Fuzzy Control for Off-center Steering System of a Novel Electric Chassis Based on PWM Technology

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Abstract. A flexible chassis (FC) for an electric vehicle with four in-wheel drive motors is described in this paper. It has a unique structure with an off-center steering shaft. The driving system and steering system are combined, which has considerable advantages in terms of actuation flexibility for the confined spaces. However, there is no rigid constraint for steering, and it is difficult to coordinate the motions of electromagnetic steering lock (ESL) and the wheel. To solve this problem, a pulse-width modulation (PWM) technology is introduced to control the ESL. With the control of PWM signal, the chassis can achieve stepwise driving and steering. Then, fuzzy logic is introduced to control PWM signal of the ESL so that it can match the steering motion of the wheels. To validate the system, steering signal step input tests and sinusoidal input tests were conducted on a self-made test bench. The results demonstrate that, the off-center steering system is with good steering performance, and the linkage and tracking errors of the left and right wheel are all in an acceptable range. The proposed control strategies are feasible and effective, and can ensure smooth turning for the chassis.

1. Introduction

In many cases, there are confined and closed facilities such as greenhouses, warehouses, and orchards, where vehicles must be flexible whilst protecting the environment. The development of flexible, energy-sustainable, environmentally friendly, and intelligent vehicles for such environments is urgent [1,2]. Electric vehicles are widely recognized as an essential part of green and efficient transportation of the future. Currently, most transport equipments used in these conditions are still traditional vehicles, which are inflexible and emit exhaust fumes [3]. The development of flexible, environmental friendly, and intelligent vehicles for such environ-ments is urgent [4–6]. In recent years, four in-wheel motorized actuated electric vehicles (FIWMA-EVs) have drawn tremendous attention in terms of actuation flexibility [7,8]. However, there are still great challenges for this kind of vehicle due to the high complexity of the control system and over-actuation [9–10].

There have been various valuable studies on the FIWMA-EVs. Research on the control of wheeled mobile machinery has mainly focused on electric chassis, electric platforms, and mobile robots. Chen et al. proposed a double closed-loop proportional–integral–derivative (PID) control method with an inner current and outer speed loop to enhance controller performance, accuracy, and reliability of a motor drive tractor [11]. Jaskot et al. presented a model to examine different configurations of wheels and analyzed the effects of changing the motion parameters of a four-wheeled mobile platform [12].
Due to the precision required in confined space, various works have focused on mobile robots with high control accuracy. Ye et al. employed GPS-based navigation to assess the auto-steering performance of a four-wheel independent-steering orchard robot, obtaining satisfactory path tracking results for cornering and merging [13]. Sharifi et al. conducted modeling and simulation of a nonholonomic omnidirectional mobile robot used for data collection, monitoring and inspections in confined space [14]. To improve the driving performance of FIWMA-EVs, typical intelligent methods, such as sliding mode control, decoupling control, fault-tolerant control, neural networks, and fuzzy control, have commonly been used for coordinated steering control [15–18]. Meanwhile, classical control methodology, for example, a classical PID controller, is incapable of coping with the nonlinear problem of FIWMA-EVs [19]. Fuzzy control can be implemented more effectively and easily without complex mathematical models [20]. Additionally, it can deal with the strong nonlinear problem that affects almost all in-wheel motor driving vehicles [21].

However, these aforementioned studies on electric vehicles and mobile robots use separate systems for driving and steering. Thus, more subsystems must be controlled, and the structure of the whole vehicle is more complex as well. To the best of our knowledge, few studies have considered a simplified steering and driving control structure for electric vehicles with fewer subsystems.

This study presents an electric flexible chassis (FC) with four in-wheel driving motors and four-wheel independent steering, which is suitable for confined facilities. By employing an off-center steering shaft, the chassis structure is extremely simple. It can achieve multiple motion modes for flexible working in a narrow or closed environment [22]. However, due to the lack of a rigid constraint mechanism for steering in the mechanical structure, it is difficult to coordinate the motions of electromagnetic steering lock (ESL) and the in-wheel motor. Therefore, this study will explore a control method for off-center steering system so as to achieve coordinate control of them.

The rest of the paper is organized as follows. In Section 2, the overall structure and mathematical models are described. In Section 3, PWM control method is proposed for electromagnetic steering lock. In Section 4, the fuzzy control methodology for coordinated control of the ESL and the wheel are designed. In Section 5, the experimental validation is described. Finally, conclusions and proposals for future work are provided in Section 6.

2. Overall Structure and system modeling

2.1. Overall structure of the flexible chassis

The schematic of structure for the FC is demonstrated in Figure 1. The FC is mainly composed of four independent off-center steering mechanisms. Each off-center steering mechanism consists of an ESL (FBD-050, Taiwan KAIDE), an off-center steering shaft, an off-center arm, and an in-wheel motor (WX-WS4846, Fujitec) drive wheel. The main feature of this mechanism is that the off-center shaft leaves a certain distance from the wheel motion plane without a steering motor, and this minimize resistance to the steering structure. The steering torque is from the wheels without additional mechanical structure. The forces for driving and steering all come from in-wheel motors. Thus, the physical construction has been greatly simplified and the manufacturing cost can be reduced.

![Figure 1. Schematic for structure and ackerman steering geometry of flexible chassis](image-url)
2.2. Electromagnetic steering lock model
The ESL is a key component for the transmission of drive and steering torque. The locking torque of the ESL is expressed by

$$T_d(I) = \mu_0 R_m F_e(I)$$  \hspace{1cm} (1)

where $\mu_0$ is the static friction coefficient, $R_m$ is the radius of effective friction area, $F_e$ is the electromagnetic attraction force, $I$ is the drive current.

Function (1) can be rewritten as (2) according to the magnet parameters of the ESL.

$$T_d(I) = 1.28 \times 10^{-7} \pi^2 \frac{A_m W}{(1+\sigma)^2 h^2} I^2$$  \hspace{1cm} (2)

where $A_m$ is the effective working area of magnetic pole, $W$ is the number of field coil, $\sigma$ is the magnetic leakage, $h$ is the magnetic pole gap.

When the supply voltage of the ESL is 0 V, the locking torque is 0, and the vehicle is steered by rotating the off-center arm around the steering shaft. Conversely, when the supply voltage is 24 V, namely, the locking torque reaches the maximum, the off-center arm is fixed and the FC can move only with a fixed motion.

2.3. Two wheel steering model
The Ackerman steering geometry for the FC is shown in Figure 1. To produce steady and smooth steering, the angles of the two front wheels must be related:

$$\cot \delta_f - \cot \delta_l = \frac{B}{L}$$  \hspace{1cm} (3)

where $\delta_f$ is the steering angle of the right front wheel, $\delta_l$ is the steering angle of the left front wheel, $B$ is the distance between the left and right off-center steering shafts and $L$ is the distance between the rear and front off-center steering shafts.

In practice, there is only one input steering signal. The input steering angle $\delta_f$ is calculated by

$$\cot \delta_f = \frac{\cot \delta_l + \cot \delta_l}{2}$$  \hspace{1cm} (4)

where $\delta_f$ is the input steering angle.

3. PWM Control method
PWM is employed to control the switching of the ESL. If the PWM signal is at up level, the ESLs of the two front wheels are locked independently and the frame can be driven by the in-wheel motors. If the PWM signal is at low level, the two ESLs are released and the chassis can be steered. Assuming that both the frequency of PWM signal (The PWM ratio time is $T$) and the speed of in-wheel motor are fixed, when the PWM duty ratio $D_1$ is larger than $D_2$, the stepping angle of the off-center steering shaft $\delta_1$ will be smaller than $\delta_2$. Thus, compared with $D_2$, more steps are required to reach the target angle $\delta_0$ when the duty ratio is $D_1$, and the duration $t_1$ is longer than $t_2$. In general, the smaller the duty ratio, the faster the steering motion.

Equations (3) and (4) have given the target steering angles of two the front wheels. Further, to make the theoretical angles easy to implement on the embedded hardware of the chassis, $\Delta \delta$ is introduced as the difference between $\delta_\beta$ and $\delta_\phi$:

$$\Delta \delta = \tan^{-1} \left\{ \frac{2L \tan \delta_f}{2L - B \tan \delta_l} \right\} - \tan^{-1} \left\{ \frac{2L \tan \delta_f}{2L + B \tan \delta_l} \right\}$$  \hspace{1cm} (5)

The angle of a stepper motor is set by the number of pulses while the speed depends on the pulses frequency. The angles through which the two stepper motors rotate are $\theta_\beta$ and $\theta_\phi$, corresponding to the angle signals $\delta_\beta$ and $\delta_\phi$, respectively. The pulses difference needed to realize $\theta_\beta$ and $\theta_\phi$ is expressed by

$$\Delta n = \frac{\theta_\beta - \theta_\phi}{\theta_f}$$  \hspace{1cm} (6)

where $\theta_f$ is the step angle of the stepper motor.
The number of pulses needed to realize the steering angle $\theta_f$ is recorded as $n$. The transmission ratio between the stepper motor angle and the off-center arm angle is 10. In setting the steering to the target angles $\delta_{fl}$ and $\delta_{fr}$, the frequencies are $f_1$ and $f_2$, respectively, and they are related by

$$n \cdot \frac{1}{f_1} = (n + \Delta n) \cdot \frac{1}{f_2}$$

where $K$ is the speed transmission ratio between the steering wheel and the stepper motor.

Therefore, combining equations (5) to (7), the frequency $f_2$ can be expressed as:

$$f_2(t) = \frac{2\delta_f}{K\theta_s} \tan^{-1}\left[\frac{2L \tan \delta_f}{2L - B \tan \delta_f}\right]^{-1} - \frac{\delta_f}{K\theta_s}$$

As can be seen from equation (8), the frequency $f_2(t)$ can be obtained once the signal $\delta_f$ is given.

4. Fuzzy control for electromagnetic steering lock

Due to the nonlinearity and the switching structure of the off-center steering system, an intelligent controller is needed to control the ESL. Thus, a fuzzy method is employed to adjust the duty ratio of the PWM signal for the ESL, according to the steering intention. When the steering wheel signal is wide and changing fast, the duty ratio of the PWM signal will be reduced, which increases the length of time the ESL is released and matches the fast turning of the in-wheel motor. Similarly, the duty ratio will increase when the steering wheel signal is narrow and changing slowly, to avoid excessive steering. The inputs of the fuzzy controller are the errors of the steering angles and the error rate, denoted as $E$ and $EC$, respectively. The output is the target PWM duty ratio, denoted by $D$.

The basic domain of steering errors $E$ and steering error rate $EC$ are $[-3, 3]$ and $[-0.3, 0.3]$, respectively. The basic domain of output variable, namely, PWM signal duty ratio $D$, is $[0, 1]$. The fuzzy domain of steering errors $E$ and steering error rate $EC$ are $[-6, 6]$ and $[-1, 1]$, respectively. The fuzzy domain of PWM signal duty ratio $D$ is $[0, 1]$. Quantization factor and scaling factor were arbitrarily determined as follows. Quantization factor of steering error $E$: $k_e = 6/3$. Quantization factor of steering error rate $EC$: $k_{ec} = 6/0.3$. In this controller, seven fuzzy linguistic terms are introduced to describe the input and output variables: $E \in \{NB, NM, NS, Z, PS, PM, PB\}$, $EC \in \{NB, NM, NS, Z, PS, PM, PB\}$, $D \in \{NB, NM, NS, Z, PS, PM, PB\}$, where NB is negative big, NM is negative medium, NS is negative small, Z is zero, PS is positive small, PM is positive medium, and PB is positive big. The fuzzy unit uses triangle membership functions to fuzzify the inputs and outputs, as shown in Figure 2a, 2b and 2c. The fuzzy rules are defined by a large amount of experience in practice, which are shown in Table 1.

![Figure 2](image-url)
Table 1. Inference rules for PWM duty ratio

| U   | EC   |
|-----|------|
| NB  | NB   | NB   | NS   | Z    | PS   | PM   | PB   |
| NM  | NB   | NB   | NM   | NS   | NS   | Z    | PS   |
| NS  | NB   | NM   | NS   | NS   | Z    | PS   | PM   |
| E   | Z    | NM   | NS   | Z    | PS   | PM   | PM   |
| PS  | NM   | NS   | Z    | PS   | PS   | PM   | PB   |
| PM  | Z    | Z    | PS   | PM   | PM   | PB   | PB   |
| PB  | Z    | Z    | PS   | PM   | PM   | PB   | PB   |

5. Tests Results and Discussion

5.1. Test Method

5.1.1. Measurement Equipment. To validate the proposed control strategy fully, a handling performance test was carried out for the FC to simulate its motion on the ground using the self-made test bench [22]. Speed sensors (D046, Guangzhou Logo Electronics Company; 0–1000 r/min) are used to acquire the speed of the in-wheel motors and turntables. The steering angles of the off-center arms are measured by a multi-turn potentiometer (22HP-10, SA-KAE Company, 0–5 kΩ). The duration of steering is calculated by the clock of the data acquisition (USB7648B, Beijing Zhongtai Research Ltd.) and a computer (E40, Lenovo Corporation).

5.1.2. Evaluation Methodology. In this section, like a conventional vehicle steering test, the proposed controller is validated in two kinds of steering test, namely, steering wheel angle signal step input test and sinusoidal input test. The step signal input test approximately determines the response and steering accuracy of the FC. The sinusoidal signal input test is used to evaluate handling performance, mobility, and traceability comprehensively. Meanwhile, we use the linkage error to quantify the retention of Ackerman’s steering geometry between the two front wheels, which is defined as the error between the actual steering angle and the ideal angle of right front wheel according to the Ackerman steering principle.

In step signal input test, steering angles increased from 0° to 30° in 0.5 s. In sinusoidal signal input test, steering angles varied between -30° to 30°. The initial speed was set as 60 r/min. The test was continued until the maneuvers were completed.

5.2. Results analysis

5.2.1. Results of Step Signal Input Test. Figure 3 shows the testing results for the step signal input tests. The response time of the right and left wheel increases to 0.51 s and 0.57 s, respectively, as shown in Figures 3(a). After slight oscillations, the angle errors converge to around zero compared with the target angles for the three speeds. The results indicate that the response time increases as the speed of the driving wheels increases. The maximum overshoots are 2.43° for the left front wheel and 2.77°, for the right front wheel. The maximum linkage errors based on the Ackerman steering principle was 1.33°. Correspondingly, the average linkage error was 0.89°. These errors are acceptable in terms of the low-speed application of the chassis in these complex conditions. Therefore, according to the above analysis, the proposed controller is not only able to maintain the Ackerman steering geometry for the chassis during step steering but also it can track the target angles sensitively with only a slight overshoot.

5.2.2. Results of Sinusoidal Signal Input Test. The steering wheel angle inputs and the testing results in the sinusoidal signal input test is shown 3(b). The steering system can closely track the preset angles
with sight deviations. The maximum tracking errors are 2.29° and 2.38° for the left and right front wheels, respectively. The average tracking errors for the left and right wheels are 1.24° and 1.15°. Note that there are no obvious differences among the three speeds in terms of the maximum and the average tracking errors, which indicate that the steering system is robust to changes in the initial speed for a slowly changing steering signal. Meanwhile, the maximum linkage errors based on the Ackerman steering principle is 1.17° while the average linkage errors is 0.59°. Thus, the steering is stable in terms of the overall trends.

Through the analyses above, the steering system of FC has good steering performance and precision. The proposed method not only overcomes the linkage problem between the two front wheel angles, but also solves the matching problem between the ESL and the electric wheel.

6. Conclusions
This study proposes a control method for the motion cooperation of off-center steering system of an innovative chassis. This controller consists of a steering-angle allocation controller, a PWM signal controller, and a fuzzy recognition controller. The PWM technology was used to coordinate electromagnetic steering lock and the steering wheel in real time. The fuzzy controller was employed for the ESL to recognize the steering intention based on PWM and to match the motion of the driving wheels. The proposed controller was further validated on a self-made test bench. The results show that, with an increase of the initial speed, the linkage and tracking errors increase while the maximum lateral force declines. These errors are all in an acceptable range and steering forces can meet the requirements for steering the two front wheels. In general, by applying the proposed control strategy, the steering system has good agility, accuracy and good steering tracking performance.

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