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# 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 nearly[1]. Many humanoid robots were designed and fabricated for research purpose like ASIMO by HONDA[2], ARMAR 4 in 2013 by Karlsruhe Institute of Technology[3], HADALY2[4] and HRP II[5]. Now a days, very high intelligence based humanoid robots are developing that can behave like human[6]. 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 acceleration[7] but without considering the forces[8]. 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 DOF[9], and KHR II with 41 DOF[10]. 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 solutions[11]. 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 approach[12] and ANFIS[13]. These approaches reduce the non-convexity, and simplify with effective solution to overcome redundancy[14]. The ANFIS approach is having good result and less error compare to only fuzzy logic approach[15]. 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 touch[16]. 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 following joints notation Twisting – Revolute –Revolute - Twisting (TRR: R).

**Table 1.** DOFs of robot

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

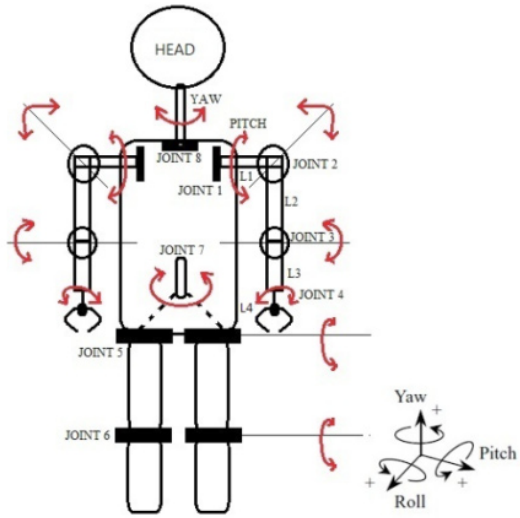


**Figure 1.** Joints and Links configuration of AKSHAR.

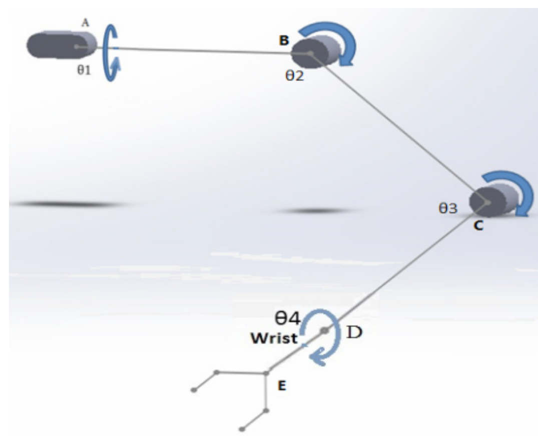


**Figure 2.** Schematic representation of Right arm.

## 3. Kinematics

### 3.1 DH Representation

In introduced a method to represent the joints and links parameters[17]. The parameters are known as DH parameter and can be represented by DH matrix or Homogeneous transformation of two jointed links as given.

i-1T_i = [■( 〖Cθ〗_↓i &– 〖Sθ〗_↓i 〖Cθ〗_↓i
〖Sθ〗_↓i 〖Sα〗_↓i&a_↓i 〖Cθ〗_↓i@Sθi& 〖Cθ〗_↓i 〖Cα〗_↓i
〖 – Cθ〗_↓i 〖Sα〗_↓i &a_↓i 〖Sθ〗_↓i@0& 〖Sα〗_↓i
〖Cα〗_↓i &d_↓i@0& 0

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.

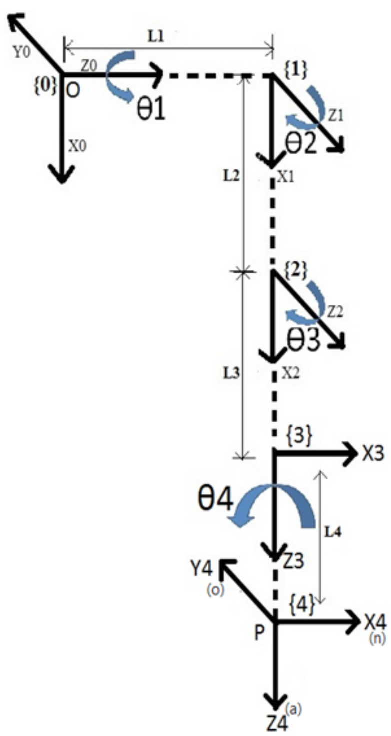


**Figure 3.** Frames assignment for right arm.

**Table 2.** The DH Parameters

| Link (i) | Frames | $a_i$ | $\alpha_i$ | $d_i$ | $\theta_i$ | Variables Range in ° |
|---|---|---|---|---|---|---|
| 1 | {0}-{1} | 0 | -90 | $L_1$ | $\theta_1$ | - 90~ 90 |
| 2 | {1}-{2} | $L_2$ | 0 | 0 | $\theta_2$ | 90~0 |
| 3 | {2}-{3} | $L_3$ | -90 | 0 | $\theta_3$-90 | - 45~45 |
| 4 | {3}-{4} | 0 | 0 | $L_4$ | $\theta_4$ | - 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,

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

$$^1T_2 = \begin{bmatrix} C_2 & -S_2 & 0 & L_2C_2 \\ S_2 & C_2 & 0 & L_2S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2T_3 = \begin{bmatrix} S_3 & 0 & C_3 & L_3S_3 \\ -C_3 & 0 & S_3 & -L_3C_3 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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

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,

$n_x = s_1s_4 + c_4[c_1c_2s_3 + c_1c_3s_2]$

$n_y = c_4[c_2s_1s_3 + c_3s_1s_2] - c_1s_4$

$n_z = c_4[c_2c_3 - s_2s_3]$

$o_x = c_4s_1 - s_4[c_1c_2s_3 + c_1c_3s_2]$

$o_y = -c_1c_4-s_4[c_2s_1s_3+c_3s_1s_2]$
$o_z = -s_4[c_2c_3-s_2s_3]$
$a_x = c_1c_2c_3-c_1s_2s_3$
$a_y = c_2c_3s_1-s_1s_2s_3$
$a_z = -c_2s_3-c_3s_2$
$d_x = L_2c_1c_2 - L_4[c_1s_2s_3-c_1c_2c_3]+L_3c_1c_2s_3+L_3c_1c_3s_2$
$d_y = L_2c_2s_1- L_4[s_1s_2s_3-c_2c_3s_1]+L_3c_2s_1s_3+L_3c_3s_1s_2$
$d_z = L_1-L_4[c_2s_3+c_3s_2]-L_2S_2+L_3c_2c_3-L_3s_2s_3$

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 parameters[18]. 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 position[19]. To solve that issue, the $L_3$ and $L_4$ are considered as coupled link because there is only twisting motion ($\theta_4$) 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,

$$C_3 = \frac{Nx^2 + Ny^2 - L_2{}^2 - L_3{}^2}{2L_2L_3} \tag{3}$$

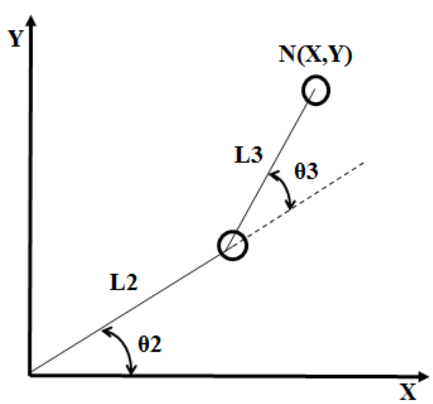


**Figure 4.** Inverse kinematic model of the humanoid arm.

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

$$C_2 = \frac{N_x(L_2 + L_3C_3) + [\![(N]\!]_y L_3 S_3)}{Nx^2 + Ny^2} \tag{5}$$

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

The values of $\theta_1$ and $\theta_2$ can be obtained by the above equations,

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

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

### *4.2.2 ANFIS*

ANFIS is introduced to reduce the error in any system and to increase the performance index[20]. ANFIS is a effective method which combines neuro and fuzzy approach[21]. 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 $\theta_2$ and 180 epochs for $\theta_3$ 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° 45° 0° 45°], 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□, the different solutions for $\theta_2$ and $\theta_3$ is obtained through MATLAB program. From the simulation, 256 different values of X-Y coordinates for all the possible values of $\theta_2$ and $\theta_3$ are obtained as shown in Figure 5.

## 5.3 Inverse Kinematics

### *5.3.1 Geometry Method*

The inverse kinematic simulation for finding $\theta_2$ and $\theta_3$ 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 |

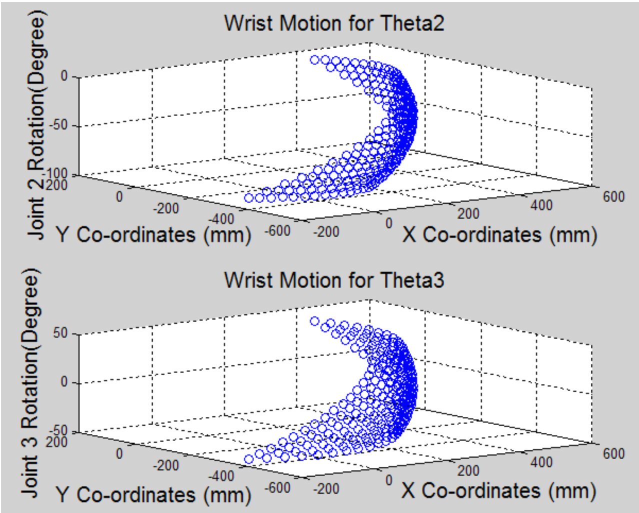


**Figure 5.** Multiple positions of the arm using forward kinematics.

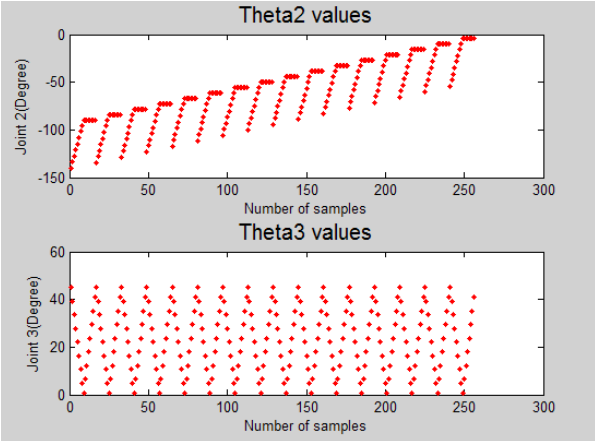


**Figure 6.** Inverse kinematic solutions by geometry method.

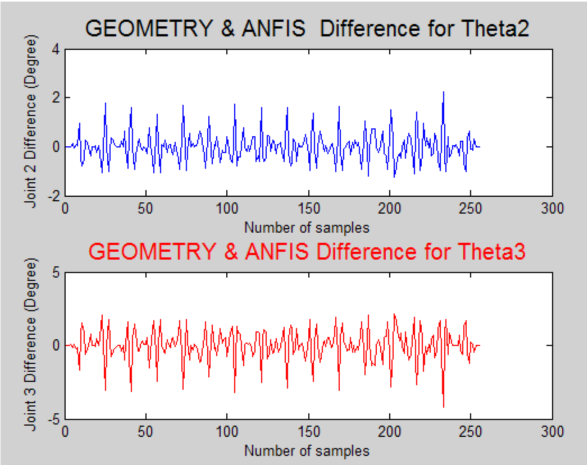


**Figure 7.** Difference between ANFIS and Geometry result.

## 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.

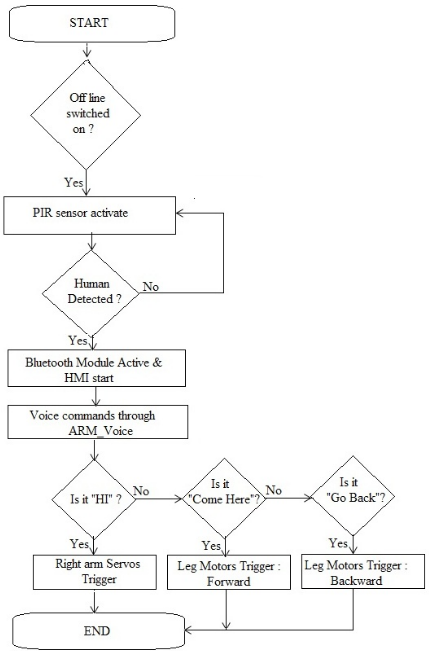


**Figure 8.** Flowchart of control system.

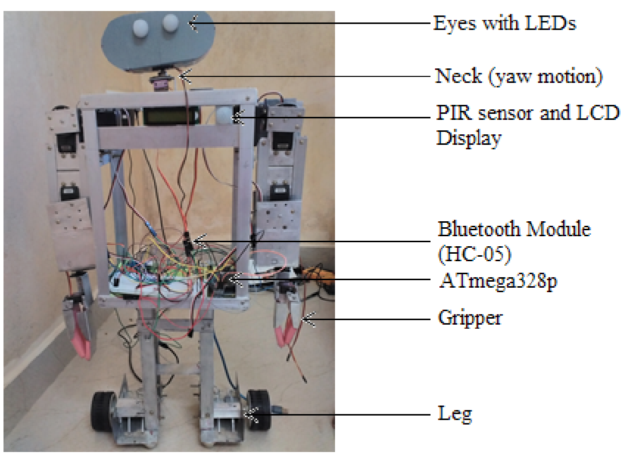


**Figure 9.** Voice Control System Test.

## 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 ($\theta_2$ and $\theta_3$) 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 $\theta_2$ and $\theta_3$ values between the forward kinematic (actual) and geometry solutions for the given joint angles are found to be 13.09° for $\theta_2$ and 24.96° for $\theta_3$. 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° and 50.28° than the actual values of $\theta_2$. Similarly, the minimum and maximum deviation of $\theta_3$ is found to be 1.36e -12° 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

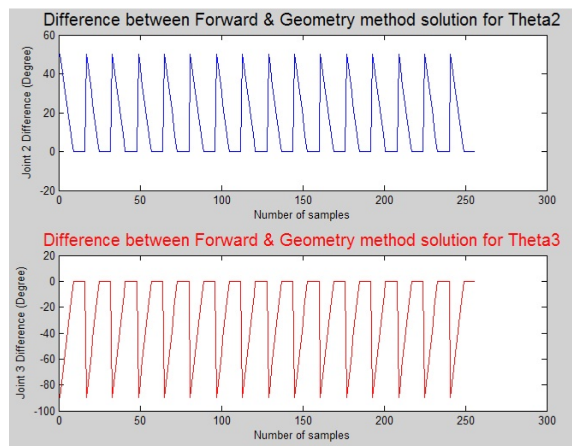


**Figure 10.** Comparison of Actual and Geometry method solution.

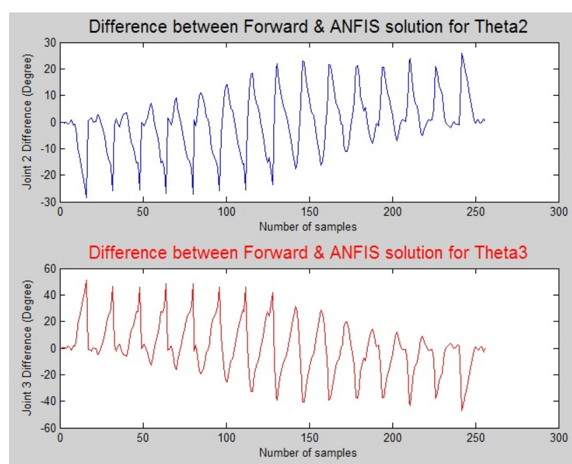


**Figure11.** Comparison of Actual and ANFIS solution

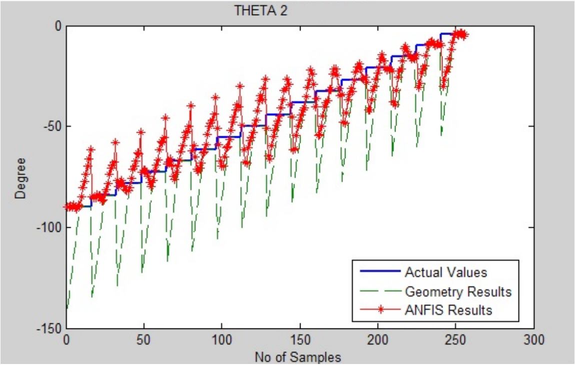


**Figure12.** Comparison of DH, Geometry, ANFIS methods solution for $\theta_2$.

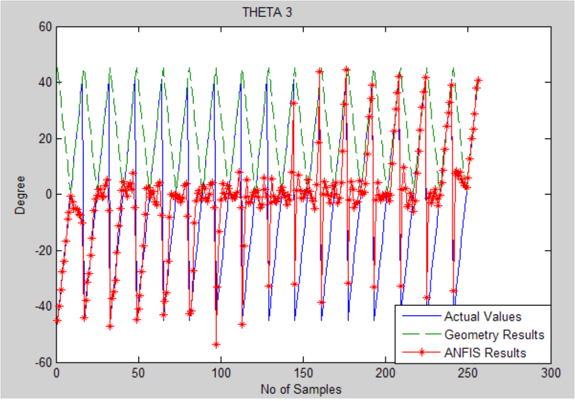


**Figure 13.** Comparison of DH, Geometry, ANFIS methods solution for $\theta_3$.

numerical simulation results, the average difference between forward kinematic solutions and ANFIS predicted values of $\theta_2$ and $\theta_3$ are found to be 2.657e-05º and 7.114e-05º which is very less and found to be negligible. From the results, it is also found that $\theta_2$ having the minimum and maximum deviation of 0.0369º to 28.58º than the actual values of $\theta_2$. Similarly, the minimum and maximum deviation of $\theta_3$ is found to be 0.023º and 51.28º than the actual values.

Figure 12 and Figure 13 shows the comparative results of DH convention, geometry and ANFIS methods for $\theta_2$ and $\theta_3$. 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 50.28º for $\theta_2$ and 90º for $\theta_3$. Similarly, the maximum difference between forward kinematic solutions and ANFIS predicted values are found to be 28.58º for $\theta_2$ and 51.28º for $\theta_3$ 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 $\theta_2$ and $\theta_3$ after trained with 5 membership function and 200 epochs for $\theta_2$ and 180 epochs for $\theta_3$.
- 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.

## 9. References

1. Chen B, Luo M, Guo F, Chen S. Walking mechanism and kinematic analysis of humanoid robot. 2013 International Conference on Advanced Mechatronic Systems. 2013 Sep. p. 491–4.
2. Hirai K, Hirose M, Haikawa Y, Takenaka T. The development of Honda humanoid robot. Proceedings IEEE International Conference in Robotics and Automation. 1998 May. p. 1321–6.
3. Asfour T, Schill J, Peters H, Klas C, Bucker J, Sander C, Schulz S, Kargov A, Werner T, Bartenbach V. Armar-4: A 63 dof torque controlled humanoid robot. 2013 13th IEEE-RAS International Conference in Humanoid Robots (Humanoids). 2013 Oct. p. 390–6.
4. Hashimoto S, Narita S, Kasahara H, Shirai K, Kobayashi T, Takanishi A, Sugano S, Yamaguchi JI, Sawada H, Takanobu H, Shibuya K. Humanoid robots in Waseda university—Hadaly-2 and WABIAN. Autonomous Robots. 2002 Jan; 12(1):25–38.

5. Taïx M, Tran MT, Soueres P, Guigon E. Generating human-like reaching movements with a humanoid robot: A computational approach. Journal of Computational Science. 2013 Jul; 4(4):269–84.
6. Adams B, Breazeal CL, Brooks R, Scassellati B. Humanoid robots: a new kind of tool. Massachusetts Inst of Tech Cambridge Artificial Intelligence LAB. 2000.
7. Jazar RN. Theory of applied robotics: kinematics, dynamics, and control. Springer Science & Business Media. 2010 Jun.
8. Fu KS, Gonzalez R, Lee CG. Robotics: Control Sensing. Vis. Tata McGraw-Hill Education. 1988.
9. Park IW, Kim JY, Cho BK, Oh JH. Control hardware integration of a biped humanoid robot with an android head. Robotics and Autonomous Systems. 2008 Jan; 56(1):95–103.
10. Kim JY, Park IW, Oh JH. Design and walking control of the humanoid robot, KHR-2 (KAIST Humanoid Robot-2). In Proceedings of International Conference on Control, Automation and Systems. 2004 Nov. p. 1540–3.
11. Siciliano B, Sciavicco L, Villani L, Oriolo G. Robotics: modelling, planning and control. Advanced Textbooks in Control and Signal Processing. 2009.
12. De Lope J, Santos M. A method to learn the inverse kinematics of multi-link robots by evolving neuro-controllers. Neurocomputing. 2009 Aug; 72(13-15):2806–14.
13. Hendarto HA, Setiawan JD. ANFIS application for calculating inverse kinematics of programmable universal machine for assembly (PUMA) robot. 2014 1st International Conference in Information Technology, Computer and Electrical Engineering (ICITACEE). 2014 Nov. p. 35–40.
14. Reinhart RF, Steil JJ. Neural learning and dynamical selection of redundant solutions for inverse kinematic control. 2011 11th IEEE-RAS International Conference in Humanoid Robots (Humanoids). 2011 Oct. p. 564–9.
15. Bachir O, Zoubir AF. Adaptive neuro-fuzzy inference system based control of puma 600 robot manipulator. International Journal of Electrical and Computer Engineering. 2012 Feb; 2(1):90–7.
16. Cannan J, Hu H. Human-Machine Interaction (HMI): A Survey. University of Essex. 2011.
17. Mittal RK, Nagrath IJ. Robotics and control. Tata McGraw-Hill; 2003 Feb.
18. Mohamed Z, Capi G. Development of a new mobile humanoid robot for assisting elderly people. Procedia Engineering. 2012 Dec; 41:345–51.
19. Zannatha JI, Limon RC. Forward and inverse kinematics for a small-sized humanoid robot. International Conference on Electrical, Communications, and Computers, CONIELECOMP. 2009 Feb. p. 111–8.
20. Jang JS. ANFIS: adaptive-network-based fuzzy inference system. IEEE Transactions on Systems, Man and Cybernetics. 1993 May-Jun; 23(3):665–85.
21. Revathi S, Malathi A. Multi-tier framework using sugeno fuzzy inference system with swarm intelligence techniques for intrusion detection. Indian Journal of Science and Technology. 2014 Sep; 7(9):1437–43.