Systematic Study of the Research Progress in Intelligent Logistics Robot

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Abstract. This paper summarizes and discusses the electronic control technology and mechanical structure technology involved in the development and design of AGV (Automated Guided Vehicle), a branch of the rapidly developing robotic technology, and prospects its future development based on the progress and trends of existing related technologies. Firstly, it provides a brief introduction to AGVs applied in different scenarios and analyzes the unique mechanical structures for different functions. Then, it proposes three popular guidance methods and analyzes their advantages and disadvantages with examples. As one of the key technologies of intelligent warehousing, AGV path planning has always been a research hotspot at home and abroad. The tracking algorithm, as a key function of path planning, still mostly adopts the closed-loop control strategy based on error feedback to eliminate system tracking errors. This paper introduces fuzzy control and proposes an improved fuzzy PID control, and finally introduces a multi-sensor fusion algorithm, the extended Kalman filtering method.

Keywords: Automated Guided Vehicle, Path Planning, Control Algorithm, PID Control

1 Introduction

Driven by concepts such as Industry 4.0, "Made in China 2025", smart logistics and smart factories, the market for industrial mobile robots is showing a trend of rapid growth. An Automated Guided Vehicle (AGV) is equipped with automatic guidance devices such as electromagnetic or optical systems, enabling it to travel along a specified guidance path. It has safety protection and various handling functions [1]. AGVs can replace manual transfer, loading and unloading, and handling of goods, effectively reducing manual labor intensity, improving work efficiency, and enhancing safety in some dangerous and complex environments. They are currently widely used in industries such as logistics, machinery, electronics, chemicals, etc. Path planning and obstacle avoidance algorithms for AGVs are key technologies for realizing autonomous navigation of AGVs, determining whether AGVs can efficiently and safely complete tasks in complex environments. In recent years, they have become one of the important research hotspots in the field of AGVs.

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The AGV robot consists of several key components, including a navigation system, sensor system, execution system, power system, communication system, and control system. Its working principle can be summarized in three steps: "Perception, Planning, and Execution". 1) Perception: The surrounding environment is sensed through the sensor system to obtain information about the AGV's position and posture. 2) Planning: Based on the perceived information and the target position, the control system calculates the optimal path and generates an action strategy. 3) Execution: The execution system drives the AGV to move along the planned path in real-time, adjusting to adapt to environmental changes and ensuring precise arrival at the destination. Common navigation technologies used in AGVs include laser navigation, electromagnetic navigation, tape navigation, inertial navigation, visual navigation, etc. The control system is the core of AGV intelligence and automation and typically consists of both hardware and software parts. The hardware includes a main controller (such as a PLC/industrial computer), servo drivers, sensors, communication modules, etc. The software includes navigation and positioning software, motion control algorithms, task scheduling and management software, safety monitoring software, etc.[2]

Against the background of Industry 4.0 with the three main themes of "smart factory", "smart production" and "smart logistics", various traditional and emerging technologies have been or will be studied and applied in the application field of AGV. This mainly involves two aspects of technology: electronic control technology and mechanical structure technology.

2 Mechanical structure

The mechanical structure design of AGVs mainly depends on their functional requirements and application scenarios. According to their different carrying methods, they can be classified as: under-ride AGV carts [3], pull-type AGV carts [4], back-load AGV carts, lift-type AGV carts, roller AGV carts, forklift AGV carts, etc. For instance, in the operation of distribution centers, different tasks require different types of handling equipment. The required handling equipment can be mainly divided into flat handling equipment and vertical handling equipment based on the transportation mode. The purposes and working methods of different handling equipment are not the same. For forklifts, their carrying capacity can be ranked from small to large as: reach trucks, stacker trucks, low-lift trucks, and counterbalance trucks, as shown in Table 1.

Table 1. The carrying capacity of different transports [5]

Mode of transport	Device type	Peculiarity	Application scenario
Plane handling	Pallet truck	No door lifting system	Focus on handling
	Low pick forklift truck	Equipped with operating area	An operator is required to pick up the goods

	Tractor	Tractive effort	The transportation of large quantities of goods
	Stacking forklift truck	There is a door lifting system	Stacking and handling of goods
Vertical handling	Counter-weight forklift truck	There is a door lifting system	Stacking and handling of goods
	Front lift truck	The door frame can be moved in one piece	Medium height work

The forklift, as a tool for transporting goods, plays a crucial role in warehousing and logistics. The structure of the forks includes the fork blades and the fork carriage (slider). The fork blade is the primary component that enables the forklift to lift and carry loads; it is the force-bearing structure that directly supports the cargo. Additionally, mounted on the mast, it indirectly endures various forces and vibration feedback from the road surface. Its strength and stiffness performance directly affects the reliability and stability of the forklift. As shown in Figure 1, the fork force diagram analyzed by Kaiyan Li is referenced. The forklift-type AGV is transformed from a traditional forklift, incorporating functions such as the lifting mechanism of the forklift and the path tracking of the AGV into its control system. It is capable of lifting heavy loads in a single operation, with adjustable loading and unloading heights, offering flexibility and convenience. However, the forklift-type AGV performs poorly in terms of navigation and control accuracy.

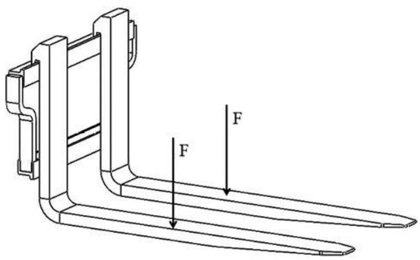

Fig. 1. Force diagram of fork structure [6]

For the assembly of automotive parts, Xilei Zhang designed a type of latent AGV, as shown in the figure 2. This AGV has a thin body that can sneak under the bottom of shelves. It is equipped with an electric lifting rod on its top. When it needs to tow a shelf, the rod is raised to pull the shelf along. When reaching the destination, the lifting rod lowers, and the AGV separates from the shelf.

The latent AGV has a low profile, with an elevating device mounted on its top. When the AGV moves under the cargo, the elevating device extends to lift the cargo and transport it to the designated location. This type of AGV is compact in size and highly flexible in handling, eliminating the need for additional loading and unloading mechanisms. However, it has limitations in intelligently handling only regularly shaped and larger-sized cargos, and it requires extremely precise positioning.

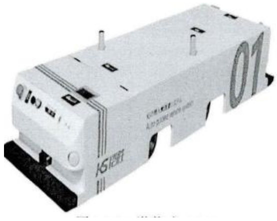

Fig. 2. Latent traction structure AGV [7]

3 Guidance mode

The guidance technology of an AGV is the core technology for AGV control, as it determines the guidance mode of the AGV [8]. The guidance modes can be mainly divided into two categories based on the form of the guidance path: fixed path guidance and free path guidance. Fixed path guidance involves setting guidance information media on the travel path. The AGV detects this information through sensors on the vehicle body, thus obtaining guidance. Its main characteristic is that the technology is relatively mature, but the initial construction is troublesome, and changing the AGV's operating route is relatively difficult. Free path guidance means that the AGV stores dimensional coordinates of the layout and autonomously determines the travel path by recognizing its current position. This type is characterized by higher manufacturing costs, but it is very easy to change the AGV's operating route, offering high flexibility.

Different types of AGV systems adopt various automatic guidance technologies. The guidance mode of an AGV not only determines the flexibility of the application system it constitutes but also affects the system's reliability and configuration cost. Below are the working principles, advantages, and disadvantages of three commonly used guidance technologies.

3.1 Laser guidance

Kunyi Zhang [9] launched lasers through a laser transmission system, and the trolley module receives the lasers to achieve laser guidance without the need for reflective panels. The system consists of two parts: the trolley module and the laser transmission system. It overcomes the shortcomings of previously needing to set up reflective panels along the route, making it more advantageous for operation in some special work situations. However, the disadvantage is that the system cost is relatively high; the scanning head needs to be at a higher position.

3.2 Visual guidance

Songlin Zhang, et al. [10] used a CCD to collect valid information on the road surface, and then utilizing advanced computer technology to recognize the relevant images, it is possible to effectively master the deviation between the path markings of a certain road section and the main driving direction of vehicles, as well as the position of vehicles. The purpose is to ensure that the AGV can operate along the established path target effectively. Compared with the traditional electromagnetic guidance mode, this operation mode has more obvious advantages in path guidance, namely: simple, efficient, flexible, high cost-effectiveness, and easy maintenance. However, the current real-time performance is poor, and the system cost is high.

3.3 Electromagnetic guidance

Xiao Xu, et al. [11] arranged the RFID reader/writer, electromagnetic sensor array, and Hall element in sequence. When the electromagnetic sensor approaches the electromagnetic guiding wire, the detected alternating current signal strengthens; otherwise, it weakens. The electromagnetic sensor array continuously senses the electromagnetic signal, calculates, and corrects the relative position of the AGV and the electromagnetic guiding wire. To address the shortcomings of traditional electromagnetic guidance methods, a dual-line track and node RFID guidance method is proposed. This technology further reduces ground and system costs and improves the flexibility of path design and modification. However, the current real-time performance is poor, and the system cost is relatively high.

4 Control system

4.1 Tracking algorithm

The control system of an AGV (Automated Guided Vehicle) consists of a host computer and a slave computer. The host computer is mainly responsible for management and decision-making, while the slave computer is in charge of implementation and execution. One of the key functions of the slave computer is path planning, which involves the most important technology, the trace search algorithm [12].

The trace search algorithm essentially reads the deviation of the tracing route. According to the deviation, it adjusts the direction of the smart car through steering gear turning or differential adjustment, making it run along the tracing route. For infrared line-following sensors, the more sensors there are, the larger the adjustment range and the higher the control accuracy, but the more port resources of the controller are occupied. Aiming at the problem that the mathematical model of some systems is not clear, a new control method combining the advantages of fuzzy control and PID control is proposed - fuzzy PID control.

4.2 Fuzzy PID Control

The PID control system takes the lateral error as the input of the driving control variable, does not rely on an accurate mathematical model, and is simple in design and high in robustness. The control output of the PID control system is adjusted according to the change of the lateral error $e(t)$, and the motion control amount $u(t)$ is obtained by adjusting the proportional, integral, and differential parameters to achieve the control of the actuator. The motion control amount based on PID control is:

$$u(t) = k_P(e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_D\frac{de(t)}{dt})$$

Fuzzy control is achieved by establishing the structure of a fuzzy controller, selecting input variables, defining input and output fuzzy sets, then defining membership functions and establishing fuzzy rules. As shown in figure 3, fuzzy PID control mainly adjusts the proportional parameter Kp, integral parameter Ki, and differential parameter Kd according to the input error variable and the change of the error. The adjusted Kp, Ki, and Kd are then outputted through the PID controller to generate the control amount, realizing the tracking control of the actuator.

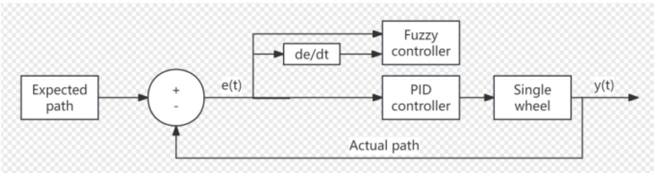

Fig. 3. Fuzzy PID control [Picture credit: Original]

Hang Li, et al. based on the improved fuzzy PID, the forklift AGV achieves curve path tracking under different load conditions. Using the improved fuzzy PID combined algorithm, a comparative analysis of the path planning of the improved fuzzy PID combination control under different load conditions was conducted, resulting in the effect pictures shown in Figures 4~7. Figures 4 and 6 show the path-tracking simulation effects at different positions. Under large load, the approach speed of the forklift AGV is faster, and the posture changes greatly. Under a small load, the approach speed is slower, the posture change is smaller, and the tracking stability is higher. Figures 5 and 7 show the path-tracking error variation curves at different positions. During the tracking process with a large load, the error decreases rapidly in the initial stage, but the stability is not high. Under a small load, the error variation in the initial stage of tracking is small, the posture stability is high, the tracking error variation in the later stage is small, and the fluctuation range is small.

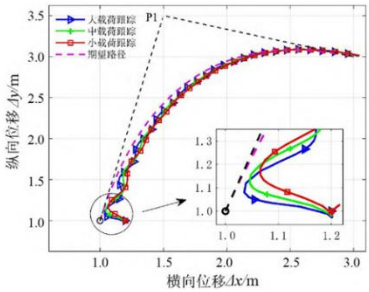

Fig. 4. P1 point path tracking effect comparison diagram [13]

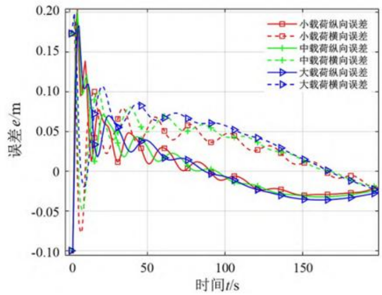

Fig. 5. P1 point path tracking deviation change curve [13]

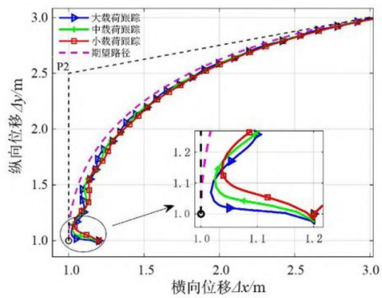

Fig. 6. P2 point path tracking effect comparison diagram [13]

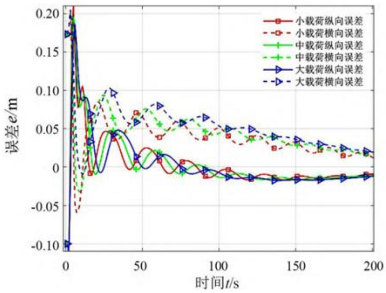

Fig. 7. P2 point path tracking deviation change curve [13]

Compared with the traditional single fuzzy control and the traditional single PID control, the fuzzy PID control gathers the advantages of both and respectively compensates for their shortcomings, thereby improving the control effect and adaptability.

4.3 Extended Kalman Filtering Method

In the face of the relatively complex indoor warehouse environment, the accuracy and robustness of the mapping algorithm using a single sensor are relatively insufficient. Therefore, it is possible to select a multi-sensor fusion mapping algorithm to improve the accuracy of 3D map establishment. For AGVs that use multiple sensors, the sensor data is relatively complex and needs to be fused and processed before it can be used. The multi-sensor data fusion algorithm is a highly efficient autoregressive filtering algorithm: the Extended Kalman Filter algorithm (EKF) [14].

Haoze Chen used the EKF to determine the accuracy of the data before and after fusion, and implemented a pose trajectory evaluation method. By collecting the pose information during the process of acquiring the AGV travel dataset, he used EVO to plot the AGV motion trajectory curve to illustrate this process. As shown in figure 8 below, it is a comparison of the trajectories before and after fusion using the extended Kalman filter algorithm.

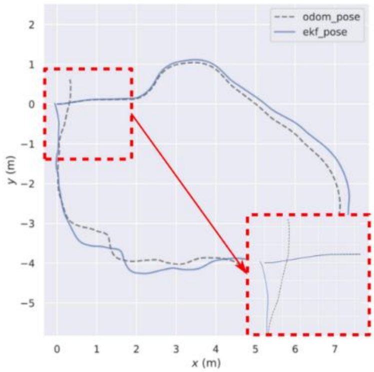

Fig. 8. Trajectory comparison before and after fusion by extended Kalman filter algorithm [15]

From the detailed trajectory in the figure, it can the odometer position and it can be concluded that compared with the odometer position and pose information, the position and pose information after fusion by the Extended Kalman Filter corresponds to a higher approximate accuracy for the starting point and target point.

The Extended Kalman Filter (EKF) algorithm is primarily used for real-time dynamic integration of data from various sensors. This technique employs a recursive process, utilizing a measurement model based on statistical characteristics to achieve optimal fusion and prediction. The EKF benefits from its linear dynamic model and the recursive nature of the algorithm, enabling it to conform to the Gaussian white noise model, thereby eliminating the need for extensive data storage and computation. Additionally, the EKF operates with minimal memory usage and incurs very low data loss, making it suitable for use in small Automated Guided Vehicles (AGVs).

5 Research Outlook

5.1 Dynamic path planning for multiple AGVs

Currently, most research on path planning is based on a single AGV. However, practical application scenarios involve multiple AGVs, forming an AGV system. The path planning algorithm for a single AGV is relatively simple but cannot be applied in scenarios with multiple AGVs. [16-18] Research has been conducted on path planning for applications involving multiple AGVs, achieving certain results. Increasing research on algorithms for practical application scenarios can enable AGVs to play a more significant role in the field of intelligent warehousing.

5.2 Integration of information technology and traditional path planning

AGV requires the configuration of multiple sensors during operation, such as speed sensors and laser sensors. Data processing of sensors and implementation of scheduling strategies require time, which necessitates high-speed computing modules in the control system to reduce delays. New generation information technologies such as NB-IOT can effectively address these issues while offering advantages like low power consumption. Therefore, an important research direction is how to integrate the new generation of information technology with traditional path planning applications to solve problems such as large-scale data transmission, data loss, and delays.

5.3 Increased integration of artificial intelligence (AI) in path planning

Currently, research on AGV path planning is relatively mature. The application of AI algorithms such as genetic algorithms and neural networks, in conjunction with traditional algorithms like PRM and RRT, has effectively improved the efficiency of sample points and accelerated the convergence speed of algorithms. Therefore, more efficient integration of AI algorithms in path planning will also be a key focus of future path planning research.

6 Conclusion

This paper provides a comprehensive overview of AGV from four aspects: machinery, guidance, control, and algorithms. Among these, the path planning algorithm is a key technology for AGV. The paper introduces the advantages and disadvantages of these algorithms and discusses some improvements made by scholars to address the limitations of the algorithms. Finally, the paper offers some prospects for future research directions in AGV path planning algorithms. As artificial intelligence, sensor technology, and computing power continue to advance, path planning technology will continue to evolve. Future path planning will be smarter, more flexible, more adaptable, and better able to respond to complex work environments and task demands. This paper summarizes the new multi-algorithm fusion methods and tools developed in the AGV research process, which are not only applicable to the AGV research problem, but also may provide reference for other similar problems.

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