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Chassis-based Brake-by-Wire and Steering Technology with Cooperative Control

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Abstract. Amidst the trends towards electrification, intelligentisation, connectivity, and sharing in the automotive industry,automotive chassis system is undergoing a profound transformation from traditional mechanical chassis to drive-by-wire chassis. This paper focuses on the cooperative control technologies of intelligent vehicle drive-by-wire chassis systems.It systematically reviews the latest research advancements and development trends, specially addressing the two core subsystems of steer-by-wire and brake-by-wire, along with their integrated coordination mechanisms. The paper first analyses the key technologies of steer-by-wire and brake-by-wire systems, explaining the three prevalent technologies currently on the market EPS, EHB, and EMB, along with their respective advantages and disadvantages. Building upon this foundation, the paper focuses on exploring the latest research advances and future development directions in multi-system coordinated control of drive-by-wire chassis systems, covering key technologies across three aspects: longitudinal, yaw, and roll stability control. Finally, the paper outlines the future trends of automotive chassis steer-by-wire technology and its cooperative control systems. Chassis-by-wire technology represents a pivotal advancement in the field of intelligent driving, and this review provides valuable reference for further research within the discipline of automotive engineering.

Keywords: Drive-by-wire chassis, steer-by-wire, brake-by-wire, multi-system coordinated control

1. Introduction

The global automotive industry is currently undergoing a huge transformation that has not been seen in a century. Cars are accelerating their shift towards electrification and intelligent systems, which demands revolutionary performance in the chassis system. The traditional mechanical hydraulic control structures previously used in powertrains, braking, steering, and suspension systems It is being comprehensively transformed into an energy line transmission and information line transmission architecture, which together are called the "X-line transmission chassis". This method requires the chassis actuator to use electricity as the driving force, which is controlled by the driver or the controller through electrical signals [1].

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X-by-Wire technology is a particularly crucial tool in the innovation of automotive electronic and electrical architectures. Its fundamental principle is to use electronic signal transmission to replace mechanic-hydraulic connecting rods, thereby enabling electronic control of chassis functions. The X-wire transmission system of the automotive chassis includes components such as sensors, controllers, and actuators. Compared with the traditional mechanical connection situation, the X-by-Wire chassis not only eliminates the traditional mechanical components, but also provides an extremely excellent response speed. At the same time, it has higher control accuracy and can better adapt to complex and changeable driving conditions [2].

The by-wire chassis provides a physical platform for the iteration of software-based automotive functions and performance. It is an indispensable prerequisite for the development of automobiles towards mobile intelligent terminals. The next-generation by-wire chassis technology has become a key focus of global automotive competition. For example, the Tesla Model 3 adopts chassis domain control technology. This approach can meet the requirements of intelligent driving for the integration of longitudinal and lateral control. Meanwhile, it also adopts an integrated casting technology, which can reduce the manufacturing cost of the chassis. The company's Cybertruck also adopts a three-motor distributed drive system, which can achieve full by-wire steering on both the front and rear axles. In China, the Yangwang U8 uses the "Easy Four" platform technology and relies on its four-motor distributed drive system to achieve extremely excellent handling stability and agile steering effects. This shift in chassis configuration has triggered a revolution in the electronic/electrical architecture. BMW has launched the industry's first architecture that can cover all powertrain systems and vehicle segments, achieving a deep integration between powertrain and driving dynamic functions, with a response delay of less than 1 millisecond

This article will first review the principles of by-wire steering and by-wire braking technologies, and then introduce several commonly used systems that apply these technologies in the current market, including EPS, EHB and EMB. Next, we will summarize the current research status of the coordinated application of steer-by-wire and steer-by-wire technology, which includes key technologies for vehicle longitudinal, yaw and lateral stability control. We will also look forward to the application prospects of steer-by-wire technology in the future field of autonomous driving.

2. Steer-by-wire system

The steer-by-wire system consists of a steering wheel module, a steering gear module, and a vehicle sensor module. The steering wheel module can be further divided into the steering wheel itself, steering wheel sensors, and road sensing circuits. The steering gear module is mainly composed of a steering gear and an actuator. The vehicle sensor module can be further subdivided into speed sensors, acceleration sensors, and yaw velocity sensors. And the controller. As shown in Figure 1, the main function of the steering control system is to convert the driver's steering input into electrical signals through torque and speed sensors. These electrical signals are then transmitted to the controller, which in turn passes them on to the actuator. This sequence can control the movement of the steering wheel and perform the steering process. For new energy vehicles equipped with steer-by-wire systems, compared with traditional vehicles, they have the following advantages. In the steer-by-wire system, the electronic controller is at the center. When it issues steering instructions, its sensitivity is higher and its reliability is also higher. There is no direct mechanical connection between the steering gear and the steering wheel. This situation provides drivers and passengers with a more comfortable operating experience and riding experience when crossing those uneven roads. The steer-by-wire system uses an electric motor as the actuator, replacing the traditional use of hydraulic oil as the transmission medium, thus truly achieving environmental sustainability [3].

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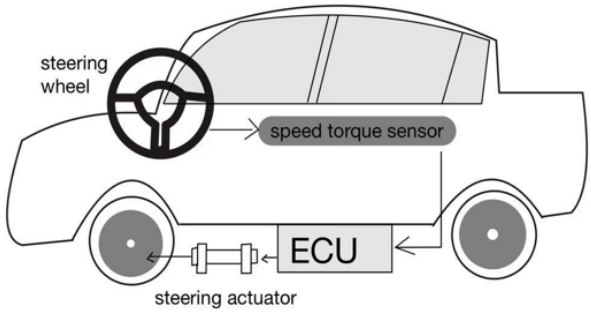


Figure 1. Schematic diagram of the electric power steering system

Currently, electrically powered electric power steering (EPS) systems are progressively becoming the mainstream in the market. The performance of EPS systems is largely dependent on their assist characteristic curves, which serve as reference signals for control algorithms. Nguyen, Tuan Anh summarises the mathematical models, structure, and applications of EPS [4]. Through the classification and analysis of various assist characteristic curves, he provides support for researchers seeking to optimise control performance.

3. Brake-by-wire system

The advancement of intelligent electric vehicle drive-by-wire chassis technology has given rise to diverse brake-by-wire (BBW) system solutions. According to prevailing research paradigms, brake-by-wire systems are primarily categorised into Electro-hydraulic brake systems (EHB) and electro-mechanical brake systems (EMB), based on whether the system retains hydraulic components [5].

3.1. Electro-Hydraulic Braking (EHB)

As shown in Fig 2, when the driver depresses the brake pedal, the resulting displacement is captured by a sensor. This sensor transmits the signal to the ECU, which integrates vehicle conditions (such as load and wheel speed) with system requirements (such as ABS and ESP activation thresholds). The ECU then calculates the required braking force for each wheel. Based on these calculations, the ECU controls an electric motor to drive a hydraulic pump (motor pump), compressing brake fluid to the target pressure and establishing the hydraulic pressure required for braking. The ECU then activates corresponding solenoid valves. High-speed solenoid valves dynamically regulate hydraulic fluid flow to each wheel according to ECU commands, precisely adjusting wheel hydraulic pressure. This action drives the brake calipers (wheel cylinders) to clamp the brake discs (drums), thereby achieving automatic braking. Features such as ABS and ESP are integrated. Simultaneously, high-precision sensors monitor pedal travel and force applied, with the ECU transmitting feedback to the driver via the pedal simulator. EHB systems are categorised into one-box and two-box configurations. The two-box configuration is exemplified by Bosch's iBooster + ESC system, comprising two independent modules. Compared to conventional mechanical braking, the two-box system offers: 1. More efficient braking energy recovery; 2. Faster response times; and finally incorporates redundant safety design within a lightweight, integrated architecture. However, the two-box approach faces challenges including lower hardware integration, greater complexity in

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coordinated control, and mandatory integration with ESC systems. This has spurred the development of a new, highly integrated solution: the Integrated Electro-Hydraulic Brake System (IEHB), which adopts a one-box configuration. The one-box solution combines the functions of the booster and ESC, offering lower costs. Compared to the two-box system, the one-box solution not only achieves higher integration but also provides complete decoupling, maximising energy recovery efficiency.

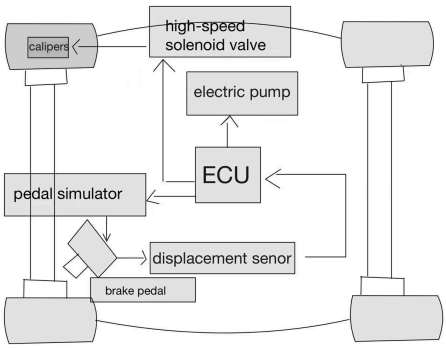


Figure 2. Schematic diagram of EHB

3.2. Electro-Mechanical Braking (EMB)

The EHB solution can be regarded as a significant advancement over traditional mechanical braking systems. However, it still retains most of the hydraulic components. The environmental adaptability of EHB is not very good, and it is particularly susceptible to temperature fluctuations. Additionally, its maintenance complexity has always been relatively high. The most crucial point is that its own response speed is limited. With the continuous development of autonomous driving technology, the demand for faster response times and greater weight reduction is becoming increasingly strong. This demand has stimulated the development of a solution that better meets the requirements of future autonomous driving - EMB. As shown in Figure 3, when the driver steps on the brake pedal or the autonomous driving system issues a command, The pedal sensor will transmit the signal to the ECU. Afterwards, the ECU will calculate the braking force required for each wheel based on factors such as vehicle speed and load, and then guide the wheel end motors to generate linear thrust. This thrust will cause the brake pads to tightly grip the brake discs, thus achieving braking. Compared with EHB, the EMB system has the following advantages: the EMB system can achieve higher energy recovery efficiency. Because it eliminates hydraulic components, it becomes lighter in weight, takes up less space, and most importantly, the EMB system can offer a faster response time.

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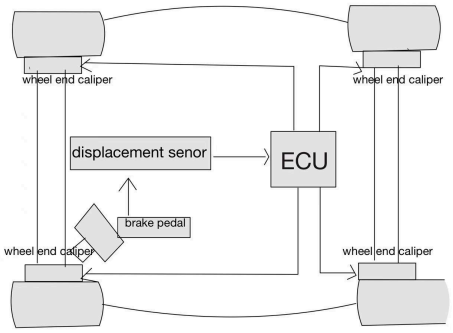


Figure 3. Schematic diagram of EMB

The foremost advantage of the EMB system lies in its complete control over the braking force of individual wheels. Zhen Wei, John Xu and Dunant Halim proposed an enhanced clamping force control architecture through research into clamping force control within the EMB system. They established an EMB test rig to validate the superior performance of the EMB system [6].

4. Research on cooperative control of wire-controlled chassis

Compared to conventionally configured chassis vehicles, fully electronic control chassis systems can significantly enhance vehicle safety under complex and extreme operating conditions through coordinated control of multiple chassis subsystems. The core processes of vehicle state/parameter estimation, vehicle stability assessment, and coordinated control of multiple chassis subsystems are crucial for ensuring safe and reliable vehicle operation. These three elements are interrelated and mutually influential. This section reviews the latest research advances and development directions in the coordinated control of multiple subsystems within fully electronic control chassis systems [7].

Full-line control chassis technology achieves significant improvements in vehicle handling stability, comfort and safety under complex conditions such as longitudinal slip, yaw and roll. This is accomplished through the coordinated control of two or more subsystems within the drive-by-wire, steering-by-wire, brake-by-wire and active suspension systems. This section summarises the key technologies for coordinated control of longitudinal, yaw and roll stability within the drive-by-wire chassis system, focusing on functional implementation

4.1. Longitudinal stability control

Vehicle longitudinal stability control mainly relies on adjusting the driving or braking torque of each wheel in real time to precisely track the required wheel slip ratio. This approach can maximize the utilization of road adhesion and also ensure that the vehicle maintains the necessary lateral stability margin. The key components of the vehicle longitudinal stability control system include the acceleration slip regulation system, also known as ASR, and the anti-lock braking system, also known as ABS [8].

4.1.1. Acceleration slip regulation

Traction control means that by limiting excessive wheel slippage caused by rapid acceleration on low-grip surfaces, the longitudinal stability of the vehicle can be enhanced. The electric drive system

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can provide a rapid response and has a high torque control accuracy. It can independently adjust the torque of each wheel. This way, the slip ratios of all four wheels can be precisely adjusted. In this way, the adhesion of the road surface can be utilized to the greatest extent under different conditions. The key technologies of traction force control mainly include longitudinal vehicle speed estimation, road surface friction coefficient estimation, and ideal torque tracking control methods.

A great deal of research has been conducted on ASR systems, and these studies can roughly be divided into two situations: torque-based variants and slipping-based variants. The current ASR system is confronted with several key challenges. The first one is that obtaining accurate vehicle speed requires a significant cost. The second challenge is that identifying the reference slip ratio in real time remains a rather challenging task. The third challenge is that a systematic and convenient method is needed to analyze the ASR system and design its controller. To address these challenges, Bai and his team designed an asrs scheme based on imprecise vehicle speed, which is a novel asrs method using a cascaded structure. Additionally, they developed a real-time reference slip ratio identification method that combines the estimation of the friction coefficient of tires on the road surface [9]. Validation through real-world road tests confirmed the effectiveness of the proposed ASR system and analytical methodology.

4.1.2. Anti-lock brake system

ABS primarily prevents wheel lock-up during emergency braking by limiting the braking force applied to all four wheels. This reduces the vehicle's stopping distance while preventing hazardous conditions such as tail-sliding, skidding, and loss of steering control. As conventional hydraulic braking systems cannot achieve rapid, precise control of hydraulic pressure, basic ABS functionality is typically realised through logic threshold methods controlling wheel slip rate. With the widespread adoption of Brake-by-Wire systems, electro-hydraulic compound braking ABS represents the future development trajectory. Its core technologies encompass precise wheel cylinder pressure control and optimised distribution of electro-hydraulic compound braking force.

Although current ABS technology delivers outstanding performance under normal road conditions, it still faces challenges in dynamic adaptation during extreme weather. Kang and his team designed an Adaptive Multi-layer Anti-lock Braking Control (AMABC) method [10]. AMABC integrates diverse control techniques, including a deceleration rate control module, a pressure optimisation module, and a fuzzy-logic-based anti-lock control module. The AMABC method intelligently adjusts multiple control strategies in real-time according to vehicle speed during braking, thereby enhancing braking performance and reducing stopping distances. Simulation experiments across various road and speed conditions demonstrate superior performance compared to conventional control methods.

4.2. Lateral stability control

The lateral stability control system is a crucial part of the vehicle's active safety system. It is also a key method to ensure that the vehicle maintains stability during driving and still has a certain degree of maneuverability. The basic principle of this system is that it can generate supplementary yaw moments by relying on differential drive or braking, as well as active front or rear wheel steering. In this way, the situation of understeering and oversteering caused by the tires reaching the longitudinal and lateral adhesion limits can be alleviated. After alleviating these conditions, the expected yaw rate of the driver can be tracked to prevent dangerous situations such as vehicle skidding or oversteering. Judging from the number of by-wire subsystems involved, This kind of control can be

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divided into single-line control subsystem yaw stability control or multi-line control subsystem collaborative control.

4.2.1. Single-wire control subsystem yaw stability control

Single-line control subsystem yaw stability control utilises a single-line control subsystem as the source of additional vehicle yaw moment. Its primary advantages lie in minimal control variables and the absence of control coupling issues between multiple subsystems. However, its applicability is limited to specific operating conditions, resulting in constrained control effectiveness. Common single-line-control subsystem yaw stability control methods include Direct Yaw-Moment Control (DYC), Active Front Steering (AFS), Active Rear Steering (ARS), and Four-Wheel Active Steering (4WAS).

Zhang, H. and J. M. Wang's team designed an integrated control system combining AFS and DYC for vehicle yaw stability control [11]. Building upon this, they proposed a generalised proportional-integral (PI) control law and developed an enhanced system. Concurrently, they introduced a controller design methodology, with simulation studies verifying that their designed controller improves both lateral stability and controllability performance.

4.2.2. Multi-wire control subsystem yaw stability control

Multiple by-wire subsystems, including steering, drive or braking, and active suspension, coordinate and control each other efficiently. This can effectively expand the operational scope of vehicle yaw stability control. As for the active steering system, it not only raises the upper limit of the additional yaw moment, It also reduces the impact of differential drive or differential braking on the vehicle's longitudinal speed. By the same principle, during the yaw control process of a vehicle, active suspension control can suppress the rolling and pitch movements of the vehicle body, thereby improving the adhesion conditions of the wheels. The coordinated control of multiple undercarriage related electric drive subsystems mainly includes several situations: one is the coordination between the longitudinal and transverse directions, and the other is the coordination between the transverse and longitudinal directions. One type is the comprehensive coordination of vertical, horizontal and vertical aspects.

4.3. Roll stability control

During vehicle design, roll stability can be enhanced by lowering the centre of gravity and optimising suspension parameters. However, in actual driving conditions, factors such as uneven load distribution, high-speed cornering, lateral road gradients, varying road surfaces, and obstacles can cause vehicles with higher centres of gravity—such as SUVs and lorries—to roll, resulting in lateral load transfer between wheels. Should this body roll prove uncontrollable, it may further cause one set of wheels to lift off the ground, potentially resulting in a rollover accident. Roll stability control aims to mitigate rollover risks by continuously monitoring and evaluating the vehicle's roll state, utilising coordinated control of line-by-wire subsystems including suspension, steering, and drive/braking. Based on the coordination type of these subsystems, roll stability control can be categorised into single-line-by-wire subsystem and multi-line-by-wire subsystem coordinated systems.

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4.3.1. Single-wire control subsystem roll stability control

Vehicle roll is primarily caused by excessive load transfer between the left and right wheels under high lateral acceleration. Single-line-control subsystem roll stability control primarily addresses this through either counteracting load transfer (direct control) or reducing vehicle lateral acceleration (indirect control). Direct control primarily generates anti-roll torque to counteract lateral load transfer through active suspension systems or active anti-roll bars. Indirect control enhances roll stability by employing measures such as braking to reduce speed, differential drive/braking to decrease yaw rate, and active front-wheel steering to minimise instantaneous turning radius.

4.3.2. Multi-wire control subsystem roll stability control

Due to the strong coupling relationship between body roll motion and the vehicle's longitudinal and yaw motions, controlling roll stability solely through a single line-control subsystem inevitably affects the vehicle's motion in other directions. Coordinated control across multiple line-control subsystems can enhance roll stability by counteracting load transfer and reducing lateral acceleration, whilst simultaneously maintaining longitudinal and yaw stability. Key technical approaches for coordinated roll stability control across multiple line-control subsystems include methods based on stability boundary partitioning and optimisation-based integrated coordinated control methods.

5. Conclusion

This article aims to explore the cutting-edge field of automotive by-wire chassis technology, taking the establishment of a high-performance and high-safety collaborative control system as the core objective. It carefully reviews the research progress in three key areas, namely automotive by-wire steering systems, by-wire braking systems, and the collaborative control of by-wire drive chassis. By providing a systematic overview of relevant theories, methods, key technologies and current engineering applications, a clear framework is offered for subsequent research and industrial implementation.

By-wire chassis technology can free the chassis from the limitations brought by mechanical transmission of force and motion. It relies on electronic channels to achieve energy and information transmission. Such a transmission method promotes the development of chassis configuration towards modularization and scalability, laying a certain foundation for the expansion of vehicle functions based on software and the improvement of vehicle performance. By-wire chassis technology is a key cornerstone for achieving advanced autonomous driving. It provides the flexibility, precision, and responsiveness required by autonomous driving systems at the execution level.

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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