Research and Design of Motion Control System Based on Visual Navigation AGV

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Abstract. Automated Guided Vehicles (AGVs) have emerged as a crucial element of intelligent logistics and automated warehousing systems, with enormous potential for a variety of uses, thanks to the quick development of manufacturing and logistics. Given its advantages over other AGV navigation techniques—such as precise location, inexpensive hardware costs, and flexible routing—visual navigation has drawn more attention from researchers. This article examines the visual navigation of AGVs' motion control system within the framework of a smart manufacturing workshop. In this study, the AGV motion control system's general design is described. The algorithm for visual placement is designed and presented second. The study then looks into a fuzzy PID control self-tuning technique. AGV path-tracking error models are created, and MATLAB simulation is used to compare fuzzy PID and traditional PID models and show the advantages and disadvantages of each control technique. The motion control system's functional implementation is finally covered. The external device interface circuits are constructed, and the hardware platform is chosen using the high-performance multi-core video processor, TMS320DM8148. The software architecture of the motion control system is built, and the development of the visual positioning and path-tracking algorithms, along with other functional modules, is finished, all while utilizing the performance benefits of ARM and DSP processors.

Keywords: Automated guided vehicles, Manual markers, Visual positioning, Fuzzy PID control.

1. Introduction

In recent years, with the rapid development of Industry 4.0, the manufacturing sector has increasingly demanded faster, more flexible, and smarter logistics handling systems. Traditional logistics systems, often relying on conveyor belts, manual forklifts, and pushcarts, tend to be inefficient and unable to operate continuously for extended periods. With the accelerating aging population in China, the production costs of traditional manual transportation methods have been steadily rising [1]. As a result, there is an urgent need to upgrade traditional logistics systems to enhance corporate competitiveness.

Since its inception, the AGV, an intelligent transport vehicle with autonomous navigation capabilities, has played an increasingly important role in industrial production and has been widely adopted in ports, airport freight operations, and smart automated factories. AGVs showcase the trend towards smarter and unmanned logistics systems through their capabilities such as autonomous start and stop, obstacle avoidance, navigation, tracking, and charging. Integrating AGVs into enterprises can significantly improve the efficiency of material handling in manufacturing workshops due to their high transmission efficiency, strong stability, and flexibility [2, 3]. AGVs also make it easier to gather logistics data, which supports the intelligent and digital transformation of industrial systems.

AGVs currently use laser, inertial, electromagnetic, and visual navigation systems. Among these is visual navigation, which does not require pre-planned courses and allows autonomous navigation, precise placement, and obstacle avoidance by using sensors to sense surrounding sceneries. This method has benefits in intelligence, accuracy, adaptability, and cost-effectiveness. In order to investigate how motion control systems steer the vehicle along the best route to its destination station, this paper makes use of AGV visual navigation technology. This research has the potential to significantly advance industrial automation and propel the manufacturing sector's modernization.

Using onboard vision sensors, AGV fixed-path navigation takes real-time pictures of a predetermined course. The system uses visual algorithms to extract the path's centerline, which enables the AGV to travel the intended path [4]. This approach is becoming more popular because it makes defining guidelines very easy. Western nations have made significant technological advancements in this field; two notable examples are the IBM Japan guideline identification system from 1988 and the University of Maryland's vision navigation system from 1985 [5]. Despite being a latecomer to the subject, China has made great strides recently, as seen by the robust path-tracking capabilities of systems such as JUTIV from Jilin University [6].

For AGVs, flexible path navigation is an unstructured navigation technique that collects environmental data in real time and predicts routes based on it, providing more flexibility [7]. One effective example is the Kiva robot, which uses QR codes to locate itself and uploads the data for processing on the cloud [8]. Significant contributions have also come from domestic research, such as Zheng Han's SLAM algorithm and Chen Zhijie's RGB-D feature extraction technique.

AGV control is based on path-tracking technology, which uses visual positioning to control vehicle movement. PID control, adaptive control, and intelligent control are the three primary control techniques [9]. While PID control is widely applied due to its simple structure, it presents challenges in parameter tuning. Adaptive and optimal control provides a more comprehensive description of AGV characteristics, whereas fuzzy control, which adapts to complex environments, is now widely used in AGV systems [10].

The purpose of this paper is to develop a motion control system for AGVs to enhance the automation and intelligence of material handling systems in the laboratory. The paper focuses on the critical technology of path tracking within the AGV motion control system, with the primary research objective being the method of AGV path tracking. The main problem addressed is how to accurately control the AGV, based on position feedback from the vision positioning method, to follow a planned path and reach the target point.

The paper begins by analyzing the kinematic principles of AGVs and based on this analysis, establishes a path-tracking error model for AGVs. After comparing various control methods, the classic PID control method was selected. To address the issue of PID parameter self-tuning, a fuzzy PID controller was designed. The feasibility of the control method was then verified through MATLAB simulations.

2. Methodology

2.1. AGV Path Tracking Error Model

In current AGV motion control systems, sensors within the navigation system typically gather information about the AGV’s motion state and its pose relative to the working environment. This information is used to detect deviations between the AGV’s actual pose and the ideal trajectory and to adjust the AGV’s movement in real time according to the degree of deviation. The goal is to control the AGV to follow the ideal planned route as closely as possible and ultimately reach the specified target position.

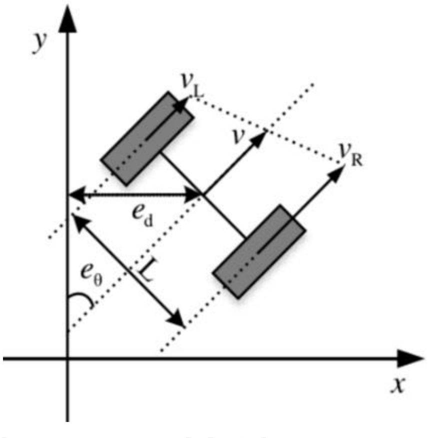


Fig. 1 Path tracking error model. (Photo/Picture credit: Original)

As shown in Fig. 1, the distance between the actual position of the AGV and the desired trajectory, denoted as e_d, along with the deviation in orientation between the actual and desired angles, denoted as e_θ, are selected. These serve as the outputs of the control system, with the inputs being the speeds of the left and right drive wheels, v_{L-}, v_R. Based on the geometric relationships illustrated in Fig. 1, it can be determined that:

$$\begin{cases} e_d = v\, sin(e_\theta) \\ e_\theta = \varpi \end{cases} \tag{1}$$

When the orientation deviation e_θ is small, sine$_\theta \approx e_\theta$. In this study, both drive wheels of the differential-drive AGV are powered by brushless DC motors. The system transfer model for the brushless DC motors can be expressed as:

$$\Delta v = v_L - v_R \tag{2}$$

Where K_1 is the back electromotive force (EMF) constant, and K_T is the torque constant. T_e represents the electromagnetic time constant, and T_L is the load torque. Based on the motor system transfer function, and considering the selection of two motors with identical parameters, K_1= K_I/60, K_2= K_T/60. To decouple the AGV's linear motion from its rotational motion, the variable Δv\Delta vΔv is introduced, and the result is derived as follows:

$$\mathrm{G(s)}=\frac{v_c K_1}{Ls^2(1+T_e s)} \tag{3}$$

3. Overview of the Fuzzy PID Control Principle

3.1. Principle of PID Control

Currently, PID remains one of the most mature and widely used control algorithms in industrial automation. It is a linear control method that first calculates the system error by finding the difference between the desired value and the actual output [11, 12]. This error is then processed through proportional, integral, and derivative operations to generate the control signal, which ultimately ensures closed-loop control of the target system. Despite the emergence of various new controllers in the field, PID controllers continue to dominate due to their simple structure, ease of implementation, and strong robustness.

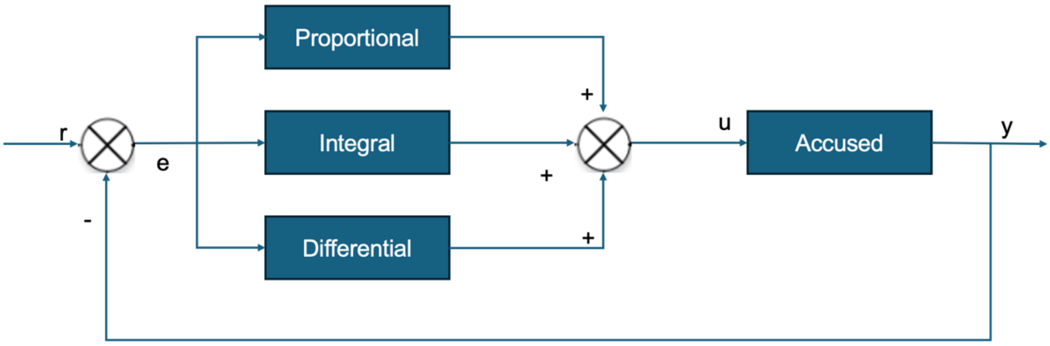


Fig. 2 PID controller. (Photo/Picture credit: Original)

The principle of the PID control system is illustrated in Fig. 2. The system compares the setpoint r(t) with the output y, resulting in the feedback or error e(t). This error e(t) is then processed through proportional, integral, and derivative calculations to produce the control output u(t), which is defined as:

$$\mathrm{u(t)} = k_p[e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d\frac{de(t)}{dt} \tag{4}$$

where k_p is the proportional gain, T_i is the integral time constant, and T_d is the derivative time constant.

In digital control systems, sampling control is employed, meaning the control output can only be calculated based on the error value at the sampling moments. Consequently, Equation (4) needs to be discretized. By using a series of sampling points kT to represent continuous time t, substituting the cumulative sum for the integral, and using increments for the derivative,

$$\mathrm{u(k)} = k_p\{e(k) + \frac{T}{T_i}\sum_{j=0}^{k} e(j) + \frac{T_d}{T}[e(k) - e(k-1)]\} \tag{5}$$

where T represents the sampling time. Since the control output u(k) directly corresponds to the position of the actuator, Equation (5) is referred to as the position-based PID algorithm. This method requires accumulating previous control outputs, which not only complicates calculations but also consumes significant memory space. To address this issue, an incremental PID algorithm is often used to avoid summation calculations. From Equation (6),

$$\Delta u(k) = (k_p + k_i + k_d)e(k) - (k_p + 2k_d)e(k-1) + k_d e(k-2) \tag{6}$$

From Equation (6), it is evident that once the three-time constants $k_i,\ k_p,\ k_d$ are determined, the control output can be calculated using only the error values from the three most recent measurements.

3.2. Fuzzy Control Principle

Fuzzy control is an intelligent control method based on fuzzy set theory, fuzzy linguistic variables, and fuzzy reasoning. The control algorithm follows this process: First, the system's output is precisely sampled. The difference between the sampled value yyy and the desired value rrr yields the system error eee. This error signal is then fuzzified to produce the fuzzy input e~\widetilde{e}e. Using e~\widetilde{e}e and the fuzzy control rules RRR, decisions are made through fuzzy reasoning to obtain the fuzzy control output u~\widetilde{u}u. Finally, defuzzification converts this fuzzy output into the actual control output uuu.

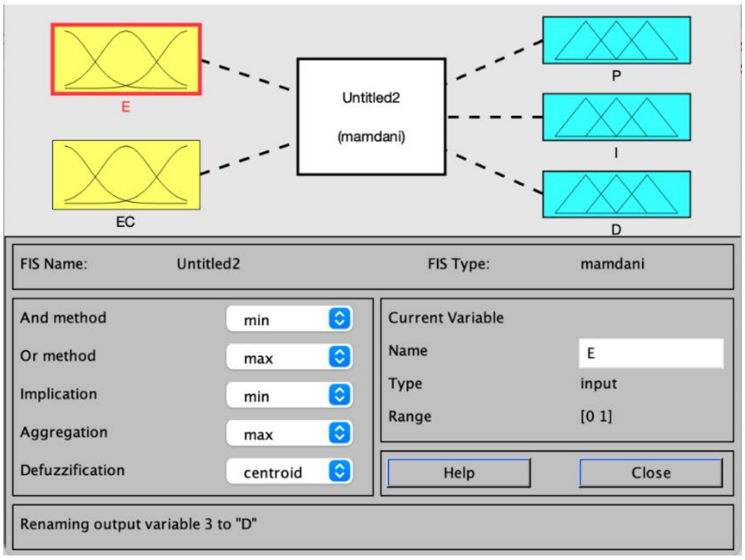
3.3. Fuzzy PID-Based Path Tracking Control

The performance of PID control depends on the appropriateness of its parameters, which typically requires experienced engineers to tune, making the process cumbersome and time-consuming. When disturbances occur, it is essential to assess the disturbances and adjust the PID parameters online. Common online self-tuning methods for PID parameters include neural network tuning, particle swarm optimization, genetic algorithms, and fuzzy control tuning. However, methods based on neural networks, particle swarms, and genetic algorithms are often complex, difficult to implement, and exhibit slow convergence rates, making them unsuitable for the real-time requirements of AGVs. In contrast, fuzzy PID control does not require precise mathematical modeling of PID parameters, and expert experience in AGV correction can be easily extracted. Thus, fuzzy PID control offers simplicity and improved real-time performance compared to the aforementioned methods. This paper employs fuzzy PID control, developing tuning rules based on past expert experience. When disturbances occur, online tuning of the PID parameters is achieved through fuzzy reasoning, enabling the controlled object to maintain stable dynamic and static states.

4. Results and Discussion

Using the established error model and the design steps for the fuzzy controller, a simulation of the AGV path-tracking model is conducted using MATLAB's Simulink library. MATLAB provides a user-friendly fuzzy control toolbox (Fuzzy Logic Toolbox), allowing users to construct fuzzy controllers directly through a graphical interface, thus eliminating unnecessary complex fuzzy mathematical calculations. The built-in fuzzy reasoning system in the toolbox consists of five components: a fuzzy rule editor, an FIS editor, a membership function editor, a rule viewer, and an output surface viewer. The rule editor is used for editing fuzzy control rules; the FIS editor allows graphical editing of the fuzzy control system's high-level attributes; the membership function editor defines the shapes of the input and output variable membership functions; the rule viewer presents the fuzzy implications of each input and output in a three-dimensional format; and the output viewer enables the observation of trends in output changes based on different inputs. The specific steps to establish the MATLAB fuzzy reasoning system are as follows:

(1) In the MATLAB command window, enter the command fuzzy to access the FIS editor interface. Select the menu command Editadd variable to add the deviation E and the rate of change of deviation Ec as input variables, along with the fuzzy controller output parameters: proportional gain Kp, integral gain Ki, and derivative gain Kd, as shown in Fig. 3.



FIS Name: Untitled2
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Current Variable
Name: E
Type: input
Range: [0 1]

Renaming output variable 3 to "D"

Fig. 3 FIS file editing interface. (Photo/Picture credit: Original)

(2) Enter the variable editing interface and set the fuzzy domains for each variable according to the design steps of the fuzzy controller outlined in the previous section. Configure the membership functions of each variable to be triangular.

(3) In the FIS editing interface, double-click on fuzzy PID (madanni) to access the rule editing interface. Select the verbose format for the rules, and based on the rule table designed in the previous summary, specify the names of the fuzzy subsets corresponding to each variable. Click the "Add rule" button to include the fuzzy rules.

(4) After specifying the fuzzy rules, you can visualize them by using the View-Rule menu command, which displays the graphical representation of the defined fuzzy rules.

Using MATLAB's Simulink tool, a path-tracking simulation model for the AGV is constructed. The Fuzzy Logic Controller module is incorporated into the model, and by double-clicking the module, you can enter the filename of the fuzzy inference system created in the previous steps to integrate the designed fuzzy controller into the simulation model. To clearly demonstrate the tracking performance of the fuzzy PID controller, both a conventional PID control system simulation model and a fuzzy PID control system simulation model are established, as shown in Figs. 4 and 5.

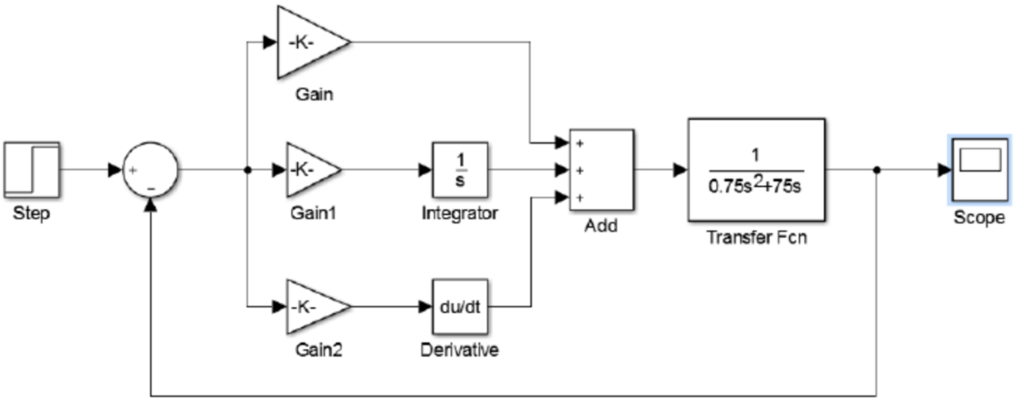


Fig. 4 PID control simulation model. (Photo/Picture credit: Original)

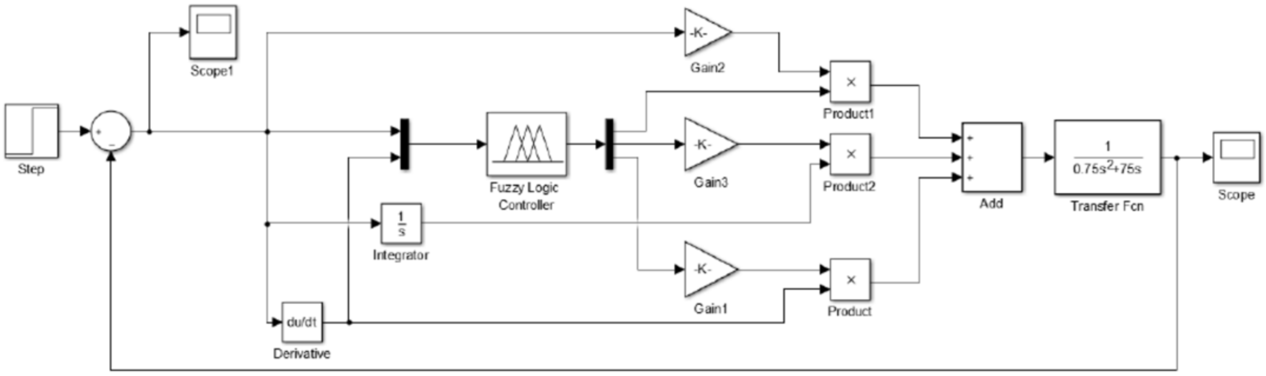


Fig. 5 Fuzzy PID control simulation model. (Photo/Picture credit: Original)

The path-following speed of the AGV is set to 1 m/s, with a computer sampling time for the simulation of 0.01 s. A position error signal of 0.1 m is applied to both the PID control simulation model and the fuzzy PID control model. The simulation results are illustrated in Fig. 6. From the figure, it can be observed that the PID controller exhibits an overshoot of 0.02, reaching this value at 0.04 s, with a settling time of 0.14 s. In contrast, the fuzzy PID controller shows an overshoot of 0.017 and a settling time of 0.06 s. In summary, the adaptive fuzzy PID control demonstrates a faster response and smaller overshoot in AGV path tracking control. This indicates that the fuzzy control algorithm enhances response speed and reduces overshoot, offering advantages over conventional PID controllers.

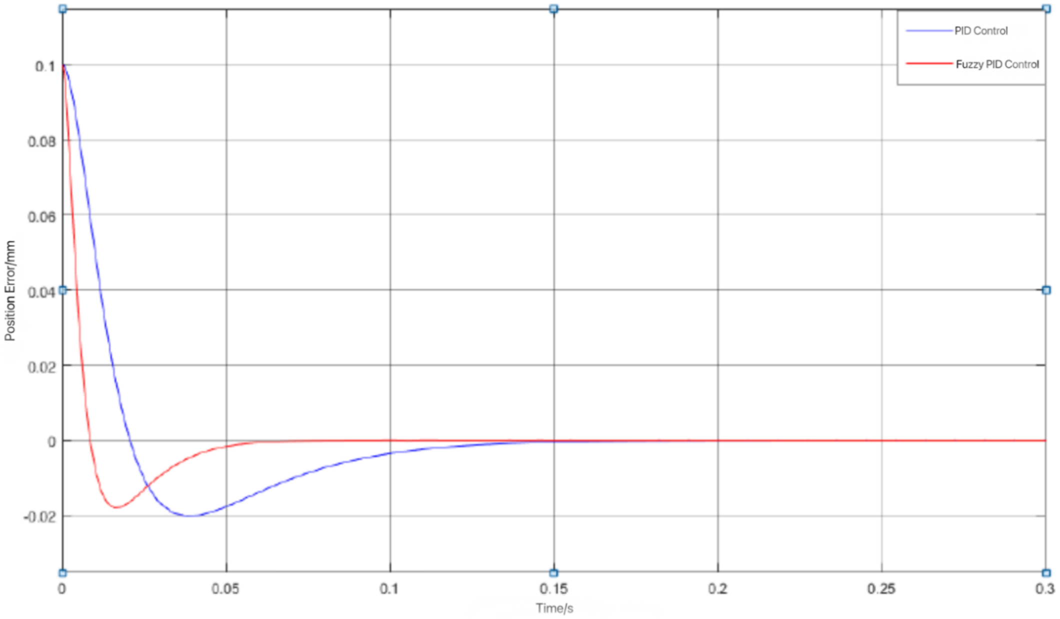


Fig. 6 Analysis of simulation results. (Photo/Picture credit: Original)

5. Limitations & Future outlooks

This paper explores the motion control system of visual navigation Automated Guided Vehicles (AGVs). Significant achievements have been made in key technologies such as visual positioning and path tracking. However, due to the complexity of the motion control issues associated with visual navigation AGVs, as well as limitations in my academic capabilities and available time, the system designed in this paper still has some shortcomings that need to be addressed. Specifically, while the fuzzy PID controller designed in this study has been validated for feasibility through MATLAB simulations, the experimental platform for the system has not yet been fully established. Therefore, the next step should involve verifying the feasibility of the designed path tracking control module on the experimental platform.

6. Conclusion

This paper begins with an exploration of key technologies such as visual positioning and path tracking for AGVs, focusing on the motion control system of visually navigated AGVs. The main components of this research are as follows:

This chapter first creates a systematic path-tracking model and examines the errors related to AGV path-tracking. After that, it describes the fundamentals of fuzzy PID control and creates an AGV route tracking fuzzy PID controller. Lastly, simulation tests are conducted after MATLAB simulation models for both conventional and fuzzy PID controllers are constructed. The findings show that for AGV trajectory tracking, the fuzzy PID controller has benefits over the traditional PID controller, including faster response times, less overshoot, and improved stability.

Building on this framework, the study creates a path-tracking model based on AGV kinematics and uses a popular PID controller to accomplish path-tracking control. A fuzzy control method is used for automatic PID controller parameter tuning to overcome the problems with standard PID controllers, such as low stability and challenging parameter tuning. To validate the reasoning behind the developed fuzzy PID control strategy, simulation models for conventional and fuzzy PID controllers are created using MATLAB's Simulink simulation module.

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