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Improving Control Stability for A Robot Arm Packaging System using Fuzzy Optimization

Zhimin Lu, Shouquan Gao, Wei Wu, Hongli Deng*, Wencan Li, Weiwei Zhang, Mengling Huang
Longyan Tobacco Industry Co., Ltd.,
No. 1299 Shengfeng Rd, Xinluo District, Longyan 364021, China
1012240592@qq.com; gsq22572@fjtic.cn; ww23017@fjtic.cn; lwc22355@fjtic.cn; zww22404@fjtic.cn; hml23122@fjtic.cn
** corresponding author: dhl23399@fjtic.cn*

Abstract—**This work addresses the issue of insufficient control stability in the robotic arm feeding system in the packaging production line by proposing an adaptive algorithm based on the fuzzy-optimized PID (Proportional-Integral-Derivative) controller. By establishing the D-H (Denavit-Hartenberg) kinematic model of the robotic arm and combining the MATLAB Robot Toolbox with the SIMULINK simulation platform, a fuzzy controller was designed with amplitude deviation and deviation rate as the inputs to dynamically adjust the PID parameters. Hardware integration was achieved based on the Mitsubishi FX2N series PLC (Programmable Logic Controller). Simulation results show that the adjustment time of the fuzzy PID control is 0.45s, which is reduced by 25% compared to the traditional PID (i.e., 0.6s), with the overshoot reduced from 6% to 0% and the steady-state error stabilized at 0mm. Through 10 sets of actual picking experiments, it was verified that the average time error under the fuzzy PID control is 0.37s with a standard deviation of 0.23s, which is a reduction of 55.4% and 85.6% compared to the traditional PID and direct start-up, respectively, which significantly improves the stability and efficiency of the robotic arm feeding system. This study proves that the fuzzy PID, through dynamic parameter optimization and disturbance compensation, can effectively address the control response delay and error accumulation of the robotic arm under non-ideal operating conditions, providing a high-precision and high-robustness solution for industrial packaging automation.**

Index Terms—**Industrial control; Fuzzy control; PID controller; Experimental test**

I. INTRODUCTION

The stability operation of the tobacco packaging production line directly influences the production efficiency, cost control, product quality, and sustainable development. Currently, the technological development of the cigarette packaging still faces many challenges. Many traditional devices rely on manual operation and fail to efficiently integrate advanced automation technologies, leading to instability in the production process, wastage of time and resources, and a negative impact on overall production efficiency. In addition, the intelligence level of current controller in the packaging production line is very low, reducing the overall collaborative efficiency of the production line. Therefore, there is an urgent need for automation innovation in the cigarette packaging process, especially in improving the intelligence and digitalization.

Introducing intelligent control technology will enable flexible production in response to market demand. Through these technological innovations, not only can production efficiency be improved and labor costs reduced, but product quality and the sustainability of the production line can also be effectively enhanced. Fuzzy theory is regarded as the most practical artificial intelligence (AI) in industry to improve the control performance [1]. Existing studies have demonstrated that the Fuzzy optimization can be used for industrial applications to improve the production control performance. However, very limited work has been reported in the tobacco packaging production line using the Fuzzy based control strategy. Based on the existing studies, it is reasonable to introduce the Fuzzy method into the robotic arm feeding system of the tobacco packaging production line to enhance the system control stability to improve the production quality and efficiency.

This paper addresses the design of a robotic arm to achieve automatic cigarette grabbing and packing. A fuzzy PID controller is proposed to improve the control stability of the robotic arm feeding system. By establishing the robotic arm motion model, the motion process of the arm is analysed. Based on the functional requirements for cigarette feeding, both simulation analysis and experimental evaluation have been carried out. The results demonstrate high control stability of the robotic arm feeding process.

The rest of this work is organized as follows. Section 2 describes the related work. Section 3 establishes the robotic arm motion model. Section 4 proposes the Fuzzy PID controller and analyses the simulation control results. Section 5 performs the experimental evaluation and Section 6 draws the concludes.

II. RELATED WORK

The stability operation of the tobacco packaging production line directly influences the production efficiency, cost control, product quality, and sustainable development. Currently, the PID control is the mainstream technique in real world applications. However, the PID parameters are fixed during the PID control process, which cannot adapt to the operation changes of the production line due to external interference and noise [2].

The Fuzzy logic is able to tune the PID parameters in a real-time manner. Wang et al. [3] implemented continuous adjustment of the cotton picking speed, conveyor belt speed, and fan speed of the robotic arm based on the fuzzy PID control theory. Meng et al. [4] designed a fuzzy adaptive PID control system for the weighing system of a packaging machine, and realized the entire control process with the PLC hardware, making the weighing process more accurate and responsive. Adar et al. [5] the applied fuzzy PID controllers for visual servo control, enhancing the precision and flexibility of the robots in performing grasping and manipulation tasks in dynamic environments. Cen et al. [6] achieved precise target positioning and control of the robotic arm using the proximal policy optimization with a fuzzy PID controller. Srivastava et al. [7] demonstrated strong robustness and adaptability by applying the neural fuzzy control to the robotic arm control, especially in dealing with dynamic changes and uncertainties. Yang et al. [8] applied the Takagi-Sugeno (T-S) fuzzy model to the robotic arm control, ensuring asymptotic stability of the closed-loop control system and optimizing the transient performance of the robotic arm. Jiang et al. [9] demonstrated that the robotic arms controlled by a fuzzy neural network (FNN) controller exhibit fast response, small overshoot, and minimal oscillation. Armendariz et al. [10] used a PID controller with constant feedback gain, ensuring the system dissipation through carefully designed damping injection, and guaranteed semi-global exponential convergence using the Lyapunov stability theory, resulting in more precise robotic arm motion. Chhabra et al. [11] proposed a nonlinear fuzzy PD-I controller based on the fractional-order calculus, providing more precise and stable control for the robotic arms. Alavandar et al. [12] proposed a novel control strategy based on a fuzzy PD+I controller for the trajectory tracking control of a six-degree-of-freedom PUMA robotic arm, making the controller more concise and efficient. Raković et al. [13] focused on the fuzzy logic controllers for controlling the brushless DC motor of a hand drive with underactuated fingers, ensuring precise control. Alizadeh et al. [14] proposed an innovative super-twisting fast non-singular terminal sliding mode control strategy, specifically addressing the trajectory control problem of a three-degree-of-freedom robotic arm, significantly improving the trajectory tracking accuracy and system response performance.

It can conclude that the Fuzzy logic is a perfect match to the PID controller in practical applications. However, very limited work has been reported in the tobacco packaging production line using the Fuzzy based control strategy. It is reasonable to explore the Fuzzy PID control in the packaging production line.

III. Establishment of the Robotic Arm Model

A. D-H Transformation

The present robotic arm is illustrated in Fig. 1. The robotic arm model is analysed using the D-H method. The D-H method describes the spatial relationship between two adjacent links by establishing the coordinate systems on each axis and using a 4×4 homogeneous transformation matrix. The D-H transformation is established based on the physical diagram of the robotic arm, as shown in Fig. 2. The parameters for each link of the robotic arm can be determined using the following four parameters, where the first two parameters describe the relationship between two adjacent link axes, while the other two describe the relationship between two adjacent links.

(1) The link twist angle: the angle at which the link axis *i*-1 rotates around the common perpendicular to reach the link axis *i*.

(2) The link length: the distance along the common perpendicular from the link axis *i*-1 to the link axis *i*.

(3) The link rotation angle: the angle at which the link *i*-1 rotates around the link axis *i* to reach the link *i*.

(4) The link offset: the distance along the common axis from the link *i*-1 to the link *i*.

Fig. 1. Physical diagram of the robotic arm.

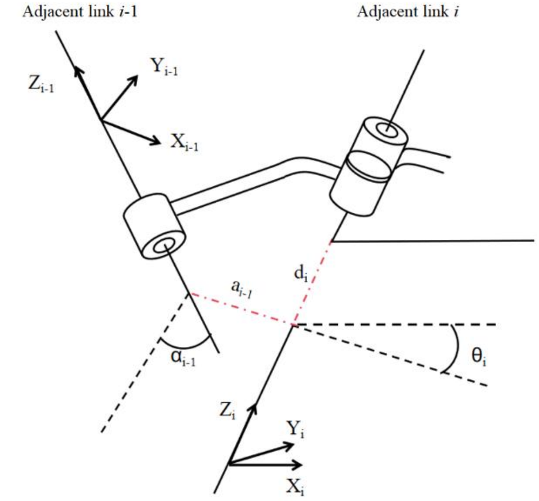


Fig. 2. Reference diagram of the D-H coordinate system.

B. Robot Arm Model

Generally, the spatial position transformation of the robotic arm links involves compound transformations, often requiring coordinate composite transformations to determine the transformation laws and, consequently, the motion form of the robotic arm in space. When the origin and direction of coordinate system *A* differ from those of the coordinate system *B*, the transformation from the coordinate system *A* to *B* is called a composite transformation. The mathematical expression for the transformation of point *P* from *A* to *B* is

$$ {}^{A}P = R\,{}^{B}P + {}^{A}P_{B} \tag{1}$$

Starting from the base of the robotic arm and performing the coordinate transformations to the end effector, each transformation is designated as *A*. The transformation matrices should be sequentially as follows.

$$ {}^{0}_{T}T = {}^{0}_{1}T\,{}^{1}_{2}T\,{}^{2}_{3}T \cdots {}^{n-1}_{n}T = A_1 A_2 A_3 \cdots A_n \tag{2}$$

The formula for calculating the transformation matrix **T** is

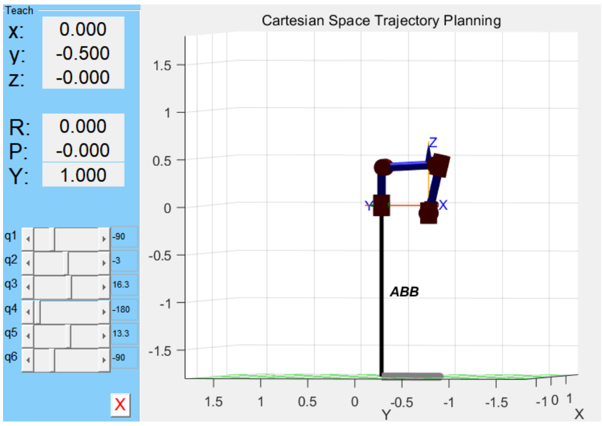
$$\begin{aligned} {}^{i-1}_{i}T &= A_i \\ &= \mathrm{Rot}(z,\theta_i)\mathrm{Trans}(0,0,d_i)\mathrm{Trans}(l_i,0,0)\mathrm{Rot}(x,\alpha_i) \\ &= \begin{bmatrix} \cos\theta_i & -\sin\theta_i & 0 & 0 \\ \sin\theta_i & \cos\theta_i & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & d_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_i & -\sin\theta_i & 0 \\ 0 & \sin\theta_i & \cos\theta_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & l_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & l_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{3}$$

The robotic arm model is established using the Robot Toolbox in MATLAB, as shown in Fig. 3 and the data in Table I describe the trajectory of the robotic arm when picking up the cigarette sticks from the cigarette sorting mechanism to the cigarette box. The model is built using the Denavit-Hartenberg (D-H) parameter table and the link function by taking into account the link angles, link rotation angles, link lengths, link twists, and link types.

The expression for the link function is

$$ L(i) = LinK([\theta_i, d_i, \beta_i, \alpha_i],'\text{standard}') \tag{1}$$

where, *i* presents the link number; θ denotes the link rotation angle; *d* denotes the link offset; α_i denotes the link twist angle; β_i denotes the link length; and the standard function is adopted.



Teach

x: 0.000
y: -0.500
z: -0.000

R: 0.000
P: -0.000
Y: 1.000

q1 -90
q2 -3
q3 16.3
q4 -180
q5 13.3
q6 -90

Fig. 3. Robotic arm model.

TABLE I. ROBOT D-H PARAMETER TABLE.

Number of links	Link twist angle (α_i)	Link rotation angle (θ_i)	Link length (β_i)	Link offset (d_i)	Rotation angle range / degree
1	-90	θ_1	175	495	$-90 \le \theta_1 \le 180$
2	0	θ_2	1095	0	$-90 \le \theta_2 \le 150$
3	-90	θ_3	175	0	$-180 \le \theta_3 \le 75$
4	90	θ_4	0	1270	$-400 \le \theta_4 \le 400$
5	90	θ_5	0	0	$-125 \le \theta_5 \le 120$
6	0	θ_6	0	135	$-400 \le \theta_6 \le 400$

IV. FUZZY PID CONTROL FOR ROBOT ARM

A. *Controller Design*

The control stability of robot arm when grasping the production is related to the frequency and amplitude of the robotic vibration. When the vibration frequency is high, the amplitude of the robotic arm is large, resulting in stronger vibrational impacts that affect the stability and continuity of the robot grasping process. The traditional PID controller can adjust the control deviation to stabilize the system; however, the fixed PID parameters and slow control response make it difficult to achieve stable control of the grasping amplitude for the robotic arms. To resolve this issue, a fuzzy PID controller is designed, as shown in Fig. 4. In the controller, an amplitude sensor collects the amplitude value δ to compare with the control reference *u*; the obtained deviation *e* and its change rate *ec* between the measured value and the reference value are used as the input variables for the Fuzzy inference module. Through the Fuzzy inference, the values of the PID parameters *Kp*, *Ki* and *Kd* are adaptively optimized during the control process. Therefore, the fuzzy inference for the robotic arm is a single-variable control system with two inputs and three outputs.

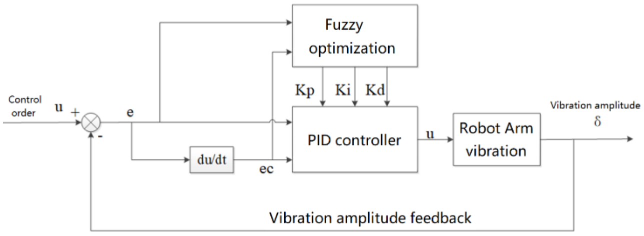
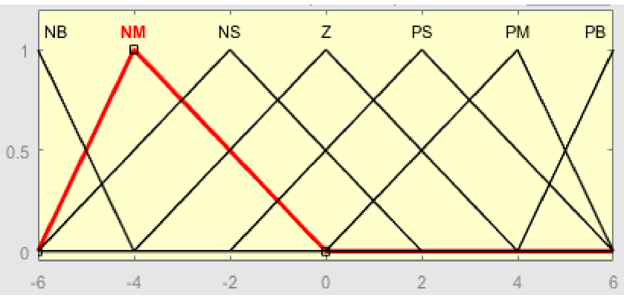


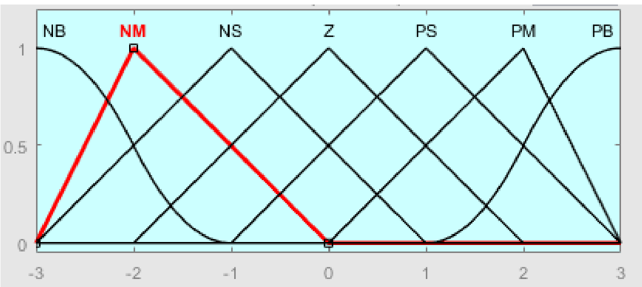
Fig. 4. Fuzzy PID Controller design.

The Fuzzy inference module is established using the MATLAB Fuzzy Logic Toolbox. The Mamdani inference is employed with the centroid method for solving the Fuzzy inference, the minimum method is used for the Fuzzy rules, and the maximum method is adopted for the Fuzzy rule composition.

The number of the Fuzzy subsets determines the control accuracy; a great number of subsets will produce higher control accuracy but requiring more computational resources. Based on the computational feasibility and practical experience, it is generally recommended to use 3 to 10 levels of the subsets. Considering the actual response speed and computational load of the robotic arm, the input and output variables of the controller are divided into 7 levels. The fuzzy sets for the input parameters *e* and *ec*, as well as the output parameters *Kp*, *Ki* and *Kd*, are defined as {B, M, S, O, D, E, F}, representing {Negative Large, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, Positive Large}. The domains of the input parameters *e* and *ec* are quantified into the standard universe as the same as [-6, -4, -2, 0, 2, 4, 6], with their membership functions being triangular, as shown in Fig. 5(a). The domains of the output parameters *Kp*, *Ki* and *Kd* are set as the same as [-3, -2, -1, 0, 1, 2, 3], with their membership functions being triangular, S-shaped, and Z-shaped, respectively, as shown in Fig. 5(b).



(a) Membership functions of input parameter *e*.



(b) Membership functions of input parameter *ec*.

Fig. 5. Membership functions of the inputs.

When the deviation *e* is large, a larger proportional coefficient and a smaller differential coefficient are selected. At the same time, to prevent the integral saturation and avoid large overshoot in the control system response, the integral term is set to 0. When the deviation *e* and the change rate of the deviation *ec* are moderate, none of the proportional, differential, and integral parameters should be too large. The integral term should be set to a smaller value, while the proportional and differential terms should be set at moderate values to ensure a good response speed for the control system. When the deviation *e* is small, to ensure good steady-state performance of the control system, the proportional and integral coefficients should be increased. At the same time, to prevent oscillation around the setpoint and considering the system anti-interference ability, a medium-sized differential coefficient is chosen. Based on these fuzzy rules, the rule table for the designed Fuzzy inference is set as shown in Table II.

TABLE II. FUZZY CONTROL RULES

e	*ec*						
	B	M	S	O	D	E	F
B	F/B/D	F/B/D	E/M/B	M/D/B	D/S/B	O/O/M	O/O/D
M	F/B/D	F/B/S	E/M/B	D/S/M	D/S/M	O/O/S	S/O/O
S	E/B/O	E/M/S	E/M/S	D/S/O	O/O/S	S/D/S	M/D/O
O	E/S/O	E/S/S	D/S/S	O/O/S	S/D/M	M/E/S	S/E/O
D	D/M/O	D/S/O	O/O/O	O/D/S	S/D/O	M/E/O	B/F/O
E	D/O/F	O/O/S	S/D/S	M/D/M	M/E/D	B/F/D	B/F/F
F	O/O/F	O/O/E	S/D/M	M/D/M	B/E/D	B/F/D	B/F/F

When the input variable *x* is fuzzified and mapped to the fuzzy quantity *X*, the output fuzzy quantity can be obtained according to the approximate inference composition rules as

$$U = XR = (XR_1) \cup (XR_2) \cup \cdots (XR_{n-1}) \cup (XR_n) \qquad (2)$$

where *R* denotes the Fuzzy rules. Since the fuzzy quantity *X* may not activate every fuzzy rule, zero terms may appear in the operation of (XR_j) (where j = 1, 2 ,... , n, with n as the rule total number). The "OR" operation in Eq. (5) will eliminate the zero terms.

Therefore, the actual fuzzy output quantity is

$$\begin{cases} K_p = k_{p0} + k_0\{e, ec\}_p \\ K_i = k_{i0} + k_1\{e, ec\}_i \\ K_d = k_{d0} + k_2\{e, ec\}_d \end{cases} \qquad (3)$$

where, k_{p0}, k_{i0} and k_{d0} are the initial values of the PID parameters, k_0, k_1 and k_2 and are the quantization factors of the fuzzy output parameters.

B. Simulation Model Based on SIMULINK

A fuzzy PID control simulation model is established using the SIMULINK module in MATLAB, as shown in Fig. 6. The control outputs of the traditional PID and the fuzzy PID are displayed on the same oscilloscope in the simulation model for comparison purpose.

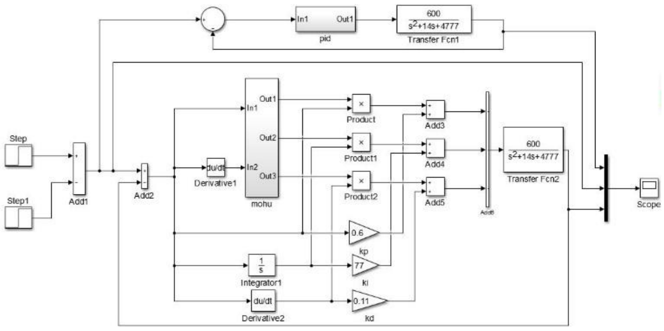
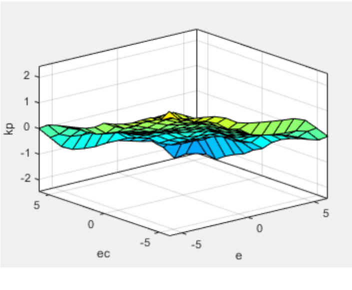
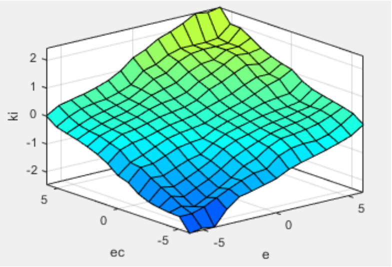


Fig. 6. The design Fuzzy PID simulation model in SIMULINK.

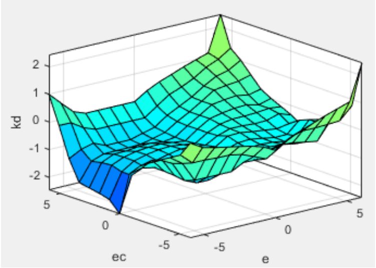
A fuzzy inference system (FIS) for the robotic arm is established using the Fuzzy Logic Toolbox in MATLAB. The relationship between the input quantities of the fuzzy control rules and the output variables is shown in Fig. 7.



(a) Observation chart of *Kp* in the Fuzzy PID.



(b) Observation chart of *Ki* in the Fuzzy PID.



(c) Observation chart of *Kd* in the Fuzzy PID.

Fig. 7. Three-dimensional (3D) view of the Fuzzy rules.

After quantifying the Fuzzy inputs *e* and *ec*, they pass through the Saturation block, which quantizes all input values to the fuzzy domain. Then, the Fuzzy inference is carried out based on the Fuzzy rules to generate the optimized PID parameters. Lastly, the PID controller will update its PID parameters to enhance its control performance.

V. SIMULATION AND EXPERIMENTAL EVALUATION

A. *Simulation Analysis*

In the traditional PID control simulation model, the trial-and-error method is used, which is based on the manual parameter tuning. By continuously adjusting the PID parameters and observing the system response, the optimal PID parameters is gradually approached. The core idea is to repeatedly experiment to find the parameter values that allow the system response to meet the expected performance criteria such as the expected overshoot, settling time, and steady-state error.

In the simulation analysis, the sampling time is set to 0.1s, the simulation time is set to 2s, the stable value is set to 1mm. The PID parameters adjusted using the trial-and-error method for the traditional PID control are 0.6, 77, and 0.12.

For the Fuzzy PID controller, the Fuzzy domain for the deviation *e* is chosen as [-0.06, 0.06], and for the deviation rate *ec* is chosen as [-0.03, 0.03]. The quantization factor for the deviation *e* in the fuzzy domain is 100, and for the deviation rate *ec* is 20; the quantization factor for *Kp* is 0.05, for *Ki* is 1.5, and for *Kd* is 0.05. The simulation results are shown in Fig. 8.

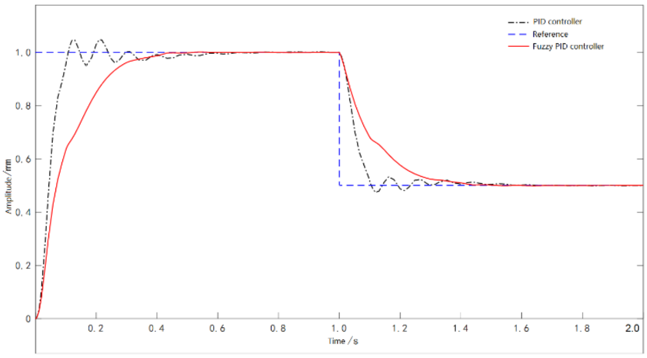


Fig. 8. Robot arm control simulation results.

In Fig. 8, it can be observed that the traditional PID control has a higher overshoot than the fuzzy PID control. The fuzzy PID control has a shorter adjustment time and only requires a slight adjustment to reach control stability. On the other hand, the traditional PID control has a longer adjustment period and exhibits larger fluctuations when reaching the steady state. This is because the PID parameters are fixed for the traditional PID controller while real-time adjusting for the Fuzzy PID controller. As a result, the Fuzzy PID control can produce better control performance by using different but proper PID parameters during the control process.

In order to further compare the control performance of the two controllers, the simulation time is set to 2s and at 1.5s an external disturbance is applied to test the controller anti-interference performance. The simulation results are shown in Fig. 9.

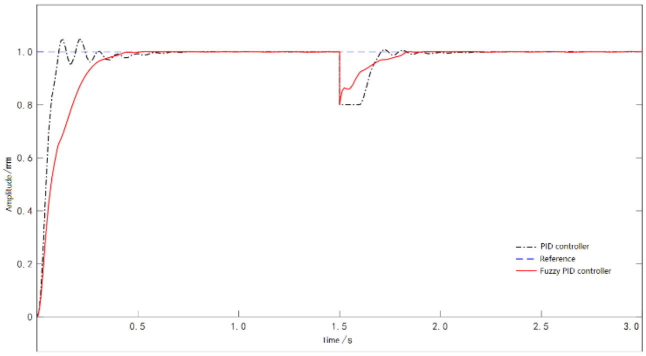


Fig. 9. Disturbance simulation results.

From Fig. 9 it can be observed that due to the extra interference, the amplitude curve shows significant fluctuations. After the disturbance occurs, both controllers can adjust according to the level of the interference. The adjustment times for the PID controller and the Fuzzy PID controller in response to the disturbance are 0.62 s and 0.46 s, respectively. From the adjustment times, it can be seen that the Fuzzy PID controller can quickly compensate the disturbance, allowing the amplitude to stabilize more rapidly.

B. *Experimental Evaluation*

In order to evaluate the actual control performance of the Fuzzy control method, a tobacco packaging platform in the Longyan Tobacco Industry Co., Ltd. is used to carry out the experiment test. The packaging platform is illustrated in Fig. 10, which consists of two robotic arms, four work slots, one controller box with PLC, and a product transmission line. The packaging boxes will be continuously placed on the work slots during the packaging process. The robot arms are controlled by the Fuzzy controller to correctly and stably grasp the products to the packaging boxes.

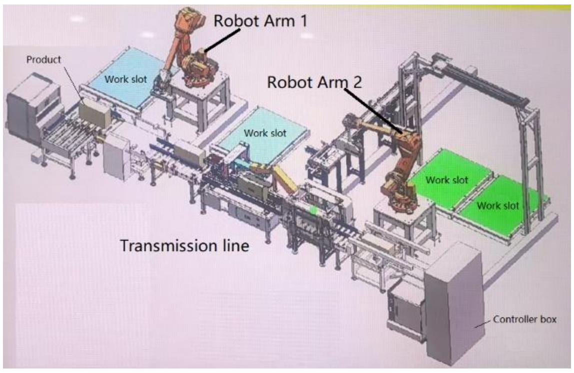


Fig. 10. The tobacco packaging platform.

Fig. 11 shows an image of the packaging platform, where the main parameters of the robotic arm (model: ABB IRB4600-40/2.55) are as follows: 6 axes, 40kg payload, 2550mm working range, 0.13-0.46mm of repeatability,: Standard IP67 protection level, and 435kg weight.

The robotic arm control system uses the Mitsubishi FX2N series PLC. The main parameters of the PLC (model: Siemens CPU 1511-1 PN) are as follows: working memory capable of storing 150KB of code and 1MB of data, 60ns Bit execution time, transmission protocol TCP/IP, and firmware version V2.9.

Fig. 11. An image of the packaging platform.

When using the PLC to program the Fuzzy control algorithm, the resolution setting value for the PLC analog input module is 1V. The Fuzzy domain of the error *e* is [-0.06, 0.06], and the Fuzzy domain of the error change rate *ec* is [-0.03, 0.03]. Based on the resolution of the analog input module, the domains of *e* and *ec* can be quantized into the PLC as [-12, 12] and [-6, 6], respectively. In the PLC programming, the CMP (Compare) instruction is used to implement the level quantization of the input value. The sampling time is set to 0.1s, and the action direction is set to the positive direction.

The experimental results for the robot arm control response are listed in Table III.

TABLE III. EXPERIMENTAL RESULTS

Response parameters	Control Method	
	PID control	Fuzzy PID control
Adjustment time (s)	0.6	0.45
Overshoot amount	6%	0
Steady-state error (mm)	0	0

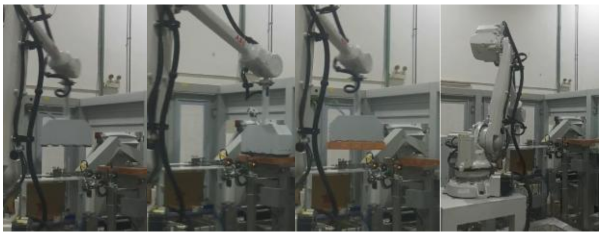
As shown in Table III, the traditional PID controller reaches a settling time of about 0.6s, with an overshoot of 6%. The Fuzzy PID controller reaches a steady state in about 0.45s, with the adjustment time being approximately one-quarter shorter than the traditional PID, resulting in a faster and smoother system response without any overshoot yet.

The experimental results indicate that the traditional PID control has a higher overshoot compared to the Fuzzy PID control. The Fuzzy PID control responds faster than the traditional PID, with a shorter adjustment time and only a slight adjustment when reaching stability. In contrast, the traditional PID control has a longer adjustment time and greater fluctuations when reaching steady state. Furthermore, during speed regulation, the Fuzzy PID algorithm responds more quickly. Therefore, it can be concluded that Fuzzy PID control is more effective for the robotic arm control.

C. Packaging Experiment Analysis

According to the actual tobacco packaging requirements, the expected time to complete one picking task is 8s. An experimental analysis of the packaging process is conducted. The timing starts when the robotic arm restarts after picking the previous row of tobacco, and stops when the robotic arm completes the 10th row of tobacco. The idea time is 80s, and the error between the idea time and the actual time is calculated. Fig. 12 describes the packaging process of the robot arm using three completed grasps with the Fuzzy control. As can be seen in Fig. 12, the robot arm is able to stably and accurately complete the grasping action to pack the products into the packaging box. A video of the packaging process of the robot arm is provided in the supplement material.

(a) First completed grasp



(b) Second completed grasp

(c) Third completed grasp

Fig. 12. Packaging process of the robot arm.

After conducting 10 test runs, the statistical errors are shown in Fig. 13. As shown in Fig. 13, when the robotic arm is started directly without a controller, there is a significant error in the picking time. With the traditional PID control, the time error is significantly reduced, while the fuzzy PID control further reduces the error. Table IV compares the statistical errors between different control methods. As can be see that the fuzzy PID control produces smallest errors, indicating significant improvement in the control stability.

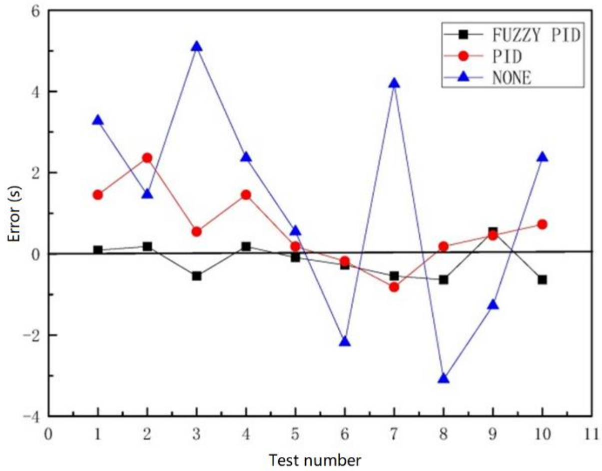


Fig. 13. Grasping time error in the experimental tests.

TABLE IV. ERROR STATISTICS TABLE

Control Method	Mean error	Standard deviation	Maximum error	Minimum error
No controller	2.57s	0.76s	5.1s	0.6s
PID controller	0.83s	0.34s	2.4s	0.1s
Fuzzy PID controller	0.37s	0.23s	0.7s	0.1s

VI. CONCLUSIONS

This study puts forward a Fuzzy PID control method for the robot arm control in the tobacco industrial packaging system. Simulation and experiments have demonstrated great improvement in the control stability when comparing the Fuzzy PID controller with the traditional PID controller. Considering that currently the industrial packaging system uses the traditional PID controller, the proposed Fuzzy PID has been embedded into the PLC of the industrial packaging system to replace the traditional PID controller to enhance the product packaging control performance. The main conclusions are drawn as follows.

(1) Simulation results verified that the designed Fuzzy PID controller exhibits a faster response speed compared to the traditional PID controller.

(2) The Fuzzy PID control algorithm was implemented through program design and development of the PLC. The speed control effect in the experiments verified the feasibility of the Fuzzy PID algorithm.

(3) In the experiments, the mean error of the Fuzzy PID is shortened more than 50% over the traditional PID controller, demonstrating higher control stability and accuracy.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] B. Y. Suprapto, S. Dwijayanti,and D. Amri, “Development of a position control system for wheeled humanoid robot movement using the swerve drive method based on Fuzzy logic type-2,” *Elektronika Ir Elektrotechnika*, vol. 30, no. 1, pp. 4-13, 2024 .

[2] L. Zhang, M. Kang, X. Liu, and Z. Li, “Position control for automatic assembly equipment using a new hybrid Fuzzy controller,” *Elektronika Ir Elektrotechnika*, vol. 30, no. 3, pp. 15-22, 2024.

[3] Y. Wang, L. Wang, G. Li, et al., "Grey prediction Fuzzy PID control method for volume flow in cotton picker," *Journal of Agricultural Mechanization Research*, vol. 42, no. 4, pp. 6–11, 2020.

[4] S. Ren, C. Yang, and X. Meng, "Research on weighing control system of fully automatic bagging packaging machine based on PLC," *Packaging Engineering*, vol. 40, no. 3, pp. 162–168, 2019.

[5] S. Alavandar and M. J. Nigam, "Fuzzy PD+I control of a six DOF robot manipulator," *Industrial Robot*, vol. 35, no. 2, pp. 125–132, 2008.

[6] Y. Cen, J. Deng, Y. Chen, et al., "Digital twin-empowered robotic arm control: An integrated PPO and Fuzzy PID approach," *Mathematics*, vol. 13, no. 2, p. 216, 2025.

[7] S. Srivastava, G. P. A., M. Gupta, et al., "A comparative study of PID and neuro-fuzzy based control schemes for a 6-DoF robotic arm," *Journal of Intelligent and Fuzzy Systems*, vol. 35, no. 5, pp. 5317–5327, 2018.

[8] W. Yang, W. Zhang, D. Xu, et al., "Fuzzy model predictive control for 2-DOF robotic arms," *Assembly Automation*, vol. 38, no. 5, pp. 568–575, 2018.

[9] X. Jiang, Z. Wang, C. Zhang, et al., "Fuzzy neural network control of the rehabilitation robotic arm driven by pneumatic muscles," *Industrial Robot*, vol. 42, no. 1, pp. 36–43, 2015.

[10] J. Armendariz, V. Parra-Vega, R. García-Rodríguez, et al., "Neuro-fuzzy self-tuning of PID control for semiglobal exponential tracking of robot arms," *Applied Soft Computing*, vol. 25, pp. 139–148, 2014.

[11] H. Chhabra, V. Mohan, A. Rani, et al., "Robust nonlinear fractional order fuzzy PD plus fuzzy I controller applied to robotic manipulator," *Neural Computing and Applications*, vol. 32, pp. 2055–2079, 2020.

[12] N. Adar, A. E. Tiryaki, and R. Kozan, "Real time visual servoing of a 6-DOF robotic arm using fuzzy-PID controller," *Acta Physica Polonica A*, vol. 128, no. 2B, 2015.

[13] M. Raković, G. Anil, Ž. Mihajlović, et al., "Fuzzy position-velocity control of underactuated finger of FTN robot hand," *Journal of Intelligent and Fuzzy Systems*, vol. 34, no. 4, pp. 2723–2736, 2018.

[14] M. Alizadeh, M. H. Samaei, M. V. Estakhri, et al., "Robust trajectory tracking of a 3-DOF robotic arm using a Super-Twisting Fast finite-time Non-singular Terminal Sliding Mode Control in the presence of perturbations," *Proceedings of the Institution of Mechanical Engineers*, 2024.