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# Designing An optimal Fuzzy-WOA Controller for Parallel Robots "Stewart Robots"

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**Abstract-** The purpose of this paper is to design and analyze a hybrid controller for controlling a parallel robot arm (stewart). In this article, the direct kinematics of the robot is solved by the quadrilateral method. The results of this analysis along with numerical inverse dynamics can be applied to a robot of a certain size that works with electric jacks. In the following, a proportional, derivative and fuzzy integral controller is proposed to control the Stewart robot. This controller is optimized with genetic algorithm and woa method. Meanwhile, fast and appropriate performance, reduction of controller rules, resistance to specific limitations and controllability have always been among the goals. Also, by separating the independent dynamic equations, due to the use of fewer sensors, it facilitates optimal implementation of fuzzy proportionality and low implementation cost. In the applications of this design, accuracy, hardness and high capacity are provided. These types of designs are used in the manufacture of medical equipment, airplane simulators, CNC machines, stadium filming. Among the advantages of this unique design, high speed and accuracy, greater hardness due to its inherent structure and the ability to move with high precision can be mentioned.

**Keywords-** Stewart Robot-Fuzzy Control-Classic –WOA-Controller-Genetic Algorithm-Inverse Dynamics-Direct Kinematics- Medical Equipment.

## Introduction

With the development of industry and the emergence of new equipment, the need to invent precision control devices becomes more apparent. In addition, the production of new generations of robots that have a special mechanism has led to more research in the field of invention of control and precision control devices and the design of robots to be designed more accurately and with higher quality. Automation has emerged in various sectors of industry and manufacturing in recent decades and is developing day by day. It has not been more than a few decades since the advent of fully mechanized factories in which all processes are automatic and manpower has no executive role, but in recent years we have seen the emergence of mechanized factories whose design, construction and operation are truly amazing. Stewart Robot A parallel robot consists of two rigid objects: a moving platform and a base bed whose position and direction of the base bed are fixed and the position and direction of the moving platform change with the length of the arms. Heading styles. One of the most important and successful applications of the Stewart mechanism is its application in various types of simulators. In fact, Stewart made his first proposal for use in the flight simulation process.

It can be said that the most important and functional which have been developed to imitate human hands [1]. Robots are more useful than human beings in these jobs for several reasons (e.g., safety, accuracy, speed, increase in generation power, and flexibility) and are used in costly, dangerous, repetitive, and tedious tasks in industry as well as in harsh environments such as space, and in nuclear reactors. When controlling the position and velocity of robotic manipulators, having knowledge of their position and velocity is important. In practice, however, disturbances affecting the manipulator, uncertainties

in the model, mismatches in system parameters, and the existence of higher-order dynamics lead to changes in model parameters that can decrease proper control and cause system instability. In recent decades, attention has been focused on controlling the movement of the robot manipulator. A variety of control methods and controllers have been implemented, each with its own advantages and disadvantages. The following
control methods are examples: robust [2, 3], optimal [4, 5], adaptive [6, 7], linear PID [8, 9], intelligent (including neural networks and fuzzy control types I and II), nonlinear sliding mode controller (SMC), inverse dynamic controller (IDC), computed torque [10], and Lyapunov-based control methods [11, 12]. PI and PID linear controls are conventional control methods for robotic manipulators that are widely used in industry [13]. As is evident, linear controls are inefficient and subject to uncertainties, and do not exhibit appropriate and robust performance. On the other hand, although local methods are fast, they do not guarantee overall convergence of the system [15].In addition, the use of global activation functions and local learning methods create that include low speed in learning, probability of failure to reach an appropriate answer, and extreme sensitivity to initial network weights. The control of the manipulator position using fuzzy and Metaheuristic algorithm has been addressed in several articles [17–20].it can be applied easily and performs well in systems that are complex, ill defined, nonlinear, and time varying. The primary advantage of fuzzy control is the use of human knowledge (expert experience), which is part of the process of control [21].the theory of fuzzy controller stability. In fact, fuzzy control cannot guarantee the stability of a system because it lacks an explicit mathematical model to show it. For example, SONG et al [22] used a fuzzy control method to control the computed. Moreover, PILTAN et al [23] applied a fuzzy logic controller for a PUMA robot.
method for nonlinear systems that has a simple design and is efficient and practical in overcoming structured uncertainties, no structured uncertainties, and external disturbances of the system. It also has a fast transient response and appears to be a highly desirable method of controlling robotic manipulators. However, its control signal is discontinuous and produces adverse chattering phenomena [28] that may stimulate the high frequency dynamics of system and, in the worst case, cause system instability. In this study, to solve the problem of chattering,
an SMC with a boundary layer is used. However, the use of this methods (fuzzy & metaheuristic) can slightly increase the steady-state error of the system.
with the investigation of the theory of fuzzy controller stability. PILTAN et al [29] used to control PUMA robot in a MATLAB/Simulink environment. CORRADINI et al [30, 31], CAPISANI et al [32–34], and JIN et al [35] implemented SMC on industrial and laboratory robotic manipulators and tested them experimentally. SOLTANPOUR et al [43, 44] presented a robust fuzzy SMC and examined a robust
fuzzy-adaptive SMC for tracking a 6-DOF robot manipulator in the presence of uncertainties. An optimal fuzzy SMC approach was used [45], and VEYSI et al [46] designed a self-adaptive optimal fuzzy SMC for tracking a 6-DOF robot manipulator in the presence of uncertainties, which led to successful results. Adaptive neuro-fuzzy control has been implemented in industrial and laboratory robotic manipulators in previous studies [47–50]. WANG et al [51] and SUN et al [52] introduced a combined SMC and neural network control method for controlling robot manipulators. WAI et al [53, 54] used a combined SMC and neuro-fuzzy control method to control a 2-link robot manipulator. HU et al [55] used a combined SMC and neural network method with a fuzzy supervisor to control a 2-link robot manipulator. introduced an optimal hybrid control approach called the optimal general fuzzy sliding mode to control electric vehicles [56]. This interesting idea can be used to control a robot manipulator.
In a recent paper [57], we combined SMC and an adaptive neuro-fuzzy network (ANFIS) with the fuzzy supervisor method to control the first three links of an IRB-120 robot. Note that this was not amature work and contained deficiencies and faults that we are trying to address to improve the control method. The results of that research will be presented in the form of a new article in the near future. 6-DOF IRB-120 robot manipulator in the presence of uncertainties. The results were simulated, tested, and compared in a MATLAB/Simulink environment. For further validation, the results were also tested and confirmed experimentally on an actual IRB-120 robot manipulator. The main contribution of the current study and its unique features are as follows: This marks that a controller has been designed for an IRB-120 industrial robot manipulator for which all of the kinematic and dynamic equations were extracted. The current study can be the beginning of more extensive studies on the design of controllers of IRB-120 robot manipulators. The problem of chattering in sliding mode controllers has been solved with the introduction of a simple control method and tiny modifications to the control input signal equation to obtain relatively suitable results. In conventional methods, fuzzy control and adaptive control or

metaheuristic algorithm have been used in place The use of each method has its own problems and complexities. Some of these problems are as follows. The main problem of the use of fuzzy control in Refs. [37–46] and [56, 57] was addressed as a lack of an explicit mathematical model. In addition, the formulation and estimation of the disturbances along with the system dynamics are difficult. The lack of an explicit mathematical model leads to the inability to investigate and guarantee the stability of a fuzzy control system. In other words, there is an inherent weakness in theoretical investigations of fuzzy controller stability. The main problem in the use of adaptive control in Refs. [37, 44, 46], and [47–50] has been explored. This problem is related to the application of adaptive parameters in the adaptive update rules, which requires more inputs and parameters in these controllers. As a result, the computation volume increases, which is not optimal. The primary problem of the use of neural networks in Refs. [47–54, 57] has been stated to be learning by the neural network. Learning by neural networks causes the transient response of the system to slow and become inappropriate. This reduces the convergence rate of the error, which is of great importance when controlling robotic manipulators [58-60]. In general, the main advantages of the proposed control method as compared to other methods are, its simplicity, the smoothness of the control scheme, and the absence of the problems and complexities mentioned above.

In this paper, we design a functional controller for the desired Stewart robot. In working with robots, direct kinematics are usually used; On the other hand, the kinematics and dynamics of the Stewart robot are completely non-linear. The use of classical control in controlling this mechanism requires having information and accurate knowledge of its dynamics; And by changing the load or the size of the robot, the dynamics of the robot will change and the controller will show different behavior.

However, it seems necessary to use an applied method that can be built and used in practice. Therefore, using the fuzzy, proportional and optimal method by genetic algorithm, we try to design an application controller that can adjust the robot in any case. Determining the fuzzy rules of a fuzzy control strategy is difficult. Fuzzy PID strategy parameters can be updated according to practical conditions. Improved robot control efficiency and accuracy based on fuzzy PID algorithm. The paper is arranged as follows: Section 2 introduces the dynamics and kinematics of the robot. Section 3 presents the PID controller and the mathematical model.

Section 4 describes the fuzzy control method. Section 5 describes the design and improvement of a fuzzy and optimized genetic algorithm PID controller. Section 6 compares the simulations between a PID controller and a fuzzy one optimized by a genetic algorithm. And Section 7 summarizes the conclusion.

**The introduction and model of the system**

Figure 1 shows the 6-DOF IRB-120 robot. It is composed of a base, waist, arm. The robot kinematic model is described by homoge- neous coordinates.

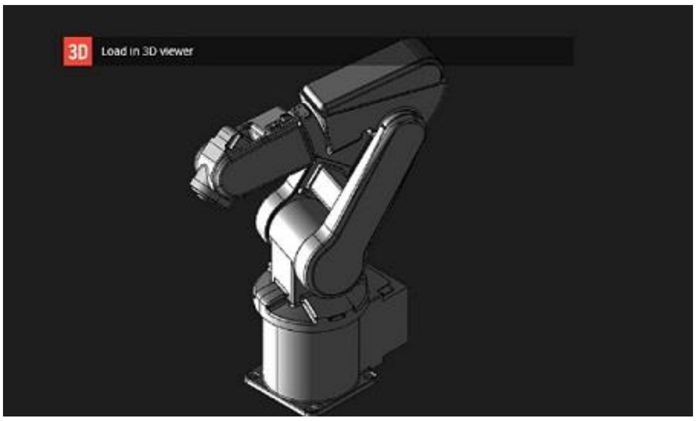



Fig. 1. The IRB-120 robot system

Table 1
D-H parameters of the IRB-120 arm

| Joint Nr | $\theta_i$ [◦] | $d_i$ [mm] | $a_i$ [mm] | $\alpha_i$ [◦] |
|---|---|---|---|---|
| 1 | $\theta_1$ | $d_1$ | 0 | 0 |
| 2 | $\theta_2$ | 0 | $a_1$ | −π/2 |
| 3 | $\theta_3$ | 0 | $a_2$ | 0 |
| 4 | $\theta_4$ | $d_4$ | $a_3$ | −π/2 |
| 5 | $\theta_5$ | 0 | 0 | π/2 |
| 6 | $\theta_6$ | 0 | 0 | −π/2 |

Table 2 Performance of IRB-120 in accordance with ISO 9283

| 1 kg picking cycle | IRB 120 |
|---|---|
| 25 x 300 x 25 mm | 0.58 s |
| 25 x 300 x 25 with 180° axis 6 reorientation | 0.92 s |
| Acceleration time 0-1 m/s | 0.07 s |
| Position repeatability | 0.01 mm |

kinematics involves geometric and time- based motion properties, in this paper, kinematics is described. The six links are built in separate coordinates; their positions and orientations are described in the coordinates

In this paper, kinematic analysis is performed. The movable plate is an equilateral triangle and the fixed plate is a regular hexagon with two consecutive corners of the two operators connected to one of the corners of the moving plate. It is noteworthy that only two interfaces are connected to each corner of the animated screen.

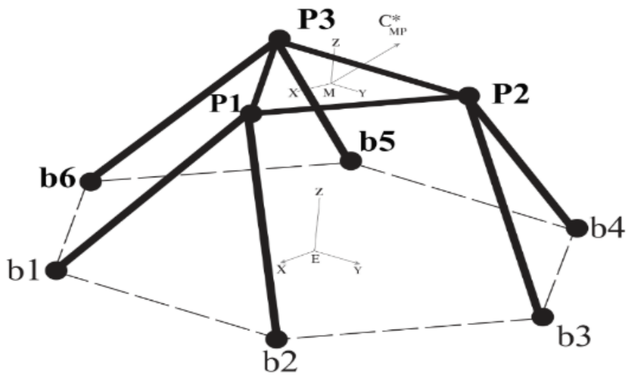



Fig. 2 Stewart mechanism

The active variables of the joint space consist of six scalar lengths for each interface or $\overline{q_i}$ which are called independent generalized coordinates. (i = 1… 6) and passive joints variables including three lengths (λ_j)¯ (J = 1.2.3) and mechanism workspace variables including 6 parameters $\Phi$،$\Psi$،$\Theta$ ،$P_z P_y P_x$ that the first three parameters represent the rotation angle, respectively The error of rotation, or rotation about the x-axis, and the rotation or rotation around the y-axis, and the rotation or rotation around the z-axis, and the second three parameters represent the position vector components of the center of the moving platform relative to the reference frame or vector $\vec{P}_E$.

The main measurable variables in the system are the length of the six interfaces that connect the two pages. Also, to calculate the direct kinematic solution, three sub-variables are used, which are the length of the direct distance between points $P_j$and point E and are represented by $\overline{\lambda_J}$ The center vector of the moving screen coordinate device is displayed in the base coordinate system with $\overrightarrow{P_E}$.[61-63] Each of the rotational motions around the axes of the coordinate system connected to the moving platform, mentioned in the above cases, can be expressed by a 3 × 3 matrix called the rotational matrix around the corresponding axis [64-69] These matrices are:

$$\text{Rroll}=\begin{bmatrix}1 & 0 & 0\\ 0 & cos\varphi & -sin\varphi\\ 0 & sin\varphi & cos\varphi\end{bmatrix}$$

$$\text{Rpitch}=\begin{bmatrix}cos\psi & 0 & sin\psi\\ 0 & 1 & 0\\ -sin\psi & 0 & cos\psi\end{bmatrix}$$

$$\text{Ryaw}=\begin{bmatrix}cos\theta & -sin\theta & 0\\ sin\theta & cos\theta & 0\\ 0 & 0 & 1\end{bmatrix}$$

The system rotation matrix is expressed as follows:

$R_{rp}= R_{roll}R_{pitch}$

In positional kinematics, by having the matrix R and the vector $\vec{P}_E$relative to the reference frame, changes in the scalar length of the interfaces or $\overline{q_\iota}$ can be obtained.

Inverse kinematics positioning:

$$\overrightarrow{P_J} = R\ M\overrightarrow{P_J}$$

To calculate the length of scalar $\overline{\lambda_J}$, the following equation can be used:

$\overline{\lambda_J}=\|\vec{P_j}\|=(\overrightarrow{P_J}.\overrightarrow{P_J})= (\ P_j^T P_j)½$

Speed inverse kinematics:

$$\Omega_{MP} =\dot{R}R^T= \begin{bmatrix}0 & -\omega_{MP_Z} & \omega_{MP_y}\\ \omega_{MP_Z} & 0 & -\omega_{MP_x}\\ -\omega_{MP_y} & \omega_{MP_x} & 0\end{bmatrix}$$

By deriving from the relationship

$\overline{q_\iota}=\|\vec{I_i}\|=(\overrightarrow{I_\iota}.\overrightarrow{I_\iota})= (\ I_i^T I_i)½$

The following matrix equation can be obtained with respect to time and by definition

$A_{6\times6}\, t_{6\times1} +B_{6\times6}\, \dot{q}_{6\times1} =0_{6\times1}$

$$A_{6\times6} =\begin{bmatrix}(\overrightarrow{P_1}\times\overrightarrow{I_1})^T & \vec{I}_1^T\\ (\overrightarrow{P_1}\times\overrightarrow{I_2})^T & \vec{I}_2^T\\ (\overrightarrow{P_2}\times\overrightarrow{I_3})^T & \vec{I}_3^T\\ (\overrightarrow{P_2}\times\overrightarrow{I_4})^T & \vec{I}_4^T\\ (\overrightarrow{P_3}\times\overrightarrow{I_5})^T & \vec{I}_5^T\\ (\overrightarrow{P_3}\times\overrightarrow{I_6})^T & \vec{I}_6^T\end{bmatrix} \quad B_{6\times6}= \begin{bmatrix}\overline{-q_1} & 0 & 0 & 0 & 0 & 0\\ 0 & \overline{-q_2} & 0 & 0 & 0 & 0\\ 0 & 0 & \overline{-q_3} & 0 & 0 & 0\\ 0 & 0 & 0 & \overline{-q_4} & 0 & 0\\ 0 & 0 & 0 & 0 & \overline{-q_5} & 0\\ 0 & 0 & 0 & 0 & 0 & \overline{-q_6}\end{bmatrix}$$

$$\overrightarrow{t_{MP}}=\begin{bmatrix}\omega_{MP}\\ \dot{\vec{P}}_E\end{bmatrix}$$

$\dot{\vec{q}}=[\dot{\vec{q}}_1\ \dot{\vec{q}}_2\ \dot{\vec{q}}_3\ \dot{\vec{q}}_4\ \dot{\vec{q}}_5\ \dot{\vec{q}}_6]$

The matrices $A_{6\times6}$ , $B_{6\times6}$ are the Jacobin matrices of the system and the vector $\dot{q}_{6\times1}$ is the generalized independent velocity vector of the system and the vector $\overrightarrow{t_{MP}}$ is the angular velocity vector of the linear velocity of the platform. They are called mobile. Now, using the matrix equation and knowing the angular velocity vector $\omega_{MP}$ from the external multiplication matrix $\overline{q_\iota}$ from the kinematic part of position and vector $\overrightarrow{P_E}$ , the rate of change of scalar length of the interfaces can be obtained as follows:

$\dot{\vec{q}}$=-$B^{-1}$A$\vec{t}$

Because the scalar length of interfaces or $\overline{q_\iota}$ is never zero, there will always be an inverse of matrix B.

At this stage of inverse kinematic analysis, because the second derivative of the periodic matrix with respect to time or $\ddot{R}$ or and the second derivative of the position vector of the geometric center of the moving platform with respect to time or $\ddot{\vec{P}}_E$ can be easily calculated by having them and calculating parameters In the previous two sections, we can calculate the rate of change of generalized independent velocities, or in other words, the generalized independent accelerations $\ddot{\overline{q_\iota}}$ as well as the rate of rate of change of passive variables or $\ddot{\overline{\lambda_J}}$

$\overline{q_\iota}=\|\vec{I_i}\|=(\overrightarrow{I_\iota}.\overrightarrow{I_\iota})= (\ I_i^T I_i)½$

$A_{6\times6}\, t_{6\times1} +B_{6\times6}\, \dot{q}_{6\times1} =0_{6\times1}$

$$\dot{B}_{6\times6}=\begin{bmatrix} -\dot{\overline{q_1}} & 0 & 0 & 0 & 0 & 0 \\ 0 & -\dot{\overline{q_2}} & 0 & 0 & 0 & 0 \\ 0 & 0 & -\dot{\overline{q_3}} & 0 & 0 & 0 \\ 0 & 0 & 0 & -\dot{\overline{q_4}} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\dot{\overline{q_5}} & 0 \\ 0 & 0 & 0 & 0 & 0 & -\dot{\overline{q_6}} \end{bmatrix}$$

$$\dot{A}_{6\times6}=\begin{bmatrix} (\Omega_{MP}\overrightarrow{P_1}\times\overrightarrow{I_1}+\overrightarrow{P_1}\times\dot{\overrightarrow{I_1}})^T & \dot{\overrightarrow{I_1}} \\ (\Omega_{MP}\overrightarrow{P_1}\times\overrightarrow{I_2}+\overrightarrow{P_1}\times\dot{\overrightarrow{I_2}})^T & \dot{\overrightarrow{I_2}} \\ (\Omega_{MP}\overrightarrow{P_2}\times\overrightarrow{I_3}+\overrightarrow{P_2}\times\dot{\overrightarrow{I_3}})^T & \dot{\overrightarrow{I_3}} \\ (\Omega_{MP}\overrightarrow{P_2}\times\overrightarrow{I_4}+\overrightarrow{P_2}\times\dot{\overrightarrow{I_4}})^T & \dot{\overrightarrow{I_4}} \\ (\Omega_{MP}\overrightarrow{P_3}\times\overrightarrow{I_5}+\overrightarrow{P_3}\times\dot{\overrightarrow{I_5}})^T & \dot{\overrightarrow{I_5}} \\ (\Omega_{MP}\overrightarrow{P_3}\times\overrightarrow{I_6}+\overrightarrow{P_3}\times\dot{\overrightarrow{I_6}})^T & \dot{\overrightarrow{I_6}} \end{bmatrix}$$

Suppose the direct distance (scalar length) between the points $P_j$ and the base reference device is displayed with λ ⃗_j, and the decision is made to find these points by the interpolation method. If the three vectors $\vec{P}_1$ $\vec{P}_2$ $\vec{P}_3$ are displayed in the reference device (base page) and the lengths of these vectors are considered as unknown variables, the relations can be converted to scalar relations using the internal multiplication relation:

$$(\vec{P_i}.\vec{P_j})_E=\vec{\lambda}_j^2$$
$$(\vec{P_i}.\vec{P_j})_E=(\overline{P_{i_1}}.\overline{P_{J_1}}+\overline{P_{i_2}}.\overline{P_{J_2}}+\overline{P_{i_3}}.\overline{P_{J_3}})$$
,
$$(\vec{P_i}-\vec{P_j})_E.(\vec{P_i}-\vec{P_j})_E=\vec{\lambda}_i^2+\vec{\lambda}_j^2-2\vec{P_i}.\vec{P_j}=\vec{C}_i^2)$$
$$\vec{\lambda}_j=\vec{P_j}=\overline{P_{J_1}}x+\overline{P_{J_2}}y+\overline{P_{J_3}}z$$

Now we can define a pyramid by defining quadrilaterals such $b_1b_2\mathrm{E}P_1$ with three $\lambda_1$ ,$\vec{q}_1$,$\vec{q}_2$ two vectors $b_1$,$b_2$. With the above information, the vertex of the point $P_1$ pyramid can be uniquely calculated and obtained.

$$\begin{bmatrix}\lambda_{11}\\ \lambda_{12}\end{bmatrix}=\begin{bmatrix}\frac{2R^2+2\lambda_1^2-L_1^2-L_2^2}{2R\sqrt{3}}\\ \frac{L_1^2-\lambda_2^2}{2}\end{bmatrix} \quad , \quad \lambda_{13}=\sqrt{|\lambda_1^2-\lambda_{11}^2-\lambda_{12}^2|}$$

$$\begin{bmatrix}\lambda_{21}\\ \lambda_{22}\end{bmatrix}=\begin{bmatrix}\cos\frac{2\pi}{3} & -\sin\frac{2\pi}{3}\\ \sin\frac{2\pi}{3} & \sin\frac{2\pi}{3}\end{bmatrix}*\begin{bmatrix}\frac{2R^2+2\lambda_2^2-L_3^2-L_4^2}{2R\sqrt{3}}\\ \frac{L_3^2-L_4^2}{2}\end{bmatrix} \quad , \quad \lambda_{23}=\sqrt{|\lambda_2^2-\lambda_{21}^2-\lambda_{22}^2|}$$

$$\begin{bmatrix}\lambda_{31}\\ \lambda_{32}\end{bmatrix}=\begin{bmatrix}\cos(-\frac{2\pi}{3}) & -\sin(-\frac{2\pi}{3})\\ \sin(-\frac{2\pi}{3}) & \cos(-\frac{2\pi}{3})\end{bmatrix}*\begin{bmatrix}\frac{2R^2+2\lambda_3^2-L_5^2-L_6^2}{2R\sqrt{3}}\\ \frac{L_5^2-L_6^2}{2}\end{bmatrix} \quad ,$$
$$\lambda_{33}=\sqrt{|\lambda_3^2-\lambda_{31}^2-\lambda_{32}^2|}$$

The geometric characteristics of a pre-designed robot are as follows. According to the figure above, the fixed platform is a regular hexagon that is placed in a circumferential circle with a radius of 104 cm. That is, each side of this hexagon is equal to 104 cm. Also, the moving platform is an equilateral triangle that is placed in a circumferential circle with a radius of 54 cm. That is, each side of this hexagon is equal to 93.5 cm. The vector of the corners of the fixed platform with respect to the reference frame E or bi The vector of the corners of the moving platform or $Pj$ with respect to the frame connected to it M is as follows:

$$b_1=\begin{bmatrix}90\\-52\\0\end{bmatrix} b_5=\begin{bmatrix}-90\\-52\\0\end{bmatrix} b_3=\begin{bmatrix}0\\-104\\0\end{bmatrix} b_2=\begin{bmatrix}90\\52\\0\end{bmatrix} b_4=\begin{bmatrix}-90\\52\\0\end{bmatrix} b_6=\begin{bmatrix}0\\-104\\0\end{bmatrix} P_1=\begin{bmatrix}52\\0\\0\end{bmatrix} P_2=\begin{bmatrix}-26\\45\\0\end{bmatrix} P_3=\begin{bmatrix}-26\\-45\\0\end{bmatrix}$$

To analyze a smooth motion for a moving platform, a sinusoidal motion with an amplitude of 20 cm is considered for the three linear coordinates x,y,$z$ In this motion, the angular coordinates of error, torsion, and rotation are kept constant and zero. The position vector of the geometric center of the moving platform is as follows:

$$M_{P_E}=\begin{bmatrix}0\\0\\1.02\end{bmatrix}+\begin{bmatrix}0.2\sin(\frac{\pi t}{3})\\0.2\cos(\frac{\pi t}{3})\\0.2\sin(\frac{\pi t}{3})\end{bmatrix}$$

**The PID controller model in a robot**

The general schematic of the robot, the feedback part and the controller is given in the figure. As shown in the figure, the desired coordinates are given to the controller input. In the feedback section, the length of the jacks is sampled and after direct kinematic solving, the current position of the robot also goes to the controller as input. The controller is inherently multi-input multi-output and simultaneously monitors and controls every 6 degrees of freedom.

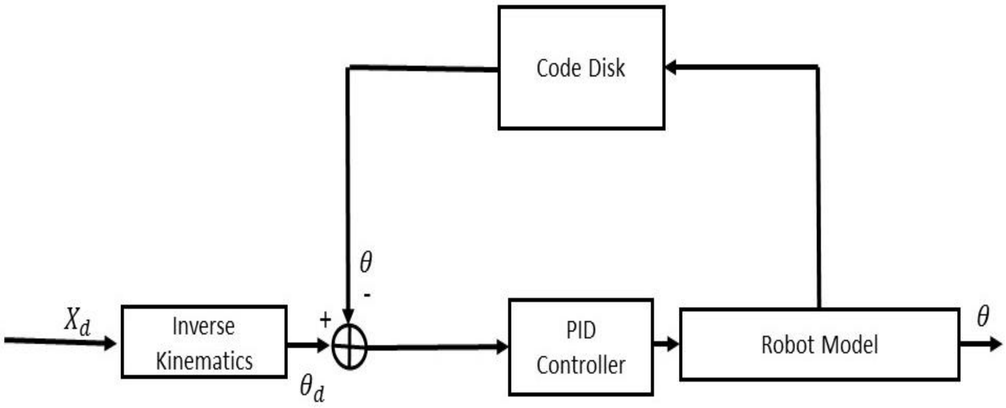



Fig. 3. The traditional PID based on position feedback

The actual true θ is calculated. Although the traditional PID controller can detect the final effect parameter values, the disadvantage of the traditional PID algorithm is obvious because its parameters cannot adjust themselves to control complex and nonlinear subjects. Therefore, this method may cause errors. Fuzzy PID can be applied to this robot, which allows it to cope with the problem of complex nonlinear systems. A fuzzy PID algorithm can adjust the parameters according to the rules designed by the experimenter.

$$u(t) = K_d(\dot{\theta_d} - \theta) - K_p(\theta_d - \theta) - K_i \int_0^t (\theta_d - \theta)\, dt = K_d \dot{e} + K_d e + K_i \int_0^t e\, dt$$

$$G(s) = \frac{u(t)}{e} = K_d s + K_p + \frac{K_i}{s}$$

The process of obtaining the ideal response from the PID controller by setting the PID is called scaling the controller. Adjusting the PID means adjusting the optimal interest rate of the fit, derivative and integral response. The PID controller is scaled to prevent distortion, meaning that it stays at a set point and follows the command, that is, if the set point changes, the controller output follows the new point. If the controller is balanced correctly, the output of the controller will follow the adjustable set point with less oscillation and less attenuation. There are trial and error methods, Ziegler-Nichols 0 method and optimization-based adjustment method to adjust the PID controller parameters. The method used in this dissertation is trial and error method and adjustment method is based on fuzzy method and optimization. In this method, where the parameters are set manually, we first increase the value of Kp until the system reaches an oscillating response, but the system should not be unstable and we set the values of Kd and Ki to zero. Then adjust the Ki value in a similar way to stop the system from oscillating, and finally adjust the Kd value for a quick response.

**FUZZY FRACTIONAL ORDER PID ALGORITHM**

Fractional Order Controller, With the development of modern technology and computer application technology, the theory of FRACTIONAL ORDER CONTROLLER BASED FUZZY CONTROL ALGORITHM fractional order calculus provides a theoretical basis and mathematical tool for the development of many disciplines. Fractional order theories and fractional order co ntroller become new research areas in the control system, the main problem is solving fractional equations. In recent years, numerical methods and algorithms of the fractional calculus improving continuously, analysis methods and control strategy of various fractional order systems are put forward, as well as design method of fractional order controller, which further promotes the application and rapid development of fractional order control.

Fractional order controller can be described by fractional differential equations. These systems that can be described by fractional model and they can be regarded as fractional order control system. From controlling theory of fractional order, closed- loop control system consists of four categories [70, 71]: integer order controller and integer order controlled targets, integer order controller and fractional order controlled targets, fractional order controller and integer order controlled targets, fractional order controller and fractional order controlled targets. App location of fractional calculus in PID controller can enhance controlling performance it is better than traditional PID controllers, significantly [72]. Theoretically, fractional order controller can be used to control targets with any orders, the traditional PID controller is just special case of fractional order controllers.

Professor I. Podlubny proved that the fractional order PIλDμ controller controls better than the integer order on fractional targets, and it can obtain better performance and robustness. The fractional order PIλDμ controller is the generalized form of the conventional PID controller, including an integration order λ and a differential order μ, λ and μ can be any real numbers.

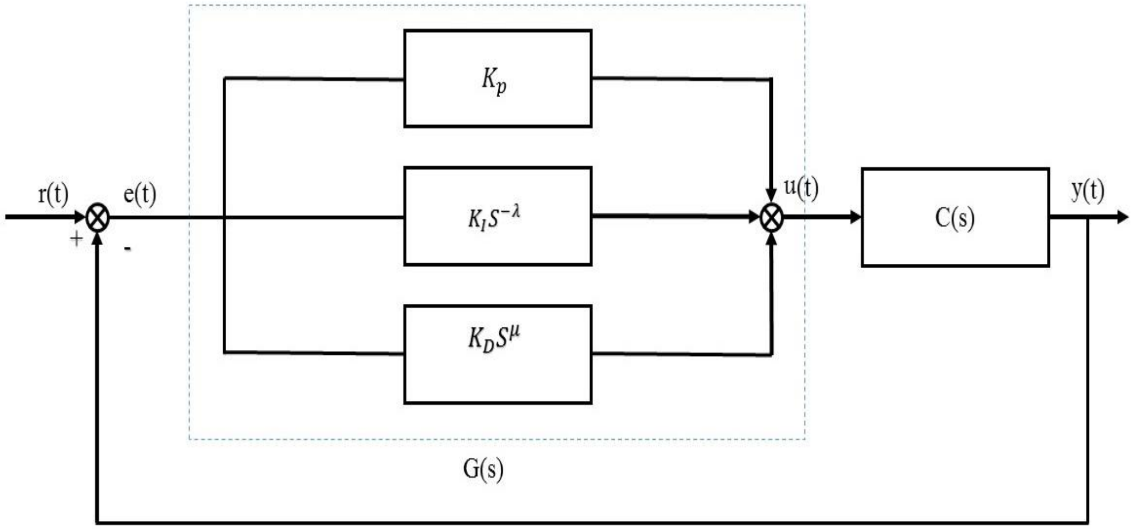



Fig. 4 . Structure diagram of the fractional order PIλDμ controller

In figure 4:

$e(t)$=$r(t)$-$y(t)$ is signal errors of system, it is input signal of fractional order controller;

r(t) is expect signal of fractional order system;

y(t) is the actual output of fractional order system;

G(s) is transfer function of fractional order PIλDμ controller;

C(s) is transfer function of controlled targets.

The transfer function of Fractional PIλDμ controller can be express equation

$$G(S) = K_P + K_I \frac{1}{S^{\lambda}} + K_D S^{\mu}$$
$$u(t) = K_P e(t) + K_I D^{\lambda} e(t) + K_D D^{\mu} e(t)$$

It is similar with integer order PID, in equation:

*K*P is the proportional factor;

*K*I is the integral coefficient;

*K*D is the differential coefficient;

*λ* is the order of integration;

*μ* is the order of differential.

The traditional integer order PID controller is a special case of fractional order PID controller when fractional order PID controller is λ = 1 and μ = 1. When λ = 1 and μ = 0, it is a integer order PI controller; when λ = 0 and μ = 1, it is a integer order PD controller; when λ = 0 and μ = 0, it is a integer order P controller, as shown in figure 5(a). Thus it can be seen which all of these types of PID controllers are special cases of fractional order PID controller [15]. Differently, the parameter values of fractional order PID controller are not on the fixed point, but on the P-I-D plane discretionarily, as shown in figure 5(b).

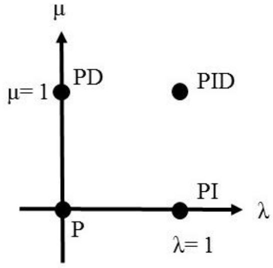



Figure 5(a). Integer order PID controller

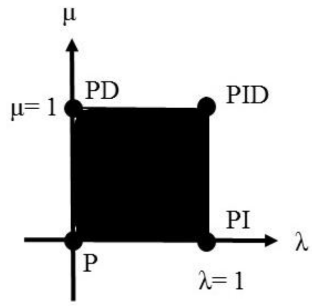



Figure 5(b). Fractional order PID controller

Compare with traditional integer order PID controller, because the fractional order PIλDμ controller has two more adjustable control parameters and μ , It is has more two design freedom. Thus, it is difficult for tuning and optimizing these five parameters. But it is easier to change frequency response of the control system by changing the order of differentiation and integration, which is compare with changing controller proportional, differential and integral coefficients. So we can get the better dynamic performance and robustness than traditional integer order PID.

Fractional Order PID Algorithm Fractional calculus as a new language, it has its own unique logic and grammar rules. Fractional calculus allows any one order to be calculus order and it is extension of classic integer calculus. Fractional calculus has no uniform mathematics definition. Currently, there are three fractional definitions [73]: Riemann-Liouvile definition, Grünwald-Lethnikov definition and Caputo definition.in the GL(Grünwald-Letnikov) fractional calculus definition

$$\boldsymbol{D_t^{\alpha}\mathcal{F}(t)=\lim_{h\to 0} h^{-\alpha}\sum_{j=0}^{[\frac{t-\alpha}{h}]}(-1)^j\binom{\alpha}{j}\mathcal{F}(t-jh)}$$

in equation:
$\boldsymbol{D_t^{\alpha}}$□is the fractional calculus operator;
□□is the calculus order, meanwhile, it could be a real number;
□□and $t$ represent the bounds of the fractional operators, $\binom{\boldsymbol{\alpha}}{\boldsymbol{j}}=\frac{\alpha!}{j!(\alpha-j)!}$
According to the GL fractional calculus definition, discretize the equation [73], the fractional order PID expression is gotten as shown in equation

$$u(k)=K_Pe(t)+K_IT_s^{\lambda}\sum_{j=0}^{k}q_j\,e(k-j)+K_DT_s^{-\mu}\sum_{j=0}^{k}d_j\,e(k-j)$$

in equation:
*Ts* is the sampling time;
*q*j and *d*j are binomial coefficients;
*u(k)* is the output of controller,
*e(k)* is the deviation of controller.

Because of its technical features, such as serious nonlinearity, variable structure and parameters, it is difficult to establish the precise mathematical model of the SRM. It could not obtain ideal performance indicators using the conventional fixed parameter PID control method with various control strategies. The order of integral and differential can be extended to any real number in conventional controller by Fractional calculus, it provide a better performance extension for the design of controller.

Fuzzy control method is a way of intelligent control method that it is used in the control engineering application widely. It is a kind of nonlinear control strategy essentially and is not depend on exact mathematical model of controlled object. It could obtain better control effect at nonlinear, time-varying, time-delay or variable structure control objects by the fuzzy control method, especially at the switched reluctance motor which is very difficult to be established the exact model. In recent years, more and more research and application have been acquired about fuzzy control method.

Combined with fractional proportional PID controller and fuzzy control logic, the fuzzy fractional PID controller can be created. It has characteristics of intelligent inference and nonlinear, particularly the PID controller based on fuzzy logic self-tuning parameters. It could obtain better control effect at complex control objects when it is used for some complex control object which is difficult to be modeled. [74] completed fuzzy fractional order PID control algorithm to fuzzy reasoning through fuzzy inference's proportional coefficient $KP$、integral coefficient $KI$ and differential coefficient $KD$ and regulated the weight of each aspect.

This paper achieve the fuzzy fractional order PID control algorithm by choosing proportional coefficient $K$P、integral order $\lambda$ and derivative order $\mu$ to complete fuzzy reasoning. The principle diagram of fuzzy fractional order PID controller is shown in figure 6. Both deviation and deviation rate are as the input of fuzzy reasoning, and proportional coefficient 、integral order and derivative order as the output of fuzzy inference, the controller object can be controlled by passing these three parameters to the fractional order PID controller

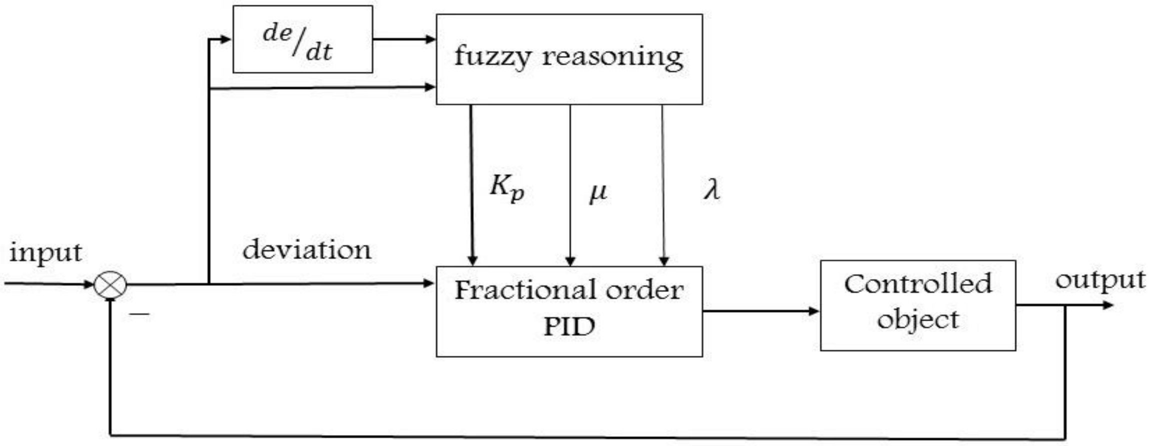



Figure 6. The principle diagram of fuzzy fractional order PID controller

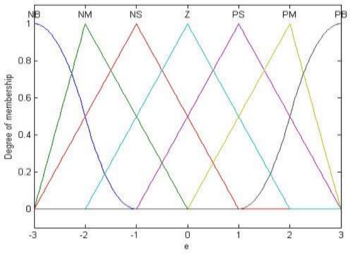
The proper movement of a robot arm can be achieved with the right settings to meet the exact needs. If the desired path is specified, the PID controller is placed in the above linear system. Features time-based geometric motion, especially interactions between different links over time. Kinematics and their position and orientation The links are described in a separate coordination. The kinematic model is based on previous calculations and the parameters of the Servo Mac link. The kinematics in question and the kinematic model and the relationship between the position $\boldsymbol{P} = (P_x,P_Y,P_Z)$ from the end of the effector and the angular joint θ According to the link to the position and orientation of the reference coordination system, inverse kinematics is used to calculate each common variable. The error between the desired joint and the actual angular joint is considered as input.

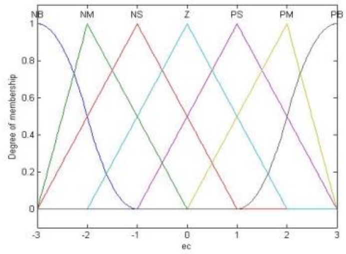
**The fuzzy PID control algorithm**

In the value controller

$ec = (\dot{\theta_d} - \dot{\theta})\, , e = (\theta_d - \theta)$

Are considered as inputs; These are exported to a robot arm by the controller model. The common angular error ec and e is transmitted to the fuzzy controller; The values Δkp, Δki "," Δkd are issued by the fuzzy controller. The values Δkp, Δki "," Δkd are considered as PID control inputs for setting the values Δkp, Δki "," Δkd ". The three optimal parameters Δkp, Δki, Δkd are set from the PID controller by the fuzzy controller. Fuzzy laws are shown as equations (5). Fuzzy subsets PB, PM, PS, Z, NS, NM, NB and fuzzy domain -3, -2, -1, 0, 1, 2, 3 where PB, PM, PS, Z, NS, NM , NB for large negative, medium negative, small negative, zero, small positive, medium positive and large positive. E indicates the error and ec indicates the error. The attribution function for each fuzzy variable is shown, which shows the membership performance curves of e, ec, 〖dK〗 _d, 〖dK〗 _i, 〖dK〗 _p, respectively. The number of fuzzy sets is selected based on the desired production needs. In general, there is no specific design method. The error between the joint angle and the actual joint angle of the final joint is considered as input, denoted by e. The value of e is fuzzy with respect to the fuzzy controller used in fuzzy operators. This is the process of fuzzy reasoning, which obtains the optimal fuzzy value. (fig 6-1,6-2,6-3)To obtain the exact value, which is used in the robot mathematical model, the desired fuzzy value must be fuzzy



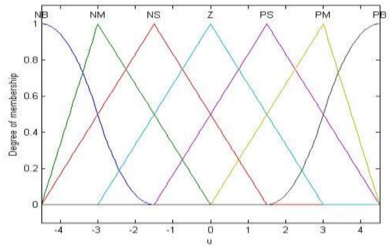




Fig 6-1 Membership function curves of *e* and *ec*
fig 6-2 Membership function curves of $dK_p$ and $dK_i$
fig 6-3 Membership function curves of $dK_d$

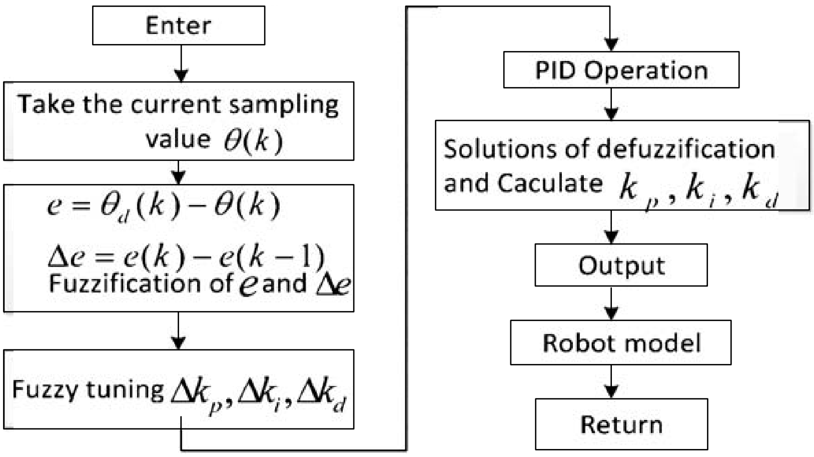



Fig 7 The fuzzy PID algorithm flow chart

Three positive fuzzy sets are needed to cover the input and output variables: The analysis of the force between the arm and the path of motion driven by the robot arm is considered. By combining the proposed paths and default conditions, three different fuzzy rules are used and three parameters Kp, Ki, Kd can be designed to be applied to the PID controller and the fuzzy PID controller. Fuzzy rules must be clearly classified to increase effectiveness. However, many rules have a negative impact on system stability. Depending on the situation, if the fuzzy sets have less than two rules, the fuzzy subset becomes NB, NS, Z, PS, PB. Because the robot arm travels irregularly, the two laws cannot meet the need for change, which must change. However, if there are too many rules, the stability of the final effect is reduced. Therefore, three fuzzy sets are more logical. In the PID system, the response speed and steady-state error are affected by the value of Kp. At the beginning of the setting, the Kp value is increased to achieve a faster response speed. In the middle of the regulation, smaller shifts and faster response times should be considered and the Kp value should be reduced. Increasing Kp in the end increases the accuracy of the arm. KpΔ is the compensatory value. Integral also fixes system steady state error. At the beginning of the adjustment, Ki is unchanged to prevent integral saturation Fig 7. In the middle of the regulation, Ki rises to ensure system stability. Finally, as Ki increases, the static error decreases. kiΔ is the compensation value. Differential can change dynamic properties. At the beginning of the adjustment, Kd is increased to prevent excessive rotation of the robot arm. In the middle of the setting, Kd is reduced to a constant. In the end, to reduce the time, Kd is further reduced

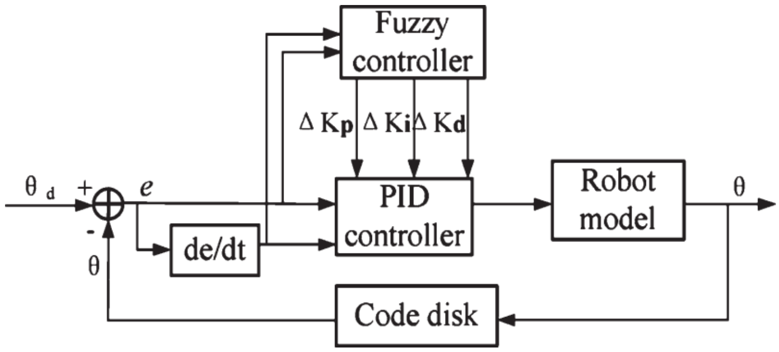



Fig 8 The fuzzy PID controller.

Fuzzy control rules When e is greater, $\Delta kp$ must be larger, kdΔ smaller and $\Delta ki = 0$ When e is an average value, $\Delta kp$ must be reduced, $and\ \Delta kd\ and\ \Delta ki$ must be of average value. When e is a smaller value, $\Delta kp$ and $\Delta\ ki$ must be greater and $\Delta kd$ must be an average value. The rules for fuzzy PID controller are as follows

$e = NL, ec = NL$ ⇒ $\Delta Kp = PL$, $\Delta Ki = NB, \Delta Kd = PS$.

$e = NM, ec = NL$ ⇒ $\Delta Kp\ is\ PL$, $\Delta Ki = NB, \Delta Kd = PS$.

$e = PL, ec = PL$ ⇒ $\Delta Kp = NL$, $\Delta Ki = PB, \Delta Kd = PB$

Table3 $\Delta Kp$

| e/ec | NL | NM | NS | ZE | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | 3 | 3 | 3 | 3 | 2 | 1 | 0 |
| NM | 3 | 3 | 3 | 3 | 2 | 0 | 0 |
| NS | 2 | 2 | 2 | 2 | 0 | 1 | 1 |
| ZE | 2 | 2 | 1 | 0 | -1 | -1 | -1 |
| PS | 1 | 1 | 0 | -2 | -2 | -2 | -2 |
| PM | 1 | 0 | -1 | -2 | -2 | -2 | -3 |
| PL | 0 | 0 | -2 | -2 | -2 | -3 | -3 |

Table 4 $\Delta Ki$

| e/ec | NL | NM | NS | ZE | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | -3 | -3 | -2 | -2 | -1 | 0 | 0 |
| NM | -3 | -3 | -2 | -1 | -1 | 0 | 0 |
| NS | -3 | -2 | -1 | -1 | 0 | 1 | 1 |
| ZE | -2 | -2 | -1 | 0 | 1 | 2 | 2 |
| PS | -2 | -1 | 0 | 1 | 1 | 2 | 3 |
| PM | 0 | 0 | 1 | -2 | 2 | 3 | 3 |
| PL | 0 | 0 | 1 | 2 | 2 | 3 | 3 |

Table 5 $\Delta Kd$

| e/ec | NL | NM | NS | ZE | PS | PM | PL |
|---|---|---|---|---|---|---|---|
| NL | 1 | -1 | -3 | -3 | -3 | -2 | 1 |
| NM | 1 | -1 | -3 | -2 | -2 | -1 | 0 |
| NS | 0 | -1 | -2 | -1 | -1 | -1 | 0 |
| ZE | 0 | -1 | -1 | -1 | -1 | -1 | 0 |
| PS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PM | 0 | 1 | 1 | 1 | 1 | 1 | 3 |
| PL | 3 | 2 | 2 | 2 | 1 | 1 | 3 |

$u(t) = \acute{K}_d(\dot{\theta_d} - \dot{\theta}) - \acute{K}_p(\theta_d - \theta) - \acute{K}_i \int_0^t (\theta_d - \theta)\, dt$

$$\acute{K}p = kp + \Delta kp$$
$$\acute{K}i = ki + \Delta ki$$
$$\acute{K}d = kd + \Delta kd$$

$\acute{K}p \,.\, \acute{K}i \,.\, \acute{K}d$

Are improved values modified by the fuzzy PID controller Kp, Ki, Kd are the main values. The center mean method was used for reduction. The output u is calculated as follows: .

$du \frac{\sum_{i=1}^{n} du_i \mu_{Ai}}{\sum_{i=1}^{n} \mu_{Ai}}$

If the input is known, the output can be calculated with the above equations. To control the path of the final effect from the combination of the above equations, Kp, Ki, Kd are obtained. The path of motion Kp, Ki, Kd is set by fuzzy PID under processing conditions.

**Experiments and simulation analysis**

Controllers built with soft computing methods such as fuzzy have excellent capabilities in dealing with indeterminate and nonlinear systems. Especially if the advantages of these methods are combined in a network such as fuzzy. But there is a point in this. Network performance is highly dependent on proper design; And this also depends on the designer's sufficient knowledge of the overall performance of the system. However, the use of the advantages of different control methods and their combination, such as proportional-fuzzy, along with taking into account the necessary considerations, provides better and newer control tools. In this paper, more than the control of the Stewart robot, it has been important to create the ability to control systems with uncertainty, several degrees of freedom and nonlinearity. They are sampled at any time. Fuzzy PID algorithm improves performance and accuracy. The simulation results show that the fuzzy PID algorithm meets the debugging processing needs and in comparison with the PID controller, the fuzzy PID controller ensures the stability of the closed loop system and selects the appropriate parameters according to the control rules. . In this paper, the results of simulating the position of a moving geometric center (Stewart) and simulating a 6-degree freedom arm using a fixed coefficient PID controller, a fuzzy controller and a fuzzy PID controller optimized by a genetic algorithm are presented. The results of arm simulation of six degrees of freedom using fixed, fuzzy and fuzzy PA controllers optimized with GA were also presented. System response performance was significantly improved by fuzzy controllers, with GA-optimized fuzz performing better than fuzzy.

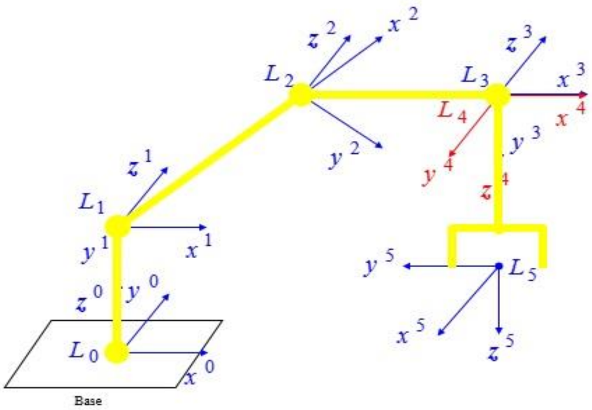



Fig 9 Dynamic analysis of the robot arm is shown

In this simulation with MATLAB, the geometric characteristics of a pre-designed robot are given in Chapter 3 and the position of the geometric center of the moving platform is shown, which indicates the distance between the corners of the moving platform and the origin of the reference device.

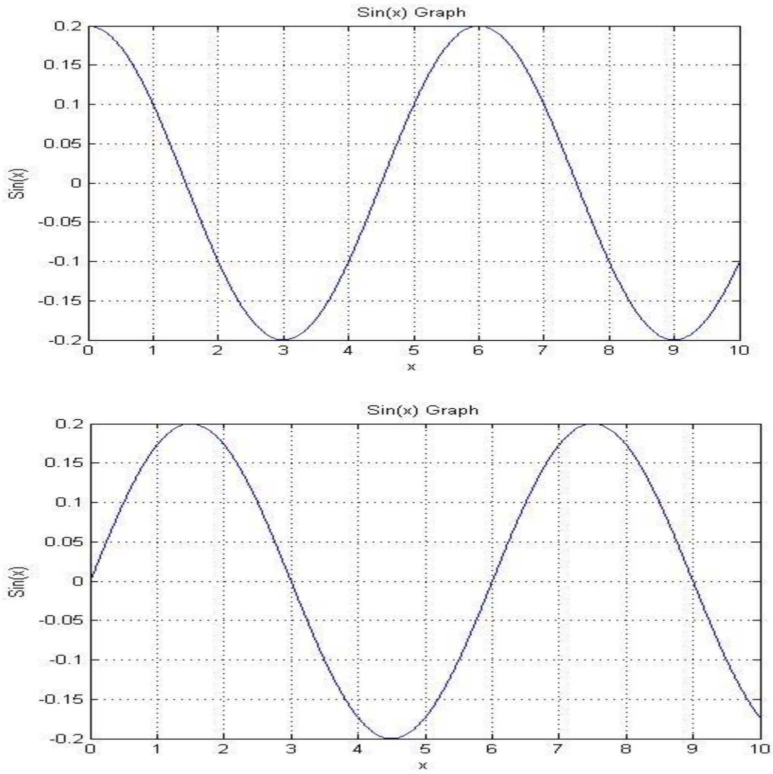



Fig 10 The system simulation is displayed using Stuart robot kinematic numerical analysis

In this section, the results of the simulation using the classic PID controller using feedback are reviewed. In this simulation, the desired value is considered. There are different methods for designing PID controller coefficients. In this research, trial and error method has been used to achieve the minimum fluctuations and the time to achieve the desired value. By optimizing fuzzy membership functions by genetic algorithm, system performance, especially error reduction, is improved. Figure 10 shows the system response to a fixed input for the intended controllers. From this figure we can see the better performance of fuzzy PID controllers and optimal fuzzy PID than PID and WOA-PID. Figure 10 shows the system response to a fixed input for the intended controllers.

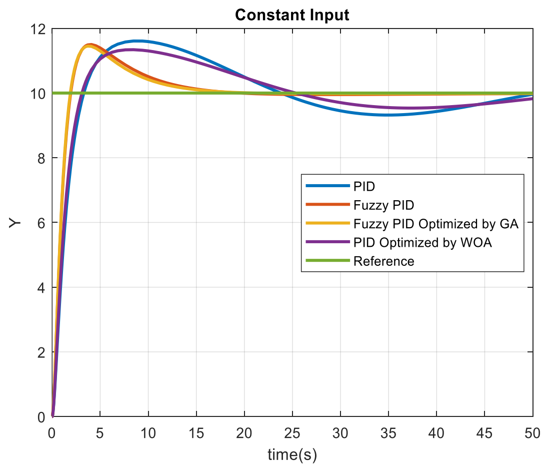



Fig 11The system output is displayed for fixed input mode

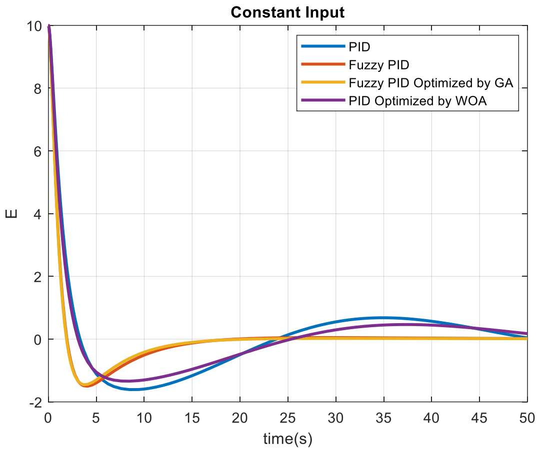



Fig 12 System error is displayed for fixed input mode

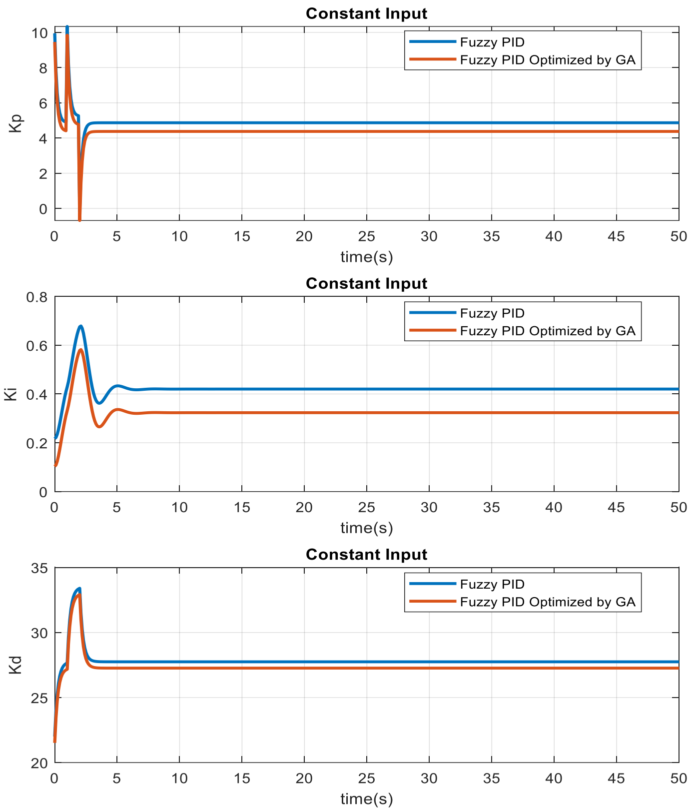



Fig 13 Simulation of the value of fuzzy and optimal PID control coefficients with genetic algorithm for fixed input mode is shown

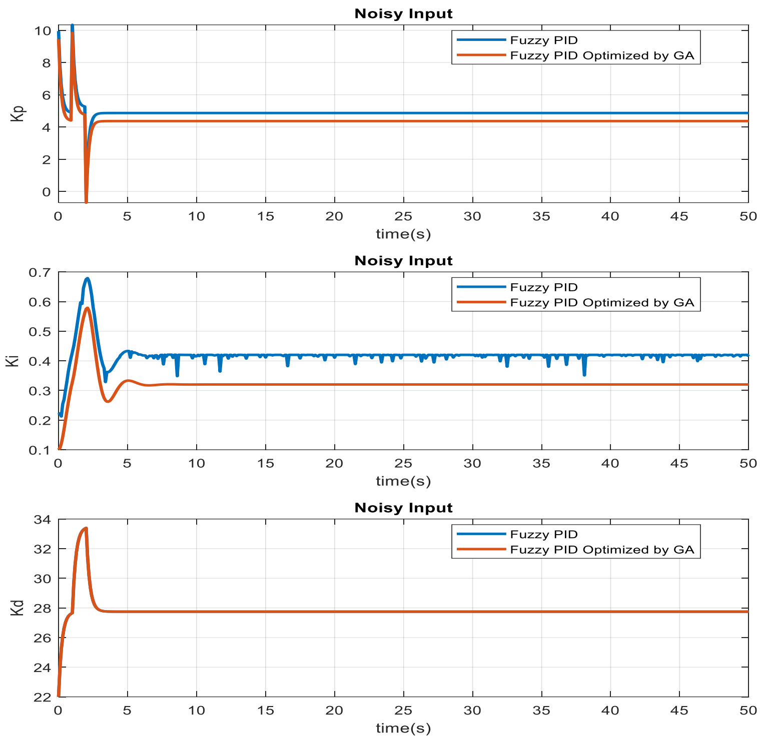



Fig 14 The coefficients of the controllers for the noise input mode are displayed

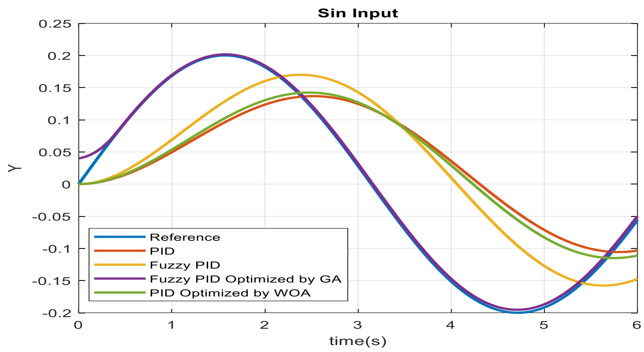



Fig 15 The system output is displayed for sine input mode

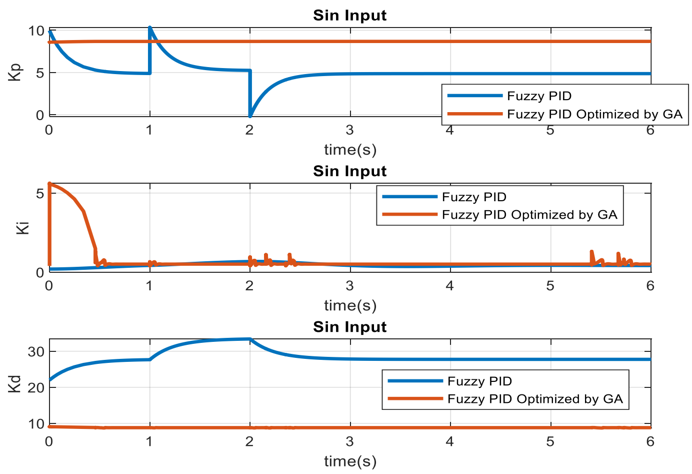



Fig16 The coefficients of the controllers for the sine input mode are displayed

**Conclusion**

From all these figures it can be seen that the fuzzy and fuzzy controllers optimized with GA performed much better than the fixed PID. The worst case scenario of uncertainty is related to Scenario 1. Although the system response with PID controller is fluctuating and has many errors, but the controllers based on fuzzy logic have been able to change the controller coefficients well by changing the conditions in the face of uncertainty. Achieve much better and less error. Among the fuzzy logic-based controllers, the GA-optimized fuzzy controller performed better because its membership functions were optimally performed by a genetic algorithm. The table below shows the values of the different indicators for different scenarios and the optimal PID, WOA-PID, fuzzy PID and fuzzy PID controllers. From the results it can be seen that the performance of fuzzy PID optimized with GA in other cases was better than other controllers.

In this paper, the results of simulation of a robot arm with six degrees of freedom using fixed, fuzzy and fuzzy PA controllers optimized with GA were presented. System response performance was significantly improved by fuzzy controllers, with GA-optimized fuzz performing better than fuzzy. In this paper, the results of simulation of a robot with six degrees of freedom using fixed PID, fuzzy PID and GA-optimized fuzzy PID controllers were presented. System response performance was significantly improved by fuzzy PID controllers, with GA-optimized fuzzy PID performing slightly better than fuzzy PID. However, to improve the performance of the system, adaptive controllers can be used, which can adjust the controller coefficients adaptively under the conditions of changes in system conditions and parameters, as well as the uncertainty of the model parameters. In general, controllers built with soft computing methods such as fuzzy have excellent capabilities in dealing with indeterminate and nonlinear systems. Especially if the advantages of these methods are combined in a network such as fuzzy PID. But there is a point in this. Although neither the designer nor the controller need to know the math inside the system, the performance of the network depends heavily on its proper design; And this also depends on the designer's sufficient knowledge of the overall performance of the system. However, using the advantages of different control methods and combining them, such as fuzzy PID and optimization with genetic algorithm (an innovative adaptive search algorithm), together with possible considerations, provides better and newer control tools. In this project, more than anything, it has been important to create the ability to control systems with uncertainty, several degrees of freedom and nonlinearity. In fact, the control goal of this system is to quickly achieve the desired amount of output, so for the first time, this hybrid model was proposed with a smooth motion analysis for the moving platform and controllers that are a combination of other controllers. To adjust the output value of the fuzzy PID controller method optimized with the Genetically Adaptive Innovative Algorithm, it has been considered in the design and the results indicate that the fuzzy PID optimized with the Genetically Adaptive Innovative Algorithm is superior to the fuzzy PID PID controllers. it works. An optimized fuzzy PID algorithm with an innovative adaptive genetic algorithm improves efficiency and accuracy. The simulation results show that the fuzzy PID algorithm optimized with the Genetically Adaptive Innovative Algorithm meets the debugging processing needs, and compared to the PID controller and the fuzzy PID controller, the fuzzy PID optimized with the innovative Genetic Adaptability Genetic Innovation Algorithm Ensures the closed loop and selects the appropriate parameters according to the control rules.

**Reference**

[1] EDWARS M. Robots in industry: An overview [J]. Applied Ergonomics, 1984, 15(1): 45–53.

[2] SAGE H G, De MATHELIN M F, OSTERTAG E. Robust control of robot manipulators: A survey [J]. International Journal of Control, 1999, 72(16): 1498–1522.

[3] KOLHE J P, SHAHEED M, CHANDAR T S, TALOLE S E. Robust control of robot manipulators based on uncertainty and disturbance estimation [J]. International Journal of Robust and Nonlinear Control, 2013, 23(1): 104–122.

[4] KHOUKHI A, HAMAM Y. Optimal control for robot manipulators. in optimization, optimal control and partial
differential equations [M]. Birkhäuser Basel: Springer, 1992: 207–218.

[5] SADATI N, BABAZADEH A. Optimal control of robot manipulators with a new two-level gradient-based approach [J]. Electrical Engineering, 2006, 88(5): 383–393.

[6] HUANG A C, CHIEN M C. Adaptive control of robot manipulators: A unified regressor-free approach [M]. World
Scientific, 2010.

[7] HSU S H, FU L C. A fully adaptive decentralized control of robot manipulators [J]. Automatics, 2006, 42(10):
1761–1767.

[8] CERVANTES I, ALVAREZ-RAMIREZ J. On the PID tracking control of robot manipulators [J]. Systems & Control Letters, 2001, 42(1): 37–46.
[9] JAFAROV E M, PARLAKÇI M A, ISTEFANOPULOS Y. A new variable structure PID-controller design for robot manipulators [J]. IEEE Transactions on Control Systems Technology, 2005, 13(1): 122–130.
[10] PILTAN F, YARMAHMOUDI M H, SHAMSODINI M, MAZLOMIAN E, HOSAINPOUR A. PUMA-560 robot manipulator position computed torque control methods using Matlab/Simulink and their integration into graduate
nonlinear control and Matlab courses [J]. International Journal of Robotics and Automation, 2012, 3(3): 167–191.
[11] BABAIASL M, GHANBARI A, NOORANI S.Anthropomorphic mechanical design and Lyapunov-based
control of a new shoulder rehabilitation system [J]. Engineering Solid Mechanics, 2014, 2(3): 151–162.
[12] MAHMOOD M, MHASKAR P. Lyapunov-based model predictive control of stochastic nonlinear systems [J].
Automatics, 2012, 48(9): 2271–2276.
[13] WEN J T, MURPHY S H. PID control for robot manipulators [M]. Rensselaer Polytechnic Institute, 1990.
[14] KHELFI M, ABDESSAMEUD A. Robust H-infinity trajectory tracking controller for a 6 Dof PUMA 560 robot
manipulator [C]// International Electric Machines & Drives Conference (IEMDC 2007). IEEE, 2007: 88–94.
[15] ANKELHED D. On design of low order H-infinity control [D]. Sweden: Linköping University Electronic Press, 2011.
[16] FAUSETT L. Fundamentals of neural networks: Architectures, algorithms, and applications [M]. USA: Prentice-Hall Press, 1994.
[17] KUMAR N, PANWAR V, SUKAVANAM N, SHARMA S P, BORM J H. Neural network based hybrid force/position control for robot manipulators [J]. International Journal of Precision Engineering and Manufacturing, 2011, 12(3):419–426.
[18] KUMAR N, PANWAR V, SUKAVANAM N, SHARMA S P, BORM J H. Neural network-based nonlinear tracking control of kinematically redundant robot manipulators [J]. Mathematical and Computer Modelling, 2011, 53(9): 1889–1901.
[19] WANG L, CHAI T, YANG C. Neural-network-based contouring control for robotic manipulators in operational
space [J]. IEEE Transactions on Control Systems Technology, 2012, 20(4): 1073–1080.
[20] YU L, FEI S, HUANG J, GAO Y. Trajectory switching control of robotic manipulators based on RBF neural networks [J]. Circuits, Systems, and Signal Processing, 2014, 33(4): 1119–1133.
[21] WANG L X. A course in fuzzy systems [M]. USA: Prentice-Hall Press, 1999.
[22] SONG Z, YI J, ZHAO D, LI X. A computed torque controller for uncertain robotic manipulator systems: Fuzzy approach [J]. Fuzzy Sets and Systems, 2005, 154(2):208–226.
[23] PILTAN F, HAGHIGHI S T, SULAIMAN N, NAZARI I, SIAMAK S. Artificial control of PUMA robot manipulator: A review of fuzzy inference engine and application to classical controller [J]. International Journal of Robotics and Automation, 2011, 2(5): 401–425.
[24] SICILIANO B, SCIAVICCO L, VILLANI L, ORIOLO G. Robotics: Modelling, planning and control [M]// Advanced Textbooks in Control and Signal Processing. Springer, 2009: 29.
[25] SPONG M W, HUTCHINSON S, VIDYASAGAR M. Robot dynamics and control [M]. New York: John Wiley & Sons, 2004.
[26] BABAIASL M, GHANBARI A, NOORANI S M R. Mechanical design, simulation and nonlinear control of a
new exoskeleton robot for use in upper-limb rehabilitation after stroke [C]// Biomedical Engineering (ICBME 2013).
Iran: IEEE, 2013: 5–10.
[27] GHOBAKHLOO A, EGHTESAD M, AZADI M. Position control of a Stewart-Gough platform using inverse
dynamics method with full dynamics [C]// International Workshop on Advanced Motion Control. IEEE, 2006: 50–55.
[28] SLOTINE J J E, LI W. Applied nonlinear control [M]. Englewood Cliffs, NJ: Prentice-Hall Press, 1991.
[29] PILTAN F, EMAMZADEH S, HIVAND Z, SHAHRIYARI F, MIRAZAEI M. PUMA-560 robot manipulator position sliding mode control methods using MATLAB/SIMULINK and their integration into graduate/undergraduate nonlinear control, robotics and MATLAB courses [J]. International Journal of Robotics and Automation, 2012, 3(3): 106–150.
[30] CORRADINI M L, FOSSI V, GIANTOMASSI A, IPPOLITI G, LONGHI S, ORLANDO G. Discrete time sliding mode control of robotic manipulators: Development and experimental validation [J]. Control Engineering Practice, 2012, 20(8): 816–822.
[31] CORRADINI M L, FOSSI V, GIANTOMASSI A, IPPOLITI G, LONGHI S, ORLANDO G. Minimal resource allocating networks for discrete time sliding mode

control of robotic manipulators [J]. IEEE Transactions on Industrial Informatics, 2012, 8(4): 733–745.

[32] CAPISANI L M, FERRARA A, MAGNANI L. Second order sliding mode motion control of rigid robot manipulators [C]// Decision and Control. IEEE, 2007: 3691–3696.

[33] CAPISANI L M, FERRARA A, MAGNANI L. Design and experimental validation of a second-order sliding-mode motion controller for robot manipulators [J]. International Journal of Control, 2009, 82(2): 365–377.

[34] CAPISANI L M, FERRARA A. Trajectory planning and second-order sliding mode motion/interaction control for robot manipulators in unknown environments [J]. IEEE Transactions on Industrial Electronics, 2012, 59(8): 3189–3198.

[35] JIN M, LEE J, CHANG P H, CHOI C. Practical nonsingular terminal sliding-mode control of robot manipulators for high-accuracy tracking control [J]. IEEE Transactions on Industrial Electronics, 2009, 56(9): 3593–3601.

[36] BABAIASL M, GOLDAR S N, BARHAGHTALAB M H, MEIGOLI V. Sliding mode control of an exoskeleton robot for use in upper-limb rehabilitation [C]// Robotics and Mechatronics (ICROM 2015). Tehran, Iran: IEEE, 2015: 694–701.

[37] NEKOUKAR V, ERFANIAN A. Adaptive fuzzy terminal sliding mode control for a class of MIMO uncertain
nonlinear systems [J]. Fuzzy Sets and Systems, 2011, 179(1): 34–49.

[38] PILTAN F, SULAIMAN N, ROOSTA S, GAVAHIAN A, SOLTANI S. Artificial chattering free on-line fuzzy sliding mode algorithm for uncertain system: Applied in robot manipulator [J]. International Journal of Engineering, 2011, 5(5): 360–379.

[39] PILTAN F, SULAIMAN N, ZARE A, ALLAHHDADI S, DIALAME M. Design adaptive fuzzy inference sliding mode algorithm: Applied to robot arm [J]. International Journal of Robotics and Automation, 2011, 2(5): 283–297.

[40] PILTAN F, AGHAYARI F, RASHIDIAN M R, SHAMSODINI M. A new estimate sliding mode fuzzy controller for robotic manipulator [J]. International Journal of Robotics and Automation, 2012, 3(1): 45–58.

[41] JALALI A, PILTAN F, GAVAHIAN A, JALALI M. Model-free adaptive fuzzy sliding mode controller optimized by particle swarm for robot manipulator [J]. International Journal of Information Engineering and Electronic Business, 2013, 5(1): 68.

[42] PILTAN F, NABAEE A, EBRAHIMI M, BAZREGAR M. Design robust fuzzy sliding mode control technique for robot manipulator systems with modeling uncertainties [J]. International Journal of Information Technology and Computer Science, 2013, 5(8): 123–135.

[43] SOLTANPOUR M R, KHOOBAN M H, SOLTANI M. Robust fuzzy sliding mode control for tracking the robot manipulator in joint space and in presence of uncertainties [J]. Robotics, 2014, 32(3): 433–446.

[44] SOLTANPOUR M R, OTADOLAJAM P, KHOOBAN M H. Robust control strategy for electrically driven robot
manipulators: Adaptive fuzzy sliding mode [J]. IET Science, Measurement & Technology, 2014, 9(3): 322–334.

[45] SOLTANPOUR M R, KHOOBAN M H. A particle swarm optimization approach for fuzzy sliding mode control for tracking the robot manipulator [J]. Nonlinear Dynamics, 2013, 74(1, 2): 467–478.

[46] VEYSI M, SOLTANPOUR M R, KHOOBAN M H. A novel self-adaptive modified bat fuzzy sliding mode control of robot manipulator in presence of uncertainties in task space [J]. Robotics, 2015, 33(10): 2045–2064.

[47] WAI R J, YANG Z W. Adaptive fuzzy neural network control design via a T–S fuzzy model for a robot manipulator including actuator dynamics [J]. IEEE Transactions on Systems, Man, and Cybernetics: Part B (Cybernetics), 2008, 38(5): 1326–1346.

[48] WAI R J, HUANG Y C, YANG Z W, SHIH C Y. Adaptive fuzzy-neural-network velocity sensorless control for robot manipulator position tracking [J]. IET Control Theory & Applications, 2010, 4(6): 1079–1093.

[49] BACHIR O, ZOUBIR A F. Adaptive neuro-fuzzy inference system based control of puma 600 robot manipulator [J]. International Journal of Electrical and Computer Engineering, 2012, 2(1): 90–97.

[50] CHAUDHARY H, PANWAR V, PRASAD R, SUKAVANAM N. Adaptive neuro fuzzy based hybrid
force/position control for an industrial robot manipulator [J]. Journal of Intelligent Manufacturing, 2016, 27(6): 1299–1308.

[51] WANG L, CHAI T, ZHAI L. Neural-network-based terminal sliding-mode control of robotic manipulators including
actuator dynamics [J]. IEEE Transactions on Industrial Electronics, 2009, 56(9): 3296–3304.

[52] SUN T, PEI H, PAN Y, ZHOU H, ZHANG C. Neural network-based sliding mode adaptive control for robot
manipulators [J]. Neurocomputing, 2011, 74(14): 2377–2384.

[53] WAI R J, MUTHUSAMY R. Fuzzy-neural-network inherited sliding-mode control for robot manipulator including actuator dynamics [J]. IEEE Transactions on

Neural Networks and Learning Systems, 2013, 24(2): 274–287.
[54] WAI R J, MUTHUSAMY R. Fuzzy-neural-network control for robot manipulator via sliding-mode design [C]// Control Conference (ASCC 2013). Asian: IEEE, 2013: 1–6.
[55] HU H, WOO P Y. Fuzzy supervisory sliding-mode and neural-network control for robotic manipulators [J]. IEEE
Transactions on Industrial Electronics, 2006, 53(3): 929–940.
[56] KHOOBAN M H, NIKNAM T, BLAABJERG F, Dehghani M. Free chattering hybrid sliding mode control for a class of non-linear systems: Electric vehicles as a case study [J]. IET Science, Measurement & Technology, 2016, 10(7): 776–785.
[57] BARHAGHTALAB M H, MEIGOLI V. Robot manipulator position control using hybrid control method based on sliding mode and ANFIS with fuzzy supervisor [J]. International Journal of Control Theory and Applications,2015, 8(4): 1281–1291.
[58] J. P. Kolhe, M. Shaheed, T. Chandar, and S. Talole, "Robust control of robot manipulators based on uncertainty and disturbance estimation," International Journal of Robust and Nonlinear Control, vol. 23, pp. 104-122, 2013.
[59] A. Mishkat and N. Verma, "ROBUST CONTROL OF ROBOTIC MANIPULATOR," 2014.
[60] P. Agnihotri, V. Banga, and E. G. Singh, "ANFIS Based Forward and inverse Kinematics of Robot Manipulator with five Degree of Freedom," 2015.
[61] H.Wang,( 2017),"Adaptive control of robot manipulators with uncertain kinematics and dynamics," IEEE Transactions on Automatic Control, vol. 62, pp. 948- 954
[62] Y.Zhao,( 2014),"Study on Predictive Control for Trajectory Tracking of Robotic Manipulator," Journal of Engineering Science & Technology Review, vol. 7
[63] Jianjun He, Hong Gu and Zhelong Wang, (2013),"Solving the forward kinematics problem of six-DOF Stewart platform using multi-task Gaussian process" journals.sagepub
[64] P.Van Cuong and W. Y. Nan, (2016),"Adaptive trajectory tracking neural network control
[65] B.Zolghadr-Asli, O. Bozorg-Haddad, X. Chu, (2018),"Crow search algorithm (CSA)". In: O. Bozorg-Haddad (eds) Advanced Optimization by Nature-Inspired Algorithms. Studies in Computational Intelligence, vol. 720. Springer,
[66] G.Li,B.Shi, and R.Liu(2019),"Dynamic Modeling and Analysis of a Novel 6-DOF RoboticCrusher Based on Movement Characteristics", hindawi
[67] N.Dersarkissian,R.Jia1,D.Feitosa,( 2018),"Control of a Two-link Robotic Arm using Fuzzy Logic International Conference on Information and Automation Mountain,China
[68] D.Pan, F. Gao, Y.J. Miao and R. Cao, Co-simulation research of a(2015), " novel exoskeleton-human robot system on humanoid gaits with Fuzzy PID/PID algorithms", Advances in Engineering Software
[69] W. Zhang, X. Gong, G. Han, Y. Zhao,( 2017) "An improved ant colony algorithm for path planning in one scenicarea with many spots", IEEE Access, vol. 5, pp. 13260-13269
[70] Li Hongsheng, "fractional-order control and PIλDμ controller design and progress", Machine Tool & Hydraulics, Vol. 35, No.7, 2007, pp. 237-240.
[71] Bhaskaran T, Chen Y Q, Xue D Y. "Practical turning of fractional order proportional and integral controller(I): tuning rule development.//Proceeedings of the ASME 2007 International Design Engineering Technical Conference & Computer and Information in Engineering Conference IDETC/CIE. Las Vegas, Nevada, USA: Design Engineering Division and Computers and Information in Engineering Division, Vol. 5, 2007, pp. 1245-1258.
[72] Petras I, Vinagre B M., "Practical application of digital fractional-order controller to temperature control", Acta Montanistica Slovaca, Vol.7, No.2, 2002, pp. 131-137.
[73] Zhao Chunna, Li Yingshun, Lu Tao, "Fractional Order Systems Analysis and Design", Beijing:Natonal Defense Industry Press, 2011.
[74] Cao Junyi, Liang Jin and Cao Binggang, "Fuzzy Fractional Order Controller Based on Fractional Calculus", Journal of Xi'an Jiaotong University, Vol.39, No.11, 2006, pp. 1246-1249.