Design and Performance Optimization of Collision Avoidance System for Mechanical Vehicles

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Abstract. A collision avoidance system is designed and optimized in this study. The architecture design, signal processing and data fusion of the system are analyzed in detail, and the sensor selection, control unit integration and algorithm optimization are discussed. In this paper, a performance optimization method based on collision prediction algorithm and real-time and stability of the system is proposed, which solves the problems of system response delay and high false alarm rate, further discusses the optimization strategy of system integration and communication module, and achieves the effect of efficient cooperation and remote monitoring between systems.

Keywords: Mechanical Vehicles; Collision Avoidance System; Signal Processing; Data Fusion.

1. Introduction

Mechanical vehicles have been widely used in industry, agriculture, construction and other fields. Due to the complex working environment, improper operators and the limitations of mechanical equipment's own perception, collision accidents occur frequently. With the development of sensor technology, intelligent control technology and communication technology, vehicle collision avoidance system has gradually become an important means to improve the safety performance of mechanical vehicles. The existing system still has shortcomings in real-time, accuracy and system integration, and further technical optimization and system design improvement are urgently needed to meet the complex requirements in practical applications.

2. Design Principle of Collision Avoidance System

2.1 System Architecture Design

The control unit adopts high-performance embedded processor or FPGA chip to ensure the computing power of the system in the case of high-speed movement. The core task of the control unit is to execute the collision prediction algorithm and send instructions to the actuator according to the prediction results. The actuator is usually integrated in the steering and braking system of the vehicle, which can automatically intervene in an emergency to avoid collision. The communication module is responsible for the interaction between vehicles and external systems, such as communication between vehicles (V2V) and communication between vehicles and infrastructure (V2X).

2.2 Signal Processing and Data Fusion

The data collected by sensors are usually disturbed by environmental noise, so it needs to be preprocessed before entering the control unit to improve the reliability and accuracy of the signal. Kalman filter is a recursive filtering algorithm widely used in dynamic systems. The mathematical model of Kalman filter can be expressed as:

$$\hat{x}_k = A\hat{x}_{k-1} + Bu_{k-1} + K_k(z_k - H\hat{x}_k)$$

Where, it is the state estimation at the moment, the state transition matrix, the control input matrix, UK1U _ {k-1} UK1 as the control input, the measured value, the observation matrix and the Kalman gain.$\hat{x}_k k A B z_k H K_k$

Weighted average filtering gives different weights to the data at different time points, and realizes the smooth processing of sudden noise. The formula is:

$$y(t)=\sum_{i=0}^{n} w_i\, x(t-i)$$

Where, it is the filtered output signal, the input signal at the first moment and the corresponding weight coefficient. The setting of weight can be adjusted according to the dynamic characteristics of the actual system to adapt to the signal characteristics under different working conditions. Due to the limitation of single sensor, multi-sensor fusion technology can provide more comprehensive and accurate environmental perception. Multi-sensor fusion based on Kalman filter can dynamically fuse data from different sensors by gradually updating, and the formula is:$y(t)x(t-i)iw_i$

$$\hat{x}_{k|k}=\hat{x}_{k|k-1}+K_k\left(z_k-H\hat{x}_{k|k-1}\right)$$

Where is the predicted value, the updated estimated value, the Kalman gain and the actual measured value. The system can fuse the data of multiple sensors, reduce the error of a single sensor and improve the overall sensing accuracy.$\hat{x}_{k|k-1}\hat{x}_{k|k}K_k z_k$

Bayesian inference model is based on the theory of conditional probability, and gives the optimal environmental state estimation by synthesizing the independent judgments of different sensors on the environment. The basic formula of Bayesian inference is:

$$P(H|E)=\frac{P(E|H)P(H)}{P(E)}$$

Among them, it is the posterior probability of the hypothesis under given evidence, the conditional probability of the evidence when the hypothesis is established, the prior probability of the hypothesis and the marginal probability of the evidence.$P(H|E)EHP(E|H)P(H)HEP(H)P(E)$

3. Performance Optimization Strategy

3.1 Optimization of Collision Prediction Algorithm

Collision prediction algorithm determines whether the system can make timely judgment and take effective protective measures before the danger occurs. The goal of optimizing the algorithm is to improve the accuracy of collision time prediction, reduce false positives and false negatives, and ensure that the system can adapt to the dynamic changes in complex environment. Traditional collision prediction algorithms, such as Time to Collision, TTC) method, rely on basic information such as vehicle speed, relative distance and moving direction for simple linear prediction. In the scene where many obstacles and dynamic targets frequently appear, the limitations of linear prediction model are obvious, which may easily lead to the lag of system response or misjudgment.

The multi-step prediction algorithm based on motion trajectory can dynamically adjust the prediction path according to the speed and acceleration changes of the obstacles in front when the vehicle is driving at high speed. The nonlinear prediction methods such as Markov chain or particle filter are adopted to overcome the limitations of linear algorithms. The advantage of nonlinear prediction model is that it can capture the dynamic changes in complex environment and bring them into collision time prediction. When turning at high speed, linear prediction may lead to inaccurate prediction because it ignores the dynamics of vehicle turning, while nonlinear model can effectively track and predict the trajectory of vehicle turning and avoid collision.

The calculation formula of the optimization algorithm can be expressed as:

$$TTC=\frac{d}{v_{\mathrm{rel}}}+\frac{1}{2}\cdot a_{\mathrm{obs}}\cdot t^2$$

Among them, the collision time is the distance between the vehicle and the obstacle, the relative speed, the acceleration of the obstacle and the time. The optimization method automatically adjusts the sensitivity of the collision prediction algorithm according to the current state of the vehicle and the complexity of the environment. When the system detects a significant change in the acceleration of the front obstacle, the algorithm will increase the prediction step accordingly, further reducing the delay and improving the accuracy of decision-making.$TTCdv_{\mathrm{rel}}a_{\mathrm{obs}}t$

3.2 Real-time and Stability Optimization

Real-time and stability are important factors affecting the reliability of collision avoidance system. Improving real-time requires the system to reduce the delay as much as possible in the process of data acquisition, processing, decision-making and execution. The system optimizes the parallel computing mechanism of data processing, and adopts high-speed embedded processor with multi-core architecture to realize the synchronous processing of data streams, which greatly reduces the computing delay and improves the response speed of the system. The traditional collision avoidance system has a response time of 300-500 milliseconds when an obstacle is detected, but the optimized system shortens the response time to 150-200 milliseconds, which significantly improves the real-time performance of the system.

Redundancy design is added to the system, and the reliability of data is improved through cross-validation of multi-sensor data. In bad weather conditions, such as fog, strong wind or rain and snow, the accuracy of the sensor may be affected. The system adopts an adaptive data weight adjustment mechanism, under which the system automatically adjusts its data weight according to the real-time state of the sensor. When the camera's visual clarity is affected by foggy weather, the system will automatically reduce the weight of camera data and increase the weight of sensor data such as millimeter-wave radar, which is less affected by the weather, thus ensuring the stability of the whole system. Table 1 shows the comparison of key performance parameters of the system before and after optimization:

Table 1. Key performance parameters of the system before and after optimization

Performance index	Before optimization	After the optimization
Response time (ms)	300-500	150-200
False alarm rate (%)	7.5	3.2
Detection accuracy (%)	92.3	96.8
Stability index	87.5	95.1

After optimization, the response time of the system is reduced by about 50%, the false alarm rate is reduced by more than 50%, and the detection accuracy is improved by 4.5 percentage points. The stability of the system in complex environment is significantly improved, and its adaptability under various working conditions is enhanced. The optimized collision avoidance system can maintain efficient operation in various application scenarios, reduce the incidence of collision accidents, and has high practical application value.

3.3 Communication Module Optimization

In the communication between vehicles, the coordination control based on V2V(Vehicle-to-Vehicle) technology can share the position information, speed, acceleration and surrounding environment data of vehicles in real time, and vehicles can actively exchange collision risk information, make avoidance decisions in advance, and reduce the probability of accidental collisions. In the aspect of remote monitoring, combined with V2X(Vehicle-to-Everything) technology, the real-time data transmission and remote command between the vehicle and the control center are realized. V2X technology can not only communicate with other vehicles, but also interact with traffic infrastructure, pedestrians and other subjects, further enhancing the breadth and depth of collision avoidance. The optimized communication system has achieved a data transmission rate of 100 Mbps, ensuring the stability of transmission and the accuracy of remote monitoring under a large amount of data. Table 2 shows the key performance data of the communication module before and after optimization:

Table 2. Key performance data of communication module before and after optimization

Performance index	Before optimization	After the optimization
V2V communication delay (ms)	100-150	40-50
Data transmission rate (Mbps)	50	100
Remote Monitoring Response Time (ms)	300	150
Communication stability index	85%	95%

The coordination ability between vehicles is significantly improved, and the response time of remote monitoring system is greatly shortened, which provides technical support for the real-time and stability of the whole system.

4. Tag

By analyzing the system architecture, signal processing and data fusion methods, this paper puts forward an optimization strategy based on multi-sensor fusion and adaptive collision prediction algorithm, and through the improvement of real-time and stability, the response speed and reliability of the system are significantly improved. The system can effectively reduce false positives and false negatives under complex working conditions, and improve the safety and work efficiency of mechanical vehicles. The system can further combine artificial intelligence technology with big data analysis to continuously optimize its performance and expand more application scenarios.

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