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Review

Towards Autonomous Driving: Review and Perspectives on Configuration and Control of Four-Wheel Independent Drive/Steering Electric Vehicles

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Abstract: In this paper, the related studies of chassis configurations and control systems for four-wheel independent drive/steering electric vehicles (4WID-4WIS EV) are reviewed and discussed. Firstly, some prototypes and integrated X-by-wire modules of 4WID-4WIS EV are introduced, and the chassis configuration of 4WID-4WIS EV is analyzed. Then, common control models of 4WID-4WIS EV, i.e., the dynamic model, kinematic model, and path tracking model, are summarized. Furthermore, the control frameworks, strategies, and algorithms of 4WID-4WIS EV are introduced and discussed, including the handling of stability control, rollover prevention control, path tracking control and active fault-tolerate control. Finally, with a view towards autonomous driving, some challenges, and perspectives for 4WID-4WIS EV are discussed.

Keywords: autonomous driving; four-wheel independent drive; four-wheel independent steering; path tracking; handling stability; active safety control; electric vehicle



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1. Introduction

Autonomous driving techniques can not only reduce human drivers' driving burden, but also advance driving safety and reduce traffic accidents. In addition to realizing zero emissions targets and reducing air pollution, electric vehicles (EVs) have better control performance than traditional fuel vehicles. Therefore, autonomous vehicles (AVs) and EVs have been a popular issue in vehicle development [1–3].

In recent years, most AVs have been studied and developed based on the traditional fuel vehicle platform, e.g., those used by Baidu, Waymo, Uber, etc. These so-called AVs are designed by applying advanced perception sensors, decision-making and control systems to the existing commercial vehicles [4]. Most autonomous driving companies are not automobile manufacturers and cannot integrate autonomous driving technology into the autonomous driving platform design, which restricts the commercial development of AVs [5]. In fact, traditional fuel vehicles are not the best autonomous driving platform. Their complex drive and transmission systems, i.e., the internal combustion engine, torque converter, etc., have slow response rates and the low control accuracy [6]. In contrast, EVs are preferred by many researchers. Without the complex drive and transmission systems, accurate control is easier to achieve [7]. As a result, the decision-making commands from the autonomous driving system can be better executed [8]. Therefore, towards future autonomous driving, autonomous mobile platforms have been widely studied, including those of Schaeffler, Protean, etc. [9–11]. In the autonomous mobile platforms, the X-by-wire chassis technique is a critical issue for accurate control [12,13].

Traditional vehicles usually adopt the centralized drive system and the front-wheel steering (FWS) system, which is a common chassis configuration. With the development of chassis modularization and electrification, the integrated X-by-wire module has been

widely studied, in which the steering system, drive system and braking system are all controlled by wire [14]. They are integrated with the vehicle suspension and make up an integrated chassis module, which is beneficial to the chassis reconstruction for different demands [15]. Due to the X-by-wire module, vehicles can easily realize accurate dynamic control to advance active safety [16]. Four X-by-wire modules make up a four-wheel independent drive/steering electric vehicle (4WID-4WIS EV). Due to the application of X-by-wire modules, the steering angle and drive/braking torque of each wheel can be controlled independently [17]. As a result, 4WID-4WIS EV can easily realize multi-objective optimization control, e.g., handling stability control, rollover prevention control and path tracking control [18]. Therefore, 4WID-4WIS EV is regarded as an ideal EV development platform by many researchers.

4WID-4WIS EV has been widely studied in recent years. Some prototypes have been designed and developed by vehicle companies and universities. Moreover, various control frameworks, algorithms and strategies have been studied as well. However, some critical issues of 4WID-4WIS EV have not been completely resolved, which prevents its commercial application. Towards autonomous driving, this paper aims to review the chassis configuration and control technique of 4WID-4WIS EV. Focusing on certain technical difficulties of 4WID-4WIS EV, some perspectives are given at the end of this paper.

The rest of this paper is organized as follows. In Section 2, the chassis configuration of 4WID-4WIS EV is introduced and analyzed. Section 3 presents the typical control models of 4WID-4WIS EV. In Section 4, control frameworks and control algorithms of 4WID-4WIS EV are reviewed. Section 5 gives the challenges and perspectives of 4WID-4WIS EVs' future development. Finally, Section 6 concludes this paper.

2. Chassis Configuration of 4WID-4WIS EV

This section mainly focuses on the chassis configuration analysis of the 4WID-4WIS EV. Firstly, the typical prototypes of 4WID-4WIS EV are introduced and the configuration analysis is conducted. Then, the key component of 4WID-4WIS EV, i.e., the X-by-wire module, is reviewed, and the comparative study of different modules is carried out. Finally, the steering modes of 4WID-4WIS EV are analyzed and the switching logic between different steering modes is introduced.

2.1. Configuration Analysis of 4WID-4WIS EV

As shown in Figure 1, the chassis of 4WID-4WIS EV is made up of four X-by-wire modules that integrate the steering, drive, braking and suspension systems. Three actuators are included in the X-by-wire module, i.e., the steering-by-wire actuator, drive-by-wire actuator, and braking-by-wire actuator. The steering-by-wire actuator is usually integrated with the steering kingpin, which can be a virtual kingpin or a component of the suspension system. The in-wheel motor is usually taken as a drive-by-wire actuator, which can be integrated with the wheel rim. Compared with the conventional centralized drive system, the drive shaft, the differential mechanism, and reducers are cancelled. An electronic hydraulic braking (EHB) system and an electronic mechanical braking (EMB) system are usually adopted as the braking-by-wire actuator [19–21].

Due to the application of X-by-wire modules, the steering angle and drive/braking torque of each wheel can be controlled independently. As a result, 4WID-4WIS EV has more degrees of freedom (DOF) in terms of control than conventional vehicles, which leads to more steering and motion modes.

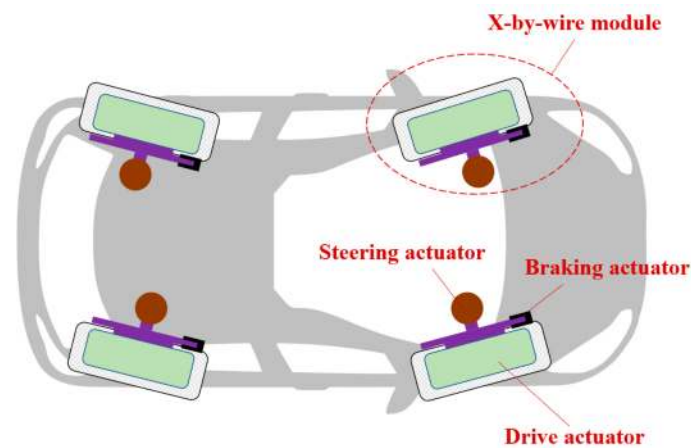


Figure 1. Chassis configuration of 4WID-4WIS EV.

2.2. Prototypes of 4WID-4WIS EV

In recent years, 4WID-4WIS EV has been widely studied by many companies and universities. Some prototypes of 4WID-4WIS EV are shown in Figure 2. As a futuristic looking vehicle, Fine-T is proposed by Toyota, which is equipped with a 4WID-4WIS technique that can realize pivot steering in favor of parking in a tighter area [22]. Additionally, Nissan also designed three generations of 4WID-4WIS concept cars, i.e., PIVO1, PIVO2 and PIVO3 [23]. ROboMObil is an autonomous 4WID-4WIS EV. With the application of the 4WID-4WIS technique, it not only shows strong maneuverability at low-speed conditions, e.g., parking, but also has good handling stability at high-speed conditions [24,25]. DFKI EO Smart 2 is a highly flexible micro-car designed for mega-cities, which is also an autonomous concept car. Besides the 4WID-4WIS technique, it can change the morphology of its height and length to further improve the maneuverability. In addition to single-vehicle autonomous driving, platooning autonomous driving can be realized with EO Smart 2 [26]. With the intelligent corner module, Schaeffler proposed the 4WID-4WIS EV Mover that is the solution to the autonomous and sustainable mobility in urban spaces [27]. With the reconstruction of the chassis configuration, Schaeffler Mover can be applied to different types of vehicles. In addition to the vehicle companies, some universities also developed some 4WID-4WIS EV prototypes, including Jilin University [28,29], The Chinese University of Hong Kong (CUHK) [30–32], Massachusetts Institute of Technology (MIT) [33], Universiti Teknologi Malaysia (UTM) [34], Tongji University [35–37], Pusan National University [38], and Iowa State University [39].

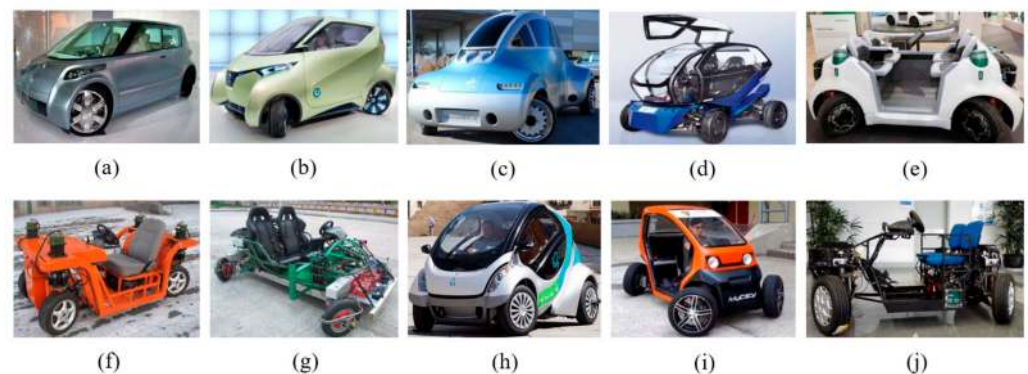


Figure 2. Prototypes of 4WID-4WIS EV: (a) Toyota Fine-T; (b) Nissan PIVO3; (c) ROboMObil; (d) DFKI EO Smart 2; (e) Schaeffler Mover; (f) Jilin University; (g) CUHK OK-1; (h) MIT Hiriko; (i) UTM; (j) Tongji University.

Table 1 shows the performance analysis of the 4WID-4WIS EV prototypes. Most of them have a 180° steering angle range, which is in favor of high maneuverability. Compared with the prototypes designed by universities, the prototypes developed by vehicle companies have higher speed, which is closer to the performance requirements of passenger cars. Some 4WID-4WIS EV prototypes can realize simple autonomous driving functions, e.g., automatic parking. ROboMObil and DFKI EO Smart 2 can realize high-level autonomous driving.

Table 1. Configuration analysis of 4WID-4WIS EV.

Prototype	Steering Angle	Speed	Autonomous Driving	Reference
Toyota Fine-T	$\pm 90^\circ$	-	×	[22]
Nissan PIVO3	$\pm 90^\circ$	-	✓	[23]
ROboMObil	$-25^\circ \sim 95^\circ$	100 km/h	✓	[24,25]
DFKI EO Smart 2	$\pm 90^\circ$	65 km/h	✓	[26]
Schaeffler Mover	$\pm 90^\circ$	60 km/h	✓	[27]
Jilin University	$\pm 90^\circ$	8 km/h	×	[28,29]
CUHK OK-1	$\pm 90^\circ$	10 km/h	✓	[30–32]
MIT Hiriko	$\pm 60^\circ$	50 km/h	×	[33]
UTM	$-60^\circ \sim 30^\circ$	30 km/h	×	[34]
Tongji University	$\pm 90^\circ$	10 km/h	✓	[35–37]
FABOT	$\pm 35^\circ$	3 km/h	×	[38]
AgRover	360°	5 km/h	✓	[39]

2.3. Integrated X-by-Wire Module of 4WID-4WIS EV

The key component of the 4WID-4WIS EV is the integrated X-by-wire module that integrates the steering, drive, braking and suspension systems. Four X-by-wire modules make up the chassis of 4WID-4WIS EVs. Figure 3 shows four typical X-by-wire modules, in which the first three are mature product prototypes. The X-by-wire modules (b) and (c) have been applied to the 4WID-4WIS EV Schaeffler Mover and ROboMObil. The last module is designed and developed by the authors.

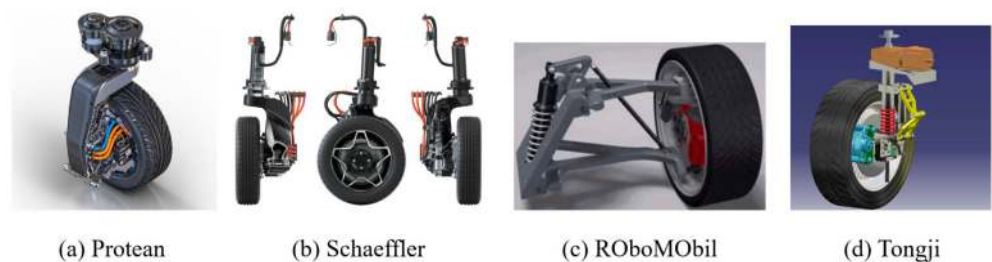


Figure 3. Integrated X-by-wire module for 4WID-4WIS EV.

Table 2 shows the structure analysis of four integrated X-by-wire modules. The steering actuators of the four X-by-wire modules have a similar structure, i.e., servo motor and reducer. However, the layout positions of the four steering actuators are different, i.e., above the wheel (Protean, Surrey, United Kingdom, and Schaeffler, Herzogenaurach, Germany), inside the wheel (ROboMObil, Wessling, Germany) and beside the wheel (Tongji, Shanghai, China). Due to different layout positions of the steering actuator, it yields various steering ranges and control issues. If the steering actuator is placed above the wheel, it can realize zero steering kingpin offset, which is able to reduce the steering resistance. However, it will increase the vertical size of the X-by-wire module. If the steering actuator is placed beside the wheel, the vertical size of the X-by-wire module can be reduced, but it brings large steering kingpin offset, which brings a challenge to the capability of the steering motor. If the steering actuator is placed inside the wheel, it can

reduce both the vertical size of the X-by-wire module and the steering kingpin offset, but it brings challenges to the layout of the in-wheel space.

Table 2. Structure analysis of integrated X-by-wire modules for 4WID-4WIS EV.

Type	Steering	Drive	Braking	Suspension
Protean	360°	In-wheel motor (80 kW, 1250 N · m)	HB + Motor	Candle type
Schaeffler	$\pm 90^\circ$	In-wheel motor (13 kW, 250 N · m)	HB + Motor	Trailing arm type
ROboMObil	$-25^\circ \sim 95^\circ$	In-wheel motor (160 N · m)	HB + Motor	Double wishbone type
Tongji	$\pm 90^\circ$	In-wheel motor (180 N · m)	HB + Motor	Candle type

The drive actuators of the four X-by-wire modules all take the in-wheel motor. The Protean X-by-wire module adopts the PD18 in-wheel motor, which has the largest power and torque among the four modules. The braking actuators of the four X-by-wire modules all take the hybrid braking system that integrates hydraulic braking (HB) and motor regenerative braking. The suspension systems of the four X-by-wire modules are different, and can be divided into three types, i.e., the candle type, trailing arm type and the double wishbone type. Compared with the candle suspension and the trailing arm suspension, the double wishbone suspension has better lateral and roll stiffness, which is in favor of safe driving in the condition of the large lateral acceleration. Therefore, it can be found from Table 1 that the design speed of ROboMObil is the largest among all prototypes, i.e., 100 km/h.

2.4. Steering Modes and Switching Logic

As mentioned above, due to the application of X-by-wire modules, the steering angle of each wheel can be controlled independently. As a result, 4WID-4WIS EV has more steering modes than traditional vehicles. The steering modes of 4WID-4WIS EV are illustrated in Figure 4, including FWS, rear-wheel steering (RWS), 4-wheel steering (4WS), oblique moving, crab moving, and pivot steering. With these steering modes, the maneuverability can be advanced remarkably, e.g., crab moving for side parking, and pivot steering for turning around in narrow spaces [40]. In addition to the maneuverability advancement at low-speed conditions, active 4WS can improve vehicles' handling stability at high-speed conditions [41,42].

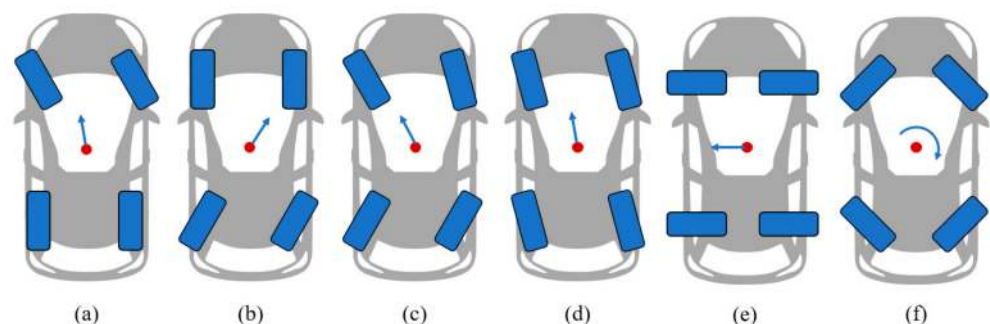


Figure 4. Steering modes of 4WID-4WIS EV: (a) FWS; (b) RWS; (c) 4WS; (d) oblique moving; (e) crab moving; (f) pivot steering.

To deal with different missions, effective switching between steering modes becomes very necessary. Based on the principle that the turning center is continuous, a logic of steering mode switching is proposed, which can realize smooth switching at low-speed conditions without stopping the car [43]. The dynamic switching logic between FWS and RWS, and FWS and 4WS, is studied, which is verified with real vehicle tests [44]. To minimize the sudden change of vehicle dynamic parameters and the energy consumption in the switching process, a B-spline curve is proposed to design the switching trajectory, which

is optimized with the multi-objective genetic algorithm [45]. Based on the kinematic model and dynamic model of 4WID-4WIS EV, a steering mode switching strategy is designed and verified [46]. To realize the switching control between FWS and 4WS at high-speed conditions, a robust controller is designed [47], which aims to achieve a smooth transition of sideslip angle and yaw rate.

3. Control Model of 4WID-4WIS EV

This section mainly reviews the common control models of 4WID-4WIS EV, including the vehicle dynamic model, vehicle kinematic model, and path tracking model.

3.1. Vehicle Dynamic Model

Vehicle dynamic model is usually used to describe the dynamics of vehicles, especially at high-speed conditions. It is mainly derived through Newton's Law. According to the number of control DOF, the vehicle dynamic model has various evolutions [48]. A complex vehicle dynamic model can accurately describe the dynamic characteristics of the vehicle. However, it will introduce difficulty to the design of controllers due to the strong nonlinearity and coupling of the complex vehicle dynamic model [49]. Although the simplified vehicle dynamic model is in favor of controller design, some assumptions are made, which are invalid at some conditions. For instance, the assumption of the linear tire model is invalid at extreme conditions [50].

As for the vehicle dynamic control, longitudinal motion, lateral motion, yaw motion and roll motion are commonly considered by researchers. Figure 5 shows the dynamic model of 4WID-4WIS EV. According to Figure 5, the four DOF vehicle dynamic model can be expressed as follows [51,52].

$$\begin{cases} m(\ddot{v}_x - v_x \beta \dot{r}) = \sum F_x - F_w - F_f \\ m v_x (\dot{\beta} + r) + m_s h_s \ddot{\phi} = \sum F_y \\ I_z \dot{r} - I_{xz} \ddot{\phi} = \sum M_z \\ I_x \ddot{\phi} - I_{xz} \dot{r} = \sum L_x \end{cases} \quad (1)$$

$$\begin{cases} \sum F_x = F_{xfl} \cos \delta_{fl} + F_{xfr} \cos \delta_{fr} + F_{xrl} \cos \delta_{rl} + F_{xrr} \cos \delta_{rr} \\ \sum F_y = F_{yfl} \cos \delta_{fl} + F_{yfr} \cos \delta_{fr} + F_{yrl} \cos \delta_{rl} + F_{yrr} \cos \delta_{rr} \\ \sum M_z = (F_{yfl} \cos \delta_{fl} + F_{yfr} \cos \delta_{fr}) l_f - (F_{yrl} \cos \delta_{rl} + F_{yrr} \cos \delta_{rr}) l_r + \Delta M_z \\ \sum L_x = m_s g h_s \phi - b_\phi \dot{\phi} - k_\phi \phi \end{cases} \quad (2)$$

where v_x denotes the longitudinal velocity. β and r denote the sideslip angle and yaw rate at the center of gravity (CG), and ϕ is the roll angle. In addition, $\sum F_x$, $\sum F_y$, $\sum M_z$ and $\sum L_x$ denote the total longitudinal tire force, lateral tire force, yaw moment and roll moment acting on the vehicle. F_w and F_f denote the wind resistance and the rolling resistance, respectively. m and m_s denote the vehicle mass and vehicle sprung mass. h_s is the height of sprung mass. I_z , I_{xz} and I_x are the yaw inertia moment, the product of inertia and the roll inertia moment. δ_i ($i = fl, fr, rl, rr$) denotes the steering angle of each wheel (fl denotes the front left wheel, fr denotes the front right wheel, rl denotes the rear left wheel, and rr denotes the rear right wheel). F_{xi} and F_{yi} ($i = fl, fr, rl, rr$) denote the longitudinal and lateral forces of each tire. k_ϕ and b_ϕ denote the roll stiffness and damping of the vehicle suspension. ΔM_z is the external yaw moment, which is generated by the torque difference between the left wheel and the right wheel.

$$\Delta M_z = [-F_{xfl} \cos \delta_{fl} + F_{xfr} \cos \delta_{fr} - F_{xrl} \cos \delta_{rl} + F_{xrr} \cos \delta_{rr}] \frac{B}{2} \quad (3)$$

where B is the vehicle track. According to different control objectives, the above 4DOF vehicle model can be simplified as a 3DOF vehicle model or a 2DOF vehicle model.

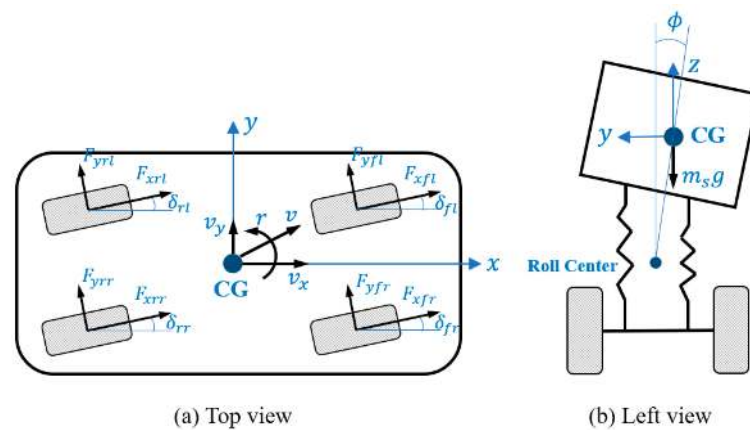


Figure 5. Dynamic model of 4WID-4WIS EV.

It can be found from Equation (2) that the vehicle dynamic model is mainly determined by the tire force F_{xi} and F_{yi} . The tire is a critical component of the vehicle, and its structural characteristics and mechanical properties (vertical force, longitudinal force, lateral force, and torque of return) have a significant impact on the dynamic performance of the vehicle (ride, handling, stability, and safety) [53]. The mechanical properties of tires are mainly affected by factors such as tire type, cornering angle, slip rate, speed, etc. Tire models describe the relationships between the tire force and these influencing factors [54].

Tire models are mainly divided into three types: theoretical models with analytical formulas obtained by simplifying the mechanics of tires; empirical models obtained by analyzing and fitting tire force characteristic test data; semi-empirical models that combines the theoretical model and the analysis of experimental data [55]. Most of the empirical or semi-empirical models have the advantages of simple representation, easy calculation, and high fitting accuracy for specific tires, e.g., the magic formula [56], Dugoff tire model [57], UniTire model [58], Burckhardt tire model [59], HSRI tire model [60], etc. The theoretical model does not require fitting of experimental parameters and has strong versatility, e.g., the Gim tire model [61], string tire model [62], Fiala tire model [63], etc. The selection of tire models depends on the actual vehicle dynamics problem to be solved, whether it needs a more accurate theoretical model for modeling, or an empirical model towards practical engineering applications.

To reduce the complexity of controller design, the four-wheel vehicle model is usually simplified as a single-track model, as shown in Figure 6. As a result, the four steering control variables are reduced to two. The steering angle transformation relationship between the two models follows the Ackerman steering geometry [64].

$$\begin{aligned} \tan \delta_{fl} &= \frac{\tan \delta_f}{1 - \frac{B}{2l} (\tan \delta_f - \tan \delta_r)}, & \tan \delta_{fr} &= \frac{\tan \delta_f}{1 + \frac{B}{2l} (\tan \delta_f - \tan \delta_r)} \\ \tan \delta_{rl} &= \frac{\tan \delta_r}{1 - \frac{B}{2l} (\tan \delta_f - \tan \delta_r)}, & \tan \delta_{rr} &= \frac{\tan \delta_r}{1 + \frac{B}{2l} (\tan \delta_f - \tan \delta_r)} \end{aligned} \quad (4)$$

where δ_f and δ_r denote the front and rear steering angles. l denotes the wheelbase.

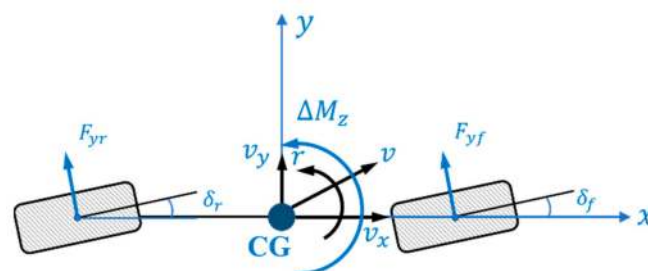


Figure 6. Single-track model for 4WID-4WIS EV.

3.2. Vehicle Kinematic Model

The vehicle kinematic model is usually used to address the motion planning and control of vehicles at low-speed conditions, e.g., automatic parking control [65]. For motion control at high-speed conditions, the vehicle dynamic model is preferred [66].

The single-track kinematic model for 4WID-4WIS EV is derived as follows [67].

$$\begin{cases} \dot{v}_x = a_x \\ \dot{\varphi} = v_x (\tan \delta_f + \tan \delta_r) / l \\ \dot{X} = v_x \cos(\beta + \varphi) / \cos \beta \\ \dot{Y} = v_x \sin(\beta + \varphi) / \cos \beta \end{cases} \quad (5)$$

where a_x denotes the longitudinal acceleration. (X, Y) is the position coordinate of the vehicle.

3.3. Path Tracking Model

According to the information difference of the target path, i.e., the target position coordinate or target path curvature, the path tracking model is divided into two types. The first kind of path tracking model is based on the given information of φ , X and Y , which aims to minimize the following errors [68].

$$\begin{cases} \Delta\varphi = \varphi - \varphi_d \\ \Delta X = X - X_d \\ \Delta Y = Y - Y_d \end{cases} \quad (6)$$

$$\begin{cases} \dot{\varphi} = r \\ \dot{X} = v_x \cos \varphi - v_y \sin \varphi \\ \dot{Y} = v_x \sin \varphi + v_y \cos \varphi \end{cases} \quad (7)$$

where φ_d , X_d and Y_d denote the desired values for the target path.

The second kind of path tracking model is derived according to the curvature information of the target path, which is illustrated in Figure 7. To make the vehicle track the target path precisely, the path-tracking problem is equivalent to minimizing the yaw angle error $\Delta\varphi$ and the lateral offset Δy , which are derived as follows [69].

$$\begin{cases} \Delta\dot{\varphi} = r - \frac{v_x}{\rho} \\ \Delta\dot{y} = v_y + v_x \Delta\varphi \end{cases} \quad (8)$$

where ρ denotes the curvature of the target path.

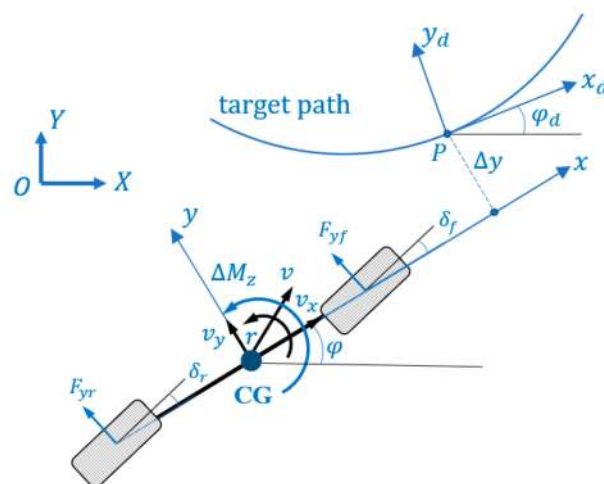


Figure 7. Path-tracking model for 4WID-4WIS EV.

4. Control of 4WID-4WIS EV for Autonomous Driving

In this section, the control framework of 4WID-4WIS EV is introduced. Then, the control algorithms and strategies of handling stability, rollover prevention and path tracking are reviewed and discussed. Finally, active fault-tolerate control algorithms for 4WID-4WIS EVs are introduced.

4.1. Control Framework of 4WID-4WIS EV

The control framework of 4WID-4WIS can be divided into two types, i.e., the coupling control framework [70] and the decoupling control framework [71], which are shown in Figure 8a,b, respectively. In the coupling control framework, the longitudinal motion control is coupled with the lateral motion control, which yields a multi-objective control. It brings a challenge to the control algorithm design. In the decoupling control framework, the longitudinal motion control is decoupled with the lateral motion control, which can reduce the complexity of controller design.

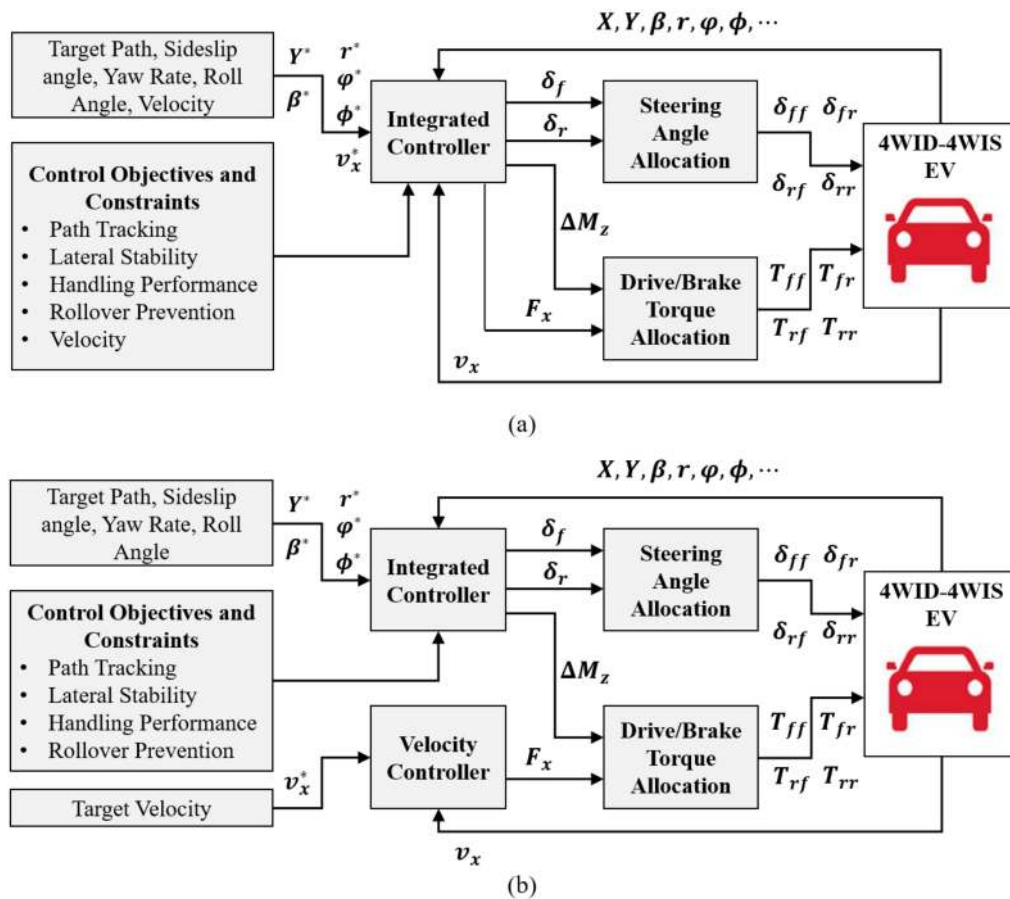


Figure 8. Control framework of 4WID-4WIS EV: (a) Coupling control framework; (b) decoupling control framework. * denotes the target reference.

From Figure 8, we can find that both the coupling control framework and the decoupling control framework consist of two levels. The high level is the controller design. According to the control objectives of path tracking, lateral stability, handling performance, rollover prevention and velocity tracking, it aims to track various references including the target path, sideslip angle, yaw rate, roll angle and velocity. During the tracking control process, various control constraints must be considered. All the control algorithms are designed with an integrated controller. Then, the integrated controller outputs the control signals to the low-level control system, i.e., the allocation level.

The allocation level includes the steering angle allocation and the torque allocation. The steering angle allocation is based on Equation (4). The torque allocation algorithm is used to adjust the total longitudinal force F_x and the external yaw moment ΔM_z , i.e., direct yaw-moment control (DYC). Various torque allocation algorithms have been studied including the direct allocation approach [72], affine control allocation [73], sequence least squares [74], weighted least squares [75], dynamic allocation [76], model predictive control (MPC) [77], etc. After torque allocation, the target drive/brake torques of four wheels will be worked out.

Finally, the allocation level will output the target steering angles and torques of four wheels to the 4WID-4WIS EV. For the closed-loop control, the vehicle's motion state and position information will be fed back to the integrated controller and velocity controller.

Due to the application of the 4WID-4WIS technique, 4WID-4WIS EV has four kinds of control strategies for dynamic control, which are listed in Table 3, i.e., active front steering (AFS), AFS + DYC, 4WS, and 4WS + DYC. Due to the various control strategies, 4WID-4WIS EVs can achieve superior driving performance compared to conventional vehicles in terms of path tracking, handling stability and rollover prevention.

Table 3. Control Strategies of 4WID-4WIS EV.

Control Strategy	Control Variable
AFS	δ_f
AFS + DYC	$\delta_f, \Delta M_z$
4WS	δ_f, δ_r
4WS + DYC	$\delta_f, \delta_r, \Delta M_z$

4.2. Handling Stability Control

The handling stability control of vehicles is defined to track the desired sideslip angle and yaw rate [78]. For traditional FWS vehicles, only the front-wheel steering angle can be controlled. When conducting the steering maneuver at high-speed conditions, the front tire lateral force may enter the saturation region, which cannot provide enough force to guarantee the lateral stability of vehicles [79]. For 4WID-4WIS EVs, since the braking and drive torque of each wheel can be controlled independently, DYC can be realized easily. As a result, the external yaw moment can make up for the lack of tire lateral force to increase the handling stability. In [80], a BP-PID controller-based multi-model control system is proposed for lateral stability improvement via DYC. In [81], a novel control algorithm of DYC based on the correctional LQR is designed to realize vehicle dynamic stability control. Based on the slide model control (SMC), a DYC-based hierarchical control strategy is proposed to improve lateral stability at driving limits [82]. By calculating the stability boundary with the phase plane method, a new extension coordinated controller is designed to improve the driving stability and handling performance, which can find the best balance between AFS and DYC [83]. To enhance the lateral stability, a robust internal model control method with a modified structure is applied to the integrated controller design of AFS + DYC [84]. The control diagram is illustrated in Figure 9.

Compared with DYC, the 4WS technique makes it easier to realize zero sideslip angle. Meanwhile, it is not necessary to deal with the allocation of the external yaw moment and the total longitudinal force [85]. In [86], the linear-parameter-varying (LPV) model is used to simplify the nonlinear model, and the decoupling control is applied to the velocity tracking control and handling stability control. In [87], considering the velocity-varying motion, a LPV controller is designed for handling stability control of 4WS. In addition, the attenuation of diagonal decoupling (ADD) control is proposed for 4WS vehicles, which shows good robustness to address uncertainties and disturbances [88]. In [89], an internal model control (IMC) strategy is proposed to address the nonlinearity of the stability control system. Additionally, the multi-input-multi-output (MIMO) IMC is adopted for vehicle stability control [90]. In [91], a handling modification method is applied to the handling stability

control of 4WS vehicles. Based on SMC, the decentralized control algorithm is robust to arbitrary lateral disturbances and can guarantee that the vehicle converges to reference yaw rate and zero sideslip [92]. Due to the advantage of strong robustness to deal with parametric uncertainties, external disturbances and sensor noise, robust control has been studied by many researchers and applied to the handling stability control in 4WS vehicles, including H2 control, H ∞ control, and μ -synthesis control [93–96]. In [97], a H2/H ∞ mixed robust controller is designed for stability control. In [98], pre-compensation decoupling control with H ∞ performance is applied to the longitudinal motion control and handling stability control. In [99], the handling stability and system robustness are advanced with the μ -synthesis robust controller. In [100], varying parameters are considered in the vehicle model and the μ -synthesis controller is designed for 4WS. Although robust control approaches show strong robustness to deal with parametric perturbations, a large range of perturbation will lead to a high-order controller, which brings large amounts of calculation to the hardware. We need to find a good balance between control performance and calculation efficiency in the controller design.

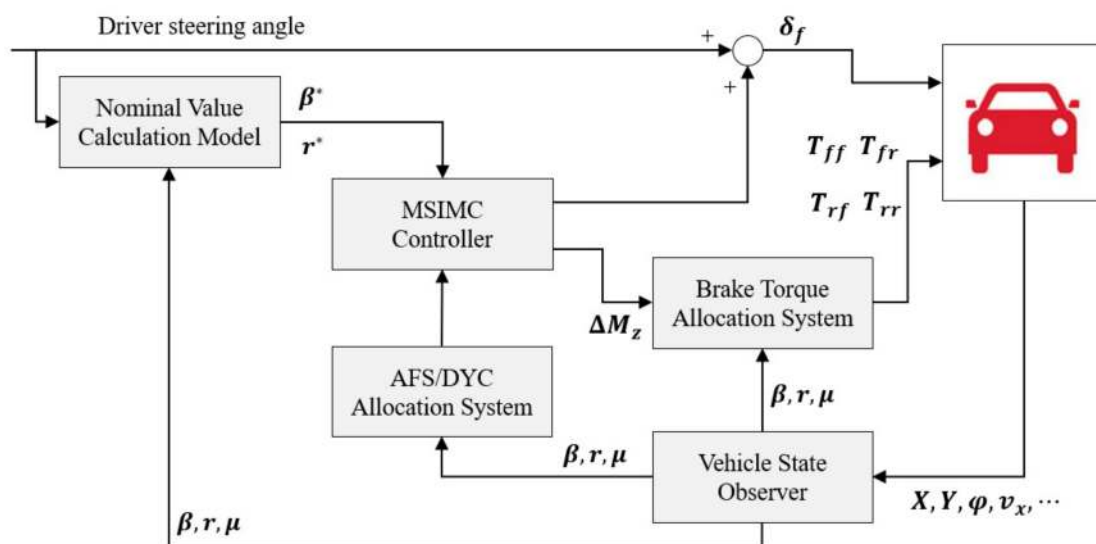


Figure 9. Control diagram of the AFS + DYC control system in [84].

With the advantages of 4WS and DYC, the combination of 4WS and DYC yields the superior handling stability for 4WID-4WS EVs [101]. In [102,103], two feed-forward and feedback controllers are designed to realize zero sideslip angle and target yaw rate tracking with the integrated control of 4WS and DYC. In [104], a robust H ∞ control approach is applied to the coordinated control of 4WS and DYC to improve handling stability in extreme conditions. In [105], fuzzy control theory is used to design the feedback controller of 4WS + DYC to improve lateral stability at high-speed conditions. To obtain a gain-scheduled controller, the LPV system is combined with the H ∞ optimal control theory for the handling stability controller design of 4WS and DYC [106]. Besides, taking the tire nonlinearity into consideration, 4WS and DYC control are combined with the active suspension control to advance both the handling stability and the ride comfort [107]. Compared with AFS, the coordinate control of 4WS and DYC can advance the active safety of AVs at extreme conditions.

4.3. Rollover Prevention Control

Although the handling stability control can enhance the lateral driving safety at driving limits, for some vehicles with high size, e.g., trucks and buses, it is necessary to consider the rollover prevention performance [108]. The rollover prevention control is usually considered with the handling stability control [109]. The rollover index (RI) is

usually used as the control performance index of rollover prevention. In [110], a RI is proposed to evaluate the rollover effect, a roll state estimator is designed, based on RI and the roll state estimator, and an integrated rollover mitigation controller is designed to reduce the danger of rollover without loss of vehicle lateral stability. Furthermore, a multiple-rollover-index (MRI) minimization approach is proposed to realize active rollover prevention control for heavy articulated vehicles [111].

Different control algorithms have been designed for rollover prevention control. In [112], a linear quadratic static output feedback (LQSOF) approach is applied to the preview controller design for vehicle rollover prevention. In [113], a nonlinear control strategy is designed, which can guarantee the handling stability while preventing rollover. In [114,115], a pulsed steering system and a hydraulic-mechanical pulsed steering system are designed, which integrate the handling stability control and rollover prevention control. In [116], linear-time-varying (LTV) MPC is applied to the integrated controller design, which can advance lateral stability, handling performance and rollover prevention via the 4WS technique. In [117], the fuzzy SMC approach is applied to the vehicle dynamic control of 4WS vehicles, which can enhance the dynamic response and deal with system nonlinearity. As Figure 10 shows, in [118], a new type of hierarchical control is proposed for 4WS vehicles, which uses the fractional SMC to obtain good robustness. Although SMC shows good performance in terms of dealing with system nonlinearity, controller chattering is still a critical issue for application.

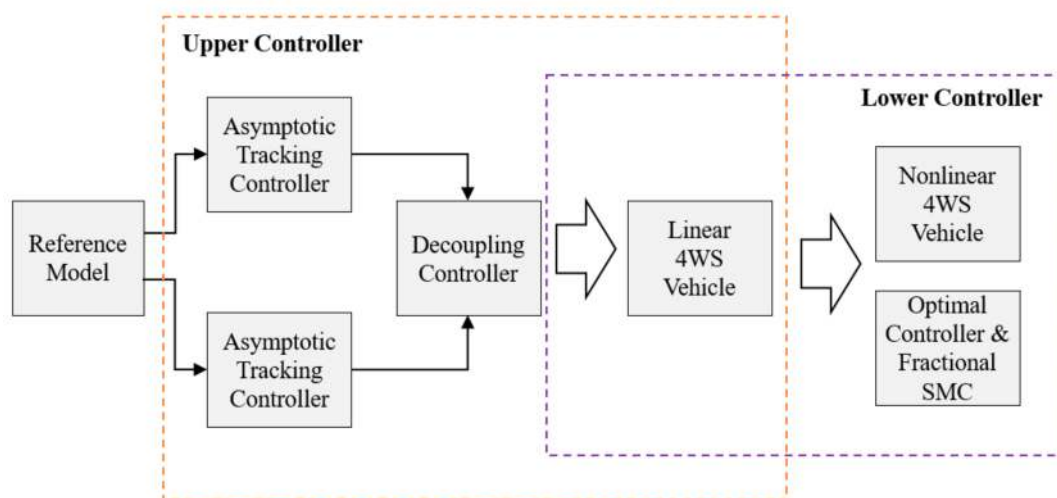


Figure 10. Control diagram of the 4WS control system in [118].

Additionally, 4WS and DYC are usually combined to advance the rollover prevention performance. With 4WS and DYC techniques, an integrated dynamic control with steering (IDCS) system is proposed to improve the handling stability and rollover prevention performance through fuzzy logic [119]. In [120], a switching MPC controller is designed to realize rollover prevention with active steering control and active differential braking control. Based on the SMC approach, a hierarchical coordinated control algorithm for integrating active steering control and driving/braking force distribution is proposed, which can enhance the handling stability and rollover prevention performance [121].

4.4. Path Tracking Control

Path tracking control is the main control task for AVs [122]. Therefore, it has been widely studied in recent years and various control algorithms have been designed. In [123], DYC is used to advance the path tracking performance, and a robust H_∞ control approach is applied to the DYC controller design. In [124], a coupling control framework is proposed based on DYC, and both the velocity tracking control and the path tracking control are considered with LTV MPC. In [125], based on LQR technique, both 4WS and DYC are utilized

to improve the path-tracking performance. To improve the robustness of the path-tracking controller, a robust path-tracking controller is designed for the 4WID-4WIS agricultural robotic vehicle with the backstepping SMC theory [126]. To improve the control accuracy of the backstepping SMC, a comprehensive method that combines feedforward and backstepping SMC is applied to the path tracking control of 4WID-4WIS EVs [127]. In [128], a four-wheel SMC steering controller is designed for the path tracking of 4WID-4WIS EVs. Meanwhile, the longitudinal velocity controller is designed with the SMC approach.

For low-speed autonomous driving, it is sufficient to consider the path tracking control. However, with the increase in vehicle speed, the issue of handling stability and rollover prevention becomes more and more prominent. The path tracking issue is needs to be considered together with handling stability at high-speed conditions, especially at extreme conditions [129]. Compared with traditional vehicles, 4WID-4WIS EV has more control DOF; therefore, it is easier to realize the integrated control of path tracking and handling stability. In [130], a LQR feedback controller is applied to the path tracking of 4WS under the condition of high-speed emergency obstacle avoidance. In addition to the path tracking issue, the issue of handling stability control is considered as well. However, LQR approach has poor robustness to deal with the system nonlinearity and uncertainties. A robust LQR controller is designed for path tracking via the integration of AFS and DYC [131]. Based on the SMC theory, an automatic path-tracking controller is designed for 4WS vehicle, which has strong robustness to deal with system uncertainties such as cornering power perturbation, path radius fluctuation, and cross wind disturbance [132]. In [133], Hamilton energy function control theory is applied to the path tracking and lateral stability control of the 4WS + DYC control system. Besides, a robust controller is applied to the integrated 4WS + DYC control system, which can not only improve the path-tracking performance and handling stability but also has good robustness to address parametric perturbation [134]. The control diagram is shown in Figure 11.

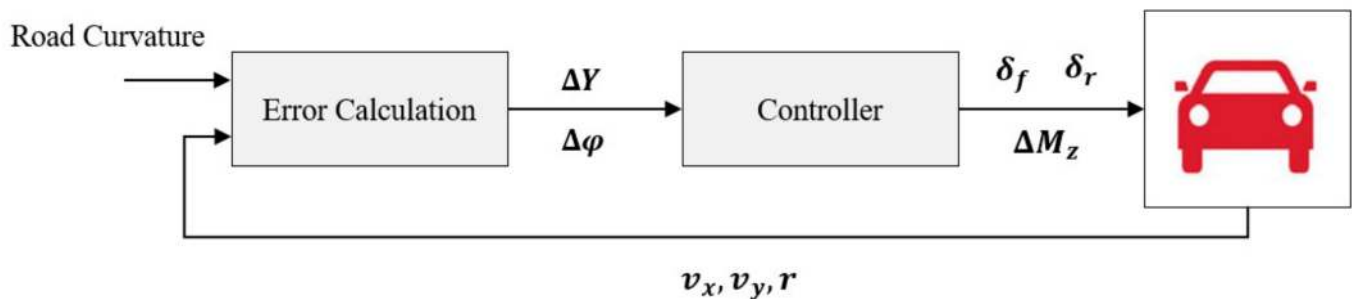


Figure 11. Control diagram of the integrated 4WS + DYC control system in [134].

Moreover, MPC has been widely applied to the path tracking control of AVs [135]. In [136], a coupling control framework is designed based on MPC, which comprehensively considers the velocity tracking control, handling stability control and path tracking control. Besides, the road adhesion coefficient is estimated to improve the control accuracy. Based on the nonlinear 4WS vehicle model, nonlinear model predictive control (NMPC) is used to design an integrated controller that considers handling stability and path tracking [137]. Although MPC has superior control accuracy than other control algorithms, the real-time optimization brings a large amount of calculation to the hardware.

Finally, Table 4 shows the summary of various control instances for 4WID-4WIS EV. It can be found that the 2DOF single track model is the most common control model for 4WID-4WIS EVs. If the longitudinal motion control or rollover prevention control is considered, another control DOF is required, which yields a 3DOF control model. To advance handling stability, rollover prevention performance and path tracking performance, different control strategies, i.e., AFS + DYC, 4WS, and 4WS + DYC, have been widely applied to the dynamic control of 4WID-4WIS EVs. Furthermore, LQR, SMC, robust control and MPC are the common control algorithms for 4WID-4WIS EVs. LQR can only deal with linear

systems. SMC and robust control have good robustness to address system uncertainties and disturbances, but their control performances are remarkably affected by the model accuracy. With model prediction and real-time optimization, MPC can realize accurate control, but the real-time optimization also brings a large amount of calculation to the hardware. Simulation, the hardware-in-the-loop (HIL) test and the road test are the three kinds of algorithm verification methods. It can be found that most papers evaluate the control algorithm with simulation. Only few papers conduct the road test. One important reason is that the techniques used for 4WID-4WIS EVs are not vary mature, especially for the X-by-wire technique, and their reliability and safety cannot be guaranteed completely. Road tests involve a degree safety risk.

Table 4. Summary of various control instances.

Reference	Control Objective	Control Model	Control Strategy	Control Algorithm	Test Environment
[80]	HS	2DOF	AFS + DYC	BP PID	Simulation
[81]	HS	2DOF	AFS + DYC	LQR	HIL Test
[82]	HS	2DOF	AFS + DYC	SMC	HIL Test
[83]	HS	2DOF	AFS + DYC	Coordinated control	HIL Test
[84]	HS	2DOF	AFS + DYC	H_∞ control	Simulation
[89]	HS	2DOF	4WS	Internal model control	Simulation
[90]	HS	2DOF	4WS	Internal model control	Simulation
[99]	HS	2DOF	4WS	μ -synthesis	Simulation
[100]	HS	2DOF	4WS	μ -synthesis	HIL Test
[92]	HS	2DOF	4WS	Feed-forward control	Simulation
[97]	HS	2DOF	4WS	H2/ H_∞	Simulation
[95]	HS	2DOF	4WS	LPV H_∞	Simulation
[96]	HS	2DOF	4WS	μ -synthesis	Road Test
[87]	HS + VC	3DOF	4WS	LPV	Simulation
[88]	HS + VC	3DOF	4WS	Decoupling control	Simulation
[98]	HS + VC	3DOF	4WS	Decoupling control	Simulation
[102]	HS	2DOF	4WS + DYC	Feed-forward, feedback	Simulation
[104]	HS	2DOF	4WS + DYC	H_∞ control	Simulation
[105]	HS	2DOF	4WS + DYC	fuzzy control	Simulation
[111]	HS + RP	3DOF	AFS + DYC	LQR	Simulation
[117]	HS + RP	3DOF	4WS	Fuzzy SMC	Simulation
[118]	HS + RP	3DOF	4WS	Fractional SMC	Simulation
[116]	HS + RP	3DOF	4WS	LTV-MPC	Simulation
[119]	HS + RP + VC	4DOF	4WS	Fuzzy logic	Simulation
[121]	HS + RP	3DOF	4WS + DYC	SMC	Simulation
[123]	PT + HS	2DOF	AFS + DYC	H_∞ control	Simulation
[124]	PT + HS + VC	3DOF	AFS + DYC	MPC	Simulation
[129]	PT + HS	2DOF	AFS + DYC	LTV-MPC	Road Test
[127]	PT + HS	2DOF	4WS	SMC	Simulation
[132]	PT + HS	2DOF	4WS	SMC	Simulation
[126]	PT + VC	3DOF	4WS	Backstepping SMC	Road Test
[136]	PT + VC	3DOF	4WS	MPC	Simulation
[137]	PT + VC	3DOF	4WS	MPC	Simulation
[125]	PT	2DOF	4WS + DYC	LQR	Simulation
[133]	PT + HS	2DOF	4WS + DYC	Hamilton	Simulation
[134]	PT + HS	2DOF	4WS + DYC	μ -synthesis	Simulation

Where HS, PT, RP, and VC are the abbreviation of handling stability, path tracking, rollover prevention and velocity control, respectively.

4.5. Active Fault-Tolerant Control

Although X-by-wire modules can bring various control strategies and steering modes to 4WID-4WIS EVs in favor of driving performance advancement, once one X-by-wire module fails, it will increase the risk of vehicle instability [138]. To address this issue, active fault-tolerant control algorithms have been widely studied [139].

In [140], an MPC-based fault tolerant control system is designed, in which one MPC is used for fault tolerant control and another MPC is used as an observer to estimate and compensate for the actuator fault. In [141], a multiple model-based fault-tolerant control system is proposed based on fuzzy logic and MPC. In [142], a dual-loop SMC is used to deal with the fault of in-wheel motor. In [143], an adaptive SMC fault-tolerant controller is designed. Furthermore, a modified SMC is applied to the active fault-tolerant control of 4WID-4WIS EV, in which the steering geometry is re-arranged according to the location of

faulty wheels [144]. In [145], a robust adaptive fault-tolerant control scheme is designed with adaptive fast terminal SMC. Moreover, game theory has been applied to the active fault-tolerant control. In [146], a cooperative game-based actuator fault-tolerant control strategy is designed based on a differential game. Additionally, feedback linearization and cooperative game theory are combined to design the fault-tolerant controller [147]. To advance the robustness of the fault-tolerant controller, a model-independent self-tuning fault-tolerant control framework is designed, which can enhance the longitudinal and lateral tracking ability under different failure conditions [148].

To improve the performance of monitor vehicle states, a fault detection and diagnosis algorithm is designed to monitor vehicle states and provide feedback containing fault information to the controller [149]. In [150], an active fault-tolerant control framework is designed, which includes a baseline controller, a set of reconfigurable controllers, a fault detection and diagnosis mechanism, and a decision mechanism.

Furthermore, control allocation methods have been widely used to realize active fault-tolerant control of 4WID-4WIS EVs [151]. In [152], an orientated tire force allocation algorithm is proposed to address the steering system fault in the path tracking process. In [29], based on the pseudo-inverse matrix, a control allocation method is introduced for decoupling of the forces and moment. Based on the LPV framework, reconfiguration control is applied to the torque allocation, which can realize velocity and path tracking even during a fault event of the steering-by-wire system [153]. In [154], based on the fault detection and diagnosis module, a reconfigurable control allocator is designed, which optimally distributes the generalized forces/moments to four wheels.

5. Challenges and Perspectives for 4WID-4WIS EV

Although 4WID-4WIS EV has superior performance than traditional vehicles, some critical technical issues related to machinery and control have not been resolved, which prevents its commercial application.

The first challenge is the high cost of 4WID-4WIS EV. Due to the application of the X-by-wire module, 12 control actuators are included in a 4WID-4WIS EV. Compared with traditional centralized-control vehicles, more actuators lead to higher cost. Therefore, cost reduction is the first consideration. The highly integrated design of the X-by-wire module and the concept of the reconfigurable chassis are good solutions. With the highly integrated X-by-wire module, the reconfigurable chassis can be formed with different numbers of X-by-wire modules according to different demands, and applied to different autonomous mobile platforms, e.g., four X-by-wire modules forming the autonomous passenger car, and eight X-by-wire modules forming the autonomous truck. Once the mission is finished, X-by-wire modules will be separated and ready for reorganization for the next mission.

The second challenge is that the mechanical structure and integration technique of the integrated X-by-wire module are not mature, especially in terms of dealing with extreme conditions. According to the literature review of the integrated X-by-wire module, it can be found that most X-by-wire modules adopt simple suspension structures, which cannot withstand huge lateral force. Therefore, existing 4WID-4WIS EVs can only travel in common conditions; they cannot deal with severe and extreme conditions. Therefore, it is necessary to design an advanced and practical X-by-wire module for the future applications of 4WID-4WIS EVs.

The third challenge is the reliability limitation of the X-by-wire technique. Compared with traditional mechanical systems, the reliability and safety of the X-by-wire technique are worse, and are generally untrustworthy. Since the 4WID-4WIS EV has 12 control actuators involved in steering, drive and braking, the probability of an actuator fault is still a crucial issue. Additionally, considering that the X-by-wire technique, and especially the steering-by-wire technique, is not a mature technique, it is necessary to design an effective active fault-tolerant control system to guarantee the functional safety of the system.

The last challenge is the control technique. For 4WID-4WIS EVs, which have non-linear MIMO control systems, it is not easy to deal with the parametric uncertainties,

external disturbances, and sensor noise with simple control algorithms, e.g., PID control. Although some control algorithms can realize accurate dynamic control and have good robustness, e.g., MPC, real-time optimization brings a large amount of calculation, which is a challenge for the hardware platform. Therefore, improving the computing efficiency of control algorithms is an urgent task. Additionally, as for multi-objective control, i.e., handling stability control, rollover prevention control, and path tracking control, there is no good adaptive control strategy to adjust the control priority and weighting to deal with different cases. For instance, at low-speed conditions, path tracking is the main control task. However, handling stability control and rollover prevention control must be given priority in extreme conditions.

6. Conclusions

Focusing on chassis configuration and control techniques, a literature review of— and various perspectives on—4WID-4WIS EVs are presented in this paper. Various prototypes of 4WID-4WIS EVs and integrated X-by-wire modules are introduced. Different chassis configurations and mechanical structures are compared and analyzed. Furthermore, the steering modes and switching logics of 4WID-4WIS EV are discussed. In addition, the common control models of 4WID-4WIS EV are summarized, including the kinematic model, dynamic model, and path tracking model. Based on different control models, different control objectives can be realized, including handling stability control, rollover prevention control, path tracking control, and active fault-tolerant control. For different control objectives, the control algorithms are reviewed and analyzed. Finally, for the development and application of 4WID-4WIS EV, some challenges, and perspectives are discussed, including the cost, mechanical design, control technique, etc.

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