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Review

A Review of Automobile Brake-by-Wire Control Technology

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Abstract: Brake-by-wire (BBW) technology is crucial in driverless cars. The BBW technology, which has a faster reaction time and greater stability, can improve passenger safety in driverless cars. BBW technology refers to the removal of some complicated mechanical and hydraulic components from the traditional braking system in favor of using wires to transmit braking signals, which improves braking performance. Firstly, this paper summarized BBW's development history as well as its structure, classification, and operating principles. Subsequently, various control strategies of the BBW system were analyzed, and the development trend and research status of the motor brake-control strategy and wheel-cylinder pressure-control strategy in the braking force-distribution strategy were analyzed respectively, and the brake fault-tolerance technology and regenerative-braking technology were also analyzed and summarized. Finally, this paper summarized the various technologies of BBW, taking the electromechanical brake (EMB) in the braking system as an example to discuss the current challenges and the way forward.

Keywords: brake-by-wire technology; motor brake-control strategy; wheel cylinder pressure-control strategy; brake fault-tolerance technology; regenerative-braking technology

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1. Introduction

More effective and energy-saving drive-by-wire technology has evolved with the advent of intelligent and networked automobiles [1,2]. Drive-by-wire technology was initially utilized in the aerospace industry as a crucial component of the braking system. The quick development of intelligent networked vehicles has drawn a lot of attention. For intelligent networked vehicles, the quick advancement of wire-control technology offers not only a reliable control basis but also guidance for developing unmanned vehicles [3].

The most significant and technically complex aspect of chassis technology is the brake-by-wire (BBW) system [4]. The engine, in the case of an electric vehicle, was eliminated, therefore it is unable to supply a vacuum source to the vacuum booster for engine-based braking assistance [5]. As a result, an improvement to the braking system is inevitable. Moreover, more cooperative, intelligent, and responsive motion actuators are needed for the autonomous driving of automobiles. To facilitate braking and effectively recover braking energy to extend the range of electric vehicles, brake-by-wire technology regulates the motor. At the same time, it can execute intelligent driving commands with pinpoint accuracy. The brake-by-wire system will undoubtedly be the best option for braking system improvement.

The brake-by-wire system, as an important safeguard mechanism in automobile active safety, has the advantages of environmental protection, accurate pressure regulation, and fast response time. The BBW systems can readily combine the anti-lock braking system (ABS), electronic stability controller system (ESC), and regenerative braking system (RBS) through the implementation of synergistic control techniques. Some benefits of these pairings include enhanced brake stability and energy recovery [6,7].

At the time when the BBW system had more mature technology and loading cases, some famous auto parts manufacturers in developed countries, such as Bosch, Siemens, Continental Teves in Germany, Delphi, TRW in the United States, Hyundai, Mobis, Mando in South Korea, Haldex and SKF in Sweden, had carried out research on EMB and developed their own products. Mobis and Mando in Korea, and Haldex and SKF in Sweden, had all conducted EMB research and developed their own products. A number of Chinese universities and automobile companies, including Jilin University, Tongji University, Tsinghua University, Beijing University of Technology, and Geely Automobile, developed preliminary programs [8–11].

2. Development History

Several types of braking systems have evolved since Wilhelm Maybach invented the drum brake in 1900. Their evolution can be loosely divided into the four stages listed below.

The first stage is ABS, anti-lock braking system. To achieve the best braking effect, the system may automatically alter the wheel brake force while braking. The wheels can prevent skidding during braking by regulating and managing the brake line pressure. To optimize braking performance, keep the wheels at a 15–25% slip rate of motion while rolling [12]. Proportion Integral Derivative (PID) control [13], neural network control [14], fuzzy control [15], fuzzy PID control [16], and logic threshold control [17–20] are the primary control systems utilized for automobile ABS. ABS is standard equipment in almost every car in the globe. The majority of them are based on Bosch's logic threshold ABS control system. The logical threshold control method is straightforward, easy to apply, and extremely adaptable. It maintains the slip rate and angular acceleration in the best range and is mature for the application. Today, improving control techniques is the main focus of ABS optimization. Li made improvements to the automotive ABS system and put out a plan to use the peak wheel speed linkage to address the vehicle speed and standard slip rate. To solve the control problem of an anti-lock braking system (ABS) in an automobile under many challenging driving circumstances. He created a hierarchical intelligent control system that includes organizational coordination, parameter correction, and human control [21,22].

The second stage is ESC/ESP. The electronic stability controller system (ESC) is a new type of vehicle active safety system. It is an extension of the vehicle's anti-lock braking system (ABS) and traction control system (TCS). On this basis, a transverse swing rate (yaw rate) sensor, a lateral acceleration sensor, and a steering wheel angle sensor were added to the vehicle steering when driving. Through ECU control, ensure the vehicle's stability and safety while driving, braking, and steering. The ECU electronic control ensures the vehicle's stability and safety while driving, braking, and steering. The vehicle dynamic stability control system, as shown in Figure 1, provides internal feedback control via ESP. The performance of the wheel will be unstable and non-linear at the limit of adhesion between the tire and the road. In this case, the vehicle dynamics control system will assist the car in maintaining control [23–25]. The sensors provide the ECU with information on the vehicle's current status [26]. Two new pressure limiting valves and two suction valves were added to the ABS's eight solenoid valves, totaling 12 solenoid valves capable of switching the system's active boost circuit and return circuit. To ensure the stability of the vehicle driving, solenoid valves, plunger pumps, and other key components have different parameters of the series of products, which can be diversified with the trial of different models.

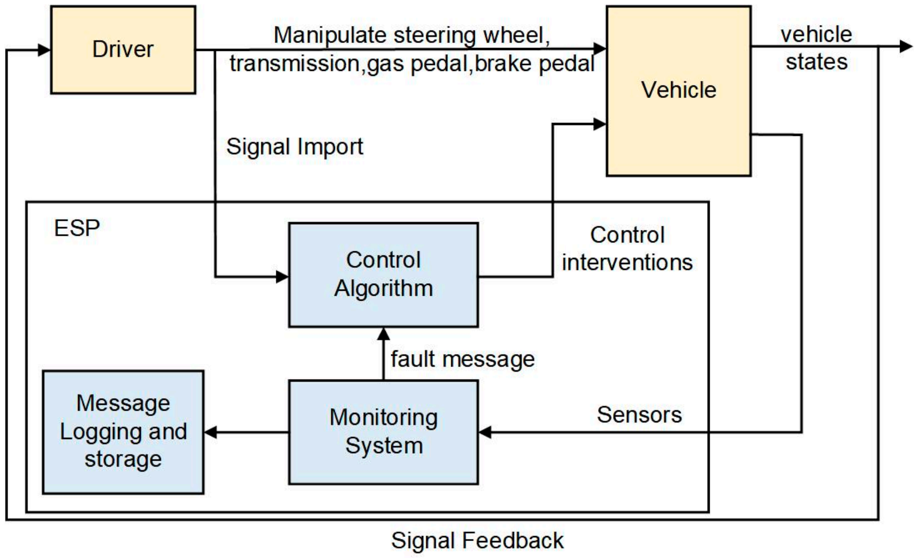

Figure 1. Components of vehicle dynamic stability control systems.

The third stage is IPB+RBU. For L3 and L4 of autopilot, Booster proposed a brake-by-wire technology, which is IPB+RBU. Integrated Power Brake (IPB) integrates brake vacuum pump, vacuum brake booster, ESP and other important actuators. In the IPB, the highly integrated power brake is complemented by a redundant brake unit. This has ensured that even in the event of an integrated power brake failure, the vehicle can stop safely and reliably without driver intervention with the following advantages:

(a) Low weight and simple arrangement;
(b) Low costs. There are no vacuum pumps and hydraulic pipes, thus reducing production costs;
(c) Short braking distances for automatic emergency braking systems thanks to the highest-pressure build-up dynamics;
(d) Long ranges. Powered by an efficient brake regeneration system, it can greatly improve the range of hybrid and electric vehicles.

By analyzing the requirements of the braking system, it is necessary to consider the design of redundant braking. In addition to the primary brake control unit, a secondary brake control unit is required, and the system should also be equipped with extended functions such as system status detection, redundancy control, and back-up vehicle stability control. Booster's solution is to use the IPB as the primary braking system to perform the braking request in most cases. In the case of IPB failure, RBU (redundant brake unit) can be used as the redundant brake.

The fourth stage is EMB. It is electromechanical and can be easily integrated with other electronic control systems of the vehicle to realize more functions, such as braking, ABS, EBS, ESP, automatic driving, and optimized energy recovery. Based on all these advantages, EMB technology is bound to develop vigorously and present serious challenges to the hydraulic braking system in the future.

EMB is a new concept of braking systems. At the stage of EMB, load, cost, reliability and other constraints have blocked the industrialization. However, as a parking brake it is used in industry. However, thanks to the advantages of fast response, energy saving and environmental protection, it has become one of the development directions of the future vehicle braking system.

3. Structure of Brake-by-Wire System

Electronic components had largely taken the role of mechanical and hydraulic components in the brake-by-wire system. The brake pedal is no longer mechanically connected to the braking wheel cylinders. Electronic brake pedal sensors monitor the driver's braking activity and translate it into electrical signals for the electronic control unit (ECU) to analyze. Then the ECU sends the proper instructions to the electric drive units, including the high-pressure accumulator and the motor. In order to produce braking power, the motor or high-pressure brake wheel cylinder eventually presses the push rod.

The brake-by-wire system can be classified into two categories: hydraulic and mechanical, depending on the various actuators. The hydraulically controlled actuation system, which includes the electro-hydraulic brake system (EHB), is structurally similar to the conventional hydraulic brake system. It only kept the original hydraulic brake system and swapped out the vacuum assist for the motor assist [27,28]. But, as an intermediate of the brake system with wire control. Major automakers continue to favor EHB due to its outstanding compatibility and simplicity of retrofitting to the original brake system for adoption. The electromechanical brake is a braking system that employs an electric signal to regulate the mechanical structure, eliminating the transmission mechanism such as hydraulic pressure, and using a motor as the power source. Being a mechanically driven system, it is more environmentally friendly and sensitive, and eliminates the brake fluid delay effect. It can also actively implement the longitudinal dynamics integration of EMB and other control systems via algorithmic advancements to achieve a better braking effect. As intelligent car technology evolves, EHB will be replaced by EMB, which is more in line with the needs of future braking systems Because of its distinct features, the EMB system is currently attracting considerable interest from Chinese and global automotive manufacturers. It will become a research center for future automobile braking.

3.1. Electro-Hydraulic Brake System (EHB)

As a transitional product between the traditional brake system and the brake-by-wire system, the operating mechanism of the EHB has replaced the traditional hydraulic brake pedal with an electronic brake pedal and used a hydraulic device instead of a bulky vacuum booster. The hydraulic control unit in the EHB automatically adjusts the braking pressure of the wheels according to different driving conditions to provide sufficient braking force. EHB has eliminated the coupling between the brake pedal and the driver without a vacuum booster, with advantages of compact structure, convenient and reliable control, low braking noise, and good braking comfort. The composition of EHB system can be seen in Figure 2 [29,30]. EHB can also control the braking force of each wheel individually to easily maximize the braking energy recovery. Therefore, EHB has special application value for electric vehicles. Dependent on the hydraulic drive unit, EHB can be classified as a high-pressure accumulator type or an electric pump type. Table 1 displays the hydraulic control system for the electro-hydraulic braking system.

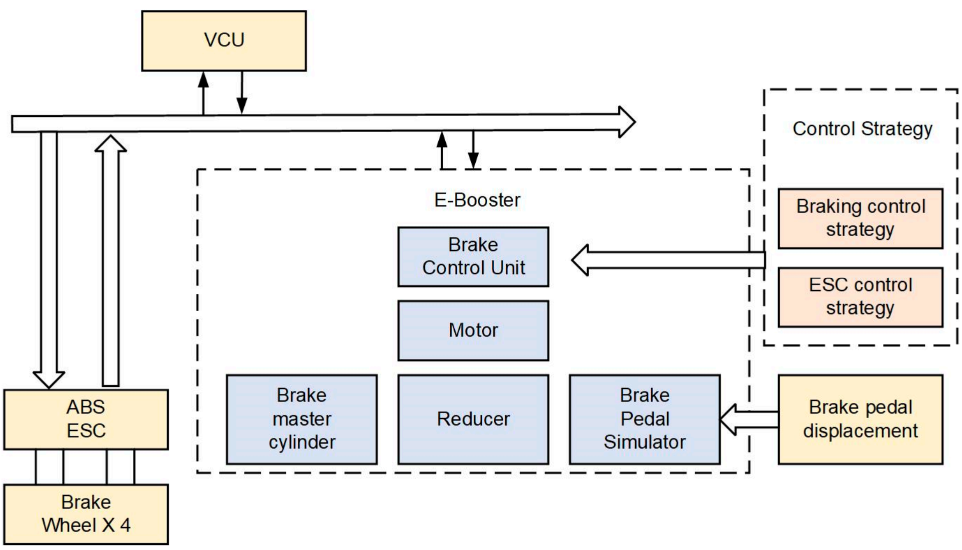

Figure 2. The composition of EHB system.

Table 1. Hydraulic pressure-control scheme of master cylinder of electro-hydraulic braking system.

Hydraulic Drive Unit Form	Control Variable	Control Algorithm	Reference
Motor and Electric hydraulic pump	Main cylinder hydraulic pressure	Feedback control	[31–33]
		PID control	[34]
		Taguchi method and Segmentation PI control	[34]
		Gain scheduling PI control	[35]
		Feedforward and feedback control	[36]
		Friction compensation and PID control	[37]
		Friction compensation and adaptive robust control	[37]
		Friction compensation and sliding mode variable structure control	[38]
	Main cylinder piston push rod displacement	PID control	[39,40]
		Sliding mode variable structure control	[40]
		Prediction based on hydraulic model	[39]
	Motor rotation angle	Feedback control	[41]
	Main cylinder hydraulic pressure and main cylinder piston push rod displacement	Switching control	[42]
		Cascade control	[43]
		Cascade anti-winding control	[44]
	Main cylinder hydraulic pressure and motor current	Cascade control	[45]
Hydraulic pump and high pressure accumulator	Main cylinder hydraulic pressure	Switch control	[46]
		Pulse width modulation control	[41]
		PID control	[47]
		Sliding mode variable structure control	[48]

3.1.1. High Pressure Accumulator Type

Among them, the hydraulic brake system of high-pressure accumulator type provides the master cylinder hydraulic or wheel cylinder braking force through the high-pressure accumulator high-pressure energy. Thus, the dynamic regulation of braking force is achieved. After obtaining the driver's intention through the brake analog pedal, ECU sends a command to the vehicle controller. The high pressure accumulator, solenoid valve and pump are controlled to produce appropriate hydraulic pressure. When pressure in the high-pressure accumulator is insufficient, the hydraulic pump will pressurize the high-pressure accumulator.

In the 1990s, when braking systems were still in their infancy, a high-pressure accumulator kind of hydraulic braking system was devised to overcome the problem of the brake pump's delayed response and low flow rate. In which high pressure is generated by an electric motor plunger pump and stored in advance in a high-pressure accumulator. The high-pressure accumulator received braking fluid at a faster pace, which shortened the brake's response time. When the brake was activated, the high pressure was swiftly released [49]. In 1994, the first high-pressure accumulator brake system was created. It's created using analogy and Saber modeling. Toyota then introduced the first direct-drive wheel cylinder actuator-equipped EHB into production. It has two linear solenoid valves installed in the hydraulic adjustment unit, allowing for accurate control of the pressure in each wheel cylinder. In the system failure backup braking circuit, the front and rear chambers of the brake master cylinder were connected to each of the 4-wheel cylinders via switching solenoid valves. Also, the hydraulic adjustment unit's high-pressure accumulator, hydraulic pump, and motor were all detached separately. To implement the hydraulic power-assist function, the high-pressure accumulator outlet was connected to the brake master cylinder [50]. Bosch improved the design of the Sensotronic Brake Control (SBC), which was based on Toyota and shared many structural and functional similarities with the EHB. With the evident exception that the hydraulic adjustment unit of SBC was outfitted with two separate pistons for the front axle brake circuit. In the event of a system failure, the SBC system can only brake on the front axle wheels. The high-pressure nitrogen leakage from the high-pressure accumulator can be efficiently eliminated by the separating pistons on the front axle brake circuit [8]. The Mercedes R230 SL received the design for the first time in 2001. The high-pressure accumulator received high pressure from the electric motor, which was used to immediately supply braking pressure to the wheel cylinders [51]. They were made by Bosch, Siemens, Continental Teves, and Toyota [52–54]. These pioneering producers and researchers gave EHB a direction for future study. For the earlier concepts, Li proposed an electro-hydraulic braking system and its braking control method using a high-pressure accumulator. The high-pressure accumulator enabled the brake system to be realized with quick and precise pressure control and provided the driver with good pedal feedback.

3.1.2. Electric Pump Type

In the 1990s, Bosch designed and built the first EHB system based on the more mature ESP system and conducted real-world tests with good results [55]. The electric pump hydraulic braking system is driven by an actuator that directly drives the master cylinder for braking. The design retains the traditional brake anti-lock system ABS (Anti-lock Brake System), and also has the advantages of high control reliability and small changes to the traditional structure, which is now one of the mainstream development trends of the brake-by-wire system. Sun proposed a pump-controlled direct-drive the brake-by-wire unit, which uses pump-controlled direct-drive volumetric servo technology, and directly drives the bidirectional gear pump, to achieve control and rapid adjustment of the brake wheel cylinder pressure, eliminate the throttling loss of the valve control system, and effectively improve the system efficiency. The rotary motor output shaft directly drives the hydraulic pump scheme, and the hydraulic pump forward outlet port is connected to the brake wheel cylinder, that is, the hydraulic pump directly drives the wheel cylinder piston, and the forward inlet port is connected to the low-pressure accumulator to realize the function of controlling the wheel cylinder pressure [56].

Gu presented a passenger automobile brake-by-wire technology. A primary pressure supply unit was directly powered by an electric motor, and an auxiliary pressure supply unit with a high-pressure accumulator was also part of the system. The synergistic action of the two units results in accurate pressure regulation [57]. Li suggested a direct-actuated valve-based quick reaction braking system. It reduced the number of solenoid valves that needed to be configured by driving the valve spool directly with a solenoid linear actuator. And the sliding film variable structure control and adaptive robust control [58] swiftly modify the oil pressure of the brake wheel cylinder; Gong created a novel electromagnetic linear actuator-based braking unit for the all-electric driving characteristics of electric cars. By driving the electro-hydraulic brake unit directly to improve braking performance [59]. As a result, some manufacturers created electronic wedge brake (EWB). This is a self-excitation function linear actuation system [60]. Jo researched EWB modeling and control. A new single-motor EWB has been created. Controlling electronic actuators and self-exciting wedge mechanisms provided braking power. Because EWB did not require vacuum boosters or master cylinders, they were straightforward to configure in the cabin [61]. Streli and Balogh created a mechanical model that takes frictional factors into account and an EWB controller. A sliding mode controller was developed based on a dynamic equation model of the electronic wedge brake. Based on a simplified electronic wedge brake model, Kwangjin Han accomplished clamping force prediction and provided a contact point identification technique. Simulation and experimentation with a prototype EHB were used to confirm this controller's effectiveness [60]. The findings demonstrate that, in comparison to the pre-optimized EHB system, the optimized EHB system can provide the same vehicle stabilization with less boost torque during braking [62].

3.2. Electromechanical Braking System (EMB)

EMB stands for electronically managed mechanical braking. It entirely gets rid of the hydraulic system. It offers features like an efficient structure and environmental protection, among others. Due to the absence of the braking fluid's delay effect, it is also incredibly sensitive. The management of braking pressure is more exact with active braking function. EMB can simultaneously disconnect the brake pedal force and guarantee pedal feeling in the vehicle. To increase the rate of energy recovery when used in conjunction with the higher controller without altering the system's organizational structure. Simple adjustments to the control algorithm level can integrate EMB with the longitudinal dynamics of other systems. Decoupled composite braking systems can be implemented with wire-controlled actuation. EHB and EMB are two types of linear control technology currently in use. On the basis of Conventional Hydraulic Brake (CHB), EHB adds brake pedal sensor, pedal stroke simulator, master cylinder pressure sensor, pressure regulator, and pressure controller, and each wheel's braking force can be independently controlled. The EHB is based on the hydraulic circuit of the conventional automotive braking system and has a number of inherent flaws, including numerous hydraulic lines, a sizable vacuum booster, a challenging layout and assembly, a lengthy response time to braking, a high level of pedal vibration, and high manufacturing and maintenance costs. Instead of a hydraulic circuit, EMB is an electromechanical system composed primarily of pedal simulators, EMB actuators, and controllers that control the clamping force of the actuator to achieve independent control of each wheel braking force. EMB has numerous advantages over EHB, as shown in Table 2 [6,63].

Table 2. Performance comparison of various brake.

Type	Advantages	Disadvantages
CHB	(1) Large brake power (2) Proven technology	(1) Non-continuous control of braking force (2) Brake pedal jitter (3) Long braking force response time (4) Requiring complex electronics (5) Complex hydraulic circuit (6) Pollution of the environment
EHB	(1) High power (2) Braking power four-wheel independent control (3) Can be coupled with regenerative braking	(1) Non-continuous control of braking force (2) Brake pedal jitter (3) Long braking force response time (4) Requiring complex electronics (5) Pollution of the environment
EMB	(1) Braking power four-wheel independent control (2) No pedal jitter (3) Fast response of braking force control (4) Facilitates coupling with other active safety control systems (5) Light weight and small size (6) Avoids brake drag	(1) Need for redundant design (2) Requiring a power supply system of 42 V or more

The EMB is made up of a brake actuator on the brake wheel (which includes a torque motor, gear reducer, differential mechanism, motion converter, and brake caliper), and a central controller, the structure of which is represented in Figure 3. The motor serves as the primary driving source, with the reducer and torsion mechanism amplifying the spinning torque. The rotating motion of the motor is converted into the linear motion of the brake caliper by the motion conversion mechanism (ball screw structure or bevel gear structure), which then acts on the brake disc in the blocking condition.

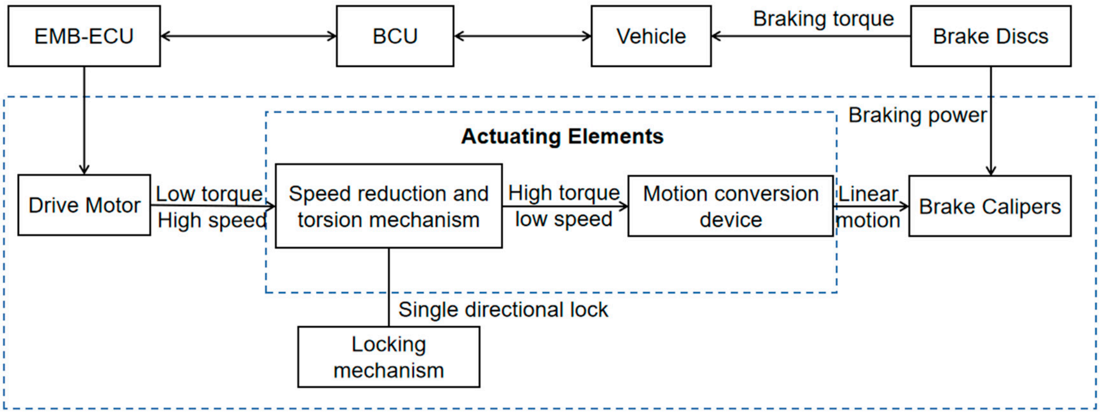

Figure 3. Electromechanical brake system structure composition.

As shown in Figure 4, The EMB actuator is designed using the vehicle's braking performance requirements and installation space limitations as input, the actuator's size limitation, the target maximum braking clamping force and its response time, the braking gap and its gap elimination time, and other performance objectives [64]. The performance criteria for electrical components, mechanical transmission components, and sensors are then obtained individually. Finally, the performance parameters of the specific motor type, operating range, rotational inertia, mass, operating voltage, and operating current, etc., are added to the design of the motor and its drive controller, the design of transmission parts, and the selection of sensors, and the detailed design of the actuator is realized.

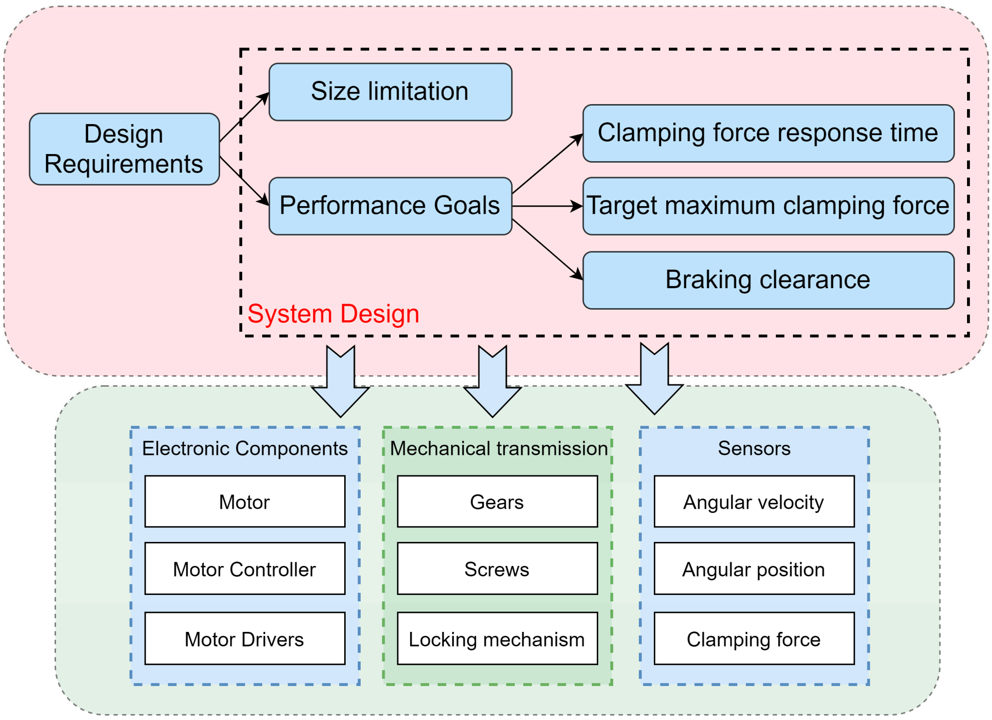

Figure 4. The flowchart of EMB actuator design.

Electromechanical brake systems were first applied in aircraft, such as the U.S. F-15 fighter jets. A new generation of aircraft will use brake-by-wire technology, according to a 2004 statement from Boeing. Numerous automotive companies and research institutions have become interested in EMB as a result of its successful use in the aviation industry. And it gradually moved on to the field of automotive braking [65,66].

For example, Bosch, Siemens, and Continental Teves in Germany, Delphi and TRW in the United States, Hyundai Mobis and Mando in Korea, Inc., have all demonstrated a great interest in researching EMB actuators since the 1990s. In Sweden, Haldex, SKF had investigated EMB, created their own EMB actuators, and conducted a number of studies on them [67,68].

The EMB designed by Bosch adopts the structure of external motor rotor [67,68]. The motor drove the internal planetary wheel system, and then the rotational motion exported from the planetary wheel system was converted into linear motion through the bevel gear structure. The gears would push the friction blocks to compress the brake discs to achieve the deceleration effect. This structure is more compact and more complex. The planetary gear reducer with a ball screw mechanism was chosen as the answer by the majority of the businesses represented by Continental Teves. The parking brake gear construction was likewise fixedly attached to the rotor. The solenoid's magnetism was dissipated while braking. To fix the rotor, the pawl made contact with the gear. The braking force already applied before halting was maintained in order to achieve the parking brake function, locking the entire transmission mechanism.

Nowadays, EMB research has been conducted in China, with universities serving as the primary research subjects. Early Chinese research on the EMB system dates back to a 2005 patent application by Tsinghua University. Tsinghua University's Zhao examined and compiled data on the structural designs of EMB actuators used both domestically and overseas. A structural plan with a torque motor, planetary gear reduction, and ball screw was his suggestion. The EMB controller without a pressure sensor was created by Han from Jilin University, who also finished the off-line simulation and debugging. Li from Chongqing University finished designing the braking control algorithm for the EMB technology after analyzing the response characteristics of the actuator. The stiffness of the brake caliper and ball screw, which impact the stability of the EMB, were looked into modeling studies by Yu of Shenyang University of Technology and colleagues, who also adjusted the EMB's structural properties. In the design of the EMB actuator, Yun of Zhejiang University converted the rotor to a hollow type and positioned the motion translation mechanism in this area [27,28,69–72]. Based on the existing commercial vehicle disc brake, Song proposed a commercial vehicle driving and parking brake electromechanical actuator based on a dual motor and self-locking mechanism. Sun proposed a dual-planetary EMB system based on the front-drive electric vehicle. Compared with the ordinary EMB structure, the structure of the dual-planetary EMB is optimized, which effectively reduces the motor power and improves the actuator performance. Aiming at the problems of large volume and low braking performance of commercial bus brakes, Shen proposed an auxiliary braking actuator-double stator eddy current brake and main braking actuator-electro-mechanical brake. Hye-Yeon Ryu proposed an EMB system using a motor controller without a large braking force. Zhou proposed an EMB system based on slip rate control. It is concluded that the system can improve the braking effect. Giseo proposed a new EMB clamping force controller, which can control the additional cost of existing sensor installation and response delay. It can be seen that with continuous research and development, electromechanical braking is expected to be popularized in the braking system of future automobiles due to its many advantages.

Research on EMB started late in China. So far, research on EMB systems in domestic universities and research institutes is still based on prototypes and has not yet been commercially applied. In general, there is still a large gap compared with foreign technologies, and the unremitting efforts of relevant scientific and technical workers are needed to narrow the technology gap and catch up with imported advanced levels [67]. Hence, as intelligent technologies and electrification continue to advance. The EMB will almost certainly be more up to date. Because of its distinct advantages, the EMB system is currently attracting considerable interest from domestic and foreign automobile manufacturers. It has become a research priority in the field of automotive braking. However, due to the high safety risk of motor power supply failure, the EMB system still has a long way to go before it can enter mass production without an additional backup mechanism for brake failure [6,64].

4. The Control Strategy of BBW System

4.1. Motor Braking Force Distribution Strategy

In the process of braking force distribution control of the brake-by-wire system, there are mainly electric machine power control and wheel cylinder pressure control. Reasonable distribution of braking force of motor and hydraulic system can improve the braking stability of BBW system, shorten the braking distance and increase the braking comfort. The traditional braking force distribution strategy is usually set up in the form of fixed ratio function of axle load or vehicle deceleration. As the fixed ratio function of the brake force distribution system has a simple and poor adaptability, it cannot better perform the performance of the braking system. Therefore, it is necessary to optimize the design of the braking force distribution control strategy to continuously improve the vehicle braking performance.

The braking force distribution method based on the slip rate is a more reliable distribution method to realize the electric mechanism power distribution. Li at Shanghai Jiaotong University used the control distribution algorithm to achieve the optimal distribution of the tire force based on the symbol-holding quadratic programming method [73]. Peng proposed an optimal braking force distribution strategy along with the constrained optimization problem based on the slip rate as a real-time solution method. The proposed optimal braking force distribution strategy can always ensure that the front wheel slip rate is higher than the rear wheel slip rate under different braking conditions. As a result, it not only improves the stability of vehicle braking, but also shortens the braking distance [74]. For the braking force distribution, H Fennel proposed that the slip rate of the rear wheels should track that of the front wheels in a fixed ratio [75]. In contrast, the ratio is divided into four segments for separate control in the literature [76]. Zhang proposed a hierarchical control system to solve the problems of poor anti-interference performance, poor electromechanical coordination performance and large target tracking errors when autonomous vehicles perform braking. In the upper-level controller, a feedback controller is built based on the desired speed sequence of the unmanned system. The desired braking deceleration is used as the front-end input to compensate for the target braking torque, and the speed error used as the feedback input to correct the target torque difference. In the lower controller, a coordinated braking force distribution algorithm based on fuzzy control is established by considering the characteristics of mechanical braking and motor braking [77].

4.2. Wheel Cylinder Pressure-Control strategy

The introduction of the brake master cylinder has caused a response delay in the linear hydraulic brake system. Frictional nonlinearity and initial pressure difference have different effects on pressure control. A digitally controlled proportional valve is the most effective and straightforward method in achieving efficient brake pressure modulation. It can achieve the continuous control of hydraulic fluid flow, and thus go on to achieve linear control of hydraulic pressure. To improve the control accuracy of wheel cylinder hydraulics and the performance of the hydraulic braking system, researchers at home and abroad had conducted a comprehensive study on the design and control methods of hydraulic actuators. Li proposed a pressure-control strategy. Based on the open-loop test analysis of the electric master cylinder, the integrated in-line hydraulic brake (IEHB) system was designed. Combined with the pressure segmentation control architecture, a feed forward and feedback PID method based on the auxiliary boost coefficient compensation was used to regulate the electric master cylinder. And a logic valving method was used to control the booster valve, pressure reducing valve and electric pump. Thus, the design of a pressure controller based on this IEHB system was realized [78]. Chen Lv proposed a novel sliding mode control method based on high precision hydraulic feedback modulation. A hydraulic brake system dynamics model including valve dynamics was established. An open-loop load pressure control method based on the linear relationship between pressure drop and coil current in the critical open-loop equilibrium state of the valve was proposed, and the effectiveness and superior performance of the proposed closed-loop modulation method verified [79].

4.3. Stability Control Strategy Technology

For conventional cars, the electronic stability controller (ESC) system is controlled by direct transverse moment. As the wire-controlled actuation technology increasingly develops, electrical signal transmission has replaced the conventional automotive drive line. It can make the most of the advantages such as the rapid electrical signal transmission to improve the handling stability of the vehicle [80,81]. Therefore, it is urgent to research the dynamics stability control system of brake-by-wire.

Vehicle stability control parameters include the lateral stability control of the vehicle. Factors affecting the lateral stability of the vehicle mainly include the yaw rate and the sideslip angle of the mass center. For the vehicle stability control, there are four main control methods directly transverse moment control, active front wheel steering, active suspension and active anti-roll stabilizer [82,83].

The transverse moment stabilization control system mainly adopts a hierarchical control structure. The computation time is thus reduced by establishing a parallel controller. Its good real-time performance can meet the requirements of the braking system. In response to the above issues, Qin proposed a structure of the new stable hierarchical control system. Based on the feedforward joint control, the upper layer is an additional transverse moment controller, which is able to resist the influence of changing road adhesion conditions. The lower-level torque distribution controller adopts an optimal distribution control algorithm to achieve independent and optimal distribution of braking force to all four wheels of the vehicle [84].

The structure divides the whole control system into three layers as follows:

(1) The layer of vehicle state observation: Real-time monitoring of vehicle parameters;

(2) The layer of motion control target tracking decision: When the vehicle has a tendency to destabilize, the magnitude of the transverse swing torque to prevent transverse swing instability will be calculated according to the driver's intention and the actual state of the vehicle;

(3) The layer of torque distribution control: Optimally distributes the additional transverse sway torque to the brake actuators of the four wheels when the vehicle dynamics constraints are satisfied.

Currently, the dynamics stability control system is mainly through tracking control of the yaw rate and the centroid sideslip angle. Tracking control of yaw rate is commonly used in the regular vehicle driving, which can ensure the vehicle handling stability during normal driving, but it may fail under extreme working conditions. Tracking control of centroid sideslip angle is a good complement to this defect, which can quickly adjust the vehicle state when it loses stability control and ensure the normal vehicle driving. Therefore, most of the research on vehicle stability control focus on coordinating tracking control of the yaw rate and the centroid sideslip angle, and the two cooperate to ensure the handling stability and improve driving comfort and safety.

Mirzaeinejad H et al. proposed a vehicle stability control system as shown in Figure 5. The designed control system is divided into two layers. The upper layer calculates the front outer yaw moment and the corrected lateral force referring to the yaw rate and proposes an algorithm for the distribution of tire braking force. In the lower layer, a new nonlinear multivariable controller is optimally designed. The weighted combination of the front outer yaw moment, corrected lateral force and the tracking error are used to define the vehicle stability performance index. The defined performance index is minimized to obtain a closed form multivariate control law. Through the proposed fuzzy scheduling method, the designed integrated controller is automatically tuned so that the weighting factors can change softly under different driving conditions, thus realizing the adaptive regulation of vehicle stability control [85].

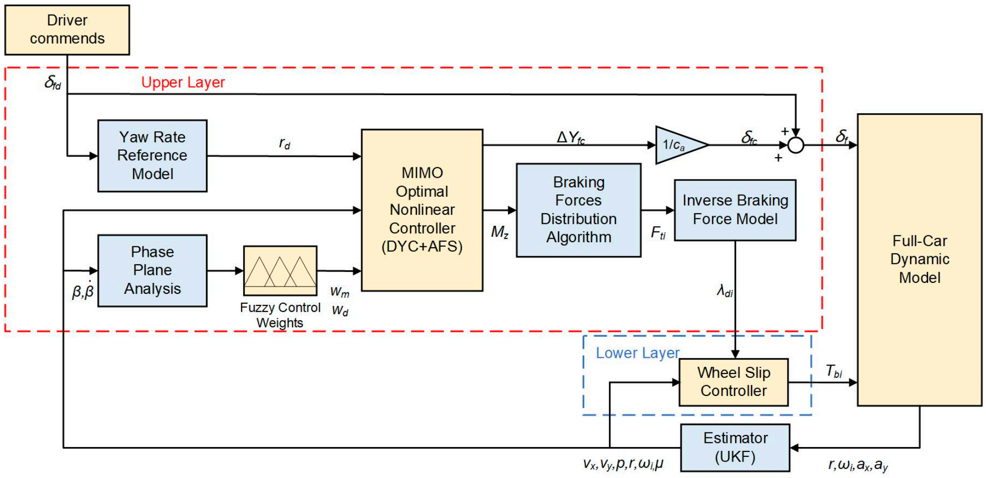

Figure 5. Overall structure of the proposed integrated control system.

Besides, the research on vehicle stability control focuses on the tracking control of yaw rate and center point sideslip angle under extreme operating conditions. Various control algorithms have been used, such as sliding mode control [86,87], fuzzy logic control [88], control allocation methods [89], optimal control [90,91], model predictive control strategies [92], and robust control [93]. In the literature, an extra direct yaw moment control was obtained in real time by tracking and controlling the angular velocity of the transverse swing and the lateral deflection angle of mass center of a robust controller [94]. The literature proposed a vehicle stability control algorithm based on brake-by-wire, which adds a brake redundancy to the vehicle stability control to improve the braking safety [95]. It also proposed a cooperative control of vehicle lateral stability using active front-wheel steering and differential braking, which softly constrains the yaw rate velocity by a model prediction algorithm and controls the centroid sideslip angle to always stay within a certain range so as to maintain the stability and comfort during driving [96].

4.4. Brake Fault-Tolerant Technology

The brake-by-wire system is expected to completely replace conventional braking systems because of advantages of fast response and high accuracy. However, all mechanical connections between the brake pedal and the brake actuator have been eliminated in the brake-by-wire system. While providing better braking performance, this also poses significant safety challenges to the in-line braking systems. A fault-tolerant and fail-safe system architecture is therefore needed. Given such issues, experts have put forth some solutions. Based on the analysis of transient fault propagation characteristics of BBW systems, Shuang Huang proposed a hierarchical transient fault-tolerance scheme with embedded intelligence and resilient coordination. In this scheme, most transient faults can be quickly handled at the node level by a feature-code-based detection method. The remaining are those that cannot be detected directly at the node level. Transient faults that degrade the system performance through fault propagation and evolution can be detected and recovered at the system level by functional and structural models. A sliding mode control algorithm and task reassignment strategy were designed [97]. A comprehensive review of fault-tolerant brake-by-wire system was presented in the literature [98], which discussed fault detection methods for low-cost components, analyzes fault-tolerant design principles between sensors, actuators, communications and provided comprehensive considerations. Liu at Tsinghua University conducted a redundant braking design for the ABS module in the brake-by-wire and designed a redundant ABS control system architecture. By recognizing the driver's driving signals such as braking, steering and driving, estimating and monitoring each state parameter during vehicle braking, the redundant ABS control system can determine the intervention and withdrawal timing of the redundant braking function through driving intention and vehicle parameters. Among them, pressure controls used variable to gain PID control. When the redundant ABS control system works, the SMC (sliding mode control) algorithm will be used to control the slip rate of the wheels, thus realizing the redundant ABS control function of the vehicle and improving driving safety [99].

4.5. Regenerative Braking Technology

The concept of energy conservation and environmental protection takes root. People pursue green and renewable environmental energy such as automobile fuel and pay more and more attention to the energy utilization of automobiles [100]. Therefore, the research on automotive energy recovery system is particularly important. Automotive braking energy recovery [101], also known as regenerative braking technology, is a process of vehicle deceleration and braking. Through the energy conversion device, it can convert part of the braking kinetic energy into other forms of energy. While maintaining a steady deceleration of the vehicle, the energy will be saved to a device such as a battery, capacitor or high-speed flywheel for reuse in the vehicle [102,103]. The schematic of the comprehensive vehicle energy recovery system can be seen in Figure 6. Fuel economy can be effectively improved by efficient utilization of regenerative braking and improvement of regenerative braking energy. Current research on regenerative braking technology focuses on the synergistic control of regenerative braking and hydraulic braking. It is necessary to ensure that the total braking force matches the braking force required by the driver [104,105]. This paper analyzes the structure and characteristics of various researchers on braking regeneration strategies in a comparative manner. The following Table 3 describes the relevant researches:

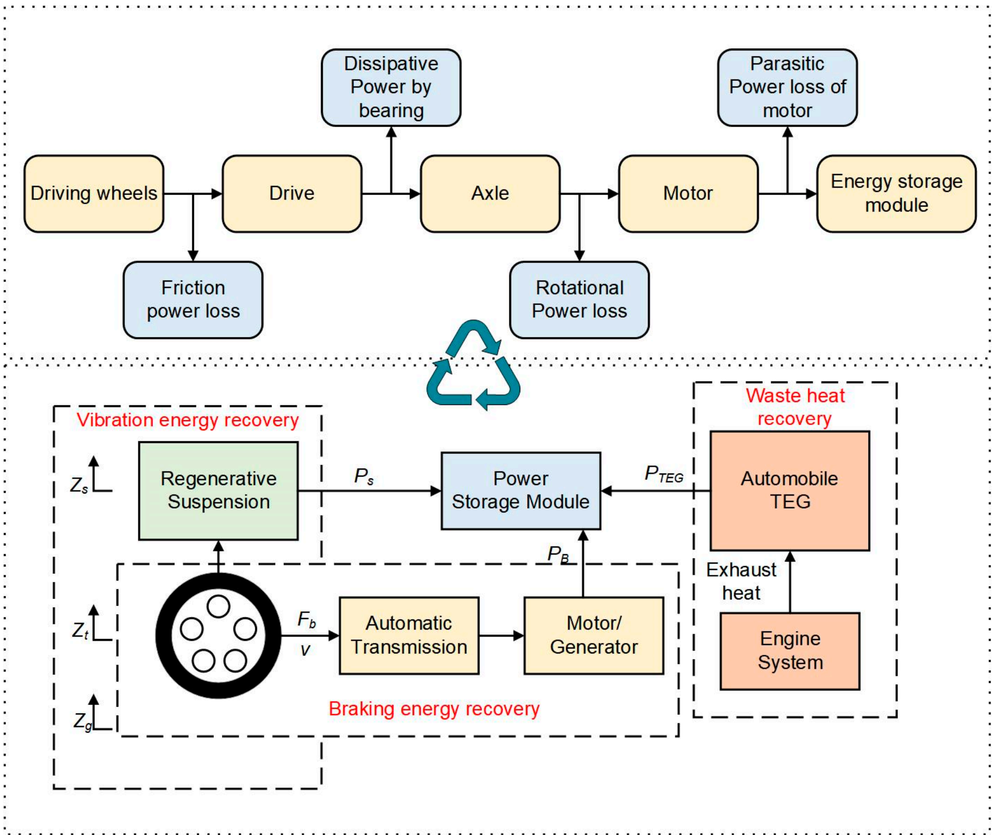

Figure 6. Schematic of the comprehensive vehicle energy recovery system.

Table 3. List of relevant studies on braking.

Topics	Goals	Reference
A refined energy management strategy.	(1) Modeling the vehicle energy recovery system; (2) An assistant power balance strategy(APBS); (3) Bench tests;	[106]
Electro-hydraulic proportional control for brake energy regeneration.	(1) Maximized the recovery of braking energy; (2) Driver's braking feel;	[107]
Development of hydraulic servo brake system for cooperative control with regenerative brake.	(1) To adjusting the stroke simulator mechanism; (2) Sliding mode control used to feedback control solenoid valves;	[48]
A fuzzy-logic-based regenerative braking strategy (RBS) integrated with series regenerative braking.	(1) According to the distribution law to calculate the braking force; (2) According to the fuzzy logic controller to determine the regenerative braking force;	[108]
A control strategy combining the logic threshold method and the key parameter optimization algorithm.	(1) To combine the merits of both batteries; (2) Proposed a logical threshold method; (3) To real-time control the torque distribute;	[109]
The integration of sensor-based wire-controlled dynamic fault-tolerant drive	(1) The different sensor measurement transitions, drive input drive profiles and redundancy management algorithm; (2) Improve the conversion performance of the sensor;	[110]

5. Challenges and Future Directions of EMB

The EMB system provides a way for the development of intelligent driving. However, up to now, the brake-by-wire system still cannot be put into use on a large scale, indicating that there are still many issues to be solved.

(1) Safety issues. In the process of automobile development, automobile safety is the first factor to be considered in the design of automobile structure. Automobile safety can be divided into active safety and passive safety. Among them, the braking system belongs to the category of active safety. In order to ensure the safety of drivers and passengers, the design scheme of braking redundancy should be fully considered when designing the electromechanical braking system. The biggest application scenario of EMB system is commercial vehicles. For commercial vehicles, they need to face many complex road conditions, such as high temperature, plateau cold road, muddy road and so on. As the installation form of EMB is similar to that of hub motor, a large number of vibration frequencies will be transmitted to the system, causing the socket to become loose and the actuator to break. In addition, the severe environment will lead to EMB system sensor detection failure due to high temperature or cold. Therefore, the brake redundancy design of EMB will become a significant obstacle to further growth;

(2) Stable response of EMB. EMB is transmitted by electrical signals. The sensor collects the braking signal of the brake simulation pedal and transmits it to the actuator, and the braking time is very short. Therefore, the sensitivity of the sensor will greatly affect the response time of EMB. However, at this point, the sensor's delayed reaction is an issue;

(3) Energy demand of braking force. The traditional vehicle power supply is generally 12 V, and the driving motor of the electromechanical braking system adopts a voltage of 42 V, because it is beneficial to improve the performance of the actuator. However, the high voltage brought by the 42 V power supply system will bring issues such as line insulation, withstand voltage and electromagnetic interference, which also poses a threat to the longevity of the vehicle's complete circuit system;

(4) Accurate control of cars with different parameters. Due to the uncertainty of the vehicle's driving conditions, cargo quality and the nonlinearity of braking, it is difficult to achieve precise control of braking force. Therefore, the next stage of EMB research will be to achieve accurate estimation of vehicle parameters and accurate control of braking force.

This requires the use of a variety of control methods to achieve the most suitable control of vehicle braking, and to continuously improve it to improve control accuracy.

EMB will be more in line with the characteristics of automobile integration, intelligence and automation, and more suitable for the future development direction of automobiles. In view of the problems existing in EMB, the development trend is as follows:

- Study the control methods suitable for various road conditions;
- Design a more compact structure with good seismic performance;
- Develop sensors with stable performance and high sensitivity.

In a word, the improvement, optimization, research and development of these technologies of EMB system have important value and role in improving the safety performance of automobile driving, and are conducive to promoting the development of vehicle intelligence and automatic driving technology.

6. Conclusions

As an emerging product of the era, the brake-by-wire system can provide more stable and faster braking performance for automotive braking. It also puts strict requirements on the control accuracy and robustness of the wire-controlled actuation system. The EHB based on the traditional valve technology has the advantages of high control reliability, low energy consumption, low price and easy modification on the traditional braking system. At present, the improvement of the brake-by-wire system mainly focuses on reducing energy consumption. The main strategies include:

(1) Use Two box or One box architecture solution;

(2) Improve braking accuracy by improving the control module of hydraulic adjustment unit or brake motor;

(3) Design the control method of high pressure accumulator to reduce the braking time and energy consumption;

(4) Design brake regeneration system to improve brake energy utilization.

At present, what is more widely deployed in the brake-by-wire system is EHB. EHB technology is more mature, and more adaptable to the market demand. EHB will be the direction of wireless control braking development at this stage. EMB, due to superior technical conditions, high cost, redundancy backup and thermal reliability technology, still needs to be improved. At present, there is still some distance from full commercialization. However, as the most advanced technology in braking system, EMB system has the advantages of high response speed, energy saving and environmental protection to which the traditional braking systems including EHB cannot be compared. It can be applied in L4 and L5 of automatic driving. For the research of EMB, we can only take this opportunity to rise to the challenges and carry out continuous research in the development of EMB system, and gradually deepen and refine our work. We believe that in the future, when various difficulties that constrain the development of EMB systems are overcome, the conditions for EMB industrialization will slowly mature. We also believe that the electromechanical brake technology has a bright future, and is bound to gain more and more people's attention and favor. Finally, this paper compared the advantages and disadvantages of the braking systems described in the previous paper and reviewed the efficiency of the discussed solutions used for the braking systems. The following Table 4 can describe the comparison of braking system solutions.

Table 4. Braking system solution comparison.

Type	EHB	EMB
Definition	Electro-hydraulic brake, retaining part of the hydraulic system	Electromechanical brake, no hydraulic system
Volume	Poor integration and large volume	Good integration and small size
Number of motors	One motor (in hydraulic pump)	4 motors (at the wheel)
Cost	Low Cost	High cost (the main cost is focused on the design and modification of the motor)
Response Speed	120 ms	90 ms
Brake Redundancy	A redundant system is available. If both the EHB and the redundant solution fail, it can still be changed to an unassisted hydraulic brake	No redundant system, it needs to ensure power stability and fault tolerance of each node in the communication system
Complexity	Simple structure and easy to control	Complex structure and difficult to control
Power density	Adopting brushless direct current motor, with higher power density	Adopt permanent magnet synchronous motor, less power density
Braking force	High braking power	Low braking force
Brake fluid safety	Brake fluid leakage will lead to short circuit failure of electronic components	No brake fluid, safe and light weight
Comfort	Poor comfort	Good comfort
Disadvantage	Still requires vacuum system, which increases energy consumption and noise	No redundant system, hub size limits the motor power and its operating environment, which is a great test for the motor's permanent magnets and semiconductor components

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Abbreviations

The following abbreviations are used in this manuscript:

ABS	Anti-lock Braking System
BBW	Brake-By-Wire
CHB	Conventional Hydraulic Brake
EBS	Electronic Braking System
ECU	Electronic Control Unit
EHB	Electro-Hydraulic Brake
EMB	Electromechanical Brake
ESC	Electronic Stability Controller
ESP	Electronic Stability Program

EWB	Electronic Wedge Brake
IEHB	Integrated In-line Hydraulic Brake
IPB	Integrated Power Brake
PID	Proportion Integral Derivative
RBS	Regenerative Braking System
RBU	Redundant Brake Unit
SBC	Sensotronic Brake Control
SMC	Sliding Mode Control
TCS	Traction Control System
TEG	Thermoelectric Generators
UKF	Unscented Kalman Filter
VCU	Vehicle Control Unit

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