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Implementation of Fuzzy-PID Controller on Two-Link Robot

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Abstract:- The aim of this research is to design and practically implement a Fuzzy-PID controller along with solving the direct and inverse kinematics problems of a two-link robot for the joints of this robot. The subject of this study is a sentinel robot, whose main task is targeting, intruder detection, and shooting towards it. In general, the goal is for the weapon tip mounted on this robot to track a pre-defined path in three-dimensional space. This motion is converted to the movement of each joint by the inverse kinematics of the robot. It is required for each joint to move separately according to the desired path curve obtained from the inverse kinematics of the robot. This is done by a PID controller in which the coefficients KP, KI, and KD are adjusted by the fuzzy controller at each moment. The implementation of an intelligent controller practically on this robot is done by writing control algorithms in the C language on Arduino-based ARM microcontroller boards. In this research, by combining fuzzy control and classical PID control, the Fuzzy-PID control algorithm was created. This controller adjusts PID coefficients online and is resistant. According to the results obtained from the simulations, it is evident that this controller has desirable and robust performance in controlling the motion of the two-link sentinel robot.

Keywords*: Two-Link Robot, PID Controller, Fuzzy Control, Intelligent Controller*

Introduction

Today, the use of robots in industries has led to improved quality, increased production rates, and reduced product costs, ultimately enhancing productivity. With the emergence of robots as a controlled system, various methods including classical (linear and nonlinear), intelligent, and hybrid control methods have been proposed for their control. Among these, classical control methods have a broader application and range from simple proportional-integral-derivative (PID) controllers to more advanced nonlinear controllers like sliding mode, adaptive, and backstepping controllers. Intelligent methods have also been applied in various forms, including fuzzy controllers, neural controllers, and hybrid neuro-fuzzy controllers. In most studies, classical and intelligent controllers have been designed separately, and we see fewer combinations of these two. With the advent of high-speed and high-memory computers, the use of intelligent methods such as neural networks and fuzzy logic has become more prevalent. Recently, fuzzy controllers have become a suitable replacement for conventional controllers due to their ability to model complex systems that are either impossible or at least difficult to model using classical mathematical modeling methods. Fuzzy logic is a solution through which complex systems, which are challenging to model using classical mathematics and modeling methods, can be easily and much more flexibly modeled. Fuzzy logic stands opposed to binary or Aristotelian logic, which sees everything in terms of black and white, yes and no, zero and one, etc., and departs from absolute certainty.

In the field of fuzzy control in recent decades, there have been successful research endeavors, some of which are highlighted below. In [5], the structure of adaptive fuzzy controllers was proposed by Mr. Wang, and the stability and membership functions of the fuzzy controllers were examined. In [6], an adaptive fuzzy control system based on sliding mode for a robot arm was presented, where the adaptive fuzzy system with reference points (RP) was demonstrated, and their derivatives as inputs could estimate the nonlinear dynamics of the robot near the switching surface. The stability of the system and tracking error were converged using Lyapunov theory.

In [7], modeling and simulation of the two-link skilled robot arm based on the Takagi-Sugeno fuzzy descriptor method have been discussed. In [8], a robust sliding mode-fuzzy controller for uncertain nonlinear systems has been derived, utilizing a fuzzy controller to obtain a smooth boundary layer for the sliding surface. In [9], a fuzzy neural controller has been employed for controlling a quadruped robot. To ensure system stability and performance monitoring of the neural-fuzzy controller, a Bang-Bang controller has been applied. Simulation results demonstrate the proximity of the desired path to the controlled path under the supervision of the controllers.

In [10], a fuzzy controller has been utilized for controlling a gate in automation. By using this controller, the gate opening speed has been obtained based on different walking speeds and distances from the gate. Analysis results show that the implemented fuzzy logic controls operate in less time and with greater confidence compared to conventional controls.

In [11], a sliding mode fuzzy controller has been employed to control the Skilled two-link robot arm with the aim of tracking the robot's path curve. According to the conducted analysis, it is evident that the robot can track input and output data resulting from experiments and move dynamically under the equilibrium of fuzzy control algorithms.

In [12], a robust fuzzy PD controller has been implemented for a class of second-order nonlinear multi-input-multi-output systems for the Skilled robotic arm. The system's stability is based on Lyapunov theory. The control law result is the stability and capability to launch dynamic system variables in a linguistic manner.

In [13], the feasibility of fuzzy logic-based active force control for operating a two-link planar arm using a pair of artificial pneumatic muscles has been examined. Fuzzy logic is used as a method to estimate the best inertia matrix value for the AFC mechanism. In the variable fuzzy control structure, one of the prominent features is that the transient response in reaching the goal may significantly improve. This result has been stated in [14], and the obtained results demonstrate good responses in all initial conditions.

In [15], a self-tuning real-time Bang-Bang fuzzy controller has been proposed for controlling a rigid and flexible two-link arm of a skilled robot. TSK fuzzy control has been utilized, providing good performance in tracking and controlling the robot's position.

In [16], a self-tuning fuzzy PID controller has been employed to enhance the performance of an aircraft control system. In [17], a new method for controlling the speed of a DC motor using fractional-order fuzzy PID has been applied, and the performance of FFPID has been compared with PID and fractional-order PID controllers in overshoot, rise time, settling time, and steady-state error. Simulation results show that FFPID has better performance compared to other controllers. In [18], the development of sliding mode-fuzzy control based on the variable boundary layer has been presented. Fuzzy inference mechanism has been used to adjust the boundary layer thickness for on-spot control (on the line). In [19], a fuzzy-neural network with a sliding mode controller has been designed for a robot arm, resulting in desirable strength and precise position tracking at a high level.

In [20], in order to cover various common industrial processes, the transfer function of four groups of processes has been considered as a representative and normal PID controllers and fuzzy PID controllers have been simulated and compared in the Simulink environment of MATLAB for these processes. The results of this research indicate that the fuzzy PID controller has less overshoot, less settling time, less rise time, and less absolute integral error compared to the normal PID controller. In [21], a hybrid fuzzy control method for a SCARA robot has been proposed. The combined controller in this article is a combination of a direct fuzzy controller, an indirect fuzzy controller, and an observer controller. The unique feature of the controller used in this system is that there is no need for a mathematical model of the system, and the controller is able to estimate the parameters of the system online. In [22], the speed of a controlled DC motor has been controlled using a fuzzy-PID controller. In this article, a self-tuning fuzzy-PID controller design method with two inputs and three outputs has been introduced, and a fuzzy toolbox in MATLAB has been used to design the fuzzy controller. The fuzzy controller adjusts the proportional, integral, and derivative gains of the PID controller based on speed error and speed error derivative. The results of this simulation have been compared with a normal PID controller and a self-tuning PID controller, and it turns out that the fuzzy-PID controller shows better performance with better dynamic response, shorter response time, less overshoot, and less steady-state error.

Until now, extensive discussions on identification and control, including the implementation of PID controllers, have been carried out on the research security robot. Considering the nonlinear dynamics, mechanical issues, uncertainties, and unmodeled dynamics of the system, it is evident from the results of these efforts that linear controllers have not provided satisfactory responses and do not meet the control requirements. With the rapid advancement of robotics and the increasing demand for military, medical, and industrial robots, modeling and controlling robots for optimal performance require advanced and intelligent controllers. On the other hand, while modeling the dynamics of robots and identifying their parameters may lead to more precise controller designs, it is sometimes a challenging and time-consuming task. Therefore, model-independent intelligent controllers can be a more suitable option in such cases. Taking these factors into account, it was decided to design and implement an intelligent controller for the research robot. Since a fuzzy controller is not dependent on the system model and does not involve unknown parameters of the system dynamics, we chose to combine this controller with a PID controller for controlling the two-link surveillance robot.

Therefore, the aim of this research is to practically design and implement a set of controllers, including PID, direct fuzzy, and a combination of fuzzy-PID, for controlling a two-link mechanical arm existing in the Robotics Research Center of the Islamic Azad University, Najafabad Branch. In this regard, by calculating the forward and inverse kinematics of the robot, we proceed to design a trajectory controller for this robot. Then, two regulation and trajectory tracking problems are examined using the aforementioned controllers for this robot. After implementing the controller, the results obtained are used for comparison through the stated methods.

Design and Implementation of Controller for Surveillance Robot

The research robot introduced as the Surveillance Robot in this study is a two-link robot with a weapon mounted on it. The dynamic identification process of this robot has been previously conducted in [23]. A considerable amount of time has passed since the last launch of this robot, and initially, essential information about the proper functioning of the motors, gearboxes, joints, and links of the robot was not available. In order to carry out the initial launch and performance testing of the various parts of the robot, a PID controller was designed for the mentioned robot. The goal of designing this controller, in addition to understanding how the various parts of the robot function, is to investigate the feasibility of implementing intelligent algorithms and more advanced controllers on this robot.

Designing a PID Controller

A PID controller consists of three components: proportional, integral, and derivative, with its continuous-time equation given as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \qquad (1)$$

In this equation, the proportional term, with the gain K_p, is dependent on the current error. The integral term, with the gain K_d, accumulates past errors. The derivative term, with the gain K_d, estimates future error based on current changes.

Now, considering that this equation needs to be implemented in the control hardware, it must be discretized. In other words, information processing occurs in the discrete-time domain.

The discrete-time PID algorithm is expressed as:

$$u(t_k) = K_p e(t_k) + K_i \sum_{i=1}^{k} e(t_i)\,\Delta t + K_d \frac{e(t_k) - e(t_{k-1})}{\Delta t} \qquad (2)$$

The proportional gain K_p, which is multiplied by the system error, induces a linear response to the error component. By appropriately tuning the proportional controllers, higher accuracy and sensitivity can be achieved in controlling a process. Proportional controllers are unable to completely eliminate the error, and there is a discrepancy between the process output and the desired value in the steady state. An excessive increase in K_p leads to system response oscillation.

Designing a PID Controller

The PID controller performs proportional, integral, and derivative operations on the error signal. In fact, the PID controller encompasses all the properties of P, I, and D controllers. The PID controller is used to maintain the system output at the setpoint and respond quickly to external disturbances.

An important consideration in the practical implementation of this controller, in addition to the integral term locking mode mentioned earlier, is the amplification of measurement noise by the derivative term and sometimes the undesired amplification or attenuation during controller operation. Practical solutions for addressing this issue include using low-pass filters or, for example, taking the average of the derivative term value at each moment. In this thesis, low-pass filters have been used to address this issue.

Designing a Fuzzy Controller

A PID controller alone is not capable of achieving the desired control for this robot. Therefore, there is a need for a more advanced controller to control this system.

The present research employs fuzzy logic for control. A control problem can be described as a set of equations governing a number of state variables, one (or more) of which is a control variable that can take any value within specified bounds. Thus, a fuzzy logic controller approximates a control function in a way that the value(s) of the variable(s) are given as a function of the state variables at any given time. The task of the controller is to execute the control function that brings each state variable to a desired value. The fuzzy controller used here is mostly known as an error-based fuzzy controller. In this type of controller, the inputs are the error and the derivative of the system error.

Here, for each of the input variables to the controller as well as the output variables of the controller, seven fuzzy sets are considered: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). Membership functions are defined in both triangular and Gaussian forms. Figures (1) and (2) show membership functions in triangular form, while Figures (3) to (6) show membership functions in Gaussian form for the input and output fuzzy sets. The ranges of these functions are specified in these figures.

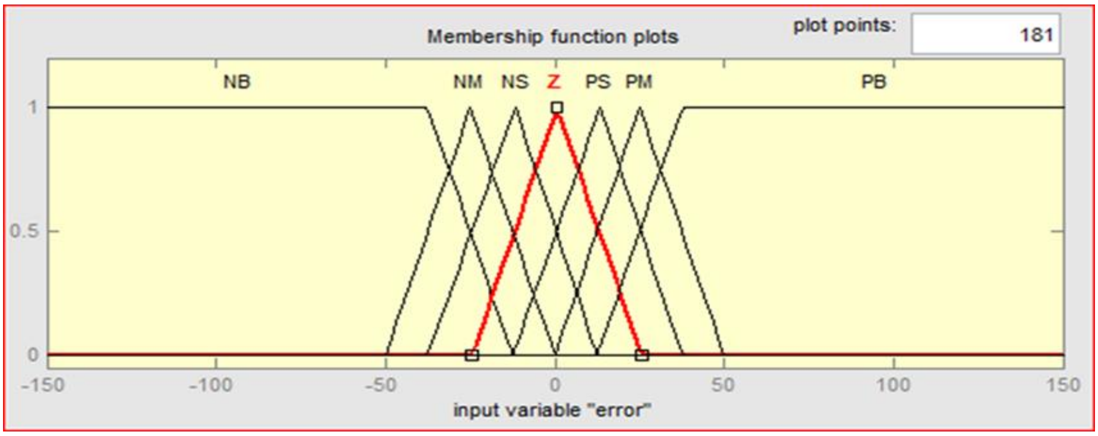

Figure 1: Triangular Membership Functions for Error and Derivative of Error Inputs

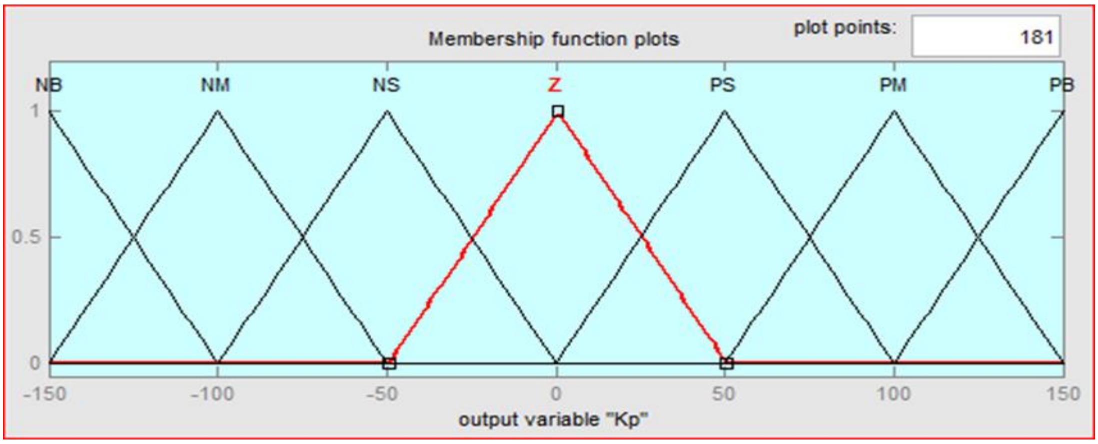

Figure 2: Triangular Membership Functions for Fuzzy Outputs (PID Gains)

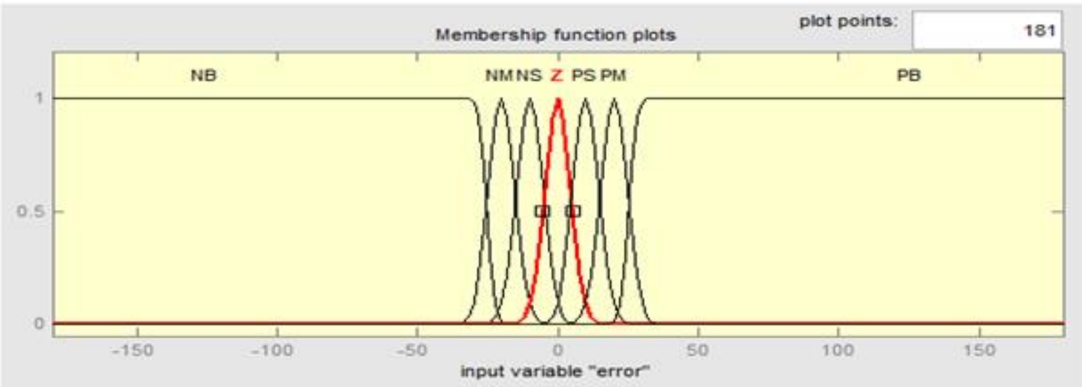

Figure 3: Gaussian Membership Functions for Error Input

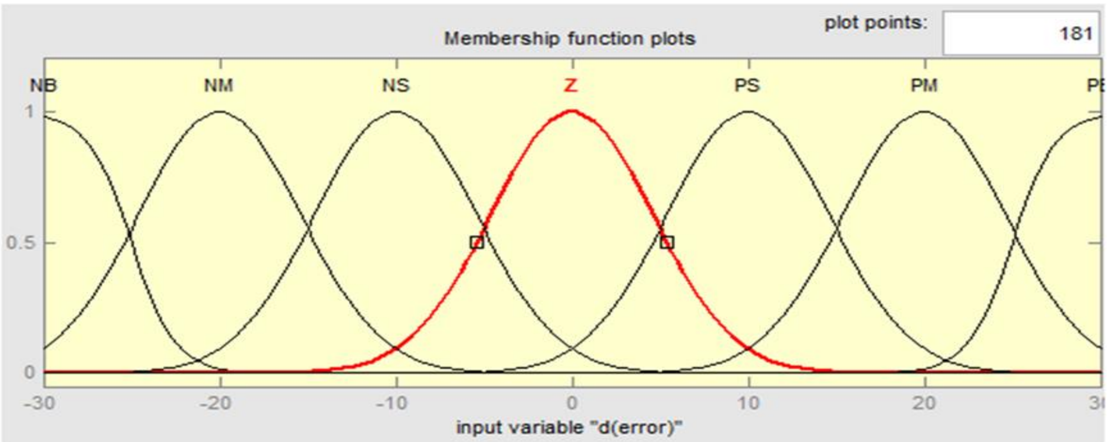

Figure 4: Gaussian Membership Functions for Derivative of Error Input

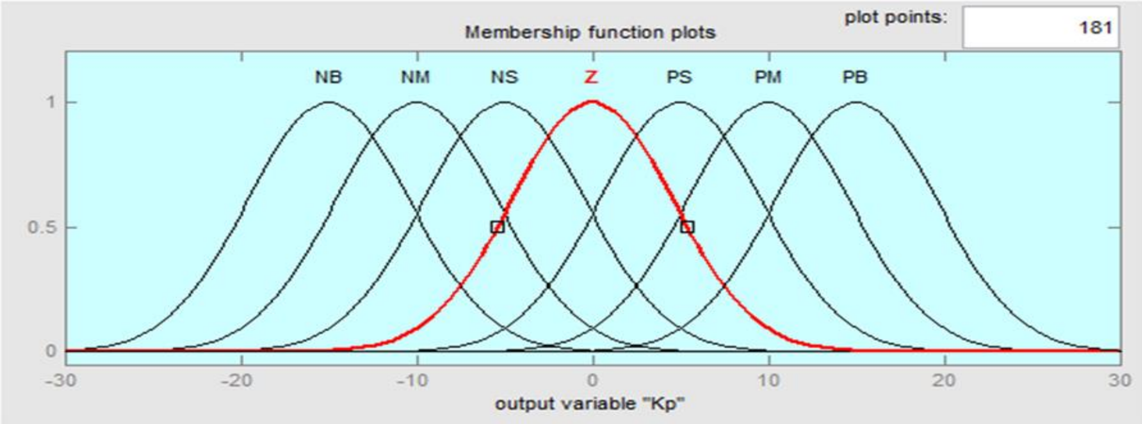

Figure 5: Gaussian Membership Functions for Proportional Gain Output

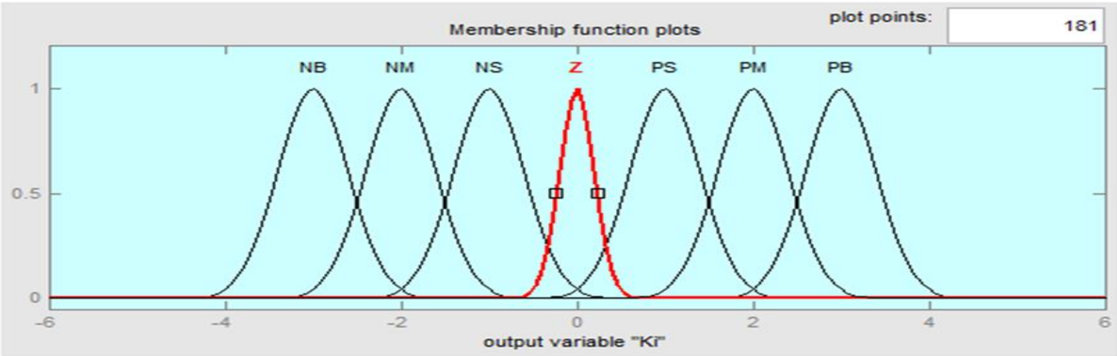

Figure 6: Gaussian Membership Functions for Integral and Derivative Gains (Ki, Kd) Output

Since the controller has two inputs, each with seven membership functions, a complete rule base for this system consists of 49 rules. By examining the fuzzy rules and considering experimental issues, the following rule bases are suitable for the system under control:

Table 1. Fuzzy Rule Base for Kp Output

dE \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PM	PS	NB	NB	NB	NB
NM	PM	PS	Z	PS	NB	NS	Z
NS	PB	PM	PS	PM	PS	PM	PB
Z	PB	PM	PS	Z	PS	PM	PB
PS	PB	PM	PS	NS	PS	PM	PB
PM	Z	NS	NM	NS	Z	PS	PM
PB	NB	NB	NB	NS	PS	PM	PB

Table 2. Fuzzy Rule Base for Ki Output

dE \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PM	PB	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NS	NM
Z	NM	NS	Z	Z	Z	NS	NM
PS	NM	NS	Z	PS	PS	PM	PB
PM	Z	Z	PS	PM	PM	PB	PB
PB	Z	PS	PB	PB	PB	PB	PB

Table 3. Fuzzy Rule Base for Kd Output

dE \ E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PM	PM	PS	PS	PS	Z	Z
NS	PM	PS	Z	Z	Z	NS	NM
Z	NB	NM	Z	Z	Z	PS	PM
PS	NM	NS	Z	Z	Z	PS	PM
PM	Z	Z	PS	PM	PB	PB	PB
PB	Z	PS	PB	PB	PB	PB	PB

The output of the fuzzy controller needs to be converted into crisp values before applying it to the robot. This conversion is done using defuzzification methods. There are different methods for defuzzification. The most common methods are the Center of Gravity (COG) and the Center of Sums (COS) methods. The Center of Sums method is computationally simpler, as it eliminates the integration operator compared to the Center of Gravity method. In terms of accuracy, it does not have a fundamental difference from the Center of Gravity method. Therefore, in this research, the Center of Sums defuzzification method has been used.

Hardware of the Guard Robot Control System

As shown in Figure (7), to control the position or speed of an electric motor shaft, the hardware of the guard robot system must consist of four parts: the controller, driver, motor, and encoder, forming a closed-loop controller.

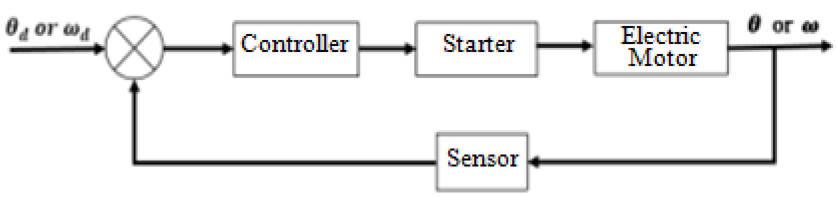

Figure 7 : Closed-Loop Control System

Based on the block diagram of the closed-loop control system used for controlling the position and speed of electric motors as shown in Figure (7), and with the expansion of the necessary information and hardware for this issue, a two-link guard robot control system is formed. The Arduino Uno control board is used as the controller hardware, the L298 motor driver is used as the motor driver block, ZGA60FM-G electric motors are used as the supplier of robot driving force, and LPD3806 incremental encoders are used in the sensor block to play the role of feedback from the system output.

The driving force of this robot is provided by DC electric motors. Considering the weight of the weapon and the dynamic structure of the robot, a torque of about 20 kg/cm is required. To meet this requirement and ensure the robot's operation, motors with the specifications of 12 volts, 10 watts, 30 kg/cm torque, and a speed ratio of 10 RPM for the movement of the first link and 5 RPM for the second link have been used in its construction.

In this robot, two LPD3806 incremental encoders are used, which operate with a working voltage in the range of 5 to 24 volts DC and are of the two-phase type. The resolution of these encoders is 400 pulses per revolution.

The auxiliary hardware is a two-channel full-bridge driver based on the L298 chip. This auxiliary hardware is designed for driving inductive loads such as relays, stepper motors, and DC motors. In this research, given the suitable and efficient specifications of this board, this auxiliary hardware was used as the motor driver.

A simple camera is used in this research, which is placed on the robot's link. By using available programs for face detection, the coordinates of the upper half of the face are determined and applied to the robot as the desired coordinates in the control problem. It is observed that the final executor of the robot (end of the weapon) moves towards the desired point in the shortest time. The best targeting in the shortest time is achieved by the fuzzy-PID control algorithm with Gaussian membership functions.

Findings

Since the discussed robot system is a nonlinear system with unmodeled dynamics and parametric uncertainties, which makes it difficult to obtain the dynamic model of this system with significant challenges, a model-independent controller was used to enhance the level of control. In this study, a fuzzy controller was selected for this purpose. After designing the fuzzy-PID controller, the regulation and tracking problem for the new controller (fuzzy-PID) was investigated. In the design of the fuzzy controller, membership functions were considered once in triangular form and once in Gaussian form. The results of implementing these controllers and the conducted evaluations are presented below.

To compare the performance of each controller, a criterion based on the error values of each control algorithm was obtained using MATLAB software and the "trapz" command, which was calculated in each section.

1. **PID Controller Tuning Problem**

To solve the tuning problem, by applying specific coordinates to the robot, the system output, which is the coordinates of the end point of the final executor of the robot, was obtained and compared with the desired coordinates applied.

The PID controller coefficients in this section for proportional, integral, and derivative gains are 0.2, 0.068, and 0.008 for the first link, and 4.4, 0.072, and 0.005 for the second link, respectively. Figures (8) and (9) respectively show the desired angular position applied to the first and second links of the robot, and the position obtained from the movement of the first and second links of the robot.

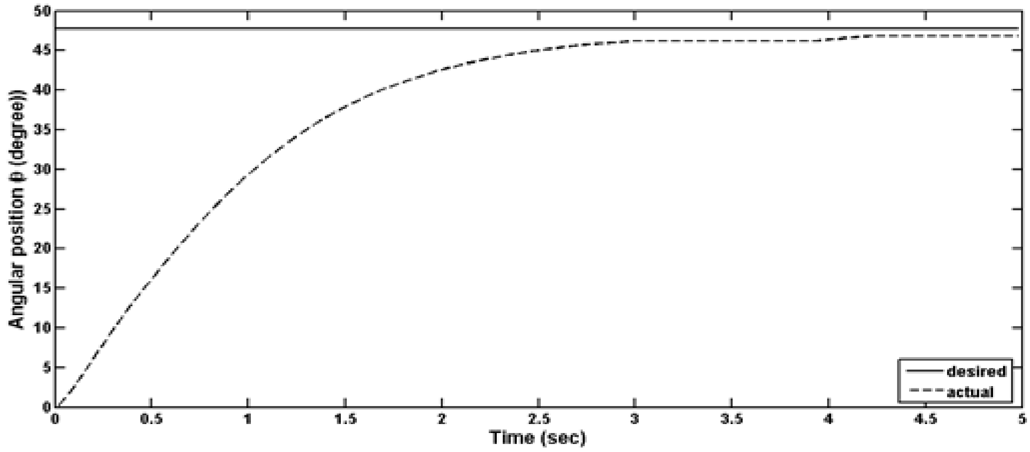

Figure 8: Display of Desired Angular Position and Actual Angular Position of Link 1

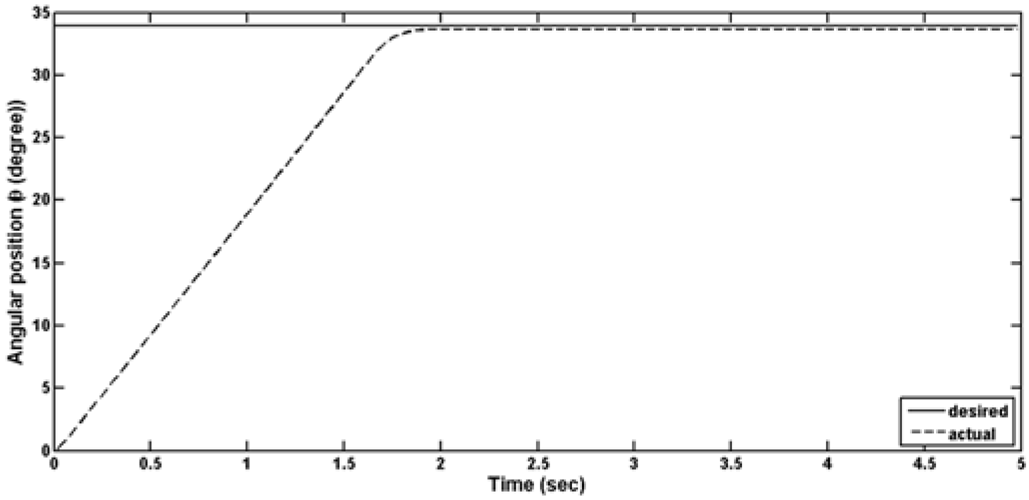

Figure 9: Display of Desired Angular Position and Actual Angular Position of Link 2

As observed, the result obtained from the PID control algorithm in the tuning problem is accompanied by an error. The value of this error, which is the difference between the desired values and the actual values, is specified for Link 1 in Figure (10) and for Link 2 in Figure (11).

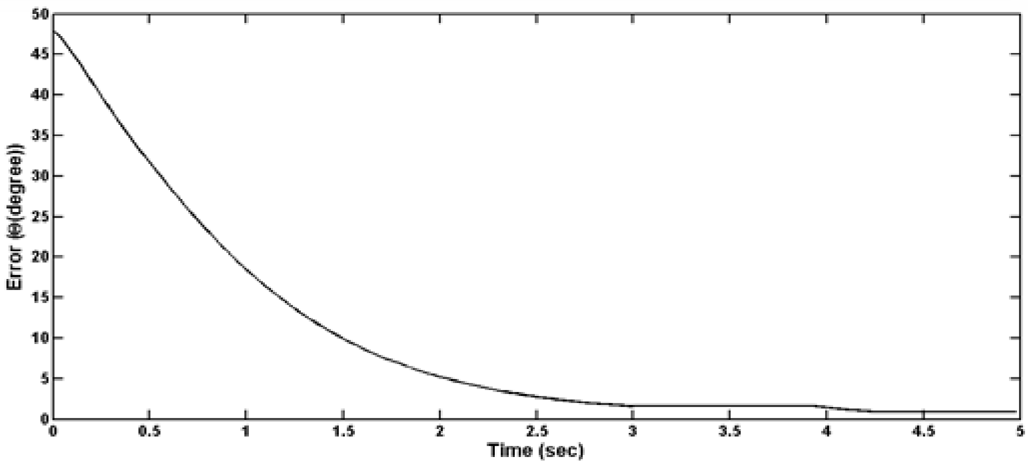

Figure 10: Display of Position Error for Link 1

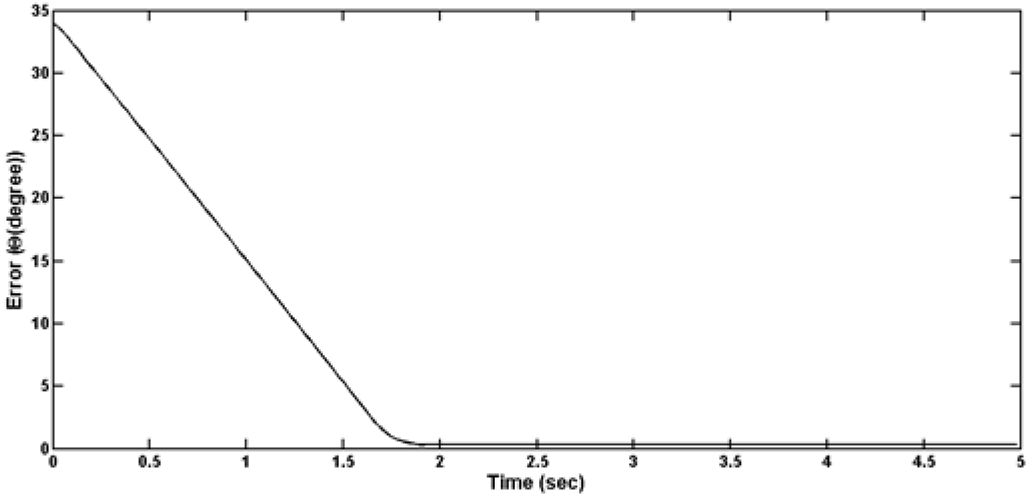

Figure 11: Display of Position Error for Link 2

The control signal plots for Link 1 and Link 2 are also shown in Figures (12) and (13) respectively.

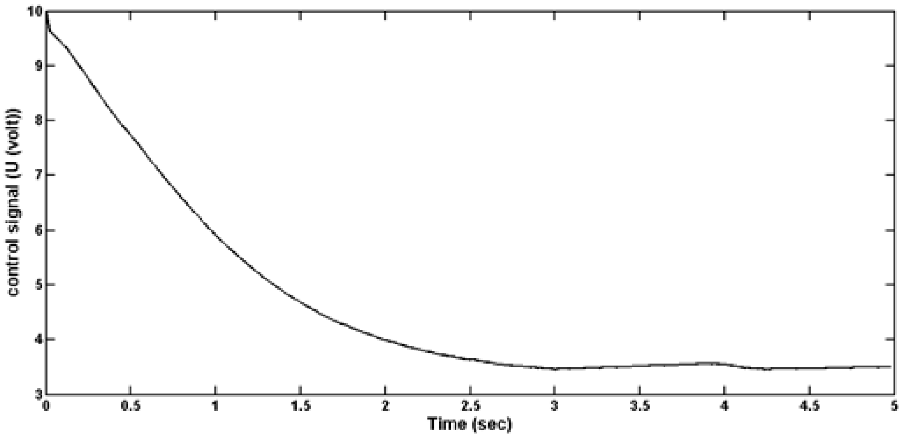

Figure 12: Display of Control Signal for Link 1

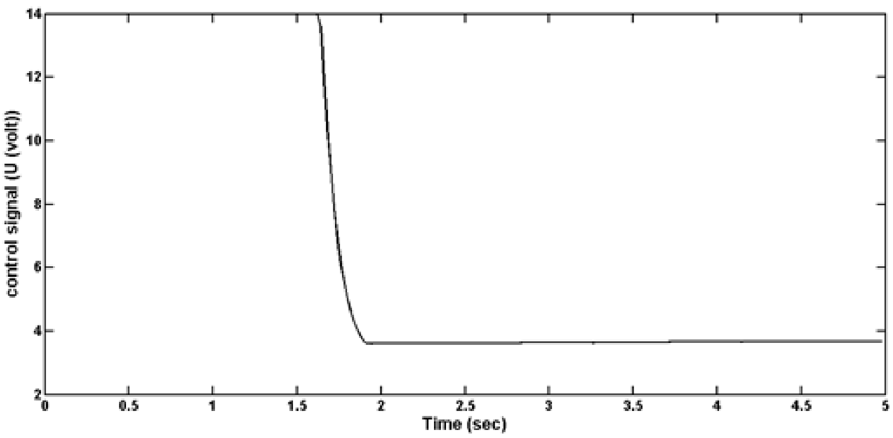

Figure 13: Display of Control Signal for Link 2

Finally, the final executor's position in three-dimensional Cartesian space is shown in Figure (14).

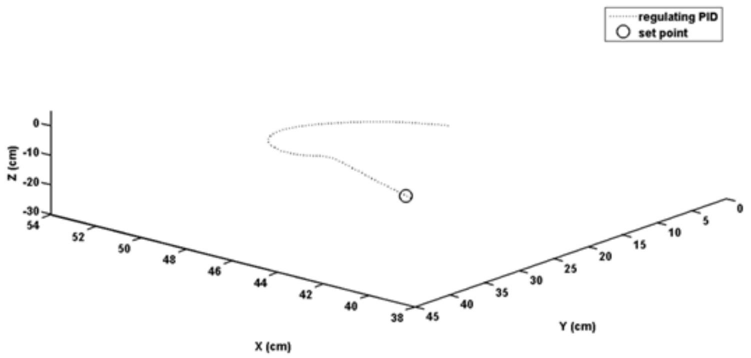

Figure 14: Display of Final Executor's Position in Cartesian Task Space with PID Controller

Using the `trapz` command, the error value is calculated based on this criterion. According to Table (4), we calculate once from the square of the error signal and again using its absolute value.

Table 4: Calculation of the `trapz` criterion for the PID controller in the tuning state

Tuning the PID Controller	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	1261.2	51.2166	698.4572	33.4071

2. **Tuning the Fuzzy-PID Controller with Triangular Fuzzy Membership Functions**

Now, in order to improve the results obtained from the PID controller, we apply the intelligent fuzzy-PID controller to the system. It is expected that the results obtained from this controller will be close to the desired values to a large extent. Problem of tuning Fuzzy-PID controller with triangular fuzzy membership functions. Now, in order to improve the results obtained from the PID controller, we apply the intelligent Fuzzy-PID controller to the system. It is expected that the results obtained from this controller will be much closer to the desired values.

In this section, in the fuzzy part, the scale factors for error and error change are 2.5 and 0.25, respectively, and the weighting factors for proportional, integral, and derivative coefficients for the first link are 1.197, 0.00002, and 0.00005 respectively. For the second link, they are 2.48, 0.00002, and 0.00005, respectively. Also, the proportional, integral, and derivative coefficients for the PID controller for the first link are 0.2, 0.68, and 0.0008 respectively, and for the second link, they are 4.4, 0.72, and 0.0005, respectively.

Table 5: Calculation of trapz metric for Fuzzy-PID controller in tuning mode.

Tuning the PID Controller	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	980.4814	30.5782	674.5548	29.8568

3. **The problem of tuning the Fuzzy-PID controller with Gaussian fuzzy membership functions**

By changing the fuzzy membership functions from triangular to Gaussian form, we reexamine the problem of tuning the Fuzzy-PID controller. In this section, in the fuzzy part, the weighting factors for error and error change are 2.5 and 0.25, respectively, and the weighting factors for proportional, integral, and derivative coefficients for the first link are 3, 0.00001, and 0.00005, respectively. For the second link, they are 4.9, 0.000027, and 0.00005, respectively. Also, the proportional, integral, and derivative coefficients for the PID controller are the same as the previous section.

Table 6: Calculation of trapz metric for Fuzzy-PID controller with Gaussian membership functions in tuning mode.

Tuning the PID Controller	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	955.9313	29.5011	658.0437	29.0086

4. Results of the PID Controller Tracking Problem

In solving the tracking problem, the trajectory curves for the parameters $\boldsymbol{\theta}$ and φ are obtained from equations (3) and (4). Equation (3) is used to generate a triangular wave to determine the motion path of link one [m1.ref], and equation (4) is used to generate a sinusoidal wave as the motion path of link two.

$$\theta(\mathrm{t}) = \frac{8}{\pi^2}\sum_{k=0}^{10}(-1)^k \frac{\sin(2\pi(2k+1)ft)}{(2k+1)^2} \qquad (3)$$

Where f is the sampling frequency with a value of 0.11, and t is the time interval in the range of [0 ~ 27] seconds.

$$\varphi(t) = 20\sin(t-1.5)+20 \qquad (4)$$

Now, as a first step in solving the tracking problem, we use a PID controller with proportional, integral, and derivative coefficients of 1.2, 0.09, and 0.0008 respectively for link one, and 2.5, 0.085, and 0.0005, respectively for link two. The target path is defined by equations (3) and (4).

Since the final end-effector position in Cartesian space and the calculation of control performance based on the final end-effector position in Cartesian space are the main subjects of the tracking problem, by converting the joint coordinates of the robot under direct kinematic considerations to Cartesian coordinates, it can be observed in Figure (15).

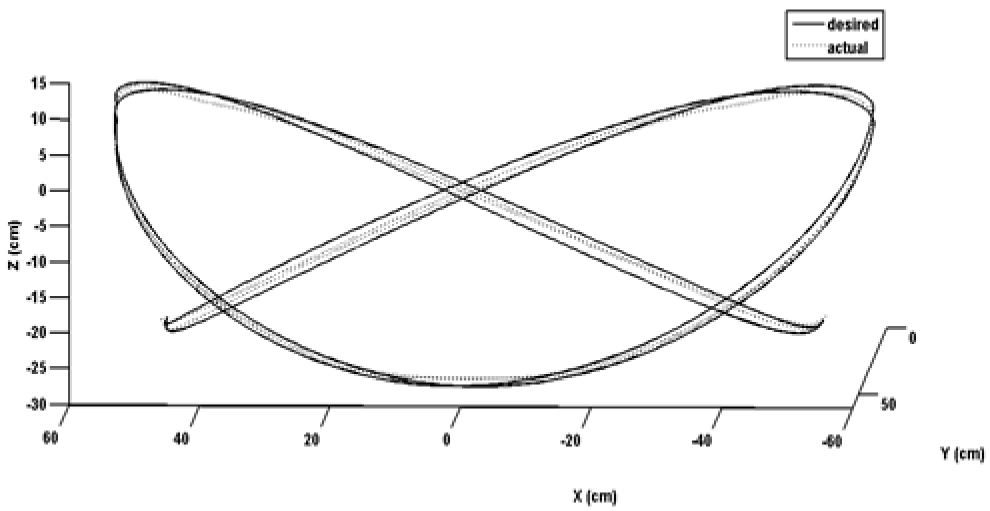

Figure 15: Display of Position Tracking by the Final Executor in Cartesian Task Space with PID Controller

The error index according to the trapz criterion can be calculated as shown in Table (7).

Table 7: Calculation of trapz Criterion for PID Controller in Tracking Mode

PID Controller Tracking	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	1608.3	205.0957	371.9631	91.7497

5. Results of Tracking Problem with Fuzzy-PID Controller using Triangular Membership Functions

In the previous section, where the error value was considerable and satisfactory, control efficiency was not achieved. Now, by employing the Fuzzy-PID controller with triangular membership functions, an attempt is made to improve the results. In the fuzzy section, the weighting factors for error and error changes are 2.5 and 0.25, respectively. The weighting factors for the proportional, integral, and derivative coefficients for both link one and two are the same, and they are 10, 0.00002, and 0.00005, respectively. Additionally, the proportional, integral, and derivative coefficients for the PID controller for link one are 1.2, 0.09, and 0.0008, respectively, and for link two, they are 2.5, 0.085, and 0.005, respectively.

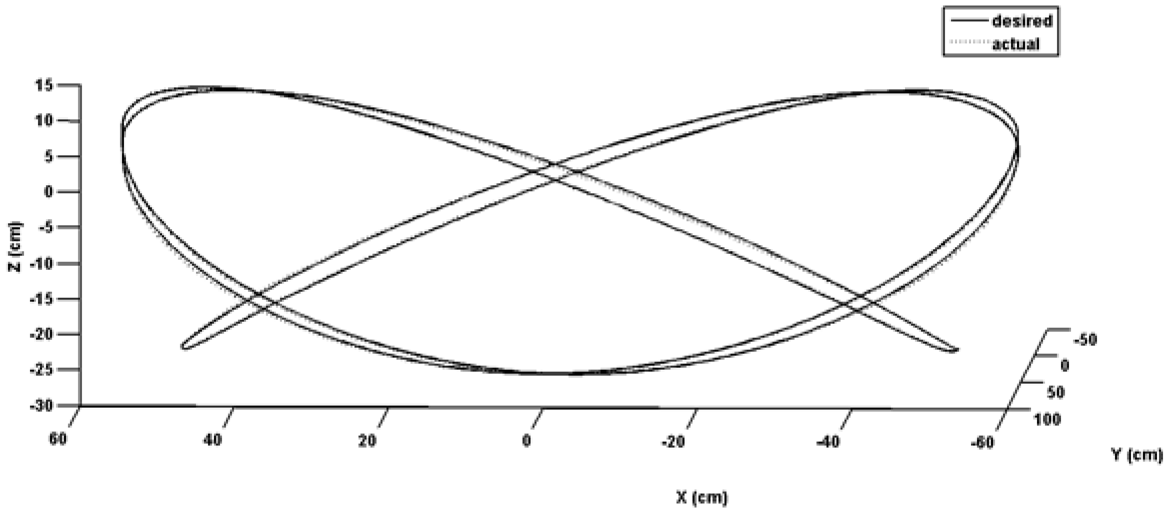

Figure 16: Display of Tracking Position by the Final Effector in Task Space with Fuzzy-PID Controller

Table 8: Calculation of the trapz Metric for Fuzzy-PID Controller in Tracking Mode

PID Controller Tracking	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	46.2831	28.1188	3.6227	9.2040

6. Results of Tracking Problem with Fuzzy-PID Controller using Gaussian Membership Functions

The membership functions of the fuzzy controller are changed to Gaussian form, and the tracking problem with the Fuzzy-PID controller is investigated. In the fuzzy section, the weighting factors for error and error changes are 2.5 and 0.25, respectively. The weighting factors for the proportional, integral, and derivative coefficients for link one are 33, 0.000095, and 0.00005, respectively, and for link two, they are 15, 0.00005, and 0.00005, respectively. Additionally, the proportional, integral, and derivative coefficients for the PID controller remain the same as in the previous section.

Table 9: Calculation of the trapz Metric for Fuzzy-PID Controller with Gaussian Membership Functions in Tracking Mode

Tracking with Fuzzy-PID Controller (using Gaussian Membership Functions)	First Link		Second Link	
	Trapz(tt,error.^2)	Trapz(tt,abs(error))	Trapz(tt,error.^2)	Trapz(tt,abs(error))
	20.9997	14.0819	1.5041	6.0172

Conclusion

In this study, a fuzzy-PID controller was designed for a two-link robot. PID controllers are commonly used for process control due to their robust performance and simple structure. However, they may not provide satisfactory control for nonlinear system models. The development of intelligent control theories has led to the emergence of combined controllers, including fuzzy logic-based PID controllers. By combining the concepts of intelligent control with classical PID control, the advantages of both can be utilized to achieve better control algorithms. Fuzzy controllers are based on fuzzy sets, linguistic variables, and fuzzy logic reasoning. One of the characteristics of these controllers is that they do not require an accurate model of the system. Such controllers exhibit high resilience.

In this research, the fuzzy-PID control algorithm was developed by integrating fuzzy control and classical PID control. This controller adjusts the PID coefficients online and possesses robustness characteristics. The simulation results demonstrate that this controller exhibits satisfactory and robust performance in controlling the motion of the two-link vigilant robot.

Based on the results obtained from the adaptive fuzzy controller using Takagi-Sugeno fuzzy systems, it is recommended to employ position measurement sensors with higher accuracy to improve the accuracy of the system model. Additionally, using a brushless motor to reduce the noise of the measured data is suggested.

References

1. Begovich, Ofelia, Edgar N. Sanchez, and Marcos Maldonado, "Takagi-Sugeno fuzzy scheme for real-time trajectory tracking of an underactuated robot.", IEEE Transactions on Control Systems Technology, Vol. 10, No. 1, 2002, pp.14-20.
2. Meza, Jose Luis, et al, "Fuzzy self-tuning PID semiglobal regulator for robot manipula- tors.",Industrial Electronics, IEEE Transactions, Vol. 59, No. 6, 2012, pp. 2709-2717.
3. Chen, Chu-Song, "Supervisory adaptive tracking control of robot manipulators using interval type-2 TSK fuzzy logic system.", Control Theory Applications, Vol. 5, No. 15, 2011, pp. 1796-1807.
4. Er, Meng Joo, Moo Teng Lim, and Hui Song Lim, "Real-time hybrid adaptive fuzzy control of a SCARA robot.", Microprocessors and Microsystems, Vol. 25, No. 8, 2001, pp. 369-378.
5. Wang, Li-Xin, "Adaptive fuzzy systems and control: design and stability analysis. Prentice-Hall, Inc., 1994.
6. Sun, F-C., Z-Q. Sun, and Gang Feng, "An adaptive fuzzy controller based on sliding mode for robot manipulators.", IEEE Transactions on, Vol. 29, No. 5, 1999, pp.661-667.
7. Schulte, Horst, and Kevin Guelton, "Modelling and simulation of two-link robot ma- nipulators based on Takagi Sugeno fuzzy descriptor systems.", Industrial Technology, IEEE International Conference on. IEEE, 2006.

8. Sümbül, Harun, Akif Coşkun, and Muharrem Taşdemir. "The control of an automatic door using fuzzy logic.", Innovations in Intelligent Systems and Applications (INISTA), 2011 International Symposium on. IEEE, 2011, pp. 432-435.
9. Zhong, ChunHua., "A class of fuzzy sliding-mode control simulation for two-link robot manipulators.", Fourth International Conference on Digital Image Processing, Inter- national Society for Optics and Photonics, 2012, pp. 833410-833410.
10. Sharkawy, Abdel Badie, Mahmoud M. Othman, and Abouel Makarem A. Khalil, "A robust fuzzy tracking control scheme for robotic manipulators with experimental verifi- cation.", Intelligent Control and Automation, Vol. 2, No. 02, 2011, pp.100.
11. Jahanabadi, H., Active force with fuzzy logic control of a two-link arm driven by pneu- matic artificial muscles.", Journal of Bionic Engineering, Vol. 8, No.4, 2011, pp.474-484.
12. Wang, Chun-Chich, "Fuzzy Variable Structure Control for Autonomous Orientation of Hovercraft Systems.", Robot Vision and Signal Processing (RVSP), 2011 First Inter- national Conference on. IEEE, 2011.
13. Marwan, A., et al, "Real-time on line tuning of fuzzy controller for two-link rigid- flexible robot manipulators.", Transactions of the Institute of Measurement and Control, 0142331212468373.
14. Wahid, Nurbaiti, and Nurhafizah Hassan, "Self-tuning fuzzy pid controller design for aircraft pitch control", Intelligent Systems, Modelling and Simulation (ISMS), Third International Conference on. IEEE, 2012.
15. Gupta, Suneet K., and Praveen Varshney, "Fractional fuzzy PID controller for spood control of DC motor.", Advances in Computing and Communications (ICACC), Third International Conference on. IEEE, 2013.
16. Park, S., and S. Rahmdel, "A new fuzzy sliding mode controller with auto-adjustable saturation boundary layers implemented on vehicle suspension.", 2013, pp. 1401-1410.
17. Wai, Rong-Jong, and Rajkumar Muthusamy, "Fuzzy-neural-network control for robot manipulator via sliding-mode design.", Control Conference (ASCC), 9th Asian. IEEE, 2013, pp. 1-6.
18. Khan, Asim Ali, and Nishkam Rapal, "Fuzzy PID controller: design, tuning and com- parison with conventional PID controller.". Engineering of Intelligent Systems, IEEE
19. Popescu, Marius-Constantin, et al, "Simulation hybrid fuzzy control of SCARA robot.", Wseas Transactions on systems and control Vol. 3, No. 2,2008, pp. 105-114.
20. Bansal, Umesh Kumar, and Rakesh Narvey, "Speed Control of DC Motor Using Fuzzy PID Controller.", Advance in Electronic and Electric Engineering, Vol. 3, 2003, pp. 1209-1220.
21. Kuo, Yong-Lin, and Shib-Min Liu, "Position Control of a Serial Manipulator Using Fuzzy-PID Controllers.", International Journal of Automation and Smart Technology, Vol. 5, No. 1, 2015, pp. 18-26.
22. Akbar, M. Amirullah, "Simulation of fuzzy logic control for DC servo motor using Arduino based on MATLAB/Simulink.", Intelligent Autonomous Agents, Networks and Systems (INAGENTSYS), IEEE International Conference on. IEEE, 2014, pp. 42-46.
23. **Hamid Reza Eslami, Abbas Chatraei, Maede Narimani**" Identifying The Dynamic Model of the 2-Link Robots in A Functional Study", Journal of Harbin Engineering University, Vol. 44 No. 9 (2023): Issue 9