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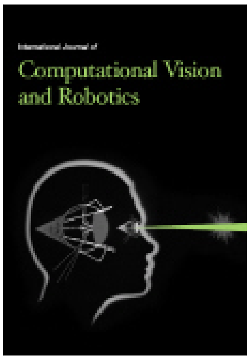

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Abstract: Delta robot are widely used to achieve positioning tasks with high speed and accuracy, which require a control model to move the platform of delta robot along a specific coordinate. This paper presents a control system based on fuzzy controller to achieve the motion control and applies this system on the model of delta robot, which is capable of carrying out the motion with three translational degrees of freedom. The proposed control system evaluates the applied angular position on the motor's joint depended on the output of inverse kinematics and ANFIS then move the end effector in the translation coordinates (X, Y and Z). Results from both inverse kinematics equations and from the delta robot after applied proposed control system show that there is a difference in the translation coordinates by around 5 cm in X direction, 2 cm in Y direction and 1 cm in Z direction. This difference is due to the effect of the friction in the joint of the delta robot, which is negligible in the inverse kinematics analysis. Finally, the validation of proposed control system for a delta robot is verified with minimum errors.

Keywords: delta robot; inverse kinematics; fuzzy control; adaptive neuro fuzzy interference system; ANFIS.

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1 Introduction

Delta robot is a one of the parallel robots which has a fixed base and moving platform interconnected by three identical links in parallelogram form (Damic et al., 2018). Delta robot has broadly applied in factories due to their properties such as high speed, high rigidity, and high accuracy (Kuo and Huang, 2017).

MATLAB software is used for complicated numerical calculations. Simulink is a part of MATLAB software, used for representing dynamic system in a block diagram form. Simulation system is also possible in Simulink package by imported CAD solid model. This allows control systems for the model to be constructed and graphical visualisation of results to be obtained (Łygas et al., 2016).

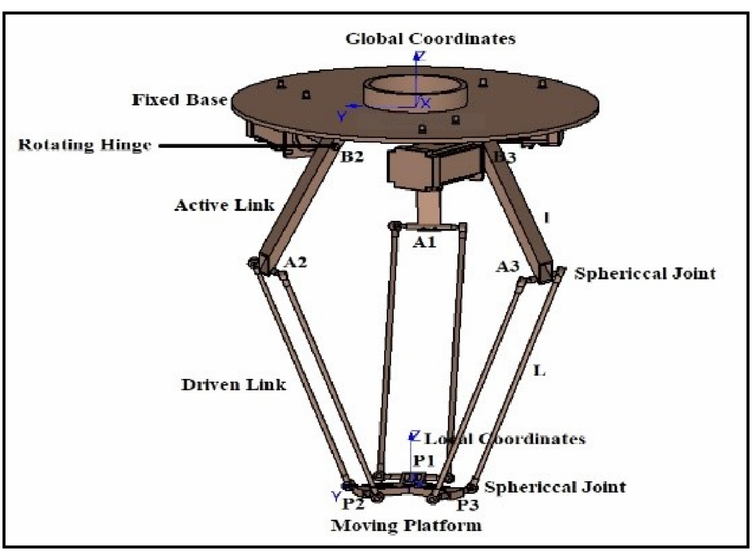
In lately years, there are various researchers developed the motion control of a delta robot. Afroun et al. (2006) explained a technique for optimal motion of delta robot by used a cubic spline function to evaluate the Cartesian coordinates of delta robot. This function is applied to move the robot from point to point or along a path motion. Zhang et al. (2012) developed a delta robot motion using a sine motion profile, the robot become faster and smoother due to smoothing of the trajectory. Sine motion profile modified based on non-zero initial and final velocities. Also, the dynamic model of the robot is derived. Kovar et al. (2012) designed a model of delta parallel robot with mounted camera to recording pictures for the surfaces. The motion of the robot controlled by used MATLAB software and NI Labview program. Lin et al. (2013) applied a robust controller for a delta robot to make a robot move smoothly and precisely, then verified a robust controller by experiments. The results explained that a manifold deformation design scheme has better control system than PID controller. Huo et al. (2015) implemented a real time control system, to control delta parallel robot for force and position. It designed in Linux CNC program to meet specific requirements for delta robot. Young and Lin (2016) developed the mechanism of delta robot to perform the motion for the robot in spherical form. The results showed this method is suitable for usage and the errors in millimetres. Kuo and Huang (2017) applied a simple method of control system to a delta parallel robot to achieve the position control. This control system applied on the torques of the motors depended on kinematics and dynamics analysis by used encoder. Ngo et al. (2017) designed a motion controller technique to enhance the performance of delta robot. The operation of controller evaluated by make several experimental tests and the results showed that the motion controller technique satisfied the requirements of factories. Jian and Lou (2017) proposed a motion control system depended on kinematics equations of delta robot at high velocity. This control system verified the application and performance of the robot with precision and stability. Nguyen et al. (2017) used a non-geometric method for solving the inverse kinematics equations of delta parallel robot and derived the control system to move the robot along specific path. A control system is proposed by used PID controller to ensure the moving platform tracking the desired path with high accuracy. Angel and Viola (2018) employed PID controller for tracking tasks in 3DoF parallel delta robot with computed torque control technique. Delta robot designed by used Solidworks program and simulated the control system in Simulink software. Liu et al. (2019) analysed the kinematics equations of delta parallel robot and designed a model of the robot in Solidworks program. Then imported this model by SimMechanics in MATLAB software to simulate the motion of delta robot.

This paper aims to provide a fuzzy controller based on adaptive neuro fuzzy inference system (ANFIS) for the motion of the delta robot (translation coordinates *X*, *Y*, *Z*) as actual position, where the computed actual position are compared with inverse kinematics analysis as desired position to get the errors between them. These errors are predict at any point during the movement of the end effector for delta robot from initial to final position.

2 Kinematics analysis of delta parallel robot

The delta parallel robot presented in this paper consists of a fixed base, three active links, three driven links, and the moving platform (end effector). The active links receives the input angular motion from motors and moves the end effector in translation motion along *X*, *Y* and *Z* directions. The fixed base and the active link are connected by rotating hinge at B1, B2, and B3, the active link and driven link are connected by spherical joints at *A*1, *A*2 and *A*3, and the driven link and the end effector are also connected by spherical joints at *P*1, *P*2 and *P*3. There are two coordinates system global coordinates system at fixed base and local coordinates system at moving platform. The model of the delta robot is shown in Figure 1. The dimensions of the fixed base, active links, moving platform, and driven links shown in Figures 2, 3, 4 and 5, respectively.

Figure 1 The model of the delta robot (see online version for colours)



The angular motion variables θ_1, θ_2, and θ_3 are provided from three motors at $B1$, $B2$ and $B3$ and equal to zero when the active links are in horizontal plane. The moving platform is translated in X, Y and Z direction.

Kinematics analysis consists of two parts as follow:

- inverse kinematics analysis (to calculate the angular motion variables θ_1, θ_2 and θ_3 in terms of the translated coordinates X, Y and Z)
- forward kinematics analysis (to calculate the translated coordinates X, Y and Z in terms of the angular motion variables θ_1, θ_2 and θ_3).

Figure 2 The dimensions of the fixed base (see online version for colours)

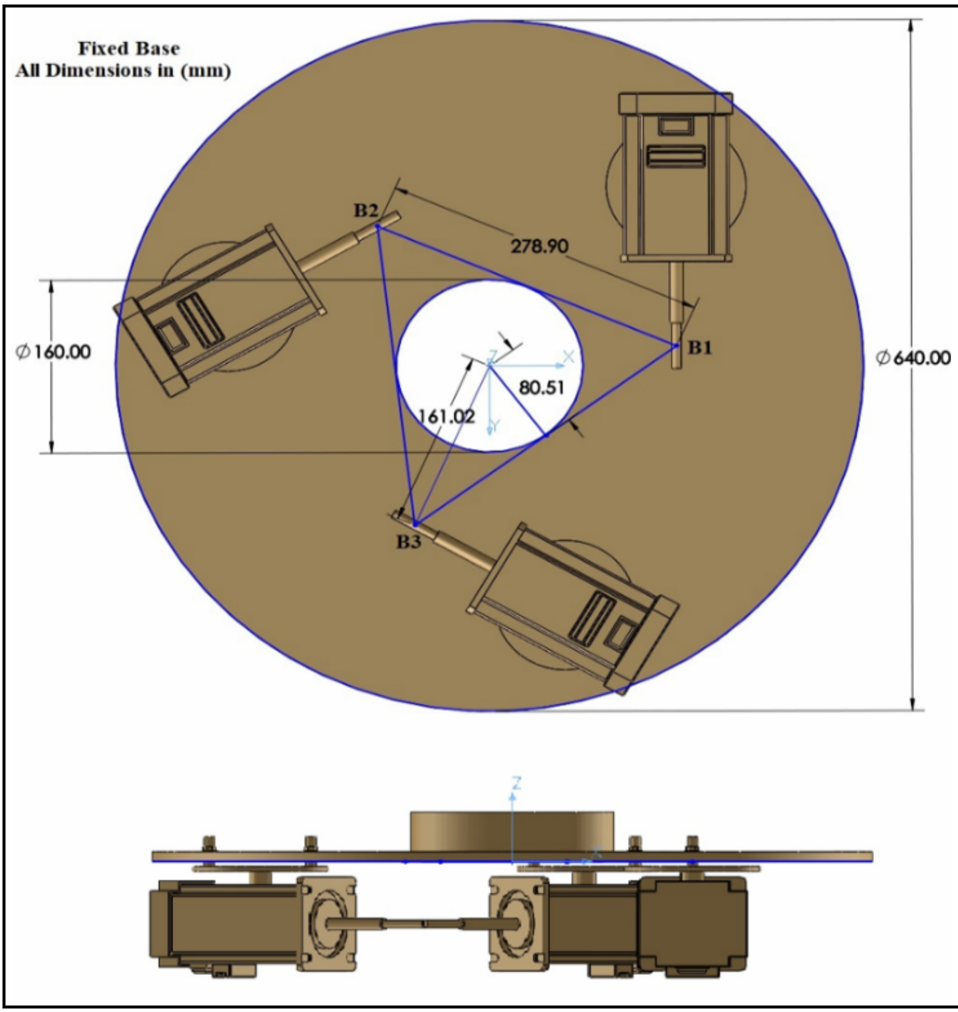


Figure 3 The dimensions of the active link (see online version for colours)

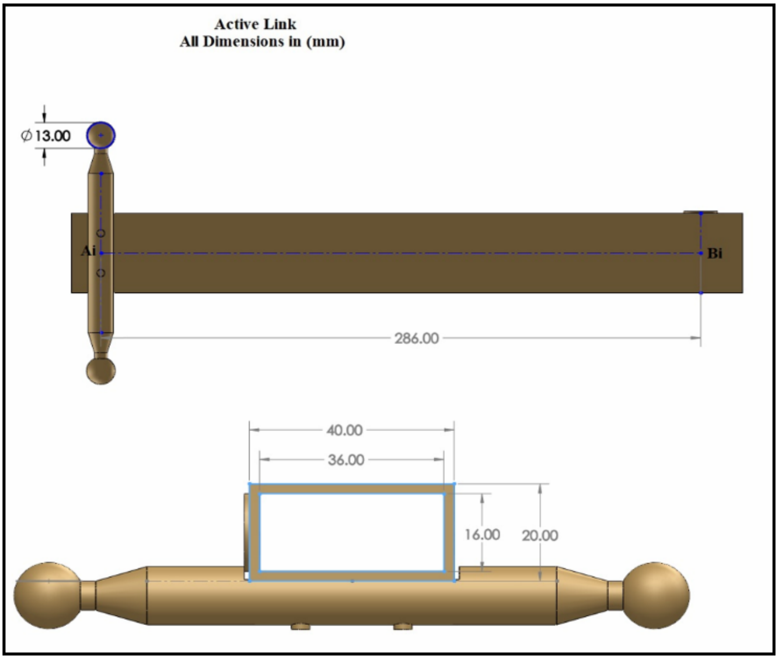


Figure 4 The dimensions of the moving platform (see online version for colours)

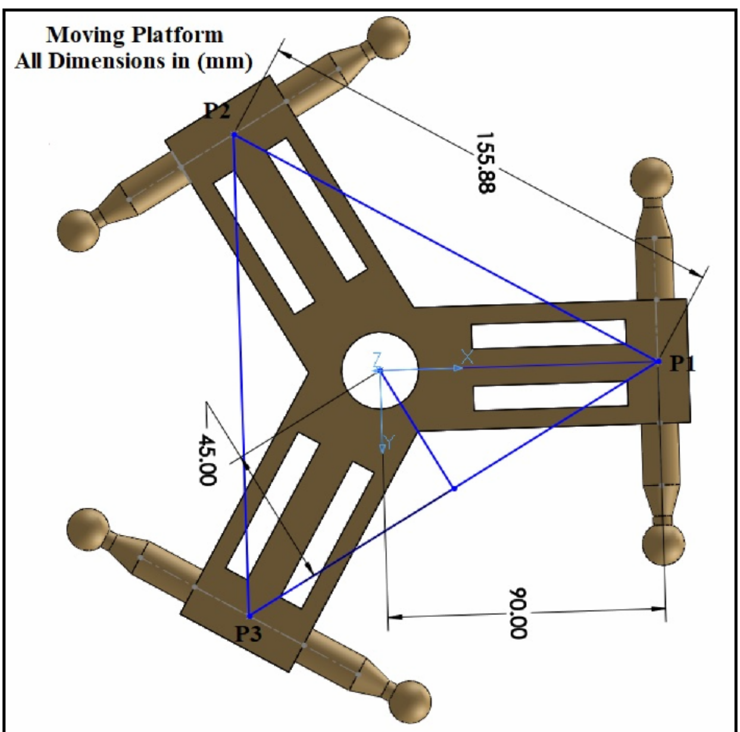
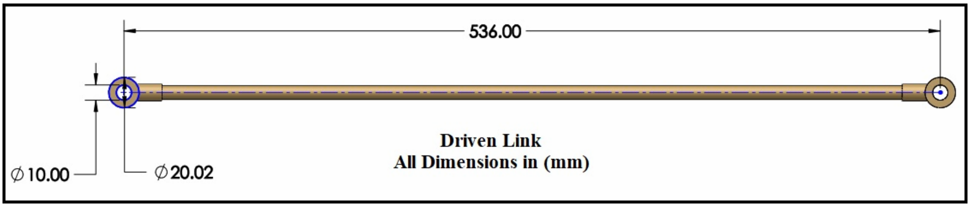


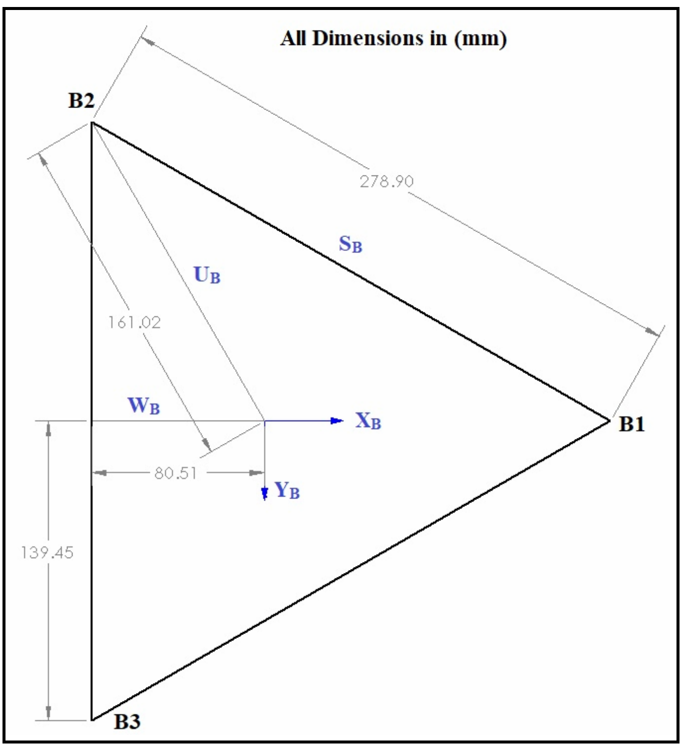
Figure 5 The dimensions of the driven link (see online version for colours)



3 Inverse kinematics equations

The geometric details of the fixed base and moving platform shown in Figures 6 and 7, respectively.

Figure 6 Geometric details of the fixed base (see online version for colours)



The points B_i are constant in the fixed base frame $\{B\}$ (global coordinates system) and the points P_i are constant in the moving platform frame $\{P\}$ (local coordinates system), therefore, the following coordinates can be obtained as:

$$^{B}B_1 = \begin{bmatrix} U_B \\ 0 \\ 0 \end{bmatrix}, \; ^{B}B_2 = \begin{bmatrix} -W_B \\ 0.5S_B \\ 0 \end{bmatrix}, \; ^{B}B_3 = \begin{bmatrix} -W_B \\ -0.5S_B \\ 0 \end{bmatrix},$$

$$ {}^{P}P_1 = \begin{bmatrix} U_P \\ 0 \\ 0 \end{bmatrix},\ {}^{P}P_2 = \begin{bmatrix} -W_P \\ 0.5S_P \\ 0 \end{bmatrix},\ {}^{P}P_3 = \begin{bmatrix} -W_P \\ -0.5S_P \\ 0 \end{bmatrix} $$

The dimensions of the delta robot are presented in Table 1.

Figure 7 Geometric details of the moving platform (see online version for colours)

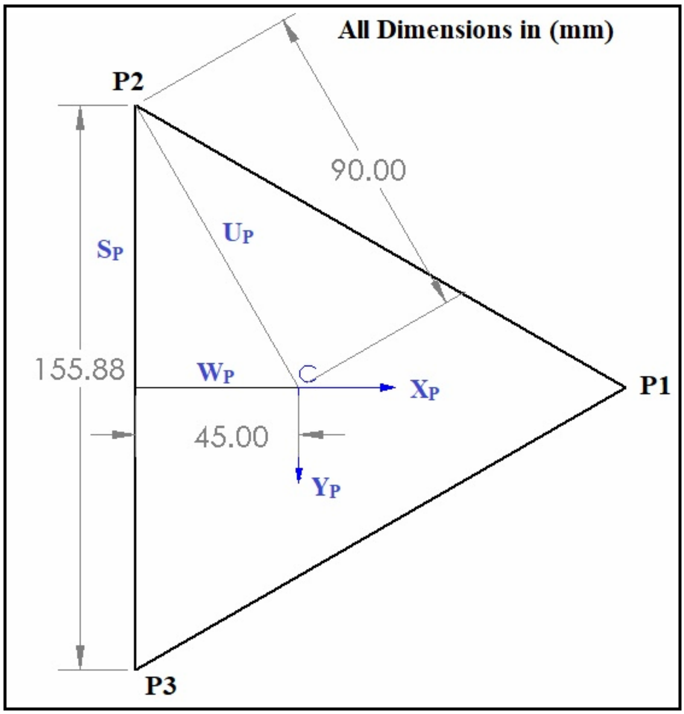
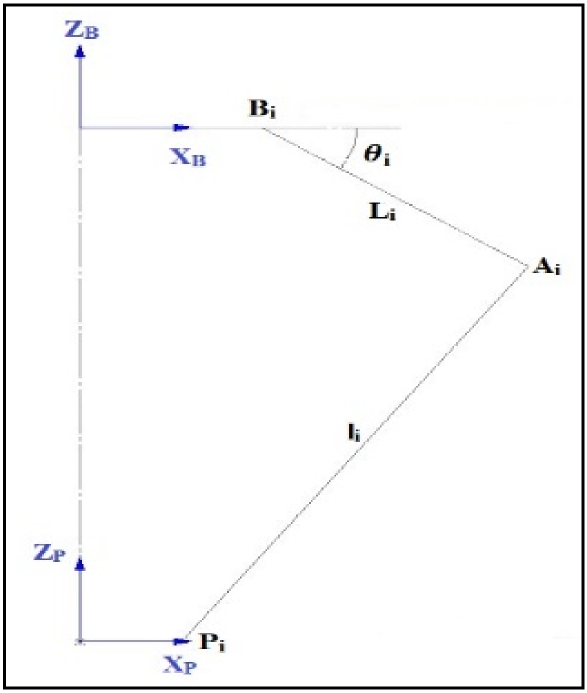


Table 1 The dimensions of the delta robot

No.	*Symbol*	*Definition*	*Value (mm)*
1	S_B	Side length of triangle for fixed base	278.9
2	U_B	Distance from centre to vertex of triangle for fixed base	161.02
3	W_B	Distance from centre to midpoint side of triangle for fixed base	80.51
4	S_P	Side length of triangle for moving platform	155.88
5	U_P	Distance from centre to vertex of triangle for moving platform	90
6	W_P	Distance from centre to midpoint side of triangle for moving platform	45
7	L	Length of active link	286
8	l	Length of driven link	536

Figure 8 Kinematics analysis for delta parallel robot (see online version for colours)



From the kinematics analysis shown in Figure 8, three equations for delta parallel robot can be derived:

$$\left[{}^{B}B_i\right]+\left[{}^{B}L_i\right]+\left[{}^{B}l_i\right]=\left[{}^{B}P_p\right]+\left[{}^{B}_{P}R\right]\left[{}^{P}P_i\right]$$

$$\left[{}^{B}P_p\right]=\begin{bmatrix}X\\Y\\Z\end{bmatrix}$$

where i = 1, 2, 3

$\left[{}^{B}B_i\right]$ the coordinates of the points at the fixed base in the global coordinated system

$\left[{}^{B}L_i\right]$ the length of the active link in the global coordinated system

$\left[{}^{B}l_i\right]$ the length of the driven link in the global coordinated system

$\left[{}^{B}P_p\right]$ the coordinates of the centre point at the moving platform in the global coordinated system

$\left[{}^{B}_{P}R\right]$ the rotation matrix of the moving platform with respect to fixed base, and equal to $[I_3]$, because there are no rotations for moving platform only translation motion.

$$[{}^{B}l_1] = [{}^{B}P_p] + [{}^{p}P_1] - [{}^{B}B_1] - [{}^{B}L_1]$$

$$[{}^{B}l_1] = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} U_P \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} U_B \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} L\cos\theta_1 \\ 0 \\ -L\sin\theta_1 \end{bmatrix} = \begin{bmatrix} X + U_P - U_B - L\cos\theta_1 \\ Y \\ Z + L\sin\theta_1 \end{bmatrix}$$

Using the following substitutions (Craig, 2022) and the dimensions of the delta robot as shown in Table 1:

$$t_i = \tan\frac{\theta_i}{2}$$

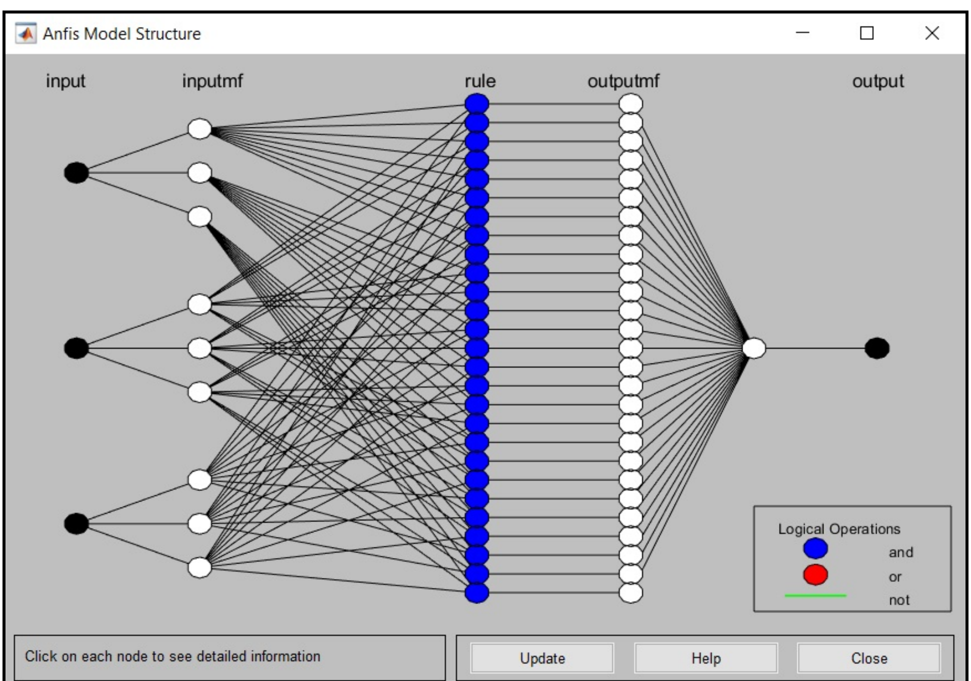
$$\cos\theta_i = \frac{1 - t_i^2}{1 + t_i^2}$$

$$\sin\theta_i = \frac{2t_i}{1 + t_i^2}$$

4 Adaptive neuro fuzzy inference system

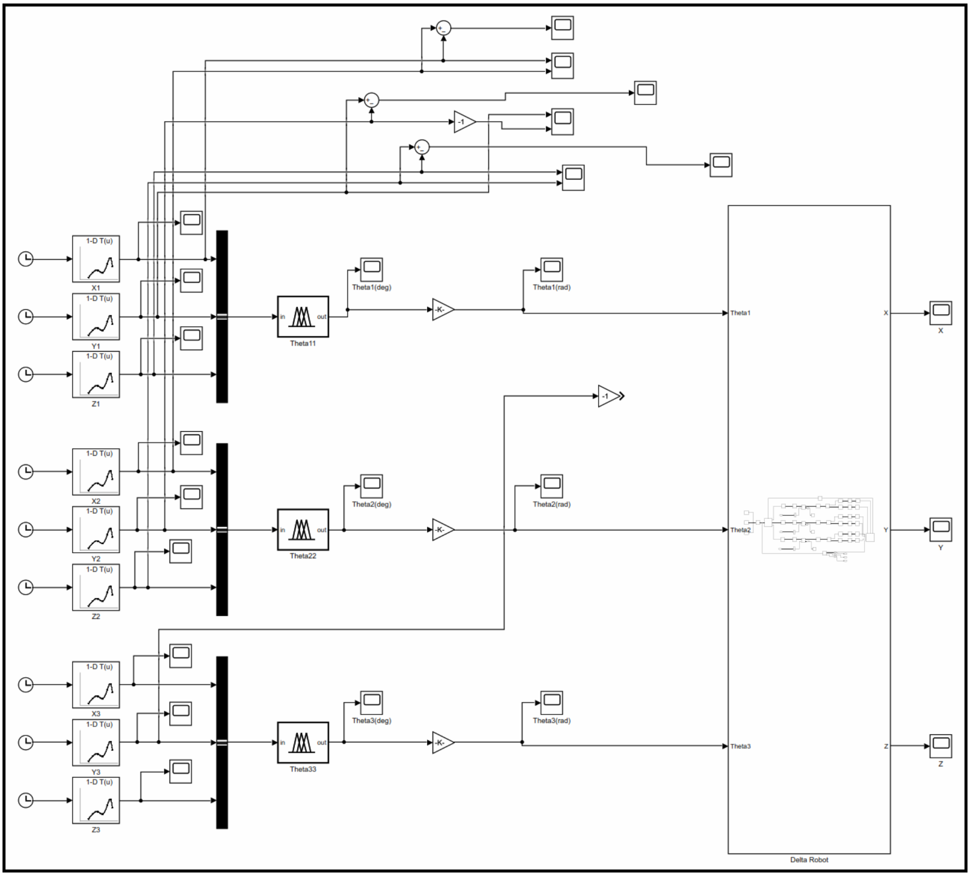
This section presents the ANFIS's properties and computation. ANFIS is a system that combines artificial neural network learning with fuzzy logic decision making (Figure 9).

Figure 9 The structure of ANFIS for each joint (see online version for colours)



Data input (X, Y and Z coordinates) and output (θ_1, θ_2 and θ_3) are collected from actual model of delta robot. This simulation makes use of three ANFIS to forecast the values of the robot's three joint variables. The values of the robot's three joint variables are predicted by the ANFIS model in Fig. 10, which represents the block diagram of the delta robot.

Figure 10 Block diagram of the delta robot



In order to perform control of the delta robot, fuzzy control is used and the model of the robot is implemented in MATLAB/Simulink as shown in Figure 11. Inverse equations of the system are obtained using equation (47) in Simulink. The Simulink model of the delta robot with controller is shown in Figure 12.

The actual and desired positions of the moving platform (X, Y and Z) are obtained, and errors are computed in order to provide the control system for delta robot. System block diagram includes the model of the delta robot, inverse kinematic and fuzzy blocks (contain ANFIS). It is provided to validate the proposed system control with regard to various desired trajectories.

Figure 11 The model of the delta robot (see online version for colours)

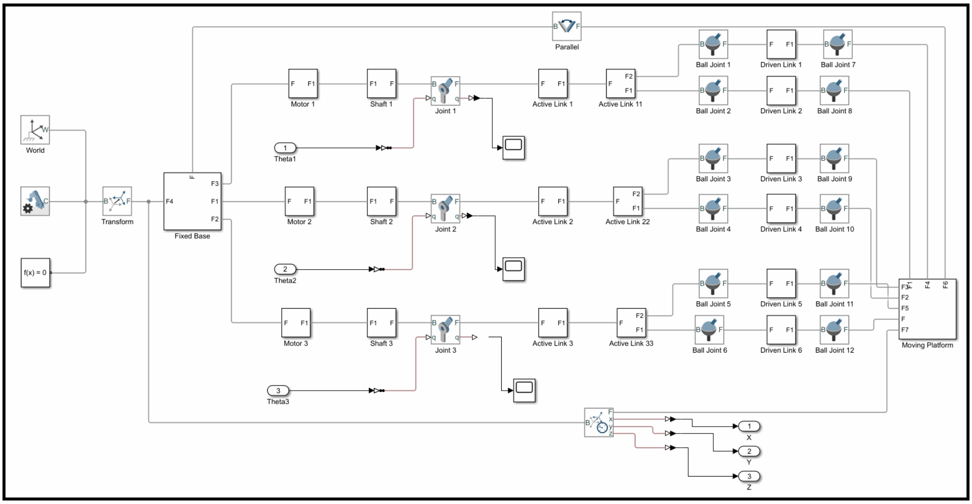
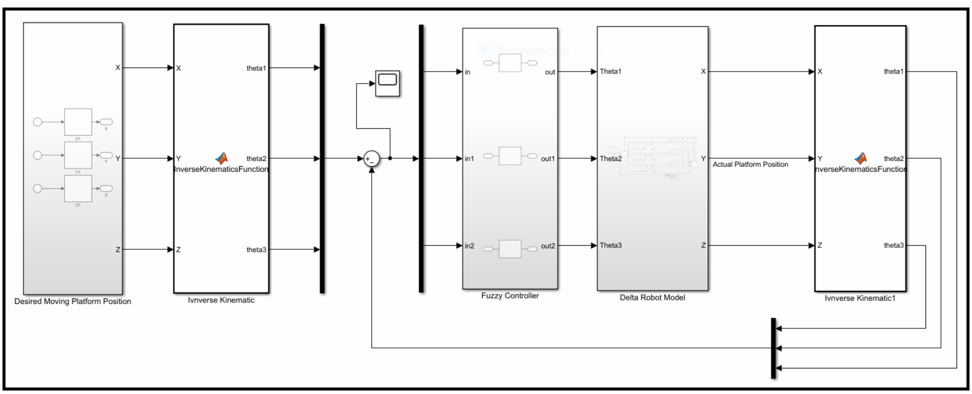


Figure 12 The Simulink model of the delta robot (see online version for colours)



5 Results and discussion

This part presents the results of motion control for the end effector of delta robot using the fuzzy controller and compare with inverse kinematics analysis. First, the ANFIS techniques will be used in the fuzzy control system, where the parameters for the control system based on the angular position on the three motors (θ_1, θ_2 and θ_3). Secondly, using Simulink fuzzy controller to simulate the motion control of delta robot in the specific path to compute the coordinates of end effector for this robot. Finally, the motion coordinates of the end effector (*X*, *Y* and *Z*) are presented from inverse kinematics analysis as desired position and from controller as actual position as shown in Figures 13, 14 and 15.

A Simulink model is achieved based on Figure 12 to compute the errors between desired position (inverse kinematics) and actual position (delta robot model) (Figures 16, 17 and 18). The error of circular path for the moving platform in desired and actual shows in Figure 19, where the error not exceeded 3%.

Figure 13 X coordinates (desired and actual) of the moving platform (see online version for colours)

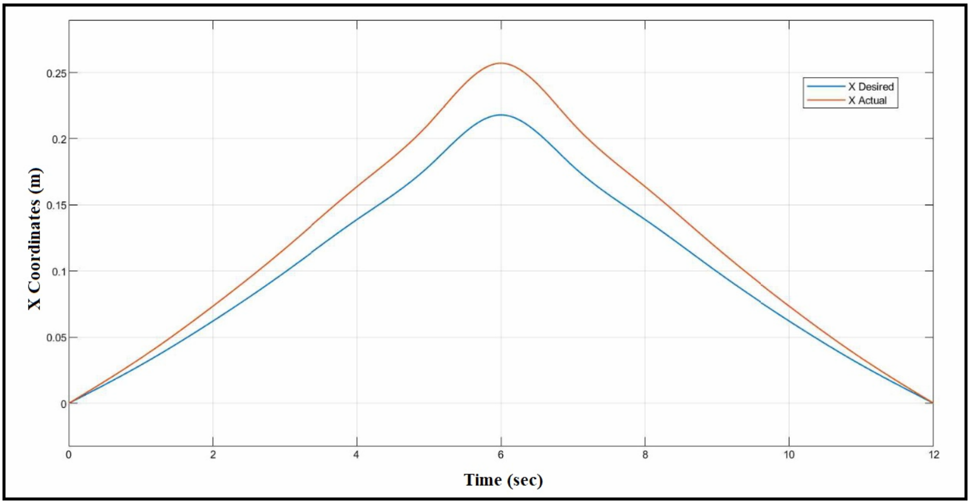


Figure 14 Y coordinates (desired and actual) of the moving platform (see online version for colours)

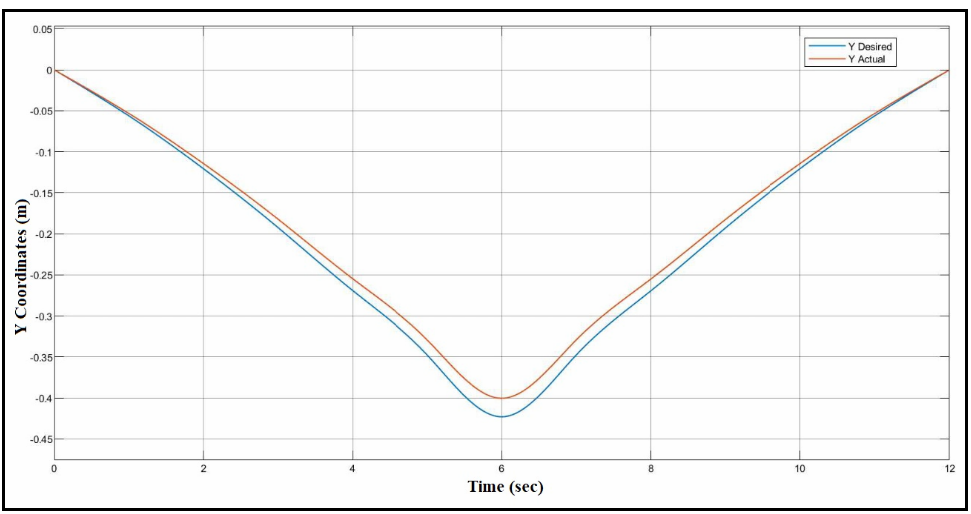


Figure 15 Z coordinates (desired and actual) of the moving platform (see online version for colours)

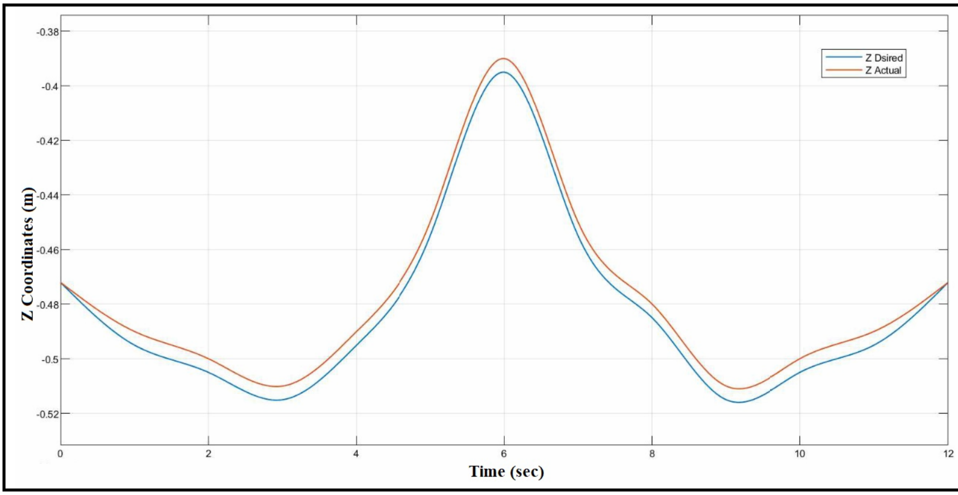
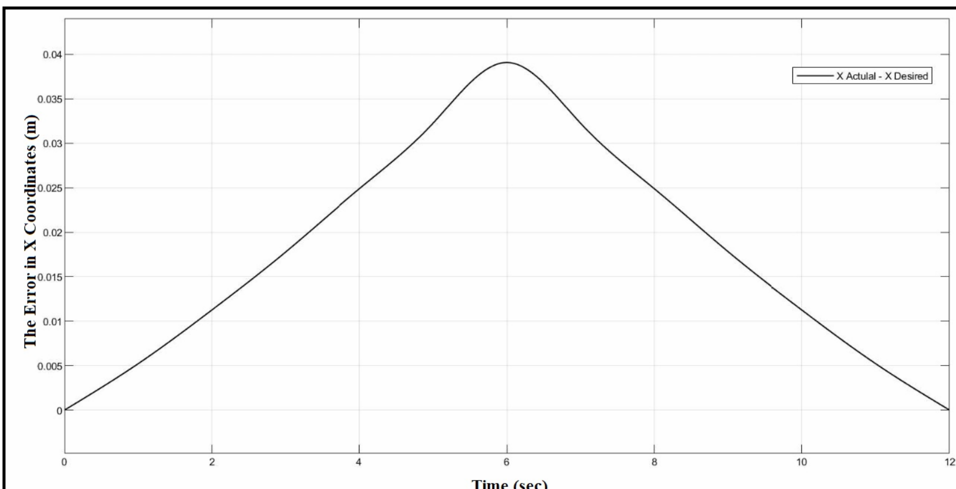


Figure 16 The error in X coordinates (desired and actual) of the moving platform (see online version for colours)



The results of the proposed control system shows that the maximum difference in motion of the end effector of the delta robot are equal to 5 cm in X direction, 2 cm in Y direction and 1 cm in Z direction at the same angular positions. Since this difference due to the friction effect do not take in the calculation of the inverse kinematics equation.

Figure 17 The error in Y coordinates (desired and actual) of the moving platform (see online version for colours)

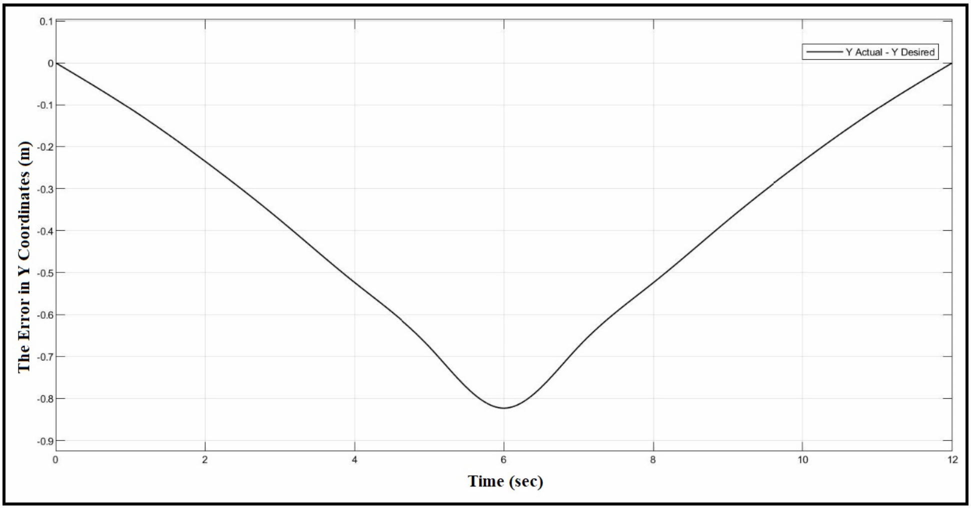


Figure 18 The error in Z coordinates (desired and actual) of the moving platform (see online version for colours)

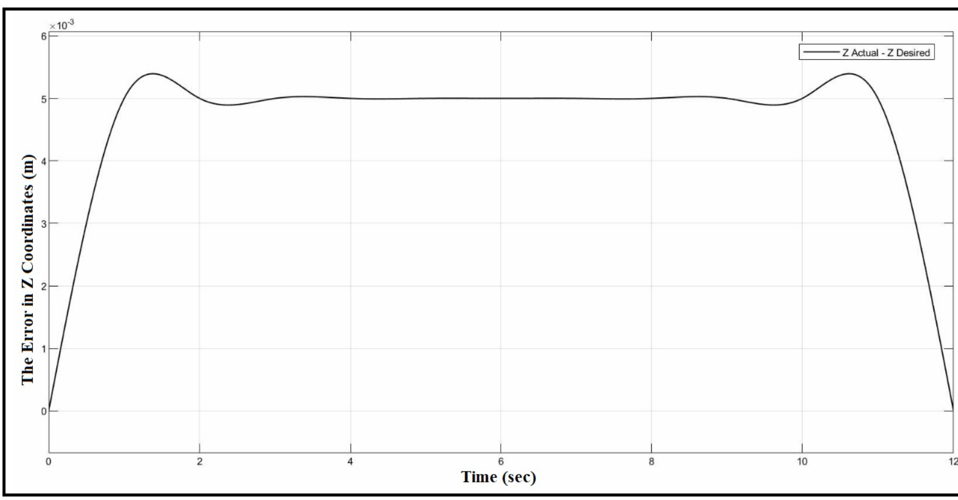
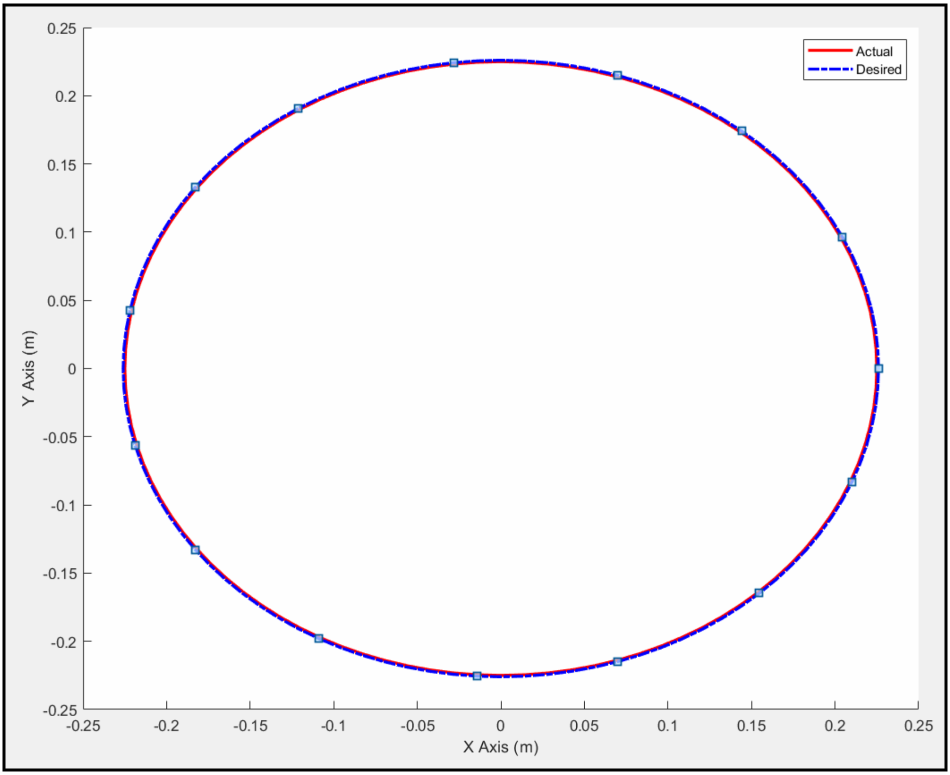


Figure 19 The error of circular path for the moving platform in desired and actual position (see online version for colours)



6 Conclusions

This paper explains how to use ANFIS in fuzzy controller, which applied to a delta parallel robot with three degrees of freedom (*X*, *Y* and *Z*) and driven by angular position applied on three motors. This controller system is applied to motion of the end effector to make a delta robot move with high speed and accuracy. The proposed control system is verified with minimum errors between the end effector translation coordinates (*X*, *Y* and *Z*) in actual and desired, which is used as feedback in fuzzy controller. In addition, design the model of delta robot with fuzzy controlled based on ANFIS, and the results compared with the results from inverse kinematics calculations. The results show that the proposed control system gives better motion accuracy.

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