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Vehicle Sensor Steering System Control Based on Steering by Wire and Active Fault Tolerance

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Abstract

As a key intelligent vehicle chassis component, the Steer-by-Wire (SBW) system features a simplified structure but faces severe operational stability risks from simultaneous multi-sensor failures. This article develops an active fault-tolerant framework for the SBW system, focusing on addressing the challenge of multiple sensor failures occurring simultaneously. By establishing a dynamic model and using sliding mode control method for SBW steering control, this paper proposes a front wheel active steering system that combines ideal speed ratio and linear quadratic regulator (LQR). In addition, a vehicle state estimation method based on an improved generalized Kalman filter was designed, and a sensor fault diagnosis strategy was constructed using the residual principle to achieve fault-tolerant control of faulty sensors. The experimental results show that the scheme has excellent anti-interference performance, significantly improves the system's fault tolerance(FT), and reduces potential traffic accidents.

Keywords: Steering by wire, Active fault tolerance, Vehicle sensors, Steering by wire system.

1. Introduction

The automotive industry is an important pillar industry of the national economy. In 2015, China released "Made in China 2025", which clearly defined the core path for the automotive industry's transformation towards intelligent connectivity. It proposes a domain controller scheme for different intelligent functions to achieve integrated control of multi-dimensional driving assistance functions [1]. Breakthroughs in related technologies will further enhance the independent innovation capacity of China's automotive industry and strengthen the international competitiveness of domestic brands [2-4].

In the "Development Plan for the New Energy Vehicle Industry (2021-2035)" released in October 2020, the electric power steering gear, which has long been monopolized by foreign capital, was listed as a key area for research and development. The breakthrough of such "bottleneck" technologies is the key for China's new energy vehicle industry to achieve sustainable development and has significant practical significance for promoting the overall transformation and upgrading of the automotive industry.

As the core link of human-vehicle interaction, the core function of the automotive steering system is to help drivers precisely control the vehicle's driving trajectory [5]. During vehicle operation, the steering system must possess high precision, high reliability and sensitive response characteristics to ensure driving safety. At the same time, to adapt to complex and changeable working conditions, its handling performance also needs to reach a relatively high standard.

The core function of the steering system is to precisely control the vehicle's driving direction. In addition, as the wheels are in direct contact with the road surface, the SBW system can feed back the real-time driving status of the vehicle to the steering wheel, helping the driver perceive the road conditions [6]. After going through multiple stages of technological innovation such as mechanical, hydraulic and electronic control, SBW has become the most advanced steering technology solution in the current automotive field.

SBW is a new type of steering system with broad application prospects. Firstly, the system ECU can dynamically adjust the transmission ratio according to real-time working conditions, ensuring the lightness of steering while reducing the driver's control burden. Secondly, the design of eliminating the mechanical steering column can free up more cabin space, reserve installation margin for passive safety devices, and enhance the vehicle's collision safety performance. Thirdly, it can seamlessly collaborate with on-board safety systems such as ABS, ESP, and TCS, facilitating the integrated integration of the vehicle's control system [7].

Based on these advantages, SBW can be further extended to the field of active vehicle steering. However, it should be noted that as a typical mechatronic system, SBW also faces unique safety and reliability challenges. Faults in

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system components can easily affect the overall handling safety of the vehicle.

Fault-tolerant control is a key technology for enhancing the reliability of complex control systems. Its core lies in maintaining the expected functionality of the system even when components fail through specific control strategies. Complete fault-tolerant control first requires timely identification of faults and then the realization of fault-tolerant operation of the system [8].

It can be seen from this that fault detection is the prerequisite for fault-tolerant control, and an effective fault-tolerant strategy is the core guarantee for maintaining normal operation of the system under fault conditions.

However, technological breakthroughs in this field still face many core challenges. Firstly, the SBW system has strict requirements for real-time performance, which poses a severe test to the system's low-latency control capability. Secondly, active fault-tolerant technology faces the challenge of balancing reliability and complexity, which may introduce new operational uncertainties due to multi-module coupling. Thirdly, there are still shortcomings in system safety redundancy. Once the SBW system malfunctions, it is very likely to cause serious traffic accidents. Therefore, the safe and stable operation capability under extreme working conditions is a technical bottleneck that needs to be urgently broken through.

Existing studies have carried out extensive explorations around SBW system control and active fault-tolerant technology, but their technical solutions still have certain limitations. Most studies have insufficient coverage of complex scenarios where multiple sensors fail simultaneously. Meanwhile, although some studies have introduced mature algorithms such as Kalman filtering, they have not carried out targeted integration and optimization in combination with the working condition characteristics of the SBW system, resulting in limited robustness of the algorithms under actual complex working conditions [6,8].

Based on the above research gaps, this paper analyzes the influence mechanism of different fault types on the steering control strategy, and then designs an active fault-tolerant control strategy adapted to the sensor fault scenarios. The effectiveness of the strategy is verified through simulation experiments. Aiming at the problems of low steering accuracy, sluggish response and sensor failure in complex environments of traditional steering systems, this paper proposes a steering control strategy that integrates the SBW architecture and active fault-tolerant mechanism. Based on the technical characteristics of the SBW system, mature algorithms such as sliding mode control, Kalman filtering and LQRare scenario-based integrated. Achieve precise control of the vehicle's steering process and enhance the comprehensive performance of the steering system; At the same time, the control parameters can be adjusted in real time according to the working status of the sensor to ensure that the vehicle can still maintain stable driving in the case of sensor failure.

2. DRIVE-BY-WIRE STEERING SYSTEM AND ITS MODEL

2.1. SBW technology

Based on domestic and foreign literature research, the key technologies of SBW system can be summarized as follows:

1. Road sensing simulation technology. The SBW system eliminates the mechanical connection between the steering wheel and the steering wheel, resulting in the inability to directly transmit wheel alignment torque to the steering wheel. Therefore, how to provide a realistic road feel for the driver through the control of the road sensing motor has become one of the core challenges of the SBW system [9-11]. The key to this technology lies in accurately extracting the wheel return torque information. Currently, the mainstream solutions are divided into two categories: model estimation and direct sensor measurement.
2. The angle tracking control technology for the steering actuator motor. The parameters of the SBW system steering actuator are difficult to accurately measure and are susceptible to external interference; Meanwhile, the load force transmitted from the road surface to the wheels exhibits strong nonlinear characteristics [12]. These factors significantly increase the difficulty of tracking and controlling the target steering angle of the motor, therefore, improving the robustness of the angle tracking control algorithm is crucial.
3. Variable transmission ratio technology. With the help of a wire control mechanism, the SBW system can dynamically adjust the steering transmission ratio, effectively improving vehicle handling stability. Reasonable changes in transmission ratio can balance the flexibility of low-speed driving and the stability of high-speed driving. Based on this, optimizing steering strategies combined with driver driving characteristics has become one of the research directions.
4. Fault detection and fault-tolerant control technology. The SBW system requires a vehicle safety level of D, and any component failure in the system directly threatens driving safety. Therefore, fault diagnosis and FT technology are the core support to ensure the safe operation of SBW vehicles.
5. Active steering technology. The wire control structure of the SBW system provides a hardware foundation for the implementation of active steering control function [13]. This technology can assist vehicles in completing emergency obstacle avoidance and is currently a research hotspot in SBW systems.

2.2. Structure of SBW system

The structure and main functions of each component are described in the following sections (Figure 1).

This module integrates core components such as the steering wheel, can accurately identify the driver's operation, convert the steering wheel Angle into an electrical signal and transmit it to the ECU module [14]; Meanwhile, the ECU module can calculate and generate corresponding torque instructions based on the torque fed back from the road surface to the wheels, drive the road sensing motor to output matching torque feedback, and enable the driver to perceive the road conditions.

The steering execution module is mainly used to execute vehicle steering instructions. After the ECU module sends the control signal to the steering actuator module, the steering actuator motor generates the corresponding torque based on the signal and drives the steering wheel through mechanical transmission to complete the steering action [15].

The ECU needs to simultaneously realize the vehicle's electronic control, self-check and fault diagnosis functions. Firstly, relying on the road feel simulation algorithm and combining the vehicle position information collected by the sensors, the rotation angles of the front and rear wheels and the steering wheel are precisely controlled, and the control quantities are transmitted to the corresponding motors. At the same time, instructions are issued based on the steering wheel torque to drive the motor to perform relevant operations, and the driver's control behavior can be identified in real time. When the driver makes an operational mistake, the system will prioritize ensuring the vehicle's stability in an emergency and block the driver's improper control instructions. In addition, the ECU also needs to conduct real-time estimation of the status of the wired steering system and determine the vehicle's operating conditions through the controller. If a vehicle breaks down, its handling performance will deteriorate significantly and may even cause traffic accidents.

2.3. Steering control principle of SBW system

The principles for SBW operation are shown in Figure 2. In SBW, the steering wheel Angle δ_SW measured by the steering wheel Angle sensor in the steering wheel assembly is converted into a digital signal and transmitted to the ECU. The ECU calculated the required front wheel Angle δ_i based on the speed ratio at the time. According to the measured yaw Angle and lateral acceleration information, the ECU calculates the compensation Angle ΔΔ of the front wheel, and obtains the output Angle δ_f^*=δ_i+Δδ of the front wheel.

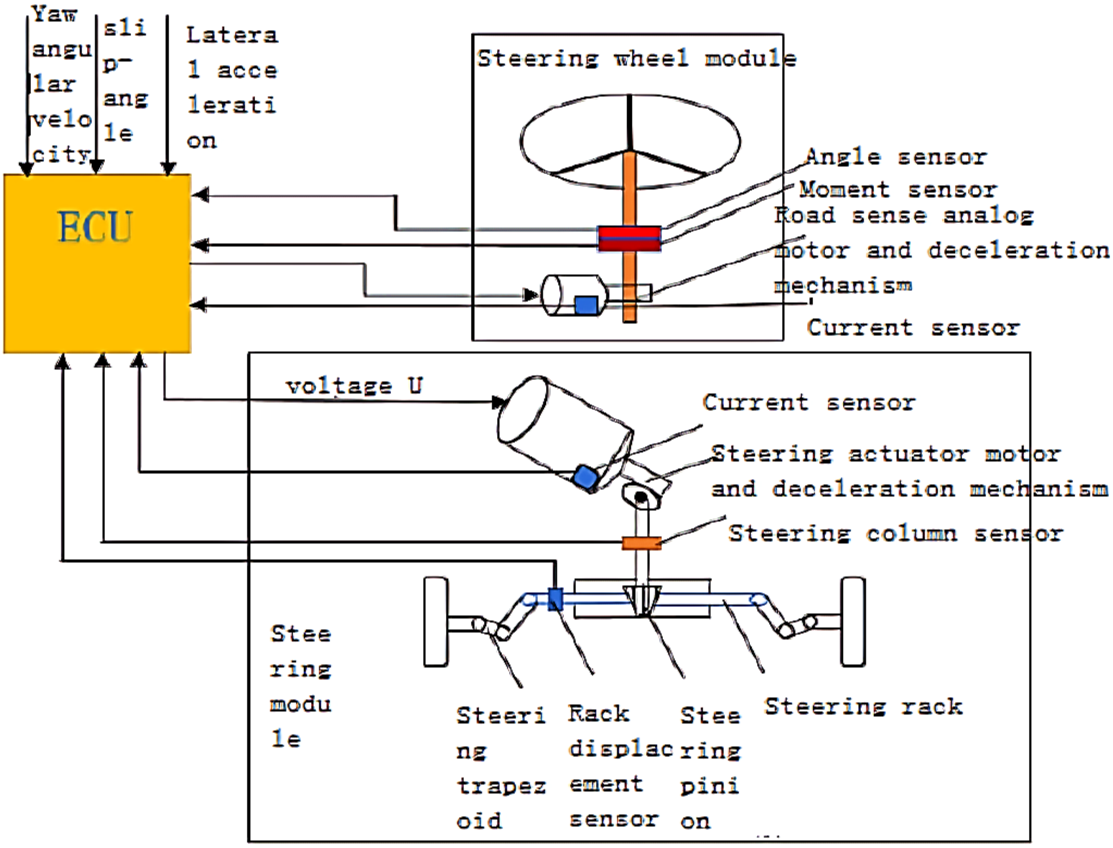


Figure 1. Structure diagram of SBW system

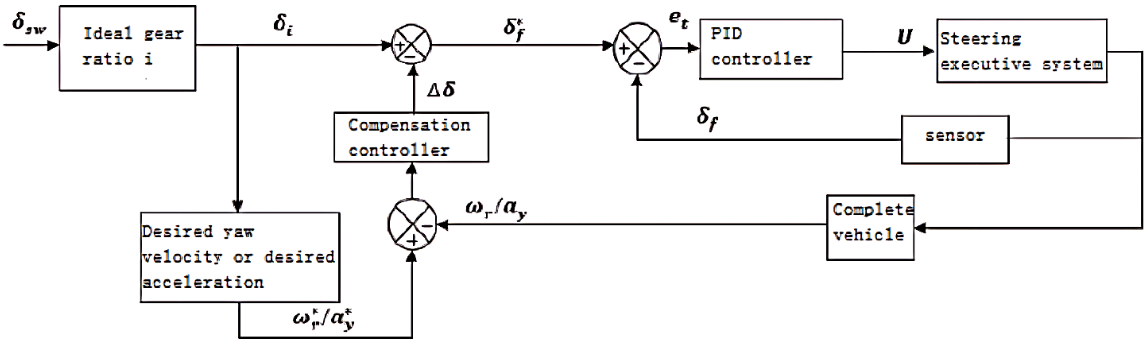


Figure 2. Schematic diagram of steering control of SBW system

Based on the above analysis, if the yaw velocity and lateral acceleration sensors malfunction during driving, the front wheel compensation Angle Δδ output by the compensation controller will deviate, which can easily cause the vehicle to run off the curve and trigger a serious traffic accident. In addition, if the front wheel Angle sensor fails, the voltage output of the steering motor will be inaccurate, making it difficult to ensure the safe steering of the vehicle. Therefore, in light of the steering control strategy requirements of the SBW system, it is urgently necessary to conduct research on the fault-tolerant control method of the Angle sensor in the SBW module.

2.4. Modeling of SBW system

This paper studies the fault-tolerant control of SBW sensor, and does not involve the steering wheel module, so only the steering execution module needs to be built. The construction of the steering execution module needs to consider the following parts.

1. First of all, the steering executive assembly needs to be built, and the controller transmits the control signal to the steering motor through the wire, and then the steering motor transmits the steering torque to the rack and pinion steering device. The steering executive assembly can be represented as:

$$k_g T_m - T_t = J_m \ddot{\delta}_m + B_m \dot{\delta}_m \tag{1}$$

Wherein: k_g represents the transmission ratio of the reducer; T_m is the output torque; T_t denotes the pinion torque; J_m and B_m stand for the equivalent moment of inertia and equivalent damping, respectively, between the motor and the pinion;δ_m refers to the angular displacement of the motor.

2. Then build the steering motor in the steering execution module, and the motor for steering can be expressed as:

$$\begin{cases} U_m = R_m \imath_m + L_m \imath_m + K_m \dot{\delta}_m \\ T_m = k_m \imath_m \end{cases} \tag{2}$$

Wherein: U_m is the voltage; R_m denotes the resistance; i_m represents the current; L_m stands for the inductance; K_m is the back electromotive force coefficient; T_m refers to the output torque; k_m denotes the torque coefficient.

3. In addition, it is also necessary to build a rack-and-pinion steering model, which can be expressed as:

$$M_r \ddot{x}_r + B_r \dot{x}_r + M = k_f T_f \tag{3}$$

Wherein: M_r is the mass of the rack; B_r represents the damping coefficient of the rack; M denotes the main pin righting torque; and k_f is the transmission ratio from the pinion to the steering wheel.

The typical engineering values of the key parameters in formulas (1) - (3) :k_g=15,J_m= 0.02 kg·m^2,B_m= 0.05 N·m·s/rad,R_m= 2.5 ,L_m= 0.003 H,K_m= 0.06 V·s/rad,k_m= 0.06 N·m/A,M_r = 8 kg,B_r= 150 N·s/m.

3. DRIVE-BY-WIRE STEERING CONTROL STRATEGY

3.1. System control strategy analysis

The core of the SBW system controller is to construct an appropriate control strategy, which is generally divided into upper-level and lower-level control.

Feedforward control enables SBW vehicles to possess the steady-state characteristics of traditional mechanical steering. Feedback control collects driving state parameters through sensors and solves the front wheel compensation Angle Δδ to enhance lateral damping.

The road feel simulation control strategy relies on the automatic centering feature of the steering wheel to feed back the movement force of the vehicle and tires to the driver in the form of torque, and at the same time regulates the output matching torque of the road feel motor to achieve precise transmission of road feel.

The steering motor control strategy takes the measured front wheel Angle as the feedback quantity. After comparing it with the target front wheel Angle δ_f^*, the driving voltage is calculated by the algorithm to achieve precise tracking of the Angle.

The control strategy of the road sensing motor compares the measured value of the tire self-centering torque with the target torque M_h, providing a basis for torque adjustment.

For the feedback compensation control link of the front-end active steering system, LQR is introduced to achieve the optimal setting of control parameters. The performance index function of the LQR controller is defined as $J = \int_0^\infty (X^T Q X + U^T R U) dt$, where $X = [\gamma - \gamma_d, a_y - a_{yd}]^T$ is the state deviation vector. γ_d represents the ideal yaw velocity, a_yd represents the ideal lateral acceleration, and $U = \Delta\delta$ is the compensation for the front wheel Angle control quantity. Q is the state weight matrix, and R is the control quantity weight matrix. Take $R = 0.5$. The optimal feedback gain matrix K is obtained by solving the Rickati equation $PA + A^T P - PBR^{-1}B^T P + Q = 0$, and then the compensation Angle $\Delta\delta = -KX$ is obtained, achieving precise correction of the target Angle of the front wheel.

3.2. Design of variable transmission ratio of SBW system

3.2.1. Angular transmission ratio characteristics

As can be seen from Figure 3, at a high speed, the yaw rate coefficient of the mechanically steering vehicle will decrease with the increase of the speed. At this time, the driver needs to adjust the steering wheel frequently to adapt to the real-time response of the vehicle. This increases the burden on the driver. Therefore, in the conventional mechanical guiding system, there is often a problem that the transmission ratio cannot meet the needs well.

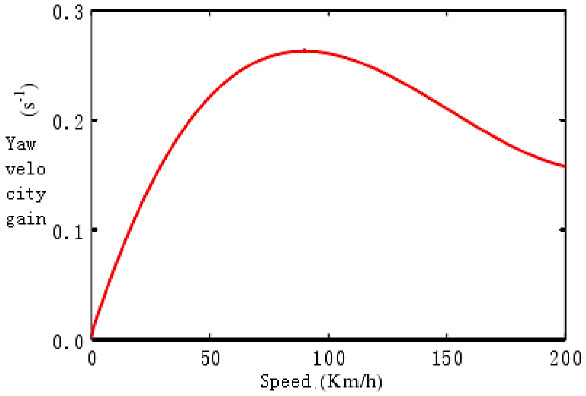


Figure 3. Variation curve of yaw speed gain related to steering wheel with speed

3.2.2. Variable transmission ratio design

Based on the monorail model, the yaw velocity gain related to the Angle of the front wheel is derived:

$$G_f^{\gamma}=\frac{\gamma}{\delta_f}=\frac{u/L}{1+Ku^2} \tag{4}$$

Assume that the yaw speed associated with the steering wheel Angle is fixed:

$$G_{SW}^{\gamma}=\frac{\gamma}{\delta_{SW}}=K_r \tag{5}$$

The ideal transmission ratio is:

$$i=\frac{\delta_{SW}}{\delta_f}=\frac{u/L}{1+Ku^2}\cdot\frac{1}{K_r} \tag{6}$$

K_r selected 0.2, 0.25 and 0.3 respectively for quantitative analysis, and calculated the curve of the ideal transmission ratio changing with the speed.

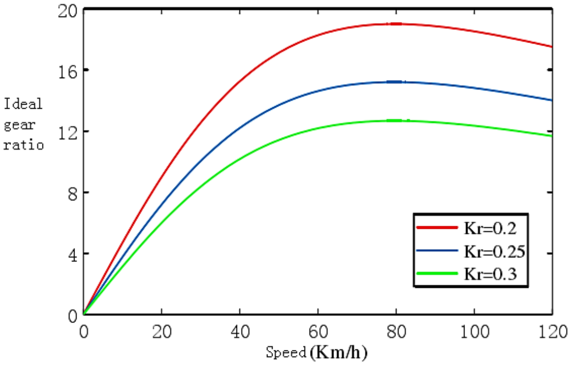


Figure 4. Curve of ideal transmission ratio changing with speed

The variable gear ratio designed by the constant increment method has certain limitations: when the vehicle is driving at low speed, the variable speed ratio designed by the constant offset speed gain is too small, which will make the maximum Angle range of the steering disk exceed, and the motor's power and torque are required to be higher. When the speed is faster, due to the large size of the gearbox, the driver must grip the steering wheel to avoid losing control, so the angular ratio of the steering system must be controlled (Figure 4).

The ideal transmission ratio is 6~24. By changing the Angle between the steering wheel and the front wheel at regular intervals, the gear ratio at different speeds can be obtained. These conclusions show that:

1. If the steering wheel ratio is set to 6, the speed range from 0 to 20 km/h can improve the sensitivity of the car at low RPM. As speed increases, so does the steering rate.
2. At the center of the steering wheel, the turning rate changes greatly, which makes the car more sensitive to turning, thus improving the car's handling performance.
3. When the speed is 120 km/h, the turning rate is set to the maximum of 24, which meets the design requirements and can improve the driving stability of the car.

3.3. Sliding mode controller design

To achieve precise tracking of the steering execution motor's rotation Angle, a sliding mode control algorithm is introduced into the steering motor control strategy. Its core mathematical definition is as follows:

1. Definition of the sliding surface.The deviation between the target motor rotation Angle δ_m^* and the actual rotation Angle δ_m is defined as $e=\delta_m^*-\delta_m$, and the sliding surface function is: $s=\dot{e}+\lambda e$, where λ=15.
2. Control law design. By selecting the exponential approach law $\dot{s}=-\varepsilon\mathrm{sign}(s)-ks$ (where $\varepsilon=0.8$, k=10), and combining formulas 1 and 2, the expected torque T_m^* of the steering motor is derived: $T_m^*=\frac{1}{k_g}\left[J_m\left(\ddot{\delta}_m^*-\lambda\dot{e}\right)+B_m\left(\dot{\delta}_m^*-\lambda e\right)+T_t\right]$

Further obtain the correlation expression of the motor control voltage U_m.

4. FAULT-TOLERANT CONTROL STRATEGY OF VEHICLE SENSOR IN SBW SYSTEM

4.1. Fault tolerant control method selection

FT methods include hardware FT and software FT. Hardware FT is to add a system or part of the system to replace the original system failure can not work normally, FT control is more reliable, the corresponding increase in costs; Software FT refers to system self-diagnosis, fault detection, fault analysis and fault compensation. The fault compensation can be algorithm reconstruction or control of normal system parts to minimize the loss. Different systems have different characteristics, and their fault-tolerant control can be divided into:

1. Model-based approach

This method needs to establish a more accurate mathematical model for the system. Its advantage is that it can diagnose the dynamic characteristics of the system in real time, but its disadvantage is that the accuracy of the model will greatly affect the diagnosis results. In addition, external disturbance and noise will also affect the diagnosis results. The methods based on control system model can be divided into state estimation method and parameter estimation method.

- State estimation method

When the system is faultless, the residual value is 0 or very small; When the system fails, the residual value will be large, and the fault can be located according to the residual vector. Therefore, this method can quickly locate the fault location, but because the accuracy of system establishment and the change of noise and parameter perturbation will affect the fault judgment, how to set the appropriate residual threshold is extremely important for different system characteristics and external interference.

- Parameter estimation method

The cause of system failure is often that one or more components are damaged and cannot work normally. Therefore, parameter failure can be described as abnormal changes in the physical parameters of the system. The parameters of the fault system can be divided into the constant or time-varying parameters of the system and the characteristic parameters of the fault itself.

2. Methods that do not depend on analytical models.

Methods that do not rely on analytical models include signal processing, knowledge, and perceptual behavior, which do not require the establishment of mathematical models of the system. For example, as long as the input and output signals of the controlled process are known, the signal processing method can be used, which can be studied by considering the threshold value, signal conversion, etc. In recent years, the method of wavelet transform has been widely used.

A more accurate mathematical model can be established for SBW system, so the FT method based on analytical model is chosen in this paper. The two methods of state estimation and parameter estimation are compared. The method based on state estimation can ensure real-time performance, but has obvious shortcomings. It can only locate the fault location and cannot accurately judge the fault cause. The method based on parameter estimation can accurately detect faults, but its disadvantage is that it needs excitation signal and cannot guarantee the real-time requirement. Therefore, in the process of fault detection, if the advantages of the two can be combined, the effect of fault-tolerant control system will be greatly improved.

4.2. Principle of fuzzy adaptive extended Kalman filter

Kalman filters are a general term for a class of state estimation methods, and extended EKF is a typical application of them in nonlinear systems. This paper addresses the issue of accuracy attenuation caused by the fixed noise covariance of traditional EKF in vehicle state estimation. It introduces a fuzzy control module to improve it and forms the fuzzy adaptive extended Kalman filter (AFEKF). The core of AFEKF is the state predicate-update framework based on generalized Kalman filtering, which dynamically adjusts the observed noise covariance R_k through fuzzy rules. Enhance the robustness of the system's state estimation under complex working conditions.

In the engineering field, when estimating the state of the control system, the deviation of EKF ignores the higher order term, and the estimation error will accumulate over time, so the impact of the changing noise on the system cannot be ignored. In the process of estimating the state of the vehicle by using the extended Kalman filter algorithm, the value of noise is assumed to be a known constant. It can be accomplished by fuzzy control. In this way, the difference between the actual variance and the theoretical variance and the derivative of the difference in the extended Kalman filter algorithm are taken as the input of the fuzzy controller, the weight coefficient U is taken as the output of the fuzzy controller, and reasonable fuzzy control rules are set to get the observation noise covariance R_k in the adaptive extended Kalman filter algorithm.

AAFEKF algorithm can be realized by changing the value of the weight coefficient U adaptive adjustment of the noise, the weight coefficients of the output fuzzy sets U = {PVS, PS, PSM, PM, PSB, PMB, PB, PVB}, Where PVS, PSM, PSB, PMB and PVB respectively represent positive higher small, medium small, elementary large, medium large and high large.

In order to improve the estimation accuracy of vehicle state, the weight coefficient U is set to a fixed value 1 in the extended Kalman filter algorithm, and the adaptive adjustment range is 0~2.

The input quantity is the variance deviation $e = \left|\widehat{\sigma_k^2} - \sigma_k^2\right|$(domain $[0,0.5]$, fuzzy subset$\{S, MS, M, ML, L\}$ That is, small, medium, medium, medium, large, large) and the rate of deviation change $\dot{e}$ (domain $[-0.1,0.1]$, fuzzy subset$\{NB, NS, ZO, PS, PB\}$, that is, negative large, negative small, zero, positive small, large); Theory of output for the weight coefficient of U (domain $[0,2]$, fuzzy subset $\{PVS, PS, PSM, PM, PSB, PMB, PB, PVB\}$).

Both the input and output adopt triangular membership functions. The reasoning and defuzzification mechanism adopts the Mamdani reasoning method. The reasoning result is defuzzized by the centroid method to obtain the final weight coefficient U for dynamic adjustment of the observed noise covariance R_k.

4.3. Fault-tolerant control design of SBW sensor

4.3.1. Sensor status estimation

In this paper, a SBW system-vehicle-tire model is built, and the vehicle state can be estimated through AFEKF algorithm. During the actual running of the vehicle, the parameter signals of yaw velocity and lateral acceleration are easily measured, so the observation variables are selected as these two parameters. The first two parameters of the five-dimensional state quantity are the key sensor parameters of the vehicle. Together with the parameters of the lateral acceleration, the AFEKF algorithm can achieve triple redundancy of the three key parameters. Where, the lateral acceleration can be expressed as:

$$a_y = \left(\frac{ak_1 - bk_2}{mV_x}\right)\gamma + \frac{k_1 + k_2}{m}\beta - \frac{k_1}{m}\delta \tag{7}$$

Given steering wheel Angle and steering motor current, an adaptive fuzzy extended Kalman filter estimator can be used to estimate three key parameter signals of the vehicle. Given one actual signal, the estimation of the other two signals can be obtained. The vehicle state estimation logic designed for fault compensation is shown in Figure 5.

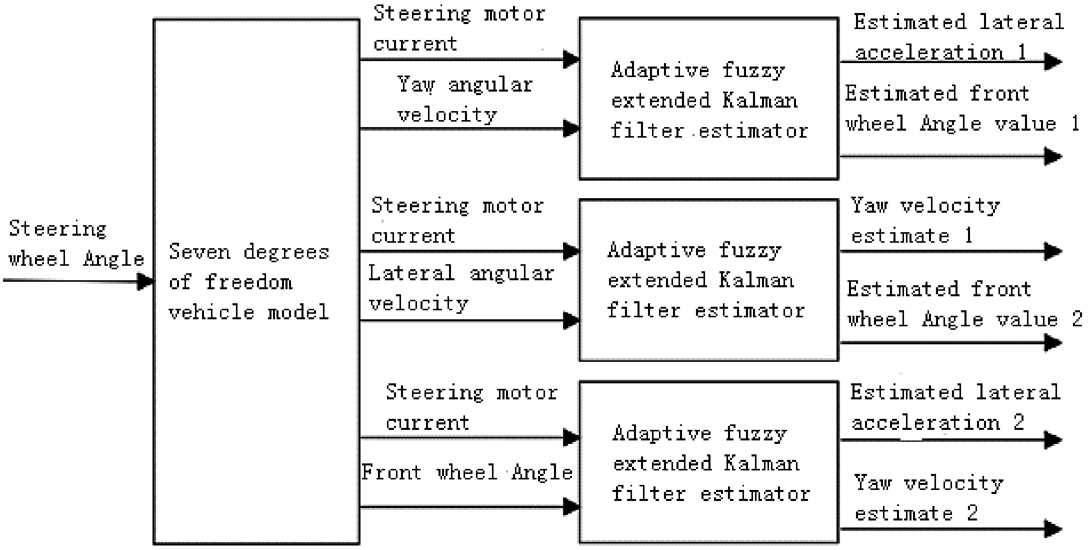


Figure 5. Logic block diagram of vehicle state estimation for fault compensation

4.3.2. Sensor fault detection

Assume that δ_1 is the front wheel Angle estimated by lateral acceleration a_y, δ_2 is the front wheel Angle estimated by yaw velocity γ, and δ_3 is the actual measured front wheel Angle. Subtract and take absolute values of the two Angle parameters respectively, and the difference can be expressed as:

$$\begin{cases} S_1 = |\delta_1 - \delta_2| \\ S_2 = |\delta_1 - \delta_3| \\ S_3 = |\delta_2 - \delta_3| \end{cases} \tag{8}$$

The three differences are defined as residual vectors [S_1, S_2, S_3], and appropriate threshold values need to be set to determine whether the system is faulty. By corresponding the residual vectors to the sensor fault diagnosis logic in Table 1, specific sensor faults can be identified for subsequent FT signal compensation.

Table 1. Sensor fault diagnosis logic table

	S_1	S_2	S_3
trouble-free	0	0	0
δ fault	0	1	1
$a_y$fault	1	1	0
γ fault	1	0	1

According to the AFEKF algorithm, two estimates of the vehicle's front wheel Angle are obtained. Combined with the above fault diagnosis method, the sensor is judged to be faulty. The specific fault diagnosis strategy flow chart is shown in Figure 6.

4.3.3. Sensor fault compensation

By means of data fusion, the real signal of the vehicle sensor and the estimated twice redundant signal are processed, the parameter signal that fails is eliminated, and the correct signal is integrated. The final output can be expressed as follows:

$$y_{iout} = \frac{R_1 y_{i1} + R_2 y_{i2} + R_3 y_{i3}}{R_1 + R_2 + R_3} \tag{9}$$

In the formula, y_1out, y_2out, and y_3out are the outputs of the above three signals respectively, and R_1, R_2, and R_3 are the weights of the three signals respectively.

In Formula (9), the allocation of weights R_1, R_2, and R_3 follows the principle of inverse variance, that is, $R_i = \frac{1}{\sigma_i^2}$ (σ_i^2 is the estimated/measured variance of the i signal). If the fault of a certain sensor is determined through the fault diagnosis logic in Table 1, its corresponding weight will be reset to 0, and the weights of the other two normal signals will be re-normalized according to the proportion of variance.

4.3.4. Sensor fault analysis

Common sensor burst failures include stuck, gain change based on transverse deviation, the mathematical model of the failure mode is as follows:

$$y_{iout}(t) = \begin{cases} a_i & Stuck\ fault \\ \beta_i y_{iin}(t) & Gain\ change\ fault \\ y_{iin}(t) + \Delta_i & Lateral\ deviation\ fault \end{cases} \tag{10}$$

Where: y_iout and y_iin represent the output and input of the i th sensor respectively; a_i is a constant; β_i is the proportional coefficient of gain change. Δ_i is a constant.

4.4. Simulation analysis

This paper considers the occurrence of parameter perturbation and sensor failure in the system. The simulation environment is set as follows:

1. It is assumed that the damping coefficients of the front wheels and the steering mechanism equivalent to the steering column, the damping coefficient of the motor shaft, and the perturbation of the front wheel side deflection stiffness parameters are set within a range of 10%.
2. Set the vehicle speed u=54km/h and the torsional stiffness of the motor as 130 N.m/rad.

Figure 7 shows an output with a fault-tolerant control feature compared to a failed output. In this chart, the black line indicates that the real output will not make an error. At time t, if a fault occurs and fault control is initiated, the fault status of each sensor is displayed in a red line in the SBW. On this basis, a fault output result based on blue dot is given.

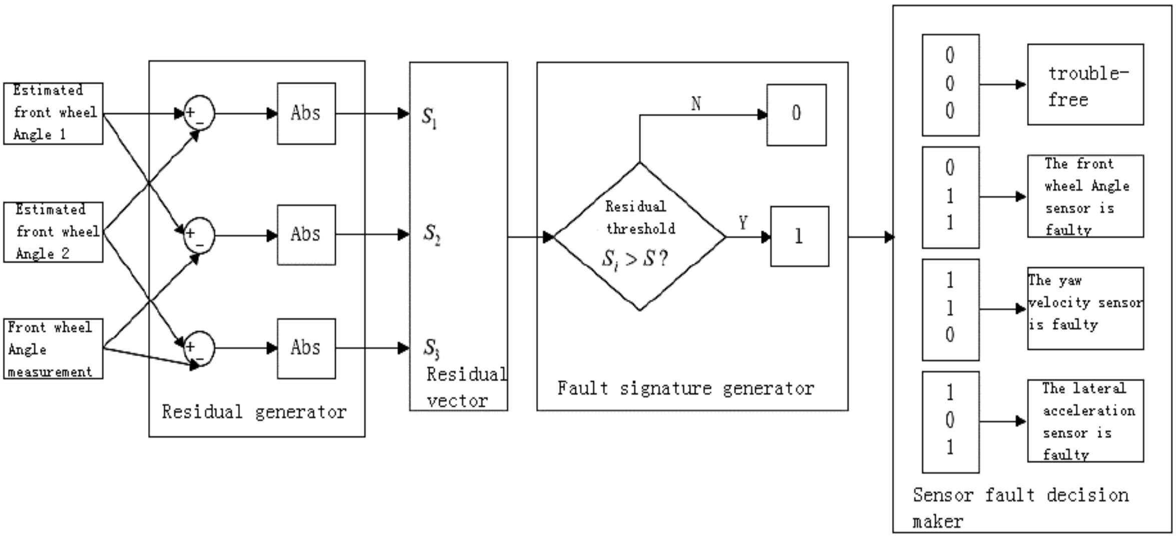
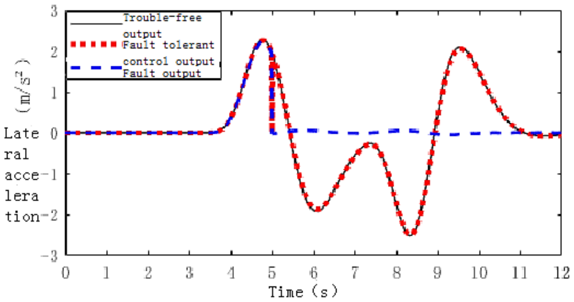
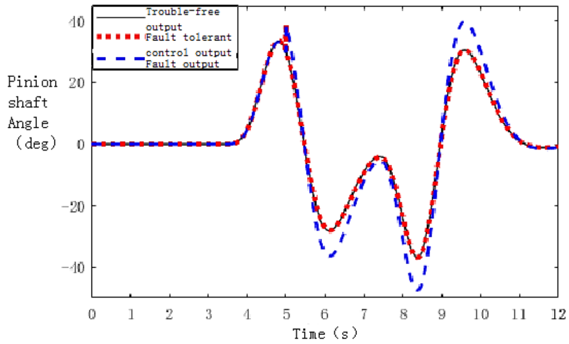


Figure 6. Troubleshooting strategy flow chart



(a) Performance comparison before and after FT of lateral acceleration sensor



(b) Performance comparison of pinion shaft Angle sensor before and after FT

Figure 7. Simultaneous interrupt-gain FT before and after comparison curve

As can be seen from Figure 7, if no error occurs in 0-5 seconds, the actual output, fault-tolerant control output, and error output are consistent. Five seconds later, the signal is disconnected from the lateral acceleration sensor. At this time, the lateral acceleration of the line control system is always 0, and the maximum lateral acceleration is 2.3 m/s. In addition, when the small Angle detector has amplification failure, its minimum deflection Angle can reach 18 degrees. After the fault-tolerant control, the output of the fault-tolerant controller of the system is exactly the same as that of the system in the fault-free state.

As shown in Figure 7, in the case of sensor failure, this method can effectively reduce the impact of fault on the steering characteristics of SBW vehicles, so that the SBW system with sensor failure has a steering performance close to zero fault.

5. CONCLUSION

Aiming at the problem that the concurrent faults of multiple sensors in the SBW system restrict the vehicle handling performance, this paper conducts research on active fault-tolerant control. (1) Propose a real-time sensor fault diagnosis scheme under multi-objective constraints and combine it with state space feedback to achieve fault identification. (2) Relying on the fault state estimation algorithm to accurately assess the overall state of the system, a full-link fault-tolerant system based on fault compensation is constructed. (3) The core value of this study focuses on the SBW multi-sensor simultaneous failure scenario, which is insufficiently covered by existing research. It integrates mature sliding mode control, adaptive Kalman filtering and other technologies in a scenario-based manner. (4) Simulation verification shows that this scheme can make the steering performance of the SBW system approach the fault-free level under failure conditions, effectively ensuring the handling stability of the vehicle after failure. It has a promising engineering prospect.

Compared with the limitation of traditional SBW fault-tolerant solutions that mainly target single sensor failures, this solution can handle concurrent failure conditions of multiple sensors. Moreover, due to its optimization based on mature algorithms, it reduces the cost of technical implementation and can be directly embedded in existing systems, providing a feasible path for the safety redundancy upgrade of intelligent chassis steering systems.

However, there are still deficiencies in the research, and real road conditions such as the nonlinearity of tires have not been included. Only sensor faults are focused on, without covering the collaborative FT of actuators and communication links. In the future, the engineering practicality can be strengthened by conducting real vehicle tests, the multi-component collaborative fault-tolerant system can be expanded, and the real-time diagnostic performance can be improved by integrating edge computing, so as to further enhance the security guarantee capacity of the solution.

In addition, although the multi-sensor concurrent fault active fault-tolerant framework for the steer-by-wire system constructed in this study has been verified to ensure the stability of vehicle steering in fault scenarios, at the verification level, this paper only completed the core test based on the typical working condition of two-lane change and did not cover complex working conditions such as low adhesion coefficient road surfaces. The generalization ability of the scheme under all working conditions awaits further verification through multi-condition joint simulation. In terms of performance evaluation, as the focus is on conducting systematic quantitative benchmarking for mainstream solutions such as fault-tolerant mechanism innovation, a standardized evaluation system needs to be established subsequently to complete horizontal comparisons.

Data Availability Statement

All data generated or analysed during this study are included in this article.

Conflict of Interest

The authors declare that they have no competing interests.

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Ethics declaration

Not applicable.

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