The Control Strategy Research of 4WID Vehicles Steering-by-Wire System

Yao Wang¹,*, Qingzhang Cheng¹,2,*, Linlin Gao² and Wenjun Zhang¹

¹School of Mechanical and Electrical, Soochow University, Jiangsu, China
²School of Automotive Engine, Changshu Institute of Technology, Jiangsu, China

*Corresponding author e-mail: 27850135@qq.com, 2860671628@qq.com

Abstract. Once the traditional electric vehicle was refitted with distributed drive (4wid) system, the increasing of vehicle's unsprung mass would significantly increase the steering resistance, as a result of that, the efficiency and accuracy of the original car's steer-by-wire (SBW) system will be reduced. In order to solve this problem, taking BAIC-EV150 for example, this paper introduced a design of SBW control strategy for 4WID vehicles, and the corresponding refitting work of real vehicle were completed. The refitted vehicle adopted dual-motor, dual-controller to coordinate control the output torque, aiming at compensating the resistance moment. Simulation and experimental results show that the controller can meet the requirements of 4WID vehicle steering, and the dual-motor steering system based on fuzzy PID control is more responsive and more accurate than the single-motor steering system which under ordinary PID control.

1. Introduction

Faced with the increasingly serious environmental problems, many countries have chosen electric vehicles as an alternative to fuel vehicles. At present, there are two main power system design schemes for electric vehicles: one is the traditional scheme based on the central motor; the other is the distributed drive (4WID) scheme based on the hub motor or the wheel-side motor. Compared with the central motor scheme, the distributed drive scheme which use a hub motor or a wheel-side motor can independently output four wheel torque. Under such characteristics, the maneuverability and steering stability of the car have been significantly improved [1], but the requirements for the accuracy of the steering system have also increased [2, 3].

To study distributed drive vehicles, the most common solution is to refit traditional electric vehicles. The distributed drive system is constructed by removing the original central motor and installing a hub motor (or wheel-side motor) on the wheel. Due to the introduction of the hub motor, each wheel has increased the mass of 40 ~ 50KG [4]. This greatly increases the unsprung mass of the vehicle, which in turn leads to greater steering inertia and steering resistance, finally resulting in a reaction delay of the steering-by-wire system and a greater degree of overshoot. Therefore, it is believed that the modified vehicle will have difficulty meeting new steering needs. In other words, the 4WID vehicles need an optimized SBW control strategy and drive system.

SBW eliminates the mechanical connection between the steering wheel and the lever[5, 8], which realizes the steering control with higher degree of freedom and stronger adaptability of operating
conditions through the decoupling of mechanical structure. Tumari [6], a foreign scholar, who used PID control algorithm to build SBW system, the simple PID controller obtained a high accuracy at medium and low speed. However, in the face of distributed driven vehicles with high unsprung load and steering damping, the control accuracy of the ordinary PID controller based on small power and single motor will decline [4], and the road sense feedback will be affected, which is difficult to adapt to the requirements of high control strength and precision of distributed driven vehicles. Foreign scholars Zaidi [7] have improved the adaptability of the SBW system to vehicle-road's nonlinear characteristics by using fuzzy control, and achieved better results at higher speeds.

This study designs and implements a steering controller based on adaptive fuzzy PID control strategy which drive a dual motor SBW system. The controller aim at improving the response speed and control accuracy of the modified vehicle which under heavy steering load and unsprung mass. Taking the BAIC-EV150 as the prototype, the modification of distributed driving system and wire controller was completed. On the basis of not changing the original wire control controller, a new PM controller was added not only to realize the CAN LAN communication between the new controller and the original controller, but also realize the closed-loop coordinated control of steering torque. Based on the co-simulation of CARSIM and SIMULINK, the comparison study of ordinary PID and adaptive fuzzy PID was carried out, and then the real vehicle test was carried out to demonstrate the reliability of the control strategy.

2. Mathematical modeling and controller design

2.1. Dynamical model of vehicle steering
The original steering motor of the modified vehicle is located at the horizontal pull rod and adopts the pinion-rack mechanism. The output torque of the motor is executed through the motor reducer and the pinion and rack reducer, then the horizontal pull rod of the vehicle is driven to move left and right to achieve steering. Its physical model is shown in figure 1.

Dynamic description of the motor:

\[
\begin{align*}
J_\theta \ddot{\theta}_\theta + B_\theta \dot{\theta}_\theta &= T_s - T_o \\
T_o &= K_x (\theta_t - x, g_x / r_y) \\
T_s &= K_f
\end{align*}
\]

Description of the motion of the left and right steering wheels:

\[
\begin{align*}
K_1 &= \frac{J_{FW1} \ddot{\theta}_{FW1} + B_{FW1} \dot{\theta}_{FW1} + T_1}{x_r / N_1 - \theta_{FW1}} \\
K_2 &= \frac{J_{FW2} \ddot{\theta}_{FW2} + B_{FW2} \dot{\theta}_{FW2} + T_2}{x_r / N_2 - \theta_{FW2}}
\end{align*}
\]

![Figure 1. Original vehicle steering system physical model.](image-url)
The meanings of parameter and simulation reference values are shown in table 1, where i =1 or 2 respectively represent left and right wheels.

| Parameter                          | Physical significance | Ref-value          |
|------------------------------------|-----------------------|--------------------|
| Torque coefficient of steering motor | $K_i$                 | 0.07-0.08          |
| Damping coefficient of steering motor | $B_i$                 | 0.0003-0.0004      |
| Torsional stiffness of motor       | $K_s$                 | 100-110            |
| Inertia of motor shaft             | $J_s$                 | 0.00015-0.00020    |
| Total reduction ratio              | $g_s$                 | 10                 |
| Steering efficiency                | $\eta_p$              | 1                  |
| Transmission ratio                 | $N_i$ (i=1 or 2)      | 0.14               |
| Torsional stiffness                | $K_i$ (i=1 or 2)      | $\approx$39000     |
| Moment of inertia of the kingpin   | $J_{FW_i}$ (i=1 or 2) | $\approx$0.82      |
| Moment of inertia of the kingpin   | $B_{KPi}$ (i=1 or 2)  | $\approx$192       |

2.2. Modification design scheme of original car

As a modified vehicle, the BAIC-EV150 needs to remove its central motor and original transmission chain then replace the original wheel hub into a hub motor to upgrading the distributed drive. At the same time, in order to prevent the collision between the outer rim of the hub and the car body, the wheel base should be widened. The modification results are shown in figure 2.

The structure diagram of the modified wire control system is shown in figure 3. Main unit including the steering wheel (1), the steering wheel Angle sensor (2), torque sensor (3), the added power motor (4), the steering wheel column clutch (5), tires (6), the original power of motor (7), the new PM steering controller (8), the original car power steering ECU (9) and CAN signal line (10).

![Figure 2. After BAIC-EV150 been add a hub motor.](image1)

![Figure 3. Structure diagram of refitted ESS.](image2)
To increase the total output torque of the steering system, an additional motor (4) was installed. At the same time, in order not to affect the original steering motor performance reliability, the PM steering controller is added for closed-loop control. Under the control of PM steering controller (8), the auxiliary torque is directly applied to the steering string through the worm gear mechanism. Original power motor (7) was under the original car power steering ECU (9) control. The original assistant torque was applied through the gear strip mechanism. At the same time the wheel clutch (5) the post under the wire control steering ECU control, through the hydraulic mechanism to the opening of the clutch, close and realize the drive-by-wire state to enter and exit.

The steering wheel Angle sensor (2) and torque sensor (3) are set on the steering string to collect the information of Angle and torque respectively. The signals which collected by the two are transmitted to the PM wire-controlled steering controller and the original vehicle power-assisted steering ECU respectively, and the LAN composed of CAN signal line (10) is inter working and sharing. The drive-by-wire steering controller downloads the speed signal and the output torque $T_1$ from the original power-assisted steering ECU through the LAN formed by the CAN line. The output torque of the assistant motor is calculated according to signal $T_1$, speed signal, steering wheel Angle signal and torque signal in the torque sensor.

### 2.3. Logic scheme of additional PM steering controller

The PM steer-by-wire controller controls the output torque of the additional assistant motor to compensate the total steering torque. The calculation method of the output torque can be summarized as formulas 3 and 4.

\[
\begin{align*}
T_c &= T_j - T_r \\
T_j &= T_k + FL \\
T_r &= T_i + T_2
\end{align*}
\]  

In the formula, $T_c$ is the output torque value of the steering wheel torque sensor, which is equal to the driver output torque value $T_j$. FL is the equivalent steering resistance after the wheel pitch is widened. The sum of FL and the alignment torque $T_h$ is the steering resistance $T_f$. The auxiliary torque $T_r$ is composed of the output torque $T_i$ of the original booster motor and the output torque $T_2$ of the additional motor.

Since the value of $T_c$ is equal to the driver's output torque, it can represent the driver's steering demand. Moreover, if the steering system can meet the steering requirements, the $T_c$ value is equal to the difference between the resistance moment $T_f$ and the moments $T_i$. Therefore, the control target can be set as $T_c$ equal to 0, that is, the moment of power finally equals the moment of resistance.

\[
\begin{align*}
T_i &= KT_1 \\
K &= AV + BT_c
\end{align*}
\]  

According to formula 4, the weighted coefficient $K$ is divided into two parts: first, the product of speed coefficient $A$ and speed $V$; The second is the product of the amplification factor $B$ and the input torque $T_c$ of the sensor. By controlling the coefficient $A$ and $B$, the output torque of the original motor can be dynamically amplified and the torque compensation can be realized. Take the steering wheel torque sensor to output $T_c$ and speed $V$ as the input of the fuzzy controller, and the proportional parameters $K_{P1}$ and $K_{P2}$ as the output. The theoretical domain of $T_c$ is $[-44n, +45N]$, and the fuzzy set is $\{NB, NM, NS, ZO, PS, PM, PB\}$; The fuzzy set of $V$ is $\{NB, NM, NS, ZO, PS, PM, PB\}$. The domain of $KP_A$ and $KP_B$ is $[-3, +3]$, and the fuzzy set is $\{NB, NS, ZO, PM, PB\}$. The membership
function adopts the common triangle membership function, because the triangle membership function has been widely used in the steering control field.

3. Co-Simulation with Matlab and Carsim

3.1. Simulation modeling
The simulation model realizes co-simulation based on Carsim and Simulink. The original steering model was modeled according to the mathematical model established in 2.1. The newly added PM steer-by-wire module is modeled according to the strategy proposed in 2.3. The actuator receives the output torque of motor 1 and 2, as well as the steering resistance torque $T_r$ output by CARSIM, and converts the input into the front wheel angular velocity $\omega_{\theta}$, which aiming a characterize the vehicle steering response. The CARSIM module used $\omega_{\theta}$ as input. It use the resistance moment, the equivalent total assist moment and the actual lateral displacement as outputs. The final co-simulation model is shown in figure 4.

![Co-simulation platform](image)

Figure 4. Co-simulation platform.

3.2. Analysis of simulation results
As shown in figure 4, the simulation model built in Simlink-Carsim was used for simulation. At the same time, double motor fuzzy PID and single motor PID was compered. In the driver model, the target steering wheel Angle is set as sinusoidal input, the amplitude is set as $\pi/2$, and the steering wheel Angle speed is set as $(\pi/3)$ rad/s, that is, the frequency is 60 degrees per second. At the same time, the output steering wheel Angle and torque in the driver model are converted into the expected front wheel Angle, which is compared with the actual vehicle front wheel Angle. At the same time, the speed is set at 35km/h in CARSIM, and the simulation results are shown in figure 5.

It can be seen from the simulation results that when the vehicle speed is 35km/h, the adaptive fuzzy PID based on the dual motor can track the desired Angle well, and there is no large amplitude error or over-regulation. However, the tracking response of ordinary PID to the desired Angle is slow, and there is an obvious overshoot. The simulation results show that under the adaptive fuzzy PID control, the maximum front wheel Angle control error is not higher than 0.1 degree, while the ordinary PID is higher than 0.5 degree.
4. Experimental verification

4.1. Design of new PM controller
The original steering controller is retained, and the newly steer-by-wire (SBW) controller is designed and developed by ourselves. The newly added controller can coordinate with the original controller in LAN to realize the wire-controlled closed-loop.

The new controller uses Freescale MC9S12 XEP100 as the core control panel prototype. The on-board processor is part of s12-32mhz series and has been widely used in the automotive control field. The power-architecture enabled MCU not only has a wide range of callable instruction sets but also have a lot easy development software for developers to implement engine management, motor control, on-board equipment and powertrain related controls.

Controller development focuses on open-source, in order to facilitate later code modification and burning. The bottom layer of the controller is implemented by standard C language, which provides LIB library and function header file for instruction invocation, and BDM interface for debugging. It’s control structure, physical drawing and engine compartment layout are shown in figure 6, 7.

![Figure 5](image5.png)

**Figure 5.** Steering response at a speed of 10m/s.

![Figure 6](image6.png)

**Figure 6.** The controller and his control logic.
4.2. Real vehicle experiment

The modified vehicle and the unmodified vehicle will be compared and tested. The single-shift line test can reflect the control ability of the controlled car's line-controlled steering system.

Using the Simulink standard C conversion platform provided by Freescale-S12 series chips, the controller model is converted into C code and recorded into PM controller. At the same time, the test vehicle is equipped with the high-precision integrated navigation and positioning system HUACEP2, which can record the position coordinates of the vehicle in real time.

The results of real vehicle experiment are shown in figure 8 and 9, in which the reference track is obtained by using the unmodified BAIC-EV150 in the single-shift line test under the same road constraints. The speed in the test is controlled at 10m/s. It is not difficult to find from the experimental results that, under the ordinary PID control, the lateral deviation of vehicle trajectory is large and the overshooting phenomenon is obvious, while the adaptive fuzzy PID is better to achieve the driver's lane change requirements, the lateral error between the controlled vehicle trajectory and the reference trajectory is small.

Meanwhile, the steering wheel Angle step input experiment is also carried out, as shown in FIG 15. The vehicle under single motor PID control is limited by the driving ability of single motor, and the response speed of the front wheel angle is so slow. Larger unsprung mass produces larger steering inertia, which leads to larger degree of overshoot and peak error. Compared with the ordinary PID control, the adaptive fuzzy PID controller with double motor has better control precision and response speed. The data shows that: at the peak, the adaptive PID reduces the peak error of %50; It also increased %30 of the response speed for SBW system before reaching the desired Angle.
5. Conclusion

1) Based on the fuzzy adaptive PID control theory, a steering system supported by a dual-motor was designed for 4WID vehicles which suffer from increase of steering resistance. The result shows that the response speed and control accuracy of SBW system was improved.

2) Based on the joint simulation platform of CARSIM and MATLAB, the fuzzy PID controller and the simple PID control strategy was compared. The result proves the advantages of adaptive fuzzy PID in the field of steering control of distributed driven vehicles.

3) A real car modification was carried out which based on the prototype of the BAIC-EV150. A real controller was designed base on Freescale-MC9S12XEP100. The single-shift line experiment and steering wheel Angle step input experiment were carried out to investigate the response of the SBW system. The results show that the adaptive fuzzy PID controller reduce %35 of response time and reduce %50 of the peak error.

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