International Journal for Housing Science and Its Applications
Publish August 6, 2025. Volume 46, Issue 3 Pages 8038-8049

https://doi.org/10.70517/ijhsa463687

Optimization of design scheme and intelligent control strategy of new high-power railroad tie laser cutting robot

Hong Zheng[1], Xulin Zhang[1,*], Junchao Wang[1], Xinghao Wang[1], Yinghao Zhao[1] and Qixiao Sun[1]
[1] Department of Mechanical Engineering, Qilu University of Technology (Shandong Academy of Sciences), Jinan, Shandong, 250353, China
Corresponding authors: (e-mail: 202201150041@stu.qlu.edu.cn).

Abstract Laser cutting technology has the advantages of high precision, high speed, good kerf quality, etc., and has a broad application prospect in the processing of railroad ties. Existing railroad tie processing equipment exists in the lack of flexibility, cutting quality fluctuations and other problems. In view of the quality control problems of railroad tie laser cutting processing, the research designed a high-power railroad tie laser cutting system based on PLC and industrial robot, and use fuzzy PID control strategy for intelligent control. The system integrates PLC technology, industrial robot technology, height-adjustment detection technology and laser cutting technology, and the influence of laser power, cutting speed, laser frequency and auxiliary gas pressure on cutting quality is studied by Box-Behnken experimental design method. The experiment was verified by LC-F1000-L fiber laser cutting machine and 3.2mm thick Q235 mild steel plate. The results show that the laser power has the most significant effect on the amount of slag hanging and roughness, and the compound correlation coefficients of the response surface fitting accuracy of the amount of slag hanging and roughness reach 0.9613 and 0.9609, respectively; after the application of the fuzzy PID controller, the response time of the Y-direction displacement is 0.4s, which is shortened by 1.86s compared with that of the traditional PID controller, while the response time of the X-direction displacement is 0.5s, which is reduced by 1.3s compared with that of the traditional PID controller. The fuzzy PID controller is better than the traditional PID controller in terms of position response characteristics and corner response characteristics. This study provides theoretical basis and practical guidance for the design of high-precision railroad tie laser cutting system, which is of great value for the improvement of railroad tie processing accuracy and production efficiency.

Index Terms laser cutting, rail sleeper processing, fuzzy PID control, industrial robot, cutting quality, intelligent control

I. Introduction

Laser cutting technology is one of the earliest and most widely used technologies in the laser processing industry, but the input cost of its application is also very high, including both the high equipment investment in the early stage, but also the high cost of the training of practitioners at the back [1]-[3]. If the training of personnel using the actual use of laser cutting equipment for training, it is bound to force the equipment production and processing interruptions, affecting the production schedule [4], [5]. At the same time, because many of these laser cutting equipment are imported from abroad, the price is very expensive, and also by the site and funding and other conditions, so the use of actual use of the equipment for training will greatly increase the cost and risk [6]-[8]. The development and application of robotics, to change this situation brings new opportunities for development.

Laser cutting robots use laser cutting, welding, punching, engraving, etc., can realize automated production and processing. And laser cutting robot technology mainly includes laser technology, control technology, robot kinematics and dynamics, robot perception technology, robot control system and other aspects. Among them, laser technology is one of the core technologies of laser robots, and its performance directly affects the operating effect of laser robots [9]-[11]. Control technology, on the other hand, is the key to realize autonomous motion and task planning of laser robots [12]. Robot kinematics and dynamics are the basis for realizing robot motion control and trajectory planning [13]. Robot perception technology is the key to realize autonomous robot perception and environment adaptation, and robot control system is the core to realize autonomous robot control and decision-making [14], [15].

Laser cutting technology, as an efficient and precise processing method, has been widely used in the field of industrial manufacturing due to its advantages of fast cutting speed, high precision and contactless processing. Traditional railroad tie processing mainly relies on mechanical cutting, flame cutting and other methods, which often have low efficiency, low precision, material waste and other problems. The introduction of laser cutting technology for the railroad sleeper processing brings revolutionary changes, its processing accuracy can reach micron level, cutting speed than the traditional way to improve 3-5 times, cutting surface smooth and flat and small heat-affected zone, effectively improve the quality and efficiency of railroad sleeper production. However, the current laser cutting technology in the application of railroad sleeper processing is still facing a lot of technical challenges, such as cutting quality is not stable, the system reliability is not enough, the level of intelligence is low, etc., which limits its popularization and application in the mass production of railroad sleeper. Especially for the complex shape, material changeable sleeper parts, how to ensure the quality stability and processing accuracy of the laser cutting process has become the focus of attention of the industry. Scholars at home and abroad for laser cutting process parameter optimization and quality control has carried out a lot of research, but specifically for the rail sleeper laser cutting systematic research is relatively insufficient. As a key support component of railroad track, the processing accuracy directly affects the quality of track laying and traffic safety, so the development of high-precision, high-reliability laser cutting system for rail sleepers is of great practical significance. In addition, the existing laser cutting control system mostly adopts the traditional PID control method, which is difficult to realize fast and accurate response in the face of complex and changing cutting environment, affecting the stability of cutting quality. Fuzzy control, as a method of transforming expert knowledge into automatic control strategy, has good adaptivity and robustness, and combined with traditional PID control, it is expected to break through the limitations of the existing control methods and improve the system control performance.

Based on the above background, this study focuses on the design optimization and intelligent control strategy research of the railroad tie laser cutting robot system. Firstly, the design of the railroad tie laser cutting system integrates PLC technology, industrial robot technology, height-adjustment detection technology and laser cutting technology to realize the flexible cutting of multi-species and small-lot inner liner specimens; secondly, through the Box-Behnken experimental design method, systematically study the influence of the process parameters, such as the laser power, the cutting speed, the laser frequency, and the pressure of the auxiliary gas on the cutting quality, and construct the mathematical parameters and the cutting quality. The mathematical model of process parameters and cutting quality is constructed; finally, the laser cutting quality controller based on fuzzy PID is designed, and the control parameters are optimized through simulation and experimental verification to improve the system response speed and control accuracy.

II. Design of railroad tie laser cutting system

II. A. Laser cutting process

II. A. 1) Principle of laser cutting

Laser cutting of rails is a technology that utilizes a high power density laser beam to process workpieces. The laser beam is projected onto the workpiece so that the material absorbs the energy of the laser beam and the resulting reaction causes the temperature around the point of laser action to rise dramatically in a short period of time. The high temperature effect causes the material to start melting and evaporating, resulting in the formation of perforations in the workpiece [16]. At the perforations, the generated slag can be effectively removed by blowing with an auxiliary gas. Accompanied by the relative movement of the equipment, the workpiece forms a slit, which ultimately realizes the laser cutting process.

II. A. 2) Laser cutting process

The laser cutting process refers to the process of processing raw materials into products using laser cutting technology. The laser cutting process studied in this paper refers specifically to plane cutting. Laser cutting process mainly includes the following 6 steps:

(1) Preparation of materials: clear processing requirements, to determine the type of processing material, thickness and other key information, the processing material will be placed in the processing area of the laser cutting equipment.

(2) Calibrate the equipment: calibrate the coordinate zero point of the laser cutting equipment, check the stability of the gas supply and the cleanliness of the lens.

(3) Setting the cutting trajectory: set the laser cutting trajectory and check whether the trajectory matches the processed material.

(4) Setting process parameters: According to the type and thickness of the material and other information, to determine the type of auxiliary gas used for cutting, the size of the gas pressure, as well as laser power, cutting speed and other process parameters.

(5) Cutting process: the laser cutting equipment carries out laser cutting on the material according to the above cutting trajectory and process parameters.

(6) Post-processing: After the laser cutting is completed, carry out operations such as picking up, deburring and grinding.

II. A. 3) Process quality of laser cutting

Laser cutting processing quality refers to the degree to which the dimensional accuracy of the workpiece, the amount of slag hanging and the surface roughness of the laser cutting process meet the requirements of the technical standards. Some of the important processing quality assessment indexes are shown below:

(1) Overshooting: In the cutting process, the material is locally melted or vaporized excessively, forming black or dark burnt areas.

(2) Hanging slag: During the cutting process, the melted material is not completely discharged and remains at the cutting edge, forming hanging slag.

(3) Slit width: the width of the slit where the material is cut.

(4) Taper of the cut: the deviation between the edges of both sides of the cut and the ideal straight line, which is manifested in the tapered shape of the cut.

(5) End surface roughness: The degree of surface roughness of the cut surface after the cut is completed.

In order to assess whether the results of laser cutting processing are in line with expectations, current research often uses qualitative or quantitative processing quality assessment methods. For the problem of cutting defects such as overcooking or hanging slag, the qualitative assessment method will regard the processing with these defects as unqualified. For indicators such as kerf width, kerf taper, and endface roughness, quantitative assessment methods are used. When comprehensively assessing multiple machining quality indicators, a single-factor analysis method, a multi-objective analysis method, or a weighted composite scoring method can be used [17].

II. B. Overall system program

The solution combines PLC technology, industrial robot technology, height-adjustment detection technology and laser cutting technology. The industrial robot is characterized by automation, flexibility and intelligence. Laser cutting is characterized by fast cutting speed, high precision and smooth cutting surface, and generally does not require secondary processing. The use of height adjuster can quickly adjust the distance between the laser head and the inner liner to keep it constant during cutting, which solves the laser cutting quality problem due to unevenness. This program can meet the requirements for cutting multiple varieties and small quantities of inner liner test pieces. The overall design adopts combined modular design. The system mainly consists of PLC and motion control module system, rotary table system with positioning support, industrial robot system, height adjuster following system, laser cutting system (including cooling of laser cutting), touch screen human-machine interaction system module, safety protection and other components. The system composition structure is shown in Figure 1.

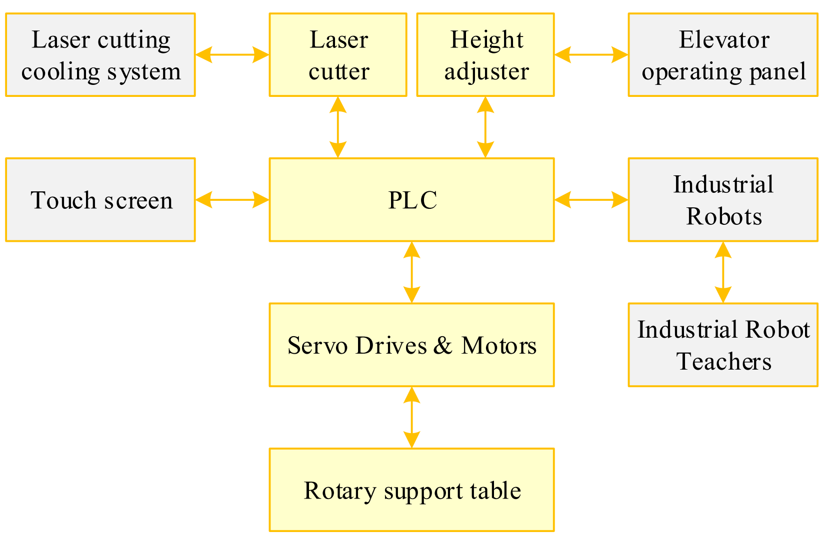


Figure 1: System frame

PLC, as the main controller in the system, mainly handles logic control and centralized processing and management of data exchange for input/output signals and so on. The industrial robot system module undertakes the task of controlling the trajectory movement of the whole equipment during the cutting process. The laser cutting head is mounted on the elevator rail and then fixed at the end of the industrial robot to follow the trajectory of the industrial robot to complete the cutting of the specimen. The touch screen as the human-computer interaction interface mainly carries out the setting of the cutting model, manual and fine-tuning operation, cutting position and speed, servo alarm and other information setting and real-time display. The motion control module controls the servo motors that support the rotary table through fiber optic communication for intermittent operation. The rotary table utilizes its upper positioning column to install and fix different types of liners and runs under the drag of the servo motor.

The control system uses CC-Link communication between the PLC and the industrial robot, and the PLC, the height adjuster and the laser cutter through the remote I/O module for data exchange and logic control. The height adjuster sends a signal to the PLC when it follows the adjustment to reach the position, and the PLC controls the laser cutting unit to cut, and at the same time carries out the control of the cooling system. The PLC and the servo drive of the rotary table control the operation of the table through the fiber optic communication of the motion module.

II. C.System Hardware Design

(1) PLC controller: the system main controller PLC selected Q02HCPU, Q02-HCPU belongs to the high-performance type CPU, I / O points up to 4096 points, the program capacity of 28K steps, the basic processing speed of 0.034 μs to meet the high-speed processing requirements. All input/output signals are electrically connected by QJ61BT11N master module and remote I/O module AJ65SBTB1-32DT. The rotary table servo drive and servo motor are used with models MR-J4-70B and HG-KR73 respectively, and the servo motor has a high-resolution absolute position encoder, and the speed-frequency response performance reaches a high speed of 2.5kHz. QD75MH4 motion control module, the use of SSCNET Ⅲ fiber optic cable, maintaining a high degree of interference resistance, full duplex 150Mbps high-speed communication, more secure and reliable drive control through fiber optic communication.

(2) Industrial robot: The MOTOMAN-GP25 Yaskawa robot body with a maximum load of 25kg and the YRC100 controller are selected. The robot has a fast synthesis speed, which enables the reduction of beat time. The robot also supports CC-Link communication, which facilitates data exchange and control with PLCs. The virtual simulation and offline programming software of MotoSimEG-VRC that accompanies it provides convenience and reference for on-site debugging.

(3) Elevator: The elevator adopts BCS100 stand-alone capacitor elevator, which adopts closed-loop control of the laser cutting capacitor follower head, provides Ethernet communication interface based on TCP/IP protocol, and can quickly realize the functions of height auto-tracking, frog-jumping uplift, and arbitrary setting of elevation on the cutting head, with a sampling frequency of up to 1,000 Hz, fast response speed, and easy to operate. Elevator using speed position double closed-loop algorithm, servo control running speed and high accuracy performance, static accuracy of 0.001mm, dynamic response accuracy of 0.05mm, the highest following speed of up to 375mm/s. Elevator to achieve a fast and accurate response to the installation of fixed guide rail put forward high requirements, according to the response requirements of the use of positioning accuracy of up to the micron level of the MGN12H linear guide rail.

(4) Laser: Innovative MFSC1000X single mode continuous welding fiber laser is used. The laser adopts water-cooled mode of operation, is a compact and efficient high-power laser, with external control interface, Ethernet interface and RS232 interface and other control modes. The external control interface has interfaces such as enable input, modulation input and fault output, which can be conveniently controlled by simple wiring.

(5) Touch screen: Prophis GC-4401W touch screen is selected as the human-computer interface, the touch screen has a serial port, Ethernet port and USB and other communication interfaces, serial communication with the PLC in this equipment, can be set to cut the type of manual and fine-tuning operations, cutting position and speed, servo alarms and other real-time display of information.

(6) Safety fence: a fence outside the working area of the industrial robot, about 2 meters high, to prevent people from accidentally entering the dangerous area. The fence has a door, left for the operator to load and unload the workpiece. Emergency stop button is installed near the fence door, in case of emergency, press the button, the equipment stops working immediately. According to the actual situation, the industrial robots and the control cabinets of the electrical system can be arranged inside the enclosure because of the small variety of products and the low frequency of model changeover.

III. Experimentation and analysis

III. A. Experimental equipment and materials

This experiment uses LC-F1000-L fiber laser cutting machine, the laser cutting system consists of fiber laser and gantry robotic arm. The fiber laser model is IPGYLS-1000, the maximum output power is 1000W, the laser beam wavelength is 1050nm, the photoelectric conversion efficiency is more than 40%. The test material is 3.2mm thick

Q235 mild steel with the size of 500mm×500mm square plate. The high-pressure auxiliary gas adopts the coaxial blowing method, the gas used is oxygen with purity (volume fraction) of 99%, the diameter of the cutting nozzle outlet is 1.1mm, the height of the nozzle from the workpiece is 0.75mm, and the defocusing amount is 1.4mm.

III. B. Experimental program

This experiment explores the effects of process parameters such as laser power, cutting speed, laser frequency, laser duty cycle and auxiliary gas pressure on laser cutting quality. Since the influence of each factor on cutting quality is not independent, Box-Behnken method is used for experimental design, and the design of the experimental program can be quickly completed by Design-Expert software.The experiment selects four factors, laser power (A), cutting speed (B), laser frequency (C) and auxiliary gas pressure (D), and three levels of each factor are coded by (-1, 0, 1) were coded, and the amount of slag hanging and roughness were selected as response targets. The value range of each factor was determined by the previous one-factor experiment, and the factor level coding is shown in Table 1.

Table 1: Factor level coding

Level	Laser power A/W	Cutting speed B/(mm·s^{-1})	Laser frequency C/Hz	Auxiliary gas pressure E/MPa
-1	500	25	300	0.3
0	700	35	750	0.7
1	1100	45	1100	0.7

III. C. Analysis of experimental results

The ANOVA of slag quantity and roughness are shown in Table 2 and Table 3. According to the analysis of variance results, it can be seen that the model has high significance, and the effect of laser power on the amount of slag and roughness is the most significant.

Table 2: Variance analysis of slag thickness

Source	SS	DF	MS	F Value	P Value
Model	0.0827	15	0.006	19.4775	<0.0001
A	0.0039	1	0.0051	9.0646	0.0103
B	0.0023	1	0.0023	5.4823	0.0337
C	0.0085	1	0.0074	28.6493	0.0014
D	0.0022	1	0.0041	11.1898	0.0054
AB	0.0041	1	0.0014	1.6314	6.797
AC	0.0305	1	0.0306	102.8171	<0.0001
AD	0.0006	1	0.0145	1.3438	0.2645
BC	0.0024	1	0.0004	0.0027	10.1571
BD	0.0012	1	0.0017	1.3443	0.2643
CD	0.0157	1	0.0008	0.0175	56.7391
A^2	0.0073	1	0.0005	0.0102	29.4108
B^2	8E-4	1	0.0001	0.7165	0.4088
C^2	0.0014	1	0.0025	8.0691	0.0129
D^2	0.0022	1	0.0013	4.4213	0.0528
Residual	0.0031	15	0.0011	-	-
Lack of fit	0.0027	11	0.0013	1.4135	0.3964
Pure error	0.0006	4	0.0002	19.4753	-
Cor total	0.0854	30	0.0041	9.0647	-

Table 3: Variance analysis of roughness

Source	SS	DF	MS	F Value	P Value
Model	879.58	15	62.75	24.26	<0.0001
A	0.28	1	0.38	0.13	0.7096
B	13.39	1	13.27	5.17	0.0374
C	368.68	1	368.65	142.39	<0.0001
D	79.97	1	79.89	30.81	<0.0001
AB	3.15	1	3.07	1.27	0.2862
AC	1.5	1	1.54	0.67	0.4555
AD	6.19	1	6.23	2.4	0.1464
BC	29.17	1	29.32	11.3	0.0044
BD	3.32	1	3.33	1.38	0.2801
CD	46.62	1	46.42	18.06	0.0031
A^2	282.99	1	283	109.24	<0.0001
B^2	4.71	1	4.84	1.82	0.1965
C^2	80.77	1	80.9	31.26	<0.0001
D^2	2.79	1	2.71	1.17	0.3219
Residual	36.41	15	2.49	-	-
Lack of fit	26.92	11	2.78	1.05	0.4613
Pure error	9.42	4	2.27	-	-
Cor total	915.66	30	-	-	-

The results of response surface fitting accuracy of slag hanging and roughness are shown in Table 4, and the complex correlation coefficients are 0.9613 and 0.9609, respectively, which are greater than 0.8, indicating that the accuracy of the established model meets the fitting requirements.

Table 4: Fitting accuracy

Response	R^2	R_{adj}^2	Precision
Slag thickness	0.9613	0.9063	20.631
Roughness	0.9609	0.9211	16.305

IV. 4. Laser cutting process quality control design and test

Fuzzy control is the use of fuzzy language control to control the expert knowledge of the control strategy into a specific strategy of automatic control control, the basic idea is to summarize the control strategy of human experts on a specific controlled object or process into a series of control laws expressed in the form of "IF-THEN", through fuzzy reasoning to arrive at a fuzzy value, solving the fuzzy control of the controlled object [18]. The fuzzy values are derived through fuzzy reasoning, and then act on the controlled object after fuzzy resolution. This chapter is based on the theory of the quality control of laser cutting system to further optimize the platform using fuzzy PID control for control system design, and simulation experiments to verify the control effect of the controller.

IV. A. Fuzzy controller design

IV. A. 1) Architectural design of the fuzzy controller

The structural design of a fuzzy controller refers to determining the input and output variables of the fuzzy controller. The number of fuzzy controller input variables is usually referred to as the dimension of the fuzzy controller. There are two types of output variables of a fuzzy controller. One is a direct absolute type of control quantity and the other is an incremental change of control quantity. At present, the incremental type is generally used, but there are systems in which the two ways are combined, such as outputting the control quantity in absolute terms when the error is large, and outputting the control quantity in increments when the error is small, by which a better rise characteristic can be obtained and the dynamic performance of the controller can be improved.

IV. A. 2) Defuzzification of clear quantities

The true domain (range of variation) of the input to a fuzzy controller is a continuous closed interval, in fuzzy control it is necessary to transform the true domain into a discrete or continuous internal domain. The transformed domain of the input is equivalent to multiplying it by a scale factor (and possibly an offset).

Generally a discrete internal domain is used, assuming that the actual range of variation of the input quantity is $[a,b]$, and the range after the transformation by the quantization factor k is $[ka,kb]$, and let the discrete internal domain of the thesis be $[-n,+n]$, and the variable Y be:

$$Y = 2n[x-(a+b)]/(a-b) \tag{1}$$

After the domain transformation, Y is still a non-ambiguous ordinary variable. Define a number of fuzzy sets for them by the size of the Y value: "Negative Large", "Negative Medium", "Negative Small", "Zero", "Positive Small", "Positive Medium", "Positive Large".

IV. A. 3) Fuzzy control rules and fuzzy inference

The selection of fuzzy control rules (i.e., fuzzy inference) is the key to the design of fuzzy controllers, including three parts of the design: selecting appropriate fuzzy linguistic variables, determining the affiliation function of each fuzzy variable and establishing the control algorithm of fuzzy controllers.

(1) Determination of fuzzy language variables

According to the living habits and production process requirements, people generally choose the following word set:

$$\begin{Bmatrix} \text{negative large, negative medium, negative small, zero,} \\ \text{positive small, positive medium, positive large} \end{Bmatrix} \tag{2}$$

Abbreviations:

$$\{NB, NM, NS, ZO, PS, PM, PB\} \tag{3}$$

The terms describing the input and output variables have fuzzy properties and can be represented by fuzzy sets. Therefore, the problem of determining fuzzy concepts can be transformed into finding the fuzzy set affiliation function.

(2) Determining the affiliation function of each fuzzy variable

The following two types of affiliation functions are commonly used:

a) Gaussian type

Gaussian-type affiliation function is a more reasonable form to describe fuzzy subsets, which can be generally described as:

$$\mu(x) = \exp[-(x-c)^2/\delta^2] \tag{4}$$

The choice of the affiliation function has a great influence on the fuzzy control performance. Generally speaking, if the change of the affiliation function is smoother, the control characteristics are also smoother and the stability of the system is better. The steeper the shape of the affiliation function, the higher the resolution and the higher the control sensitivity.

b) Triangular type

The shape and distribution of this type of the affiliation function is represented by 3 parameters and can be generally described as:

$$\mu(x) = \begin{cases} (x-a)/(b-a) \\ (x-c)/(b-c) \end{cases} \tag{5}$$

(3) Establishment of fuzzy control algorithm

A fuzzy control rule is a set of fuzzy conditional statements. In order to achieve the purpose of automatic control, using the theory of fuzzy sets and the concept of fuzzy variables, the control strategy using linguistic induction can be realized by a computer program. The commonly used fuzzy conditional statements and fuzzy relations R are as follows:

a) If A then B:

$$R = A \times B + \overline{A} \times E \tag{6}$$

b) If A then B else C:

$$R = (A \times B) + (\overline{A} \times C) \tag{7}$$

c) If A and B then C:

$$R = (A \times C) \cdot (B \times C) \tag{8}$$

d) If A then B and If A then C:

$$R = (A \times B) \cdot (A \times C) \tag{9}$$

e) If A1 then B1 or If A2 then B2:

$$R = A_1 \times B_1 + A_2 \times B_2 \tag{10}$$

When the error is large, the control volume is selected mainly to eliminate the error as soon as possible. And when the error is small, the stability of the system is the main choice of control volume to prevent the system from overshooting.

IV. A. 4) Defuzzification

The process of converting fuzzy quantities into precise quantities is called defuzzification, and the following three methods are often used for defuzzification.

(1) Maximum affiliation averaging method

The maximum affiliation averaging method selects the domain element with the largest affiliation value in the output fuzzy set as the output result, and when more than one maximum value of affiliation occurs at the same time, the average value of them is taken as the output result.

(2) Neutralization method

Taking the median method can take the domain element corresponding to the mean point of the area surrounded by the affiliation curve and the horizontal coordinate describing the output fuzzy set as the output result, which makes full use of the information contained in the output fuzzy set.

(3) Weighted average method

The weighted average method is the center of gravity method. It takes each element $X_i (i = 1, 2, \cdots, n)$ in the domain of the argument as a weighting factor of the affiliation $\mu U_i(u)$ of the output fuzzy set U_i to be adjudicated, i.e., it takes the product $x_i \mu U_i(u)(i = 1, 2, \cdots, n)$, and calculates the sum of this product and $\sum x_i \mu U_i(u)$ for the affiliation and $\sum \mu U_i(u)$ for the mean, i.e.:

$$x_0 = \sum x_i \mu U_i(u) / \sum \mu U_i(u) \tag{11}$$

The average value x_0 is the judgment result for the fuzzy set U by applying the weighted average method. This method emphasizes both the main information and other information, so it is more in line with the actual situation and widely used.

IV. A. 5) Selection of argument domains, quantization factors and scaling factors

The actual range of the input and output signals of a fuzzy controller is called the fundamental domain of the variables. The variables in the fundamental thesis are exact quantities. In contrast, fuzzy subsets are generally chosen for the domain selection, the domain of error $n > 6$, the domain of error variation $m > 6$, and the domain of control quantities $L < 7$. The quantization factor k_E for error and the quantization factor k_{EC} for error change are determined by the following 2 equations, respectively:

$$k_E = n / x_E \tag{12}$$

$$k_{EC} = m / x_{EC} \tag{13}$$

In practice, the range of basic thesis selection for error and error change is much larger than the range of fuzzy subset thesis selection, so the quantization factor is generally much larger than 1.

The control quantity derived after the fuzzy control operation is a fuzzy quantity, which can not directly control the actuator, and must be transformed into the basic theories acceptable to the control object in. The scaling factor k_U of the output control quantity is determined by the following equation:

$$k_U = U_y / L \tag{14}$$

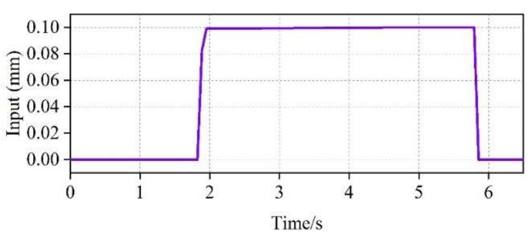
The output scaling factor, k_U, acts as the gain of the fuzzy controller, and its magnitude affects the output of the controller as well as the characteristics of the fuzzy control system. Too large a selection of k_U leads to a reduction in the degree of damping of the system, and too small a selection of k_U results in a sluggish dynamic response characteristic of the system.

IV. B. Experimental analysis of fuzzy PID controller

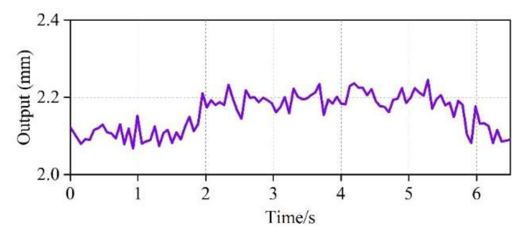
IV. B. 1) Experimental analysis of fuzzy PID controller in Y-direction

In this Y-direction non-contact fuzzy PID position control experiment, the experimental conditions are as follows: firstly, the two electromagnets 5 and 6 in the Y-direction, i.e., a group of differential electromagnets are given a bias current of 1.2A to give them a certain stiffness, i.e., in the beginning of the experiment, the size of the electromagnetic force of the two electromagnets is the same, so that the platform is in the equilibrium position. The eddy current displacement sensor will detect a displacement signal, and artificially make the reference input value the same as the eddy current displacement sensor's indication, and the control current after the fuzzy PID controller operation is added and subtracted with the pre-given 1.2A bias current, so that the electromagnets 5 and 6 constitute a differential electromagnet group. On the basis of the fuzzy PID control algorithm, according to the driving platform is the actual working condition, the quantization factor of the fuzzy PID is taken as 2, 0.01, and the proportionality factor of the fuzzy PID is selected as 5, 20, 0.0006, and the platform of the laser focus control system is controlled in real time, and when the system is in the stabilization, the system is given a displacement input signal of 0.1mm in the Y-direction, and the experimental data are observed as shown in Figure 2. Shown. (a)~(e) denote the displacement input, displacement output, control current, coil 5 current, and coil 6 current, respectively.

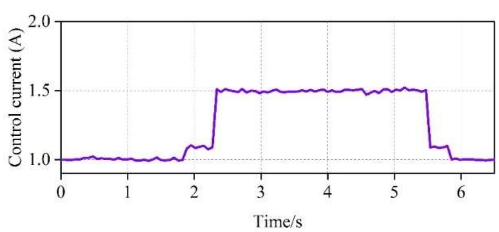
According to the experimental results, it can be seen that in the Y-direction, a displacement step signal of 0.1mm is given to the platform at 1.86s to drive the platform upward and the displacement response of the platform is stabilized at 2.2s, with a response time of 0.4s. The displacement change is transformed from 2.1mm to 2.2mm, and there is no overshooting of the system, and the current of coil 5 tends to be stabilized by changing from 2A to 2.2A, and that of coil 6 tends to be stabilized by changing from 0.5A to 0.5A, and that of coil 6 tends to be stabilized by changing from 0.5A to 0.5A. The current of coil 5 is stabilized from 2A to 2.2A, the current of coil 6 is stabilized from 0.5A to 0.3A, and the control current is stabilized from 1A to 1.5A. The displacement response time can be shortened by 1.86s compared with the traditional PID controller, and the fuzzy PID controller can make the platform have better displacement response characteristics in the Y direction, and the control characteristics of the fuzzy PID controller are better than the traditional PID controller.



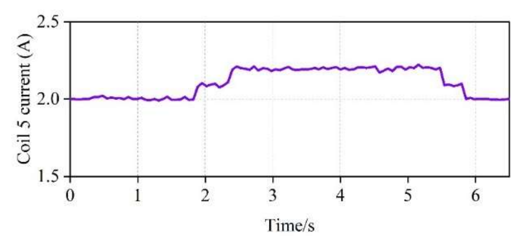
(a) Displacement input



(b) Displacement output



(c) Control current



(d) Coil 5 current

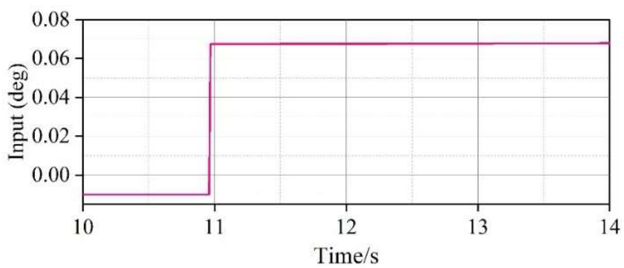
(e) Coil 6 current

Figure 2: Experiment results in Y direction with fuzzy PID

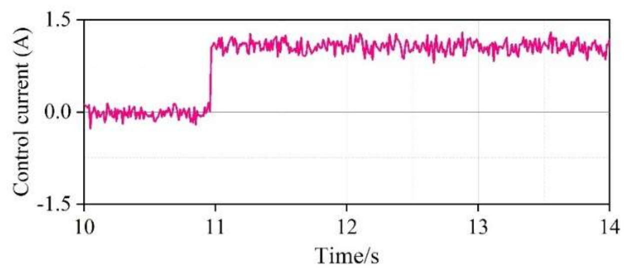
IV. B. 2) Experimental analysis of fuzzy PID controller in X-direction

In this non-contact fuzzy PID position control experiment in the X direction, the experimental conditions are as follows: first, the four electromagnets 1, 2, 3 and 4 in the X direction, that is, the bias current of the group of differential solenoids 1 and 2 and the differential electromagnets 3 and 4 passes 1.2A is given to make it have a certain stiffness, that is, at the beginning of the experiment, the electromagnetic force of the four electromagnets is the same, so that the platform remains stable near the equilibrium point. The eddy-current displacement sensor will detect two displacement signals, artificially make the reference input value the same as the indication of the eddy-current displacement sensor, and add or subtract the control current after the fuzzy PID controller calculation with the pre-given bias current of 1.2A, so that the electromagnets 1, 2, 3, and 4 constitute a differential solenoid group, and the Matlab/Simulink block diagram of the X direction experiment is similar to the Y direction experimental block diagram. On the basis of fuzzy PID control algorithm, according to the driving platform is the actual working condition, the quantization factor of fuzzy PID is taken as 2, 0.01, and the proportionality factor of fuzzy PID is selected as 5, 20, 0.0006, and real-time control is carried out on the laser focus control system, when the system is in the stabilization, the system is given a 0.1mm displacement input signal in X direction, and the two sets of differential solenoids in the X direction groups will both receive a 0.1mm displacement input signal, after the fuzzy PID operation, the experimental data are observed as shown in Figure 3. (a)~(h) denote the displacement input, horizontal upward differential solenoid control current, coil 1 current, coil 2 current, displacement output, horizontal downward differential solenoid control current, coil 3 current, coil 4 current, respectively.

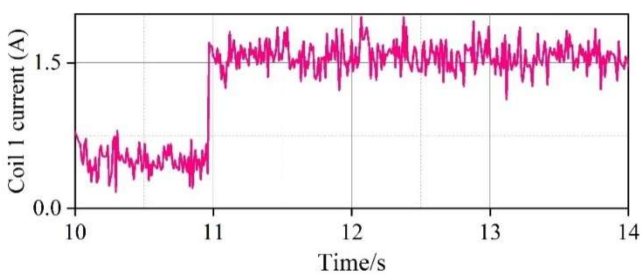
According to the experimental results, it can be seen that a displacement step signal of 0.1mm is given to the platform in the X direction at 2.5s, and the positional response of the driving platform is gradually stabilized at 3s, and the response time of the platform is 0.5s, and the position of the driving platform goes from 1.5mm to 1.6mm without overshooting. The current of coil 1 increases from 1.1A and finally stabilizes at 1.7A. The current of coil 2 decreases from 1.1A and finally stabilizes at 0.5A. The current of coil 3 increases from 1A and finally stabilizes at 1.1A. The current of coil 4 increases from 1.5A and finally stabilizes at 1.8A. Due to the force, the platform moves to the left and stabilizes at 3s, which is a reduction of 1.3% in positional response time when comparing with conventional PID. The position response time is reduced by 1.3s, and the response speed of the platform is faster and shorter than that of the traditional PID controller.



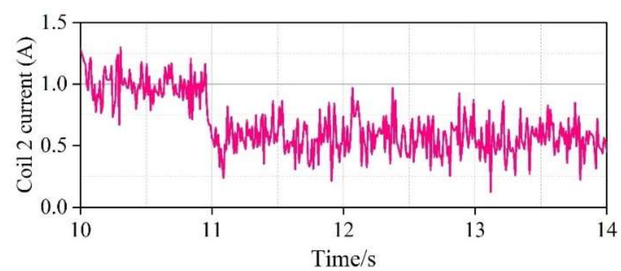
(a) Displacement input



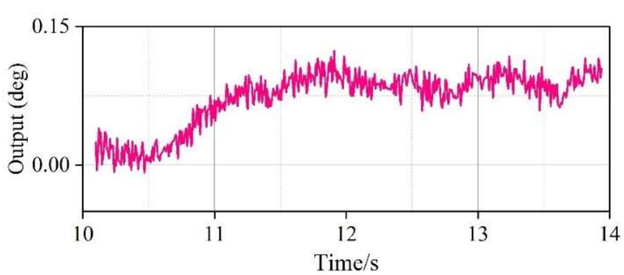
(b) The horizontal direction is the differential electromagnet control current



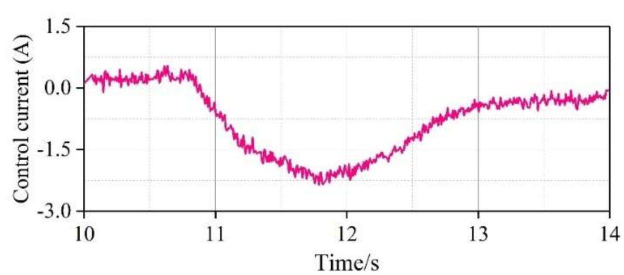
(c) Coil 1 current



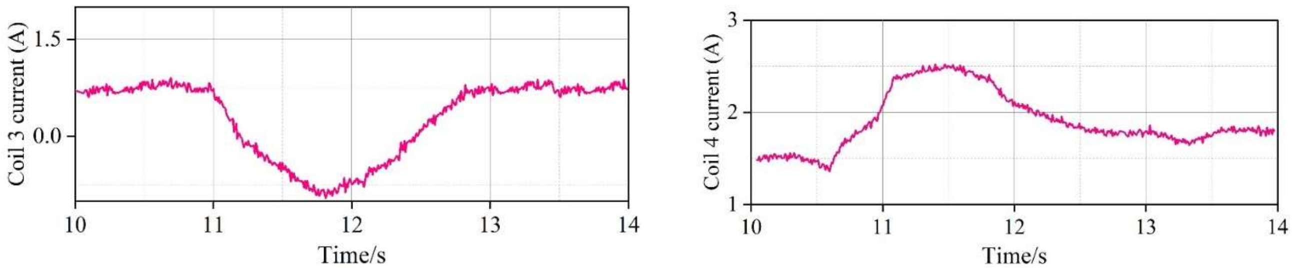
(d) Coil 2 current



(e) Displacement output



(f) The differential electromagnet control current under horizontal direction



(g) Coil 3 current (h) Coil 4 current

Figure 3: Experiment results in X direction with fuzzy PID

PID controller and fuzzy PID controller are used to experimentally analyze the driving platform of laser focus control system, and the experimental results show that both PID controller and fuzzy PID controller have better control effect on the position response characteristics and corner response characteristics of the driving platform, but the control effect of fuzzy PID controller is better than that of traditional PID controller.

V. Conclusion

The high-power railroad tie laser cutting robot system integrates PLC technology, industrial robot technology, height-adjustment detection technology and laser cutting technology to realize high-precision cutting of multi-species and small-lot inner liner specimens.The results of Box-Behnken experimental design show that the laser power has the most significant effect on the amount of slag hanging and roughness, and the compound correlation coefficients for the accuracy of the response surface fitting for the amount of slag hanging and roughness respectively reached 0.9613 and 0.9609, with high modeling accuracy. When the generalization factor of the fuzzy PID controller is set to (2, 0.01) and the scale factor is selected as (5, 20, 0.0006), the system control performance is optimal. The experimental validation shows that the fuzzy PID controller reduces the response time of the Y-direction displacement to 0.4 seconds, the X-direction displacement response time to 0.5 seconds, and the position response is free of overshooting phenomenon. Compared with the traditional PID control method, the fuzzy PID controller improves the displacement response time by 1.86 seconds and 1.3 seconds respectively, and at the same time performs better in the position response characteristics and corner response characteristics. The fuzzy control strategy effectively transforms the expert knowledge into the automatic control strategy through the control rules in the form of “IF-THEN”, improves the adaptability of the system to the complex cutting environment, and provides an effective program for the quality control of laser cutting of the railroad tie.

Patent

There is a patent named “A laser cutting robot for railway sleepers and its control method” resulting from the work reported in this manuscript.

Author Contributions

Conceptualization, **Zheng Hong**. and **Zhang Xulin**.; methodology, **Wang Xinghao**.; software, **Zhao Yinghao**.; validation, **Wang Junchao**., **Sun Qixiao**. and **Zhang Xulin**.; formal analysis, **Zheng Hong**.; investigation, **Zheng Hong**.; resources, **Wang Junchao**.; data curation, **Wang Junchao**.; writing—original draft preparation, **Zhang Xulin**.; writing—review and editing, **Zheng Hong**.; visualization, **Wang Junchao**.; supervision, **Wang Junchao**.; project administration, **Zheng Hong**.; funding acquisition, **Zheng Hong**. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by Design and System Development of High Power 3D Fiber Laser Cutting Sleeper Robot (02016395).

Institutional Review Board Statement

“Not applicable” for studies not involving humans or animals.

Data Availability Statement

The data used in this study is self-tested and self-collected except for the structural parameters from “abbirb”. As the control method designed in this paper is still being further improved, data cannot be shared at present.

Acknowledgments

The author acknowledgments the teachers from the Robotics Engineering Department of Mechanical Engineering Faculty of Qilu University of Technology for their valuable suggestions and technical support.

References

[1] Khatak, P. (2022). Laser cutting technique: A literature review. Materials today: proceedings, 56, 2484-2489.
[2] Tabie, V. M., Koranteng, M. O., Yunus, A., & Kuuyine, F. (2019). Water-jet guided laser cutting technology-an overview. Lasers in Manufacturing and Materials Processing, 6(2), 189-203.
[3] Boyu, S., Hongchao, Q., Jibin, Z., Ying, L., & Yuebin, G. (2017). Current status of water-jet guided laser cutting technology. Opto-Electronic Engineering, 44(11), 1039-1044.
[4] Kim, H. T., & Kil, S. C. (2017). High quality plasma cutting and laser cutting technology. Journal of Welding and Joining, 35(2), 30-34.
[5] Muangpool, T., & Pullteap, S. (2018, March). Reviews on laser cutting technology for industrial applications. In Third International Conference on Photonics Solutions (ICPS2017) (Vol. 10714, pp. 184-191). SPIE.
[6] He, Y., Xie, H., Ge, Y., Lin, Y., Yao, Z., Wang, B., ... & Sun, Y. (2022). Laser cutting technologies and corresponding pollution control strategy. Processes, 10(4), 732.
[7] Gerges William HABIB, A., Abdel Hafeez FARGHALI, Z., & Youssef MOHAMED, M. (2019). Problems of laser cutting in the ready made garment. International Journal of Design and Fashion Studies, 2(1), 12-17.
[8] Nedic, B., Milan, E., & Aleksijevic, M. (2016). Calculation of laser cutting costs. International Journal for Quality Research, 10(3), 487.
[9] Gyasi, E. A., Antila, A., Owusu-Ansah, P., Kah, P., & Salminen, A. (2022). Prospects of Robot Laser Cutting in the Era of Industry 4.0. World Journal of Engineering and Technology, 10(3), 639-655.
[10] Antoš, J., & Bušek, M. (2024, August). Robotic 3D Laser Cutting of Textiles. In International Conference on the Theory of Machines and Mechanisms (pp. 167-172). Cham: Springer Nature Switzerland.
[11] Liu, Y., Ning, R., Du, M., Yu, S., & Yan, Y. (2024). Online path planning of pork cutting robot using 3D laser point cloud. Industrial Robot: the international journal of robotics research and application, 51(3), 511-517.
[12] Groenhuis, V., & Stramigioli, S. (2015). Laser-cutting pneumatics. IEEE/ASME transactions on mechatronics, 21(3), 1604-1611.
[13] Zixiang, X. I. A., Xiangfu, C. U. I., & Li, Z. H. A. N. G. (2021). Design of robot laser cutting system for small hole. Manufacturing Technology & Machine Tool, (10), 14-17.
[14] Jin, X., Chen, K., Zhao, Y., Ji, J., & Jing, P. (2020). Simulation of hydraulic transplanting robot control system based on fuzzy PID controller. Measurement, 164, 108023.
[15] Tzafestas, S. G. (2018). Mobile robot control and navigation: A global overview. Journal of Intelligent & Robotic Systems, 91, 35-58.
[16] Zhang Xiaodong,Zhou Hui,Zhou Bowen,Wang Rong,Han Haobo,Jiang Xiaoyang & Li Maojun. (2022). Surface Morphology and Kerf Quality During Fiber Laser Cutting of High Volume Fraction SiC Particles-Reinforced Aluminum Matrix Composites. Journal of Materials Engineering and Performance,32(13),5906-5918.
[17] Meisam Takalloozadeh,Matthew Gilbert,Dave Allen & Giacomo Torelli. (2024). Experimental and numerical assessment of the bond behaviour of laser-cut reinforcement. Construction and Building Materials,449,137719-137719.
[18] Yu Deng & Jingang Han. (2024). Energy Management of Green Port Multi-Energy Microgrid Based on Fuzzy Logic Control. Energies,17(14),3601-3601.