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Design of a Genetic based Optimized Fuzzy Logic Controller for Enhanced Trajectory Tracking Accuracy of a 3P Robot

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***Abstract*—Robot positioning precision is critical in industrial automation. This research attempts to analyze three distinct approaches for controlling a 3P robot. The designed controllers are position PID (P-PID), position and velocity PID (PV-PID) and genetic algorithm optimized fuzzy logic controller (GA-FLC). In this regard, the mentioned system is initially described, then a position PID controller is applied to the system. In the next step, an attempt has been made to reduce the system error by adding a PID on the velocity to the previous controller as a feed forward term. Then the fuzzy logic controller (FLC) is expressed in which the input variables are the position and velocity error signals and the output is the required force desired path. Ultimately by means of genetic algorithms optimized fuzzy membership functions are achieved. The proposed method outperforms its conventional counterpart and enhances robot precision for applications that require high positioning accuracy, such as riveting, drilling, and precise assembly. The robot modeling and control design were simulated using MATLAB and Simulink software, with the obtained numerical results serving as the criterion for evaluation.**

***Index Terms*—PID Control, Position and velocity PID control, Fuzzy logic control, Genetic algorithm optimized fuzzy logic controller, 3P robotic manipulator**

I. Introduction

Robots are commonplace in most production facilities and industries. They are used to automate operations that are too hazardous, repetitive, or complicated for human operators to perform [1]. This quality makes them extremely valuable in modern industries. Due to the high work reproducibility of robots, industrial robots are widely used in mass production factory automation. Although offline programming reduces required robot teaching time significantly, the generated robot paths are based on the robot's kinematics, so whether the robot can successfully complete the task via offline programming is dependent on its absolute accuracy. Robot Denavit-Hartenberg (D-H) parameters are usually provided by the robot's manufacturers. However, actual values of these parameters may deviate from the nominal values. The reasons are errors in manufacturing, assembly and other factors, resulting in position errors of the robot EE [2]. As a result, industrial robots continue to face challenges in many low-volume applications requiring high absolute accuracy, such milling, pick-and-place, and assembly. An important method for increasing robot absolute accuracy is kinematic calibration [3]. In [4] the article proposes a controlling strategy for manipulator robots, demonstrating that linear feedback of joint values with their derivatives is effective in dynamic control. They employed a PD controller and simulated the system's response and reaction in this manner. This discovery marked the beginning of theoretical control of robotic manipulators in the academic setting. Since then, more typical feedback controllers have been introduced. Researchers demonstrated in [5] that an adaptive PD controller can be developed to assure the system's global asymptotic stability even in conditions where gravity or inertial loads are unknown. Researchers created a continuous sliding PID controller used in tracking that produce semi-global stability for all closed-loop signals [6]. The design was validated by experiments on a robotic arm. The controller was implemented and the responses were compared with both PD and PID controllers. By virtue of the data-driven modeling principle, artificial neural networks (ANN) have a promising application in modeling complex systems such as calibration [7], [8].

Fuzzy logic control algorithms [9], [10] adaptive robust control algorithms [11], and genetic-based control algorithms [12] are currently the focus of research on robot controlling approaches. In [13] a 3 degree of freedom parallel robot, which was utilized for medical and industrial purposes, was controlled by developing a fuzzy logic algorithm and provided more accurate outcome than the conventional PID controller. Noshadi et al. [14] proposed a technique for controlling the platform by an active force. For the platforms, they created a 2-level fuzzy tuning for resolving an acceleration control problem. With their method, a consistent response was provided for trajectory tracking tasks. A parametric PID variable controller, which was optimized by means of a genetic algorithm, is proposed in [15]. A key advantage of fuzzy controllers is the ability to use human skills, knowledge and understanding in designing and concluding. [16], [17]. Song et al. [18] suggested a novel approach for designing an end-effector path planning for a robot, utilizing the Bezier curve and a genetic algorithm. Wang et al. [19] proposed an optimization method based on the genetic algorithm in combination with particle swarm which had double global optimums for path planning of a welding robot. Lu et al. [20], [21] developed a new technique for optimizing the control system of a Delta parallel robot trajectory tracking, by PID-type interval type-two fuzzy logic regulator. Other methods are proposed for improving robot accuracy using an optical tracking system. [22] The proposed method is less expensive than existing laser tracker methods. The primary goals of the preceding researches were to increase the precision of robot control techniques. A suitable control software, on the other hand, must not only increase control precision, but also be simple, adaptable, robust, and stable. This study is concerned with the control of industrial robots. Model-based and model-free control are two prevalent approaches to categorizing distinct control systems. The focus of this work is on model-free approaches, specifically proportional-integral-derivative and Fuzzy controllers, in which a mathematical model of the system is not required. On the contrary, model-based controllers necessitate the presence of an analytical or experimental model of the robot. Genetic algorithms are used as an intelligent optimization approach for optimizing the Fuzzy logic controller. FLC (fuzzy logic controller) membership function parameters such as membership function base coordinates and output gain values will be tuned using the genetic algorithm optimization technique. We also examine and evaluate the performance of various controllers by modeling them in the MATLAB Simulink environment.

The following is a description of the papers structure. A brief overview of 3P cartesian robot dynamic model and path planning model given in Section II. Section III investigates P-PID, PV-PID, and fuzzy controller design. Section IV illustrates the proposed genetic algorithm optimized fuzzy controller design. Simulation results of proposed controllers are shown in Section V and Section VI concludes the paper.

II. 3P Cartesian robot dynamics model

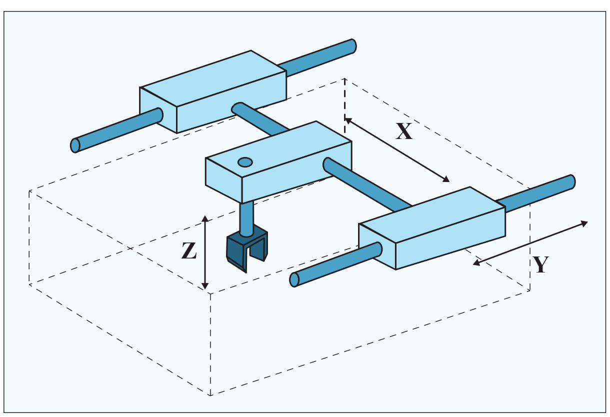

Fig. 1: Schematic of the 3P robotic manipulator

A. 3P Robot parameters

The robot physical parameters are reported in Table I. The payload weight is specified by *M*.

Each of the coordinates has movement restrictions according to (1).

TABLE I: Physical properties of simulated robotic manipulator and picked object (M is mass of object)

Link	Length (m)	Weight (kg)
1	0.5	15
2	0.5	10
3	0.2	5
M	-	1

$$\begin{aligned} 0.5 < x_e < 2 \\ 0.5 < y_e < 2 \\ 0.2 < z_e < 2.5 \end{aligned} \tag{1}$$

For an appropriate comparison of the designed controllers, the end-effector is to be displaced from the point [0.5, 0.5, 0.2] to [2, 2, 2.5]. This transmission spans the entirety of the robot's workspace.

B. 3P Robot dynamic equations

The robot has three independent linear dynamic equations on the x,y, and z-axis. The governing dynamic equations of this robot are as described in equations (2).

$$\begin{aligned} \ddot{x} &= \frac{F_1}{m_2 + m_3 + M} \\ \ddot{y} &= \frac{F_2}{m_1 + m_2 + m_3 + M} \\ \ddot{z} &= \frac{F_3 - (m_3 + M)g}{m_3 + M} \end{aligned} \tag{2}$$

A separate controller will be used for each actuator due to the dynamic independence of coordinates. Finally, the end-effector position will be controlled by the independent control of each actuator.

C. 3P Robot manipulator end-effector path planning

A path design function is defined in order to direct the robot end-effector from the initial position to the final position which is given in (3).

$$\begin{cases} S = 0.5at^2 + S_0 & if \;\; t < b \\ S = 0.5at^2 + S_0 + V_{max}(t-b) & if \;\; b < t < T-b \\ S = 0.5a(t-T-b)^2 + 0.5ab^2 \\ \quad +V_{max}(2t - T - b) + S_0 & if \;\; T-b < t \end{cases} \tag{3}$$

In the equations above *T* (10 seconds) is the total movement time and *b* (0.8 seconds) is the blend time. The resulting position of the end-effector related to the *x*, *y*, and *z* is shown in Fig. 2.

D. Evaluation Criteria

The following are some common formulas for determining total error.

$$ISE = \int e(t)^2 dt \tag{4}$$

$$IAE = \int |e(t)| dt. \tag{5}$$

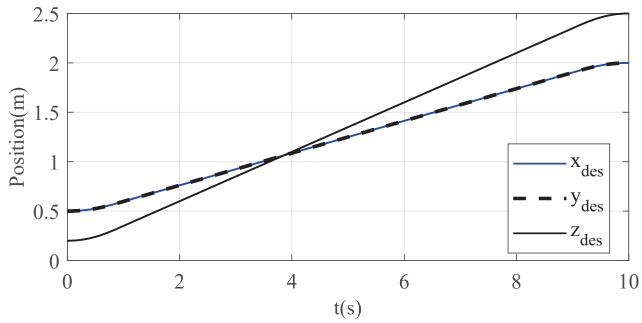

Fig. 2: The desired trajectory of robot manipulator end-effector traveling from the initial position to the final position defined by path design function. blue line shows the x coordinate desired path, dash line shows the y coordinate desired path and black line shows z coordinate desired path

Integrated squared error (ISE) is used for comparing the performance of proposed controllers in this paper. Because the ISE penalizes larger errors more that IAE, the controller is encouraged to have less error. This allows the optimization method to converge more quickly. In the conclusion, the IAE is also calculated. The IAE has the same units as position so it is useful in evaluating controllers.

III. Controller Design

We will first illustrate the three proposed controllers designed in this section. First a simple PID controller, then position velocity PID controller and ultimately Fuzzy logic (FLC) and genetic algorithm optimized Fuzzy logic controller (GAOFLC) will be presented.

A. Position PID controller

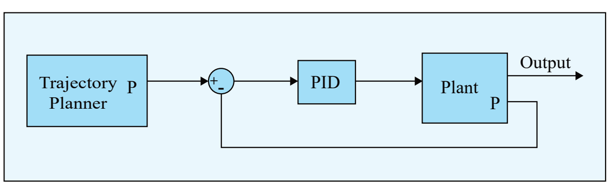

Fig. 3: Schematic of the simulated system for the PID controller

The PID controller is used as the simplist and base controller for comparison in this study. The purpose of the PID controller is to reduce the error and help follow the desired path while changing the position of the end-effector. The position error at any moment is calculated based on the difference between the position designed by the path planner and the current position of the system and is fed as input to the controller. The system was implemented in Simulink MATLAB.

$$U(t) = K_p e(t) + K_i \int e(t)dt + K_d \dot{e} \tag{6}$$

The PID coefficients are designed using MATLAB's tuning tool. For the x-direction coefficient, [36, 4, 50], y-direction coefficients [84,11,100] and for z coefficients [70,12.5,60] are obtained.

B. Position and velocity PID controller

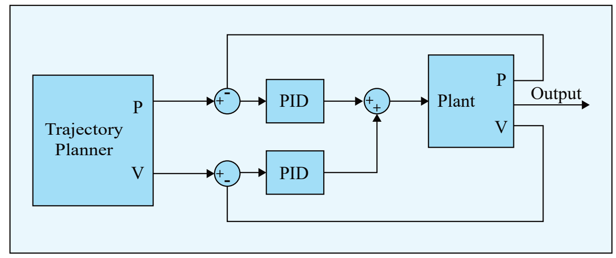

Fig. 4: Schematic of the simulated system for the velocity PID controller

To improve the PID controllers performacnce, the velocity error is added to the previous position error. Similar to before, coefficients of this controller are also determined using the MATLAB tuning tool. The xyz coordinate actuator coefficients are [574,7150, 1.5], [1540,21668,7.5], and [434,12209,0] respectively.

C. Fuzzy controller

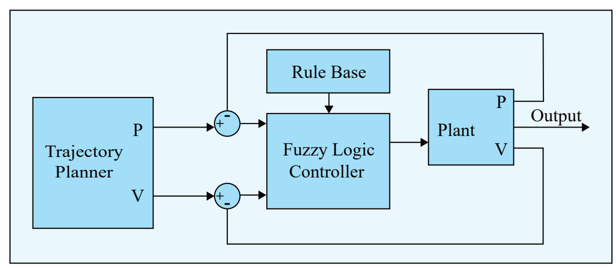

Fig. 5: Schematic of the simulated system for the velocity fuzzy logic controller

A fuzzy controller is designed to direct the system and reduce the position error. Due to the independance of the three-coordinate motion equations, a fuzzy controller is separately designed for each one. The inputs include position error and speed error, and the required force of the actuators the output of fuzzy models. The fuzzy system is based on *Mamdani inferential model* and de-fuzzification is done based on the *surface center method.*

TABLE II: Fuzzy inference rules

de/e	**NH**	**NL**	**Z**	**PL**	**PH**
NH	NE	NH	NM	NL	Z
NL	NH	NM	NL	Z	PL
Z	NM	NL	Z	PL	PM
PL	NL	Z	PL	PM	PH
PH	Z	PL	PM	PH	PE

Five triangular membership functions were assigned to each input and nine triangular membership functions were assigned to the output covering the range of [-1,1]. These functions are shown in Fig. 6.

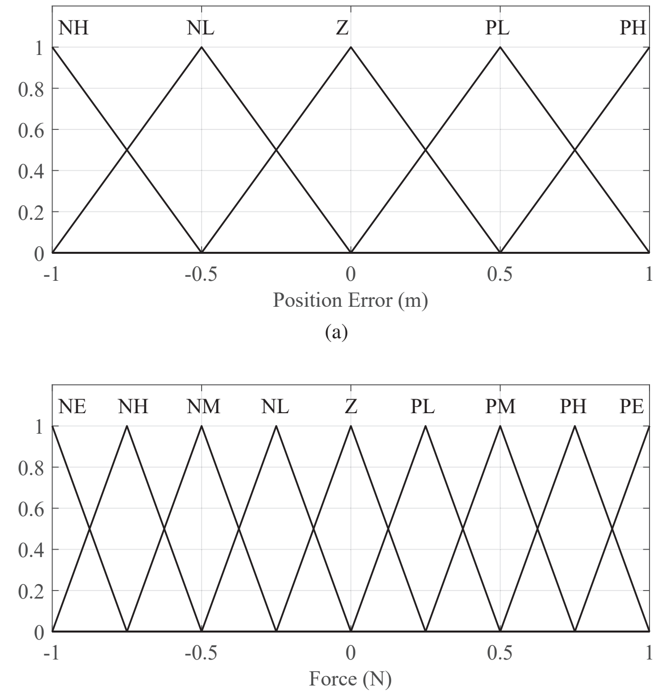

Fig. 6: In this figure, the Input-Output membership functions of the first considered controller for x y z coordinates are depicted. (a) Shows membership functions for position error and velocity error which are inputs; (b) Shows membership functions of end-effector final force which is output of controller

IV. Fuzzy controller optimization using genetic algorithms

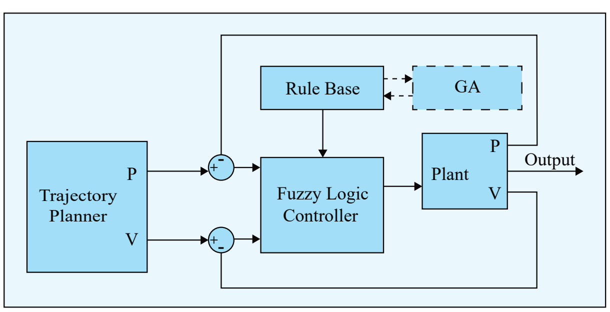

Fig. 7: Schematic of the simulated system for the genetic algorithm optimized fuzzy logic controller

Genetic algorithms are a powerfull intelligent optimization method used widely in controller design. With this method the membership functions, input and output coefficients, and fuzzy rules are optimized. The parameters and variables used are stated below.

1) Fuzzy rules: The rules are mirrored with respect to the minor-diagonal of the rule matrix.
2) Membership function: The functions are symmetric to zero and the endpoint of the membership function, i-1, the middle point of the membership function i, and the starting point, i+1, are identically defined. Therefore, we only need one variable for the input and 3 for the output membership functions leading to reduced calculation costs.
3) Input and output coefficients: a coefficient for each input and output is considered as a variable.

In summary, a total of 13 variables are considered for optimization. The cost function is sum of squared errors.

The genetic algorithm calculates 20 epochs with a population size of 40. Membership functions after optimization are shown in Fig. 8 - Fig. 10. Optimized rules between inputs and outputs are defined in Table III.

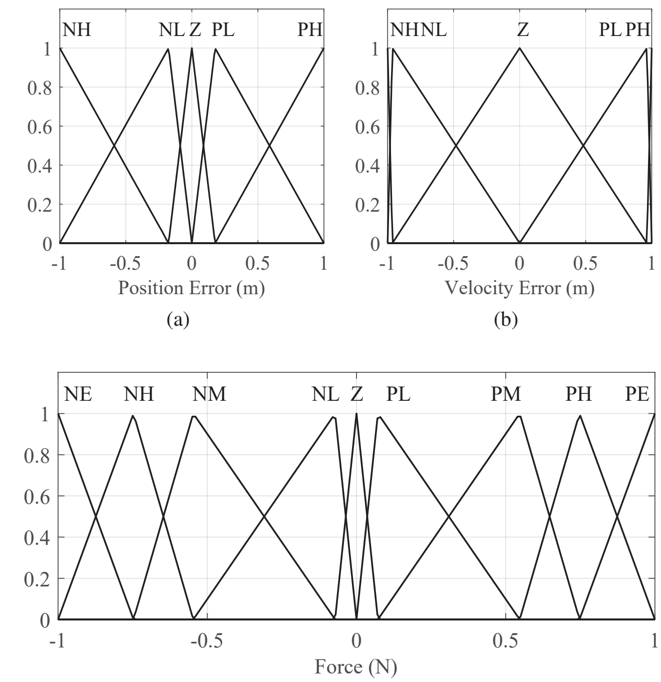

Fig. 8: Input-Output membership functions of the GA-FLC controller related to x coordinate. (a) Input membership functions related to x coordinate position error; (b) Input membership functions related to x coordinate velocity error (c) Output membership functions related to x coordinate end-effector final force

TABLE III: Optimized fuzzy inference rules

de/e	**NH**	**NL**	**Z**	**PL**	**PH**
NH	PE	NE	NH	NL	Z
NL	NE	NH	NL	Z	PL
Z	NH	NL	Z	PL	PH
PL	NL	Z	PL	PH	PE
PH	Z	PL	PH	PE	NE

V. Results

In this research, three controllers are implemented to control the position of a 3P robot end-effector. To evaluate the per-

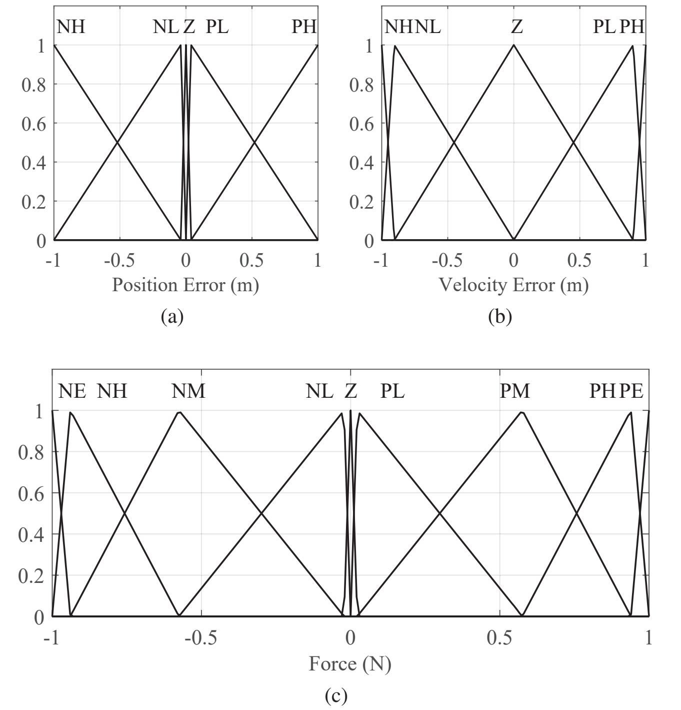

Fig. 9: Input-Output membership functions of the GA-FLC controller related to y coordinate. (a) Input membership functions related to y coordinate position error; (b) Input membership functions related to y coordinate velocity error (c) Output membership functions related to y coordinate end-effector final force

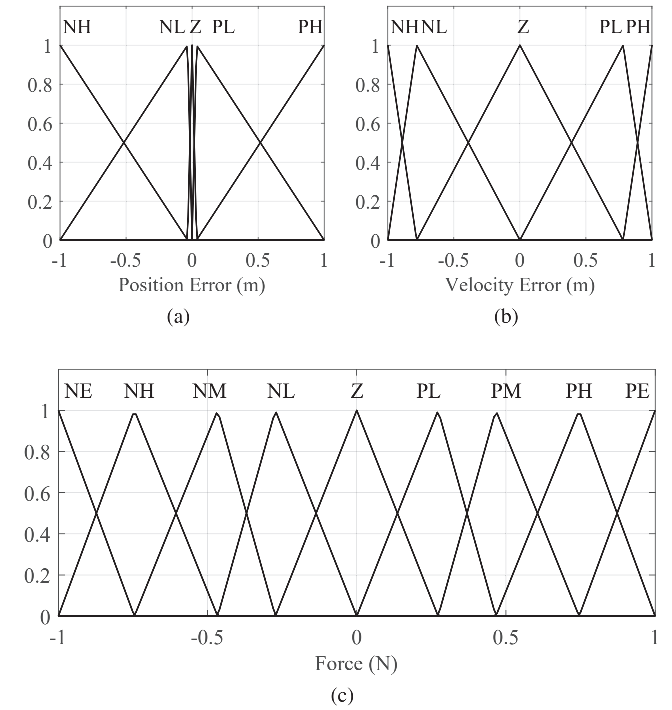

Fig. 10: Input-Output membership functions of the GA-FLC controller related to z coordinate. (a) Input membership functions related to z coordinate position error; (b) Input membership functions related to z coordinate velocity error (c) Output membership functions related to z coordinate end-effector final force

formance of the designed controllers, we examine the position error accruing between the desired path and the actual end-effector path.

TABLE IV: Summary

	$\int \lvert e_x \rvert^*$	$\int \lvert e_y \rvert^*$	$\int \lvert e_z \rvert^*$	$\int \lvert e \rvert^*$	$\int e^{2*}$	$\int \lvert u \rvert$
P-PID	1018	922	40215	42155	19670	603.6
PV-PID	6.8865	4.4391	474.6	485.9	2.2627	842.7
GA-FLC	32.9	20.8	6.7885	60.57	0.766	1647

$^*\times 10^{-4}$

By comparing the position error values of the mentioned controllers in the x, y, and z coordinates in Fig. 11, it is depicted that the optimized fuzzy controller's position error value is lower than the position and velocity PID controller and position velocity PID controller shows a far better performance compare to conventional PID. As it shown in Fig. 11 sections (e), (f) in nonlinear, time-varying, and large inertial systems, the conventional PID control strategy has some serious limitations in term of system positioning control.

To investigate the effect of nonlinearity on the evaluation of the mentioned controllers' performance in system positioning control Fig. 11 sections (e), (f) are considered. The error value rate in the optimized fuzzy controller is considerably lower than the other controllers, however the error value in the robot workspace is not zero due to the effect of weight. Thus the optimized fuzzy controller can control the non-linearity of the system well due to the use of optimized variables. The exact amount of error values in three distinct controllers depicted in Table IV

It is worth mentioning, regarding the trade-off between computational cost and accuracy of the controllers, position, and velocity PID controller shows an acceptable performance.

VI. Conclusion

The genetic algorithm is an intelligent algorithm that has demonstrated significant potential in solving parameter optimization problems. In this study, the fuzzy logic controller is developed to control the dynamic model of the 3P robot end effector, and ultimately an intelligent genetic algorithm is utilized to optimize the fuzzy controller parameters. This controller was compared with position PID controller and position velocity PID (PV-PID). Fuzzy control challenges, such as low accuracy and rough control outputs are solved. The optimized fuzzy controller allows accurate Robot positioning thus improving the control precision of the manipulator end effector.

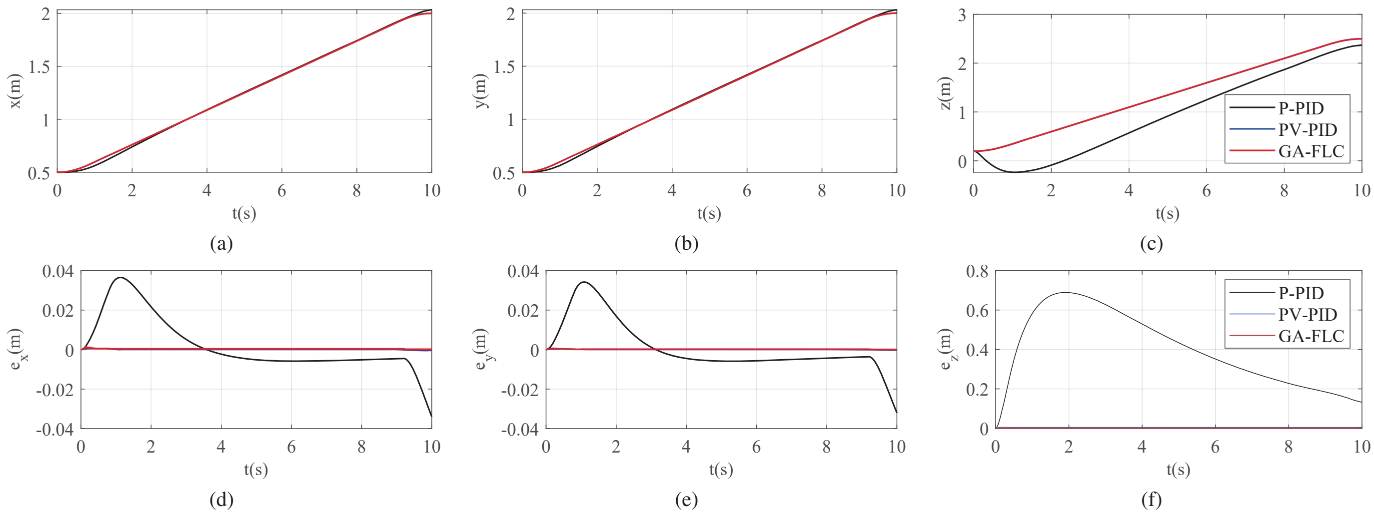

Fig. 11: Manipulator end-effector position, position error and control effort of three designed controllers. (a) End-effector x position, (b) End-effector y position, (c) End-effector z position, (d) End-effector x position error, (e) End-effector y position error (f) End-effector z position error. Black line: Position PID controller; Blue line: Position and Velocity PID controller; Red line: genetic algorithm optimized fuzzy controller.

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