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Implementation robust control technique to lateral stabilization for in-wheel motor electric vehicle

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Abstract

In this research, the presentation and development a robust control algorithm system for stabilization in-wheel motor electric vehicle by implementing the sliding mode control technique is carried out. Based on the proposed algorithm, a shared weight control is implemented between the yaw rate of vehicle and the sideslip angle of the vehicle. Also, a weighting coefficient is used using fuzzy algorithm to control the yaw torque of the vehicle. In the following, the optimal distribution of torque to the four wheels of in-wheel motor electric vehicle, considering the limit of the maximum torque of the electric motor and considering the coefficient of friction of the road surface and tire, is done. The proposed control system is jointly implemented in MATLAB/Simulink-Carsim softwares. The results of the performed simulations show the optimal and effective performance of the proposed control algorithm system.

Keywords: Sliding Surface, Lateral Stabilization, Vehicle Sideslip Angle, Robust Control.

1. Introduction

In the last decade, there have been significant improvements in the design and production of cars, which make significant changes in people's daily lives. Due to these developments, transportation has become easier and has led to the promotion of economic development. However, along with the development of the automobile industry, the side effects of the development of this industry should be mentioned, such as environmental issues, energy and fuel issues, traffic congestion, and safety, and therefore, in many advanced countries, new cars have been developed. The meaning of new cars is electric cars, which have advantages compared to internal combustion cars, for example, extremely low pollution, more favorable and easier control system, more sustainable energy consumption, etc. According to the different designs of the power transmission system in electric cars, these cars have different configurations. And it is divided into two types, the first type, electric vehicle with centralized propulsion system and the second type, electric vehicle with distributed propulsion system. [1] The first type is based on traditional development and is similar to internal combustion vehicles in terms of configuration. The structural and main difference between the first type and the car with an internal combustion engine is in the use of an electric motor instead of an internal combustion engine as an energy source. [2] And electric cars with a distributed propulsion system are divided into two main categories, respectively, the first category. , electric cars with the motor inside the wheel and the second category, electric cars with the motor near the wheel are divided. [3] Electric cars with the motor in the wheel due to their simple structure and the possibility of easy control, for their development and application in the autonomous driving control system. [4] Among the configurations of electric cars, the configuration of the car with four electric motors, the motor in the wheel, has attracted the attention of researchers and industrialists due to its advantages, for example, high maneuverability and flexibility. [5] Route design and tracking Car movement is one of the most important research fields in self-driving cars. In this topic, tracking the reference path with minimum lateral error and orientation is the main feature related to path navigation. During the tracking process, both longitudinal control and transverse control should be considered. For convenience, the longitudinal speed of the vehicle is assumed to be constant and the track is tracked with the lateral control of the vehicle. [6] There are three different methods to implement track tracking. The first method is the track tracking method based on geometry, the second method is the track tracking method based on kinematics, and the third method is the track tracking method based on the dynamic model [7] Considering that the tracking accuracy is low in the first two methods and also Difficulty in coordinating and adapting to complex driving conditions has caused these two methods to receive less attention from researchers. While the third method has been widely

noticed by researchers and industrialists [8], many control algorithms have been proposed for the third method, for example, integrator-derivative proportional control [9], fuzzy control [10], degree regulator Second linear, sliding mode control , control based on model prediction [11]. In a research, an integrator-derivative proportional control algorithm has been designed and proposed for tracking the path of an autonomous car. [12] In another research, the combination of fuzzy controller with the derivative-integrator proportional control algorithm has been used to improve the tracking of the vehicle's path.]18 [In one research, the design of the motion path based on the quadratic regulator has been done to optimize the input of the active front steering system. In a research, the motion path tracking structure based on the prediction of the model that controls the kinematics and dynamics at the same time. An acceptable performance has been designed in coordination between system performance and computational cost. In some researches, instead of tracking the route, it is used to track the rotation angle of the car around the yaw axis [13] and track the angular speed of the car around Yaw axis has been implemented. In recent years, the implementation of the quadratic linear regulator method [14], the control method based on model prediction and the sliding mode control method [15] have been widely used in the electric vehicle, the motor in the wheel. By analyzing, analyzing and observing the results of previous researches, it can be concluded that during the process of tracking the vehicle, the stability of the vehicle has a very important angle and is very important compared to the accuracy of the process of tracking the track. In a research, a torque distribution method based on tire force data has been proposed, which increases stability in electric vehicles with a motor in the wheel. [16] In a research, by creating coordination and combining two slip surfaces, it is better to improve stability during [17] In another research, it has been pointed out that the path tracking is in conflict with the dynamic stability of the vehicle in very severe driving conditions, and a coordinated mechanism has been proposed to solve the conflict problem. In addition, it is used as a technique to improve strength and resistance.
The structure of this paper is as follows: The second part introduces the dynamic model of the in-wheel motor electric vehicle. The adaptive stability control system based on the sliding mode control algorithm is introduced with details in the third section. In the fourth part, the results of the simulations are analyzed and reviewed. The conclusion is presented below.

2. Dynamic Modeling

2.1. Wheel Equation

The wheel is one of the subsystems in the analysis of the dynamic behavior of the car in acceleration and braking modes.

$$I_w \frac{d\omega_j}{dt} = T_{d_j} - T_{b_j} - F_{x_j} R - T_{Roll} \tag{1}$$

where I_w is the moment of rotational inertia of the wheel, F_x is the longitudinal force of the tire, R is the effective radius of the wheel, $T_d . T_b$ represents the braking and thrust torque, respectively. Also, the rolling resistance can be calculated using equation (2).

$$T_{Roll} = f_r R F_z \tag{2}$$

that F_z و f_r represent the rolling resistance of the tire and the normal force of the tire, respectively.

The vehicle bicycle model is shown in figure (1).

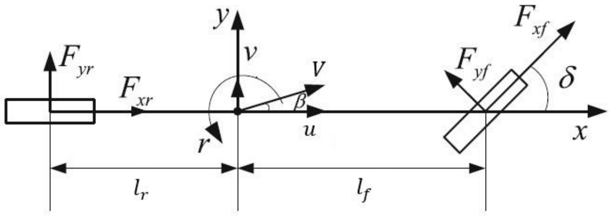

Figure 1. Vehicle bicycle model

2.2. Tire Dynamic

Assuming the linear dependence of the friction force of the tires on the vertical force of each tire, the longitudinal or transverse friction force of the tire can be expressed by equation number (3).

$$F_{Y_{\tau.\varepsilon}} = \mu_{k_{\tau.\varepsilon}} F_{z_{\tau.\varepsilon}} \, . K \in \{x.y\}. \tau \in \{f.r\}. \varepsilon \in \{l.r\} \tag{3}$$

where $F_{z_{\tau.\varepsilon}}$ represents the vertical load of each of the front and rear tires and $\mu_{k_{\tau.\varepsilon}}$ also represents the longitudinal or transverse friction coefficient of the tire. The vertical force of the tire is described by relations (4) to (7).

$$F_{z_{f.l}} = m\left[\frac{gl_r - a_x h_{cg} - F_{aero} h_{aero}/m}{2(l_f + l_r)} - \frac{l_r a_y h_{cg}}{(l_f + l_r) t_w}\right] - \frac{0.6 F_{aero}}{4} \tag{4}$$

$$F_{z_{f.r}} = m\left[\frac{gl_r - a_x h_{cg} - F_{aero} h_{aero}/m}{2(l_f + l_r)} + \frac{l_r a_y h_{cg}}{(l_f + l_r) t_w}\right] - \frac{0.6 F_{aero}}{4} \tag{5}$$

$$F_{z_{r.l}} = m\left[\frac{gl_f + a_x h_{cg} + F_{aero} h_{aero}/m}{2(l_f + l_r)} - \frac{l_f a_y h_{cg}}{(l_f + l_r) t_w}\right] - \frac{0.6 F_{aero}}{4} \tag{6}$$

$$F_{z_{r.r}} = m\left[\frac{gl_f + a_x h_{cg} + F_{aero} h_{aero}/m}{2(l_f + l_r)} + \frac{l_f a_y h_{cg}}{(l_f + l_r) t_w}\right] - \frac{0.6 F_{aero}}{4} \tag{7}$$

where h_{cg} و $h_{aero} . g$ represent the acceleration of gravity, the height of the center of aerodynamic force from the road surface and the height of the center of mass from the road surface, respectively. The expression $0.6 F_{aero}$ represents the aerodynamic force that is applied to the car in the vertical direction. In this research, it is assumed that this force is equally divided between the tires. Also, the coefficient $\mu_{K_{\tau,\varepsilon}}$ can also be calculated using the magical Pejka formula[19].

$$\mu_{k_{\tau.\varepsilon}} = \frac{\sigma_{k_{\tau.\varepsilon}}}{\sigma_{\tau.\varepsilon}} \mu_{\tau.\varepsilon} \, . k \in \{x.y\}. \tau \in \{f.r\}. \varepsilon \in \{l.r\} \tag{8}$$

$$\mu_{\tau.\varepsilon} = D_{\tau.\varepsilon} \sin(C_{\tau.\varepsilon} \arctan(B_{\tau.\varepsilon} \sigma_{\tau.\varepsilon})) \ . \ \tau \in \{f.r\} \ . \ \varepsilon \in \{l.r\} \tag{9}$$

where $B_{\tau.\varepsilon}.C_{\tau.\varepsilon}.D_{\tau.\varepsilon}$ are fixed coefficients that are specific for the tire and road in question. Also, in this research, it is assumed that these coefficients are the same for four tires. $\sigma_{\tau.\varepsilon}$ represents the total slip of the tire, which is a function of the longitudinal and transverse slips of the tire [20].

$$\sigma_{\tau.\varepsilon} = \sqrt{\sigma_{x_{\tau.\varepsilon}}{}^2 + \sigma_{y_{\tau.\varepsilon}}{}^2} \ .\tau \in \{f.r\}\,.\varepsilon \in \{l.r\} \tag{10}$$

The longitudinal slip of each of the front or rear tires is a function of the longitudinal speed of the contact point of the tire with the road surface and the longitudinal speed equivalent to the rotation of the wheel and with The relationship number (11) can be defined.

$$\sigma_{x_{\tau.\varepsilon}} = \frac{v_{rw_{\tau.\varepsilon}} - v_{cw_{\tau.\varepsilon}}}{max(v_{rw_{\tau.\varepsilon}}.v_{cw_{\tau.\varepsilon}})} \ .\tau \in \{f.r\}.\varepsilon \in \{l.r\} \tag{11}$$

The longitudinal speed of the point of contact of each tire with the road surface can be calculated with the help of relations (12) to (15).

$$v_{cw_{f.l}} = v_{cg} - r\left(\frac{T}{2} - l_f\beta\right) \tag{12}$$

$$v_{cw_{f.r}} = v_{cg} + r\left(\frac{T}{2} + l_f\beta\right) \tag{13}$$

$$v_{cw_{r.l}} = v_{cg} - r\left(\frac{T}{2} + l_r\beta\right) \tag{14}$$

$$v_{cw_{r.r}} = v_{cg} + r\left(\frac{T}{2} - l_r\beta\right) \tag{15}$$

Also, the longitudinal speed equivalent to the rotation of the wheel can also be calculated from equation (16) [18].

$$v_{rw_{\tau.\varepsilon}} = r_{w_{\tau.\varepsilon}}\omega_{\tau.\varepsilon} \ .\tau \in \{f.r\}\,.\varepsilon \in \{l.r\} \tag{16}$$

In order to calculate the transverse slip of the tire, the slip angle of the tire ($\alpha_{\tau.\varepsilon}$) should be determined first, slip angles of the front and rear tires can be determined using the relations number (17) to (20).

$$\alpha_{f.l} = \delta - arctan(\frac{v + rl_f}{u - r\,t_w/2}) \tag{17}$$

$$\alpha_{f.r} = \delta - arctan(\frac{v + rl_f}{u + r\,t_w/2}) \tag{18}$$

$$\alpha_{r.l} = -arctan(\frac{v - rl_r}{u - r\,t_w/2}) \tag{19}$$

$$\alpha_{r.r} = -arctan(\frac{v - rl_r}{u + r\,t_w/2}) \tag{20}$$

The parameters of the vehicle dynamic model are presented in table (1) [17].

Table 1.

Parameter	Symbol	Value
m	kg	1411
C_d	-	0.45
I_w	kgm^2	2.6
t_w	m	1.48
l_f	m	1.56
l_r	m	1.04
h_s	m	0.54
I_z	kgm^2	2031.4

3. Control Algorithm

In this research, the design and development of a stability control algorithm system for an in-wheel motor electric vehicle is carried out. It includes two control layers, the first layer is responsible for motion tracking and the second layer is responsible for optimal torque distribution. In the first layer, a rotational torque control algorithm is designed to achieve the goal of tracking the optimal state in real time. In the second layer, a torque distribution control algorithm is designed and developed to allocate the required torques to the in-wheel motors of the electric vehicle. The rotation torque control algorithm system of the in-wheel motor electric vehicle is designed and developed based on the sliding mode control algorithm technique to achieve the combined speed control of the rotation angle of the vehicle around the yaw axis and the side slip angle of the vehicle. The output of the control algorithm is the rotational torque, which is able to improve the stability of the vehicle. The design and selection of the sliding mode level is a key issue in the development of the sliding mode control system, which affects the dynamic quality of the system.

4. Results and Discussion

In this section, the performance of the proposed rotational torque control algorithm based on the adaptive sliding mode algorithm and the torque distribution control algorithm based on the detection of the road surface friction coefficient is analyzed. In this research, to analyze the performance of the proposed control algorithm for the implementation of the double lane change maneuver.

In this scenario, the longitudinal speed of the car is considered to be 95 km/h and the friction coefficient of the road surface and tire is considered to be 0.3. The results of the simulations can be seen in figures (2) to (7). Figure number (2) shows the movement path in the double lane change maneuver. Figure number (3) shows the changes of the weight coefficient in the surface of the sliding mode. The weighting coefficient reaches a maximum value of 0.14 in 6 seconds and then fluctuates a little. Figures (4) and (5) respectively show the speed of the rotation angle of the car around the yaw axis and the side slip angle of the car in three modes of weight coefficient. According to figure number (4), the speed of the rotation angle of the car around the yaw axis is variable in the range of ± 0.1 radians per second, and according to the three modes of the weight coefficient, it has a maximum value of 0.0761 radians per second, 0.0770 radians per second, respectively. 0 radians per second and 0.0765 radians per second. According to figure number (5), the amount of side slip angle of the car is variable in the range of ± 0.02 radians and according to the three modes of weight coefficient, it has a maximum amount of 0.0073 radians, 0.0151 radians and 0.0127 radians, respectively. It is radians. The pinhead control algorithm with different weight gain achieves different control effects. When the weight factor is 0.5, the speed of the car's rotation angle around the yaw axis and the car's side slip angle are small. However, there is also a serious lag phenomenon. When the amount of weight factor is 1 and the amount of weight factor can be changed, the amount of rotation angle of the car around the yaw axis and the amount of side slip angle of the car are large, but the response of the system is fast. In figure number (6), the simulation results of the phase plane can be seen that the enclosed area of the phase plane of the side slip angle of the car when the weight factor is 0.5 is smaller than when the weight factor is 1 and can be changed, that is, the change in the side slip angle The car is more convergent and the control effect is more favorable.

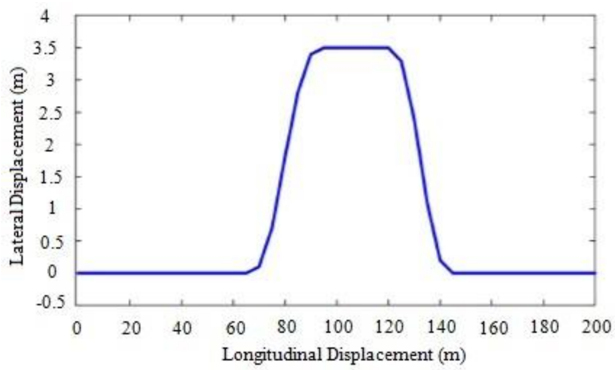

Figure 2. Vehicle movement path in double lane change scenario

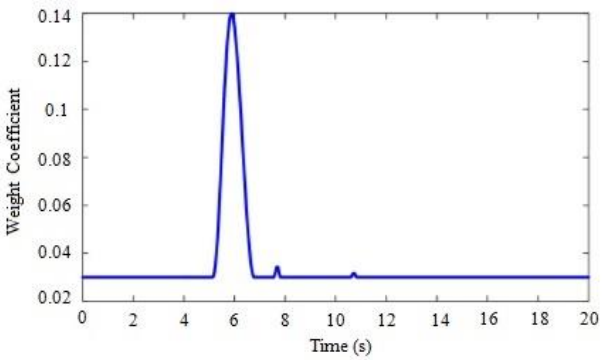

Figure 3. Weighting factor changes

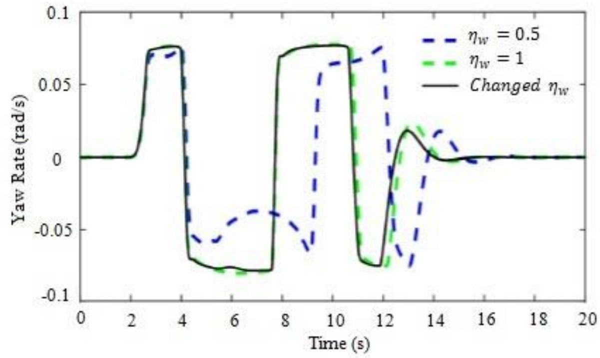

Figure 4. Changes in the speed of the vehicle's rotation angle around the yaw axis

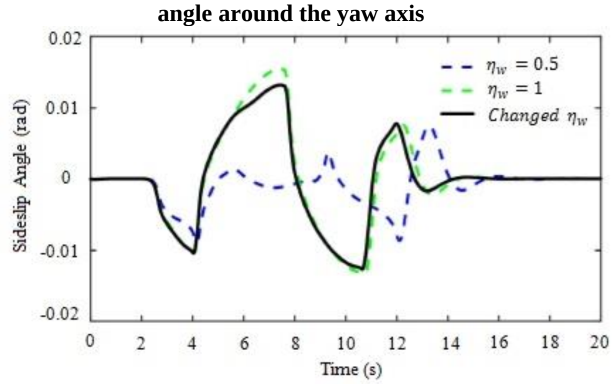

Figure 5. Changes in the angle of side slip of the vehicle in terms of time

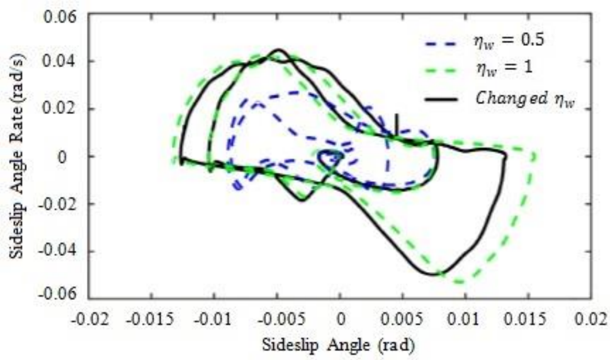

Figure 6. Sideslip angle velocity phase plane-sideslip angle

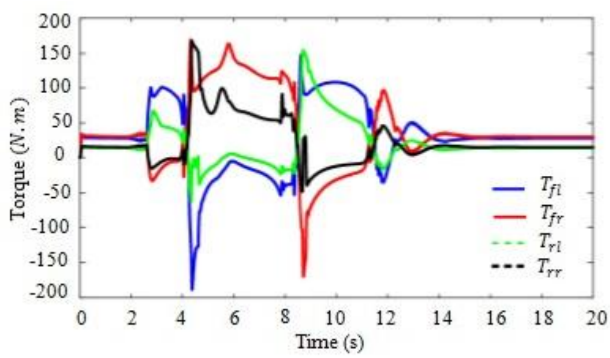

Figure 7. Torque changes over time

5. Conclusions

In this research, the design and development of a robust control algorithm system for the stabilization of the motor-in-wheel electric vehicle is carried out by using the sliding mode control method. Based on the proposed control algorithm, the first layer is based on the implementation of the adaptive sliding mode control algorithm to control the rotational torque. In the second layer, the distribution of the torque is done by using the detection of the adhesion coefficient in terms of limitations. The proposed control algorithm system is simulated based on the adaptive sliding mode, and the double line and fish hook maneuvers are used to check, analyze and validate the proposed control algorithm. The results of the simulations show the effectiveness and optimal performance of the proposed control algorithm.

6. References

[1] Hang, P.; Chen, X. Integrated chassis control algorithm design for path tracking based on four-wheel steering and direct yaw-moment control. Proc. *Inst. Mech. Eng*. Part I J. Syst. Control. Eng. 2019, 233, 625–641.

[2] Chindamo, D.; Lenzo, B.; Gadola, M. On the Vehicle Sideslip Angle Estimation: A Literature Review of Methods, Models, and Innovations. *Appl. Sci*. 2018, 8, 355.

[3] Chen, T.; Chen, L.; Xu, X.; Cai, Y.; Jiang, H.; Sun, X. Sideslip Angle Fusion Estimation Method of an Autonomous Electric Vehicle Based on Robust Cubature Kalman Filter with Redundant Measurement Information. *World Electr. Veh*. J. 2019, 10, 34.

[4] Zhou T. Adaptive sliding control based on a new reaching law. *Control Decis* 2016; 31: 1335–1338.

[5] Berntorp K, Quirynen R, Uno T, et al. Trajectory tracking for autonomous vehicles on varying road surfaces by friction-adaptive nonlinear model predictive control. *Veh Syst Dyn* 2021; 58: 705–725.

[6] Zhai, L.; Hou, R.; Sun, T.; Kavuma, S. Continuous steering stability control based on an energy-saving torque distribution algorithm for a four in-wheel-motor independent-drive electric vehicle. *Energies* 2018, 11, 350.

[7] Ghomashi M.A., Kazemi R., "Motion trajectory control and robust control based on nonlinear bicycle model to stabilization for in-wheel motor electric vehicle in emergency scenario" *Journal of Aerospace Mechanics*/ 2024/ Vol.20/ No.1/ 109-124.

[8] Zhang S, Zhao X, Zhu G, et al. Adaptive trajectory tracking control strategy of intelligent vehicle. *Int J Distrib Sens Netw* 2021; 16: 1–14.

[9] Soudbakhsh D and Eskandarian A. Comparison of linear and nonlinear controllers for active steering of vehicles in evasive manoeuvres. Proc IMechE, Part I: *J Systems and Control Engineering* 2012; 226: 215–232.

[10] Q. K. Hou, S. H. Ding, X. H. Yu, Composite super-twisting sliding mode control design for PMSM speed regulation problem based on a novel disturbance observer, *IEEE Trans. Energy Convers.*, 36 (2021), 2591–2599.

[11] J. Zhang, H. Wang, M. Ma, M. Yu, A. Yazdani, Active front steering-based electronic stability control for steer-by-wire vehicles via terminal sliding mode and extreme learning machine, *IEEE Trans. Veh. Technol*., 69 ,2020.

[12] K. Mei, S. Ding,W. X. Zheng, Fuzzy adaptive SOSM based control of a type of nonlinear systems, *IEEE Trans. Circuits Syst*. II, 69, 2022.

[13] Rahman M, Masrur M, Uddin MN (2012) Impacts of interior permanent magnet machine technology for electric vehicles. In: 2012 *IEEE International Electric Vehicle Conference*, pp. 1–5: IEEE

[14] Hartani K, Merah A, Draou A (2015) Stability enhancement of four-in-wheel motor-driven electric vehicles using an electric differential system. *J Power Elect*

[15] Sekour M, Hartani K, Merah A (2017) Electric vehicle longitudinal stability control based on a new multimachine nonlinear model predictive direct torque control. *J Adv Transp* 2017

[16] Mousavinejad E, Han Q-L, Yang F, Zhu Y, Vlacic L (2017) Integrated control of ground vehicles dynamics via advanced terminal sliding mode control. *Veh Syst Dyn* 55(2):268–294

[17] Ghomashi M.A., Kazemi R., " Motion path following coordinated control for in-wheel motor electric vehicle via implementation robust control and optimal control" *Journal of Modeling in Engineering* / 2024/ doi: 10.22075/JME.2024.31752.2531.

[18] Ding S, Liu L and Zheng WX. Sliding mode direct yaw moment control design for in-wheel electric vehicles. *IEEE Trans Ind Electron* 2020; 64(8): 6752–6762.

[19] K. Mei, C. Qian, S. Ding, Design of adaptive SOSM controller subject to disturbances with unknown magnitudes, *IEEE Trans. Circuits Syst*. I, 70 (2023), 2133–2142.ttps://doi.org/10.1109/TCSI.2023.3241291

[20] Fu C, Hoseinnezhad R, Bab-Hadiashar A, et al. Direct yaw moment control for electric and hybrid vehicles with independent motors. *Int J Veh Des* 2021; 69(1–4): 1–24.