

# Stability Control of Four-Wheel System Using Supervisor and Yaw Moment Controller

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**ABSTRACT:** In this paper, we present control system and stability of four-wheel steering system. In normal two-wheel steering mechanism the rear wheel does not play important role with respect to steering mechanism, they only follow the path directed by from two wheels. In four wheels steer, rear wheel also made to turn as the requirement of operator. To keep mechanism as simple as possible control system is important. We need to control two wheels with respect to rear wheel. The rear wheels are not going to move more than 5 degree in left or right direction. At slow speed rear wheels turns opposite to front wheels and at high speed rear wheels moves with same direction as that of front wheel does for better stability of vehicle.

**KEYWORDS:** Control system, stability, rear wheels

## I. INTRODUCTION

Four-wheel independent drive electric vehicles (FWID-EVs) have attracted considerable attention both in industry and academia due to their unique advantages, such as high reliability, good flexibility, fast response, see e.g. [1–6] and reference therein. Such metrics provide FWID-EVs with much more manoeuvrability especially under the critical cornering conditions. Under this critical condition, purely relying on the driver's driving experience is extremely unreliable because of the insufficient lateral tyre adhesion force during the cornering manoeuvre, thus it is urgent to develop a novel control strategy to assist such a vehicle operation. Besides, this FWID-EV platform is a large-size complicated electromechanical coupling system, in which a great deal of system variables is coupled together and the vehicle dynamics are highly nonlinear. Therefore, controlling such a FWID-EV system efficiently under critical cornering conditions is a very challenging task, concerning not only control system synthesis but also the driving/braking force distribution, which motivates this study.

Electric stability control (ESC), also called vehicle dynamic control or vehicle stability control, is validated to be an efficient way to enhance vehicle stability in critical conditions. In a normal driving mode, ESC is unnecessary to be activated all the time since in most cases the ordinary operation can ensure the basic vehicle movement performance. Despite extensive research developed about the control method of ESC, only few researches devoted to introducing a supervision mechanism to active ESC mode at reasonable time. In light of the supervision mechanism, there exists few literatures reporting its application in deciding the switching time between several control modes. For example, as reported in [9], Kang et al. devised a driving algorithm mainly consisting of a supervision controller to determine vehicle control mode, admissible region and desired dynamics, which improved system performance greatly. In a novel self-constructing adaptive robust fuzzy neural control scheme was proposed for tracking surface vehicles, where a robust supervisory controller was applied to enhance the robustness of the overall control system. In other similar work, the supervision mechanism was authenticated to improve the vehicle stability performance effectively. To ensure vehicle driving stability, in this case, the supervision mechanism is adopted to judge the right time to activate the ESC mode under the critical cornering situations. Besides, in addition to the supervision mechanism, the control allocation is an equally vital issue for the stability control of FWID-EV, especially during the critical cornering situations. In [14], Wang et al. presented a coordinated control algorithm for vehicle yaw stability, in which a control allocation algorithm with actuators and tyre force constraints was designed to assign the desired yaw moment. Further, three energy-efficient control allocation schemes were reported and compared for longitudinal speed tracking control of an electric ground vehicle with two pairs of in-wheel motors. Shuai et al discussed the vehicle lateral motion control problem, where a quadratic programming torque allocation algorithm was proposed with the advantage of equally and reasonably utilizing the tire-road friction of each wheel. Consider the actuator capacity, friction limits and road adhesion condition, three torque distribution methods were addressed to distribute the generalized force/moment. Nevertheless, although the previous allocation obtains predictive effects for respective control plant, the application aiming to the critical cornering situations, to the best of our knowledge, has been rarely reported.

Meanwhile, notice that the actual tyre forces have much to do with wheel slip effects, thus the wheel slip must be adequately considered as the vehicle obtains satisfactory control performance. In practice, when the slip ratio exceeds the threshold, that is the nominal optimum value, the tyre force will rapidly fall off and be insufficient to provide enough tyre force to stabilize the vehicle. To overcome this drawback, a robust wheel slip controller was designed with sliding mode control technique, by which the sufficient tyre force can be provided for vehicle stability. Later, Ricardo et al. designed a conditional integrate sliding mode wheel slip controller, and the relation between model uncertainty and torque requested by the executive command was further clarified. Whereas, these studies merely investigated slip control in the braking manoeuvre, but as for the FWID-EVs, particularly during the critical cornering situations, it is rather limited for the efficient stability control and exerting the advantages of FWID-EVs only through braking manoeuvre. Therefore, this study designs a slip ratio regulator dedicated to efficient slip regulation not only adopting the braking force, but also employing the traction force, and then providing the sufficient tyre force for maintaining vehicle stability in the critical situations. To sum up, this paper proposes a hierarchical control strategy characterized by supervision mechanism for triggering ESC mode and slip ratio regulation simultaneously to ensure the vehicle stability under the critical cornering situations. The proposed strategy consists of three modules, that is, a yaw moment controller along with a longitudinal velocity controller, a tyre force distributor, and a slip ratio regulator. Specifically, the sliding mode control and direct fuzzy adaptive techniques, due to their parametric insensitivity, strong robustness and disturbance rejection capability are utilized to construct controllers to overcome the influence of outside disturbance and uncertain rolling resistance. The contribution of this paper is threefold: 1) Focusing on the critical cornering situations, supervision mechanism is introduced to enhance vehicle driving stability, by which the yaw moment controller and slip ratio regulator can be triggered at a right time; 2) Orienting to the FWID-EV, the optimal tyre distribution scheme exhibits best stability during the dangerous critical situations, compared with the other average and dynamic distribution ones; 3) Aiming at integrating functions of controller, distributor and regulator, a three-level control strategy is proposed to assure the stability performance by harmonizing various control effects.

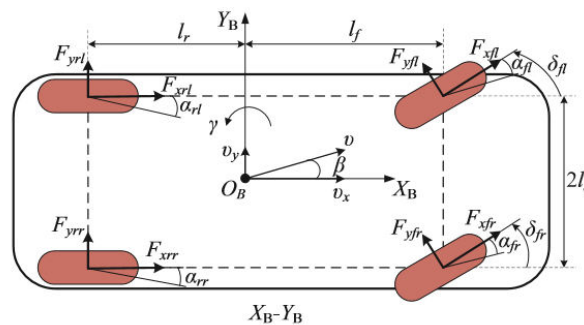


Fig. 1. Vehicle motion in yaw-plane

## II. METHODOLOGY

Control System Synthesis: -The entire control strategy with a three-level architecture is illustrated in Fig. 1, which consists of a yaw moment controller and a longitudinal velocity controller in the first level, a tyre force distributor in the second level and a slip ratio regulator in the third level. Firstly, the supervision mechanism is introduced by designing the supervisor according to the vehicle sideslip angle, yaw rate and road adhesion information, etc. If the vehicle is about to lose stability, the ESC mode will be activated and then it will generate the corrective yaw moment  $\Delta M_z$  to restore the vehicle yaw motion; otherwise, the normal mode is activated all the time, in which the additional yaw moment is zero. Also, the adaptive fuzzy longitudinal velocity controller is designed to track the desired longitudinal velocity in this level. Secondly, a tyre force distributor is presented to assign the corrective yaw moment and resultant longitudinal force to the executive wheels in the second level. Here, three distribution schemes, i.e., the average distribution, the dynamic distribution and the optimal distribution, are separately developed for comparison. Thirdly, the wheel slip regulator is proposed to regulate the respective net torque of each executive to keep the slip ratio within the slip ratio threshold in the third level. It is worth noting that the developed control strategy is essentially a hierarchical structure, whose multiple closed-loop feature enables the entire vehicle system to be more stable and robust for practical implementation.

A. Supervisor and Yaw Moment Controller :- The vehicle stability criteria are very important to the development of the supervision mechanism. For this reason, a stability criterion is thus introduced to supervise the vehicle operation condition, and further to judge whether the ESC mode is activated or not. As well known,  $\beta - \dot{\beta}$  criteria is validated to be an effective way to improve vehicle stability, thereby widely being used in vehicle stability control system . Thus, the  $\beta - \dot{\beta}$  criteria is employed here, in which the boundaries of the vehicle stability margin are governed by

$$|\beta + E_1(\mu) \cdot \dot{\beta}| \leq E_2(\mu) \tag{1}$$

Apart from vehicle sideslip angle, yaw rate is another significant index for vehicle stability. Therefore, the  $\Delta\gamma = \gamma - \dot{\gamma}$  criteria is introduced in the supervisor, as follows

$$|\Delta\gamma| \leq E_3(\delta_f, v_x) \tag{2}$$

where  $E_1$  and  $E_2$  denote the boundary coefficients given in Table I, and  $E_3 = 0.7|\dot{\gamma}|$ . In this way, (1) and (2) constitute the comprehensive criteria for the vehicle stability, that is the supervisor, which determines whether to trigger the ESC mode. Because of strong robustness and disturbance rejection capability mentioned previously, the sliding mode control technique is hence adopted to construct the corrective yaw moment controller. With the introduced corrective yaw moment  $\Delta M_z$ , the entire yaw motion presented in (Fig 1) can be repressed as

$$I_z \cdot \dot{\gamma} = l_f F_{yf} - l_r F_{yr} + \Delta M_z = M_z \tag{3}$$

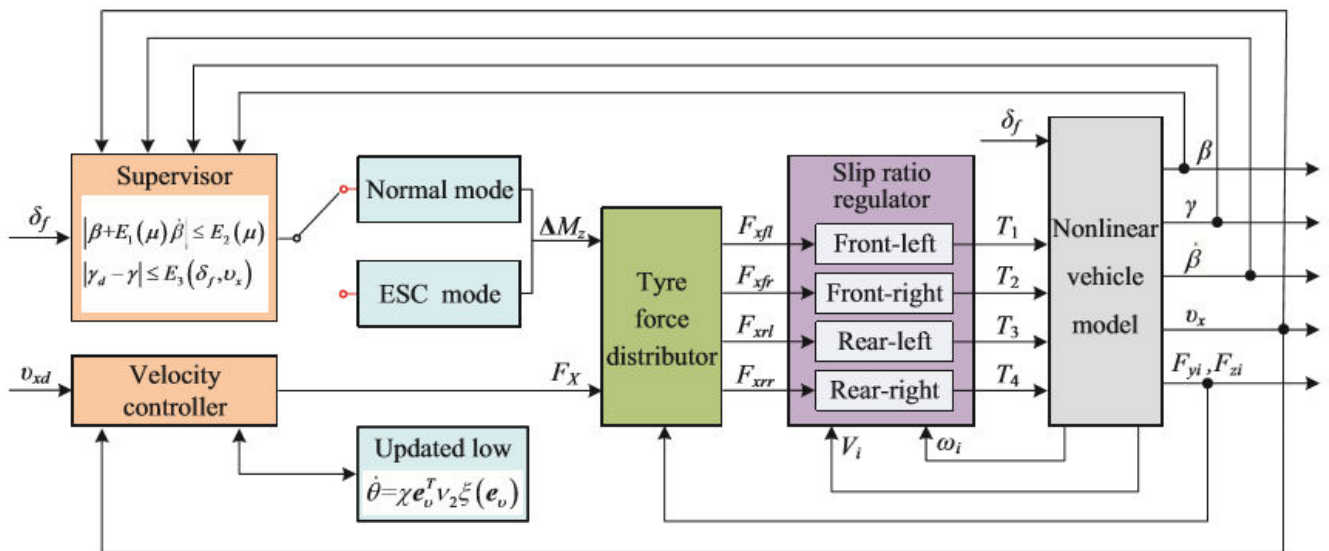


Fig. 2. Entire control architecture.

TABLE I: BOUNDARY PARAMETERS OF STABILITY MARGIN

Tire-road friction coefficient	$ \beta + E_1 \dot{\beta}  \leq E_2$	
	$E_1$	$E_2$
$\mu < 0.2$	0.284	2.577
$0.2 \leq \mu < 0.4$	0.297	3.345
$0.4 \leq \mu < 0.6$	0.303	4.228
$0.6 \leq \mu < 0.8$	0.357	4.654
$0.8 \leq \mu < 1.0$	0.357	5.573



where  $M_z$  is the total yaw moment. With simultaneous consideration of the vehicle sideslip angle and yaw rate, a composite sliding mode surface is defined as follows

$$s = \gamma d - \dot{\gamma} + \lambda(\beta d - \beta) \tag{4}$$

where  $\lambda$  is the weighting factor used to balance the control effects of the vehicle sideslip angle and yaw rate. Differentiating (12) with respect to time, it yields that

$$\dot{s} = \dot{\gamma} d - \ddot{\gamma} + \lambda(\dot{\beta} d - \ddot{\beta}) = \dot{\gamma} d - M_z/I_z + \lambda(\dot{\beta} d - \ddot{\beta}) \tag{5}$$

By the equivalent reaching law  $\dot{s} = -\eta \text{sgn}(s)$ , together with (3) and (5), the desired corrective yaw moment can be obtained by

$$\Delta M_z = -I_z(\eta \text{sgn}(s) + \lambda(\dot{\beta} d - \ddot{\beta}) + \tau d) - l_f \hat{F}_{yf} + l_r \hat{F}_{yr} + I_z \dot{\gamma} d \tag{6}$$

where  $\eta$  is the positive design parameter,  $\text{sgn}(\cdot)$  is the sign function,  $\tau d$  represents the disturbance, and  $\hat{F}_{yf}, \hat{F}_{yr}$  are the estimated lateral tyre forces of the front and rear axles, respectively (see [30] for more details about this estimation method). In addition, consider the uncertain parameter  $I_z \in [I_{zmin}, I_{zmax}]$ , the nominal value of the moment of inertia  $\bar{I}_z$  can be obtained by  $\bar{I}_z = \sqrt{I_{zmin} I_{zmax}}$ , with  $I_{zmin}, I_{zmax}$  being the minimum and maximum values of  $I_z$ , respectively.

**B. Longitudinal Velocity Controller:-** To track the desired longitudinal velocity  $v_{xd}$ , an adaptive fuzzy controller is designed in presence of uncertain roll resistance and aerodynamic term to calculate the required longitudinal force. Define the velocity tracking error as  $e_{vx} = v_{xd} - v_x$ , with vehicle longitudinal motion equation in (1), it can be induced that

$$\dot{e}_{vx} = \dot{v}_{xd} - 1/m(F_X - C_{av} v_x^2 + m v_y \dot{\gamma} - m \dot{\psi} \dot{\gamma}) \tag{7}$$

Considering the vehicle dynamics system is such sophisticated that the accuracy values are unavailable in practice, and therefore, the fuzzy logic adaptive approach is adopted to deal with this problem in view of its excellent ability of approximating an arbitrary nonlinear function. Compared with the indirect adaptive fuzzy control, the direct adaptive one possesses better approximation capability, in addition to avoiding singular problem associated with controller design process, which is thus adopted to construct controller. The direct adaptive fuzzy logic controller can be designed as follows

$$\hat{u} = \hat{u}_D(x|\theta) \tag{8}$$

where  $\hat{u}_D$  is a fuzzy logic system,  $x$  is the state-space vector, and  $\theta$  is a set of tenable parameters. By controller (8), the closed-loop dynamics can be formulated as

$$\dot{e} = \Lambda e + \rho[\hat{u}^* - \hat{u}_D(x|\theta)] \tag{9}$$

where  $\hat{u}^*$  is an optimal control input,  $e = (x_d - x, \dot{x}_d - \dot{x})^T$ ,  $\rho = [0, b]^T$ , and  $\Lambda = [0, -1; k_2, -k_1]$  with  $k_1, k_2$  being the positive design parameters. Afterwards, the optimal parameter can be given by

$$\theta^* = \arg \min_{\theta \in R_i} \left[ \sup_{x \in R^2} |\hat{u}_D(x|\theta) - \hat{u}^*| \right] \tag{10}$$

If the minimum approximation error of the control system is defined as  $\tilde{u} = \hat{u}_D(x|\theta^*) - \hat{u}^*$ , then the closed-loop dynamic error system (9) can be obtained as  $\dot{e} = \Lambda e + \rho[\hat{u}_D(x|\theta^*) - \hat{u}_D(x|\theta)] - \rho \tilde{u}$ . Furthermore, consider an fuzzy logic system, the direct fuzzy logic controller can be formulated by  $\hat{u} = \hat{u}_D(x|\theta) = \theta^T \zeta(x)$ . Finally, the closed-loop system (9) can be further formulated as

$$\dot{e} = \Lambda e + \rho(\theta^* - \theta)^T \zeta(x) - \rho \tilde{u} \tag{11}$$

Then, the parameters set can be updated in real-time with the following adaptive law

$$\dot{\theta} = \chi e^T v_2 \zeta(x) \tag{12}$$



where  $\chi$  is the positive design parameter and  $v_2$  is the last column of matrix  $Y$ . Here,  $Y$  is a positive definite matrix determining the closed-loop performance, which satisfies  $\Lambda^T Y + \Lambda Y^T = -\Gamma$ , with  $\Gamma \in R^{2 \times 2}$  being an arbitrary positive definite matrix for the second-order system.

Since  $e_{vx} = v_{xd} - v_x$ , it results in  $\dot{e}_{vx} = \dot{v}_{xd} - \dot{v}_x$ . Here,  $e_v = [e_{vx} \ e_{vy}]^T$  is chosen as the input variable of fuzzy system. Hence, the direct fuzzy adaptive controller for longitudinal velocity is obtained by

$$\hat{u}_v(e_v | \theta_v) = \theta_v^T \xi(e_v) \tag{13}$$

with the following adaptive law

$$\dot{\theta}_v = \chi e_v^T v_2 \xi(e_v) \tag{14}$$

In the end, the required resultant longitudinal force can be ultimately obtained by

$$F_X = \hat{u}_v(e_v | \theta_v). \tag{15}$$

C. Slip Ratio regulator :-When the slip ratio is fluctuating within the threshold, the net torque can be governed by  $T_i = F_{xi} r_e$ . Alternatively, when the magnitude of slip ratio  $\lambda_i$  exceeds its threshold, the slip ratio regulator will be activated to regulate the wheel slip ratio within the threshold. In particular, once the slip ratio regulator is activated, the actual slip ratio will be forced to track the desired one rather than the threshold. In this scenario, it takes the braking manoeuvre ( $r_e \omega_i < V_i$ ) for example to design the slip ratio regulator. The wheel slip ratio in the braking manoeuvre is governed by

$$\lambda_i = \frac{r_e \omega_i - V_i}{V_i} \tag{16}$$

Substituting (4) into the time derivative of (16) results in that

$$\dot{\lambda}_i = -\frac{\dot{V}_i}{V_i} (1 + \lambda_i) + \frac{r_e}{J_w V_i} (T_i - r_e F_{xi}) \tag{17}$$

To drive the actual wheel slip ratio to track the desired slip ratio, the sliding mode control technique is employed to achieve the desired slip ratio tracking. The sliding mode surface is defined as

$$s_i = \lambda_i - \lambda_{i,d} \tag{18}$$

where  $\lambda_{i,d}$  denotes the desired slip ratio. Clearly, the control objective is achieved when  $s_i = 0$ ; to realize this, the system state is driven to the sliding mode surface by introducing the following reaching law

$$\dot{s}_i = -\varepsilon_{ki} s_i - \varepsilon_{si} \text{sgn}(s_i) \tag{19}$$

where  $\varepsilon_{ki, si}$  is a positive design parameter. By solving (19), the required wheel torque can be obtained as

$$T_i = \frac{J_w V_i}{r_e} \left[ \frac{\dot{V}_i}{V_i} (1 + \lambda_i) + \frac{r_e^2 F_{xi}}{J_w V_i} - \dot{\lambda}_{i,d} - \varepsilon_{si} s_i \right] \tag{28}$$

Similarly, in the driving maneuver, namely  $r_e \omega_i > V_i$ , the corresponding wheel torque can be obtained by such procedures presented in braking condition, which can be ultimately achieved as

$$T_i = \frac{J_w \omega_i^2 r_e}{V_i} \left[ \frac{\dot{V}_i}{r_e \omega_i} + \frac{V_i}{J_w \omega_i^2} F_{xi} + \dot{\lambda}_{i,d} - \varepsilon_{si} s_i \right] \tag{21}$$

where  $T_i (i=1,2,3,4)$  denotes the expected wheel torque. Then, the output torques, together with the front-wheel steering angle signal, will act on the nonlinear vehicle model eventually.

### III. CONCLUSION

This paper reported a control strategy to improve the stability performance of FWID-EVs in the critical cornering situations by introducing the supervision mechanism for yaw moment control and slip ratio regulation simultaneously. Firstly, the supervision mechanism was introduced in both yaw moment control and slip ratio regulation for the effective control of vehicle stability during the critical situations. Secondly, ADS, DDS and ODS were discussed and contrasted separately in improving the vehicle stability subject to the control allocation of FWID-EVs. Thirdly, the three-level control strategy was presented through integrating functions of the controller, distributor and regulator.



Finally, the two critical maneuvers were conducted to verify the effectiveness of the supervision mechanism and control strategy and the efficiency of the ODS. In future, the critical cornering conditions-oriented sideslip angle estimation and the time delay problem of this supervision mechanism will be studied systematically, and then the hardware-in-the-loop (HIL) experiments will be further carried out for overall evaluation of the proposed control strategy and methods.

#### REFERENCES

- [1] Dezhi Xu, *Member, IEEE*, Yan Shi, and Zhicheng Ji, “Model-Free Adaptive Discrete-Time Integral Sliding-Mode-Constrained-Control for Autonomous 4WMV Parking Systems”, 2017.
- [2] Ming Yue, *Member, IEEE*, Lu Yang, Xi-Ming Sun, *Senior Member, IEEE*, and Weiguoxia, “Control for FWID-EVs with Supervision Mechanism in Critical Cornering Situations”, 2016.
- [3] Zhutao Zang, *Member, IEEE*, Xingtian Zhang, *Student Member, IEEE*, Hong Aagbov ye Pan, *Student Member, IEEE*, Waleed Salman, *Yagbov Rasim*, Xinglong Liu, *Student Member, IEEE*, Chunbai Wang, Yan Yang, *Student Member, IEEE*, and Xiapei Li, “A Novel System for a Space Saving 4WSWD Electric Vehicle: Design, Modelling, and Road Test”, 2016.
- [4] ziming Qi, Xu Zhao, Kuang Ma, Mathew King, Wei-Chen Lee, Ji-We-Lin, Shao-Min-Lee, “4-Wheel Independent In-Wheel-Motor Drive and Independent Steering Electric Vehicle Safety Analysis Method Based on Mass Redistribution Experiment”, 2015.
- [5] K J Yogesh, Mod. Rehan Desai, Mohammad Ali Fazal Shaikh, Praveen Gasthi, “Design and Fabrication of Four Wheel Steering Mechanism for Low Speeds”, IARJSET 2017.
- [6] Ding Zhao, Haiyang Sun, Wefeng Cui, “Research on the Platform Design and Control System for the Wheel-side Steering-Driving Coordination Vehicle”, IEEE, August 2010.
- [7] Zhurong Dong, Zhijun Deng, “Design of New Suspension for Four Wheel Independent Steering Electric Automobile”, IEEE, 2011.
- [8] Masato Itoh, Kenichiro Nonaka, Kazuma Sekiguchi, “Experimental Verification of Model Predictive Tracking and Steering Control for the Vehicle Equipped with Coaxial Steering Mechanism”, IEEE, December 2016.