of Actual and ANFIS solution

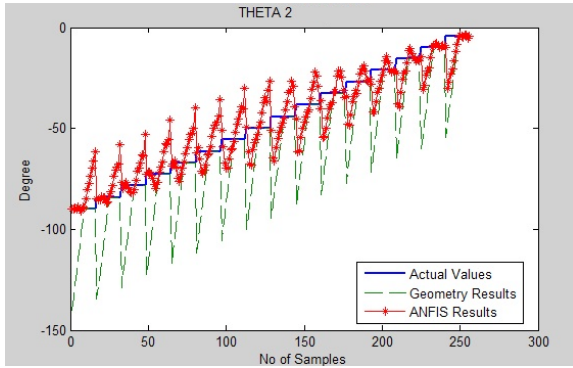


Figure 12. Comparison of DH, Geometry, ANFIS methods solution for θ_2 .

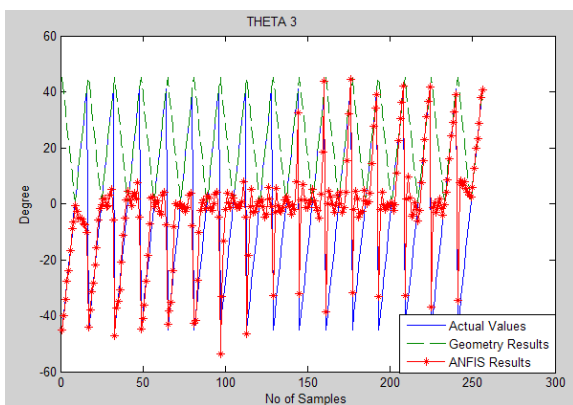


Figure 13. Comparison of DH, Geometry, ANFIS methods solution for θ_3 .

numerical simulation results, the average difference between forward kinematic solutions and ANFIS predicted values of θ_2 and θ_3 are found to be $2.657e-05^\circ$ and $7.114e-05^\circ$ which is very less and found to be negligible. From the results, it is also found that θ_2 having the minimum and maximum deviation of 0.0369° to 28.58° than the actual values of θ_2 . Similarly, the minimum and maximum deviation of θ_3 is found to be 0.023° and 51.28° than the actual values.

Figure 12 and Figure 13 shows the comparative results of DH convention, geometry and ANFIS methods for θ_2 and θ_3 . From the graph, it is found that out of 256 input values 256 approximate closure solutions are obtained by ANFIS with respect to the actual values.

8. Conclusion

The conceptual design of 14 DOF humanoid robot with voice control system is developed. A comparative kinematic

analysis of the robot arm is carried out by considering DH convention, geometry and ANFIS methods. Based on the conceptual design and kinematic analyses of the AKSHAR the following points are concluded,

- 256 forward kinematic solutions were obtained by DH transformation and 256 inverse kinematics solutions were obtained through geometry and ANFIS methods.
- From the MATLAB solution, the maximum difference between DH convention and geometry solutions for the given joint angles are found to be 50.28° for θ_2 and 90° for θ_3 . Similarly, the maximum difference between forward kinematic solutions and ANFIS predicted values are found to be 28.58° for θ_2 and 51.28° for θ_3 which is found to be negligible.
- Based on the comparative study on inverse kinematic analysis, it is found that the ANFIS predicted 43 % better than the geometry method for the actual values of θ_2 and θ_3 after trained with 5 membership function and 200 epochs for θ_2 and 180 epochs for θ_3 .
- The voice control system is developed and tested successfully with few servo motors and PIR sensor. Based on the experiments conducted, the control system can be further employed to the entire actions of humanoid robot.
- The future work of this research will be dynamic analysis to generate biped walking pattern for the humanoid robot. The implementation of IoT (Internet of Things) for controlling the AKSHAR robot.

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