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Research on Path Tracking Control Algorithm for Unmanned Driving Based on Multi-Sensor Fusion

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Abstract: ***Unmanned driving technology advances so fast that the problem about path tracking control becomes one core problem in an unmanned operating system. The traditional methodology of path tracking control includes PID and LQR, which are simple but not that effective in complicated environment conditions. In recent years, high-order control approaches like model predictive control and sliding mode control have ensured better performance in path tracking, especially while facing run-time variations and nonlinear systems. However, the significant computational intricacy associated with these methodologies limits their popularity in applications involving real-time implementation. Meanwhile, especially in those roads of very complicated composition under heavy weather conditions, the limitation is much stronger regarding the content provided by a single sensor. Arguably, therefore, multi-sensor fusion technology has emerged at this juncture. Integrating multiple sensors-lidar, camera, IMU, and GPS-will improve the accuracy and reliability of micro-path tracking of the system's environmental perception effectively. Among these, the optimization processing of sensor information by fusion algorithms such as the Kalman filter and extended Kalman filter provides quite high stability and path-tracking accuracy. This paper combines multi-sensor fusion technology with advanced control methods to analyze the current status and challenges of unmanned driving path tracking, pointing out the merits and limitations of existing technologies. Furthermore, this will be useful in developing theoretical grounds for the unmanned driving system.***

Keywords: Unmanned driving, Path tracking control, multi-sensor fusion, Model predictive control, Sliding mode control.

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1. Introduction

While rapidly improving, autonomous driving technology has already been integrated into a series of application scenarios ranging from urban transport to logistics transportation, intelligent connected vehicles, all calling for even higher requirements on the path-tracking control technology. As one of the key technologies of unmanned driving, path tracking is directly related to the safety, stability, and driving experience of the vehicle. Traditional path tracking control algorithms mainly depend on classic feedback control methods, including PID control and LQR control; however, when confronted with complex environments, dynamic obstacles, and large-scale nonlinear systems, the robustness and accuracy of these methods are often limited. Therefore, more complicated control methods such as model predictive control and sliding mode control have gradually gained attention and are widely used in path tracking tasks. However, with the increasing complexity of the environment, it is difficult for a single control algorithm to meet the high-precision and high-efficiency requirements. When facing dynamic and unknown environments, there are still prominent problems in path tracking accuracy and stability [1].

In contrast, the development of sensor technology has further brought up new hopes for path tracking of unmanned driving systems. A path-tracking method can perceive environmental situations more comprehensively and reliably by fusing data from sensors like lidar, cameras, IMU, GPS, among others. Multi-sensor fusion technology effectively improves system robustness and accuracy by integrating various sensor data [2]. However, due to the fact that each sensor has different measuring errors and noises, not to say about the operating range, in autonomous driving research up to nowadays, how to optimize a fusion approach among sensor data inputs is highly significant.

Especially in highly dynamic environments, how to coordinate each sensor work and achieve real-time and efficient fusion is a problem that many current research proposals focus on.

Therefore, the theoretical significance and realistic value of this research on multi-sensor fusion path tracking control algorithms are very important. By fusing multisensor fusion technology with advanced control algorithms, it greatly improves the accuracy and stability of path tracking, while ensuring the safety of unmanned driving systems in more complex environments. This will drive the development of unmanned driving technology greatly, affecting it, and make it a feasible technical method for constructing future intelligent transportation.

2. Overview of unmanned driving path tracking and control technology

2.1 Unmanned driving system and path tracking problem

As an advanced automation technology, the unmanned driving system can realize the independent driving of vehicles without human intervention and is widely used in logistics transportation. Path tracking is one of the most basic and core tasks in unmanned driving. Its goal is to enable the vehicle to drive along the predetermined trajectory while maintaining enough stability and safety. The path tracking problem requires not only that the vehicle track the target path precisely, but also be able to handle obstacles, traffic rules, and unstructured changes of roads in dynamic environments. Therefore, the path tracking problem is, in fact, a multi-variable multi-constrained optimization problem which involves path planning, strategy of control, and environmental perception. In practical applications, path tracking accuracy and robustness are two key factors affecting the safety and performance of unmanned driving systems. Especially in complicated traffic environments, how to guarantee the stability and real-time performance of path tracking is still a difficult problem in current research [3].

2.2 Path Tracking Control Algorithm

Path tracking is very important in unmanned driving and works to its utmost capability to keep the vehicle tracking on the target path by the best appropriate control strategy. Common methods include, but are not limited to, PID control and LQR control. The working mechanism behind them all aims to reduce path-following errors through changing control inputs with feedback [4]. However, in a complex nonlinear environment, most traditional control methods suffer from insufficient robustness, which easily leads to the accumulation of path error or even causes system instability. In recent years, some research has been done based on advanced methods such as model predictive control and sliding mode control, which has garnered wide attention. MPC can effectively take system dynamics and constraints into consideration through the optimization of future control inputs at each moment, which provides higher accuracy and stability. Sliding mode control guarantees stability of the system against uncertainty and external disturbances by designing the sliding surface. These sophisticated control algorithms can potentially face more difficulties in complex environments in order to improve the accuracy and efficiency of path tracking. However, high computational complexity of these methods, requirements of real-time performance, and computing resources also hinder practical applications.

2.3 Multi-sensor fusion technology

A single sensor cannot meet the demands brought by high-precision path tracking control; thus, with the development of unmanned driving technology, the coming of multi-sensor fusion technology has come [5]. The environment perception information will be more comprehensive and precise by combining the data of multiple sensors such as lidar, cameras, IMU, GPS, etc. Different sensors have respective advantages and limitations in various application scenarios. Lidar is good at ranging accuracy and spatial resolution, cameras can offer rich visual information, IMU can measure the dynamic state of a vehicle accurately, and GPS is used for positioning and navigation. However, a single sensor is often affected by complex factors like noise, occlusion, and illumination, reducing data reliability and accuracy. Therefore, multisensor fusion technology can reduce noise interference and improve the stability and reliability of a system through weighting and optimizing data among sensors. The common multisensor fusion algorithms include the Kalman filter, particle filter, and extended Kalman filter, which have significant importance in the course of sensor data fusion. Based on this, optimize such fusion methods to greatly raise the performance of unmanned driving path tracking in complex situations with dynamic changes [6].

3. Design of path tracking control algorithm based on multi-sensor fusion

3.1 Sensor fusion method and application

Multisensor fusion technology is based on multiple sensors for observation and then further acquiring more accurate and robust state estimation after some algorithmic processing. In the path-following control of unmanned driving, common sensors include lidar, cameras, GPS, IMU, among others. All these sensors have different measurement accuracies and cover different areas. Therefore, sensor fusion will strongly promote the reliability and accuracy of path following.

Among various approaches toward sensor fusion, the most popular one has been the Kalman Filtering; the extension, namely, the extended Kalman filter is very effective in fusing multiple sensor data in nonlinear systems. The general formula at the core of Kalman filtering is expressed as :

$$\mathbf{x}(k \mid k) = \mathbf{x}(k \mid k-1) + K(k)[\mathbf{z}(k) - h(\mathbf{x}(k \mid k-1))] \tag{1}$$

Among them, $\mathbf{x}(k \mid k)$ is the state estimate at the current moment, $\mathbf{x}(k \mid k-1)$ is the predicted state at the previous moment, $K(k)$ is the Kalman gain, and $h(\mathbf{x})$ is the measurement model function.

3.2 Design of path tracking control algorithm

The path tracking control algorithm should make the unmanned vehicle travel on the predetermined path. The most common ones are PID control, LQR control, and MPC. In this paper, a path-tracking algorithm has been designed based on a PID control system. The basic idea is to calculate the control input according to the deviation between the target path and the actual trajectory, so that the system can gradually reduce the error and stabilize the tracking path.

The control input formula of the PID controller is as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \tag{2}$$

Among them, $u(t)$ is the control input, e(t)e(t)e(t) is the trajectory error, K_p, K_i, and K_d are the proportional, integral and differential gains respectively.

In addition, in view of the complexity of unmanned vehicle path tracking, model predictive control (MPC) is applied to path tracking control. MPC generates control input by optimizing the prediction of future trajectory, and its optimization problem can be expressed as:

$$\min_{\mathbf{u}(k)} \sum_{i=k}^{k+N} \left[\left(x_i - x_{ref,i}\right)^T Q \left(x_i - x_{ref,i}\right) + \left(u_i\right)^T R u_i \right] \tag{3}$$

Where x_i is the system state, $x_{ref,i}$ is the reference trajectory point, u_i is the control input, Q and R are weight matrices, and N is the number of prediction steps. By solving this optimization problem, MPC can dynamically calculate the control input to minimize the path tracking error.

3.3 Fusion algorithm optimization and implementation

The optimization algorithm is of very great importance in a multi-sensor fusion process. Against different environmental changes and particularities in sensor characteristics, which influence system stability and robustness, this article proposes the use of an adaptive algorithm to dynamically adjust the sensor data fusion weight. Starting from the minimum mean square error criterion, it minimizes the difference between the real observation value and the estimated state.
The optimization problem can be expressed as:

$$\min_{\mathbf{w}} \sum_{k=1}^{N} \left[\mathbf{z}_k - \sum_{i=1}^{M} w_i \mathbf{z}_{i,k} \right]^2 \tag{4}$$

Among them, $\mathbf{z}_k$ is the observation value, $\mathbf{z}_{i,k}$ is the measurement value of the i th sensor, w_i is the weight coefficient of the sensor, and M is the number of sensors. By minimizing this error function, the optimal sensor weight can be obtained, thereby improving the path tracking accuracy.

In addition, the implementation of the fusion algorithm needs to consider the timeliness and synchronization of sensor data, especially in a dynamic environment, how to adjust the control strategy according to the real-time nature of sensor data to ensure the path tracking performance of the unmanned vehicle. A common practice is to use a sliding mode controller (SMC) to deal with the uncertainty and nonlinearity of the system. The control law of the sliding mode controller can be expressed as:

$$u(t) = -K \cdot \mathrm{sgn}(s(t)) \tag{5}$$

Among them, $s(t)$ is the sliding surface function, K is the control gain, and $\mathrm{sgn}(s(t))$ is the sign function. Through this control method, the external interference of the system can be effectively suppressed and the path tracking accuracy can be improved.

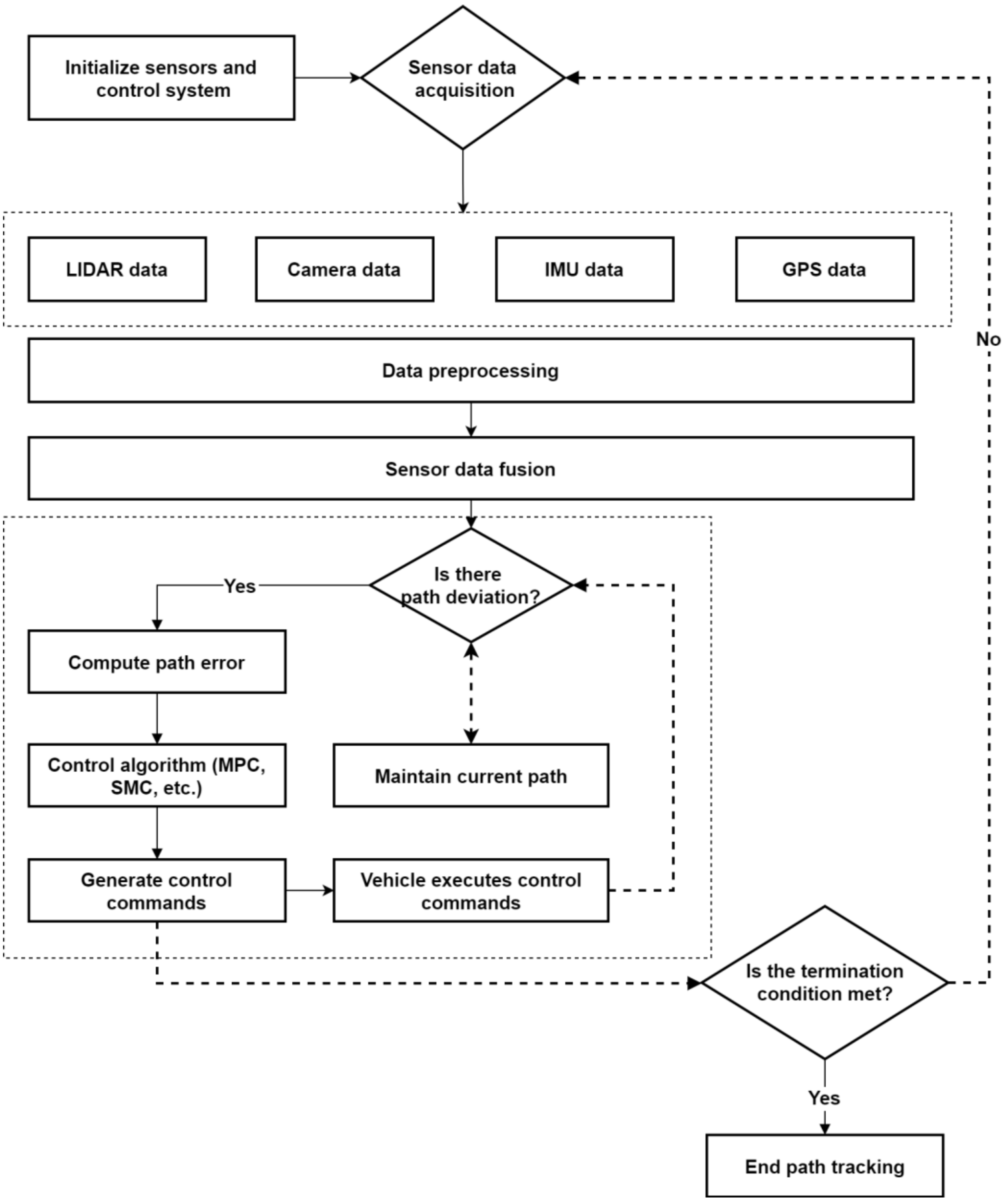

Figure 1: Core Logic of Path Tracking Control Algorithm Using Multi-Sensor Fusion

This diagram illustrates the core logic of the path tracking control algorithm using multi-sensor fusion. The process starts with acquiring data from various sensors, followed by preprocessing and fusion of the data to compute and apply control commands for precise path tracking. It continues doing so until the termination condition is reached.

4. Review and Analysis

4.1 Research Progress of Path Tracking Control Algorithms

Path tracking control has become a key technology in unmanned driving systems, studied and put into application by academics and engineering experts alike. Although MPC can provide high path tracking accuracy, the computational complexity of MPC is high. It needs frequent optimization and solution, especially in real-time applications, hence the high implementation and computational cost of the algorithm. Sliding mode control is a kind of control method with strong robustness, which can effectively deal with the uncertainties and external disturbances in the system. However, "jittering" may occur in its control process, which will have an adverse effect on the stability of the system. With the rapid development of deep learning, data-driven path tracking control methods have gradually become a research hotspot, especially in complex environments and unknown dynamics. Although deep learning methods can automatically learn control strategies, their training requires a great quantity of data and a long time, with high demands for computing resources. Real-time performance and computing efficiency is still one of the biggest challenges when applying these methods [7].

4.2 Application and Challenges of Multi-Sensor Fusion Technology

Due to continuous development in unmanned driving technology, many of the inherent shortcomings of using a single sensor have been gradually dug out. Multi-sensors fusion technology has turned out to be one of the keys toward better path tracking accuracy and robustness. Commonly used unmanned driving sensors are lidars, cameras, IMU, and GPS; all of these have different advantages and disadvantages. For instance, Lidar has poor performance under bad weather conditions, cameras do not work well in low-light conditions, and IMUs probably have drift errors. GPS signals can be easily lost in an urban canyon [1]. The shortcomings of a single sensor are effectively made up for through multi-sensor fusion technology by comprehensively processing data from different sensors, thereby enhancing the system's environmental perception ability and improving path tracking accuracy. By weighted averaging and state estimation of sensor data, more accurate positioning and motion state information can be provided. However, the applicable condition of Kalman filter is that the system must satisfy Gaussian distribution, and the processing ability of non-Gaussian noise and system nonlinearity is poor. It can then be said that an extended Kalman filter offers more flexibility in nonlinear system processes [8]. The particle filter represents one form of Bayesian filtering techniques using the Monte Carlo method. It does not depend on the Gaussian assumption; therefore, it can solve more complex nonlinear and non-Gaussian problems. On the other hand, it requires large calculation amounts and bears heavy computation overheads during real-time applications. It is still a very important research direction for unmanned driving systems how to further improve the computational efficiency and accuracy of the multi-sensor fusion algorithm [2].

4.3 Future development trend of path tracking and sensor fusion

While developing unmanned driving technology, path tracking control and sensor fusion combine more and more closely [3]. In the future, research will be carried out in a more effective and intelligent manner. In the field of path tracking control, with continuous development in deep learning and reinforcement learning technologies, path tracking systems based on an end-to-end deep neural network may appear in the future. This system can then realize effective path following without designing control rules manually; it learns the mapping from sensor data to control input automatically. Compared with traditional control methods, deep learning-based methods can learn more complex and abstract path features through large data trainings, thus providing more accurate controls in dynamic and complex environments. While researching sensor fusion algorithms is also underway, how to improve real-time performance and computation efficiency of the algorithm remains a challenge. Future research may focus on how to optimize filtering algorithms to reduce the computational burden and improve robustness in complex environments. For instance, the application of sensor fusion methodologies coupled with machine learning technology would result in broader and more complex processing for various factors in the driving environment to improve system adaptability. Besides, with computing resources in constant growth, the development tendency may be based on combining traditional control algorithms with an end-to-end deep learning technique in unmanned driving path-tracking systems.

5. Conclusion

The paper now investigates the studies on multi-sensor fusion path-tracking control algorithms for unmanned driving; with the continuous development, researchers have mainly focused on how unmanned driving technology can improve the path-tracking ability of the unmanned driving system using higher precision and robustness on account of complex environments. This paper discusses the traditional path-tracking control algorithm and its shortcomings in some detail, thereby highlighting the advantages accruing with advanced control techniques for improved path-tracking accuracy in dynamic environments and nonlinear systems, such as model predictive control and sliding mode control. Although these methods have high control accuracy and stability, the computational complexity is high, and real-time and computational efficiency is still an urgent problem to be solved.

The limits of a single sensor in solving unmanned driving systems are, however, becoming increasingly apparent as the rapid development of sensor technologies is ongoing. Multi-sensor fusion technology provides an efficient means for solving this problem. It can effectively enhance the environmental perception ability and path tracking accuracy of the system by fusing the data from different sensors. In this paper, some current common multi-sensor fusion methods, such as Kalman filtering and extended Kalman filtering, are analyzed, and their advantages and disadvantages in practical applications are pointed out, with a view to proposing the possible research direction in the future.
In a word, advanced path tracking control algorithms combined with multi-sensor fusion technology will contribute to more reliable and efficient solutions for unmanned driving systems and further promote the development of unmanned driving technology in an intelligent, safe, and practical way.

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