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Parking Path Tracking Method Based on Kalman Filter and Fuzzy Control

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Abstract

In order to solve the problem of low accuracy of automatic parking path tracking caused by noise of various sensors, a parking path tracking algorithm combining fuzzy control and Kalman filter is proposed. Firstly, the deviation model of actual driving path and reference path is established based on vehicle kinematical equation. Secondly, Kalman filter is adopted to reduce the measurement noise in vehicle position and course angle measurement data. According to the vehicle position deviation and course angle deviation, fuzzy controller is adopted to control the vehicle tracking the parking track. Thirdly, simulation model is built to verify the effectiveness of the proposed algorithm by Matlab/Simulink. Simulation results show that the proposed algorithm can effectively reduce the vehicle position deviation and course angle deviation, and improve the tracking accuracy of parking path.

Keywords

Automatic parking; Path tracking; Measurement noise; Kalman filter; Fuzzy control.

1. Introduction

With the development of automatic driving technology and the maturity of relevant intelligent algorithms, automatic parking technology develops rapidly. It solves the problem of "difficult reversing and irregular parking" and conforms to the trend of more and more compact parking spaces. Automatic parking technology mainly involves environmental awareness, parking path planning and parking path tracking. Among them, the real-time, accuracy and reliability of parking path tracking are the key to realize automatic parking.

Aiming at the problem of low tracking accuracy and large error of parking path, many intelligent vehicle-based tracking algorithms have been proposed. Zhongsheng Hou, Hangrui Dong et al. proposed an algorithm based on coordinate compensation, which further reduced the coordinate steady-state tracking error of the desired trajectory by correcting the vehicle body angle online[1]. The dynamic anti-saturation compensator proposed by Wenxu Yan et al can deal with the change amplitude and saturation velocity of system input, which can effectively reduce the tracking error of parking trajectory coordinates[2]. The automatic parallel parking control method based on fuzzy logic was proposed by Zhang Fang et al., which has a wide starting position range and can adapt to the fluctuation of speed[3]. Yaqing Tu, Hao Chen et al. established parking feature model and control mode set, determined the current feature state of vehicles through pattern recognition, and then drove the corresponding control mode to control the vehicle tracking parking path[4]. Zongzhou Wen et al. applied learning algorithm to optimize fuzzy controller parameters of automatic parking system, enabling the system to have self-learning ability, greatly reducing parking time, and realizing optimal

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control of parking path tracking[5]. Konghui Guo et al. proposed a non-time-referenced path tracking control strategy based on fixed-point tracking to solve the parking failure caused by the driver's speed control error in the parking process[6]. Haobin Jiang et al. proposed a double-closed-loop sliding mode variable structure path tracking control method, which improved the parking path tracking control accuracy[7].

The above control algorithms all have a certain degree of improvement on the tracking accuracy of the parking path. However, considering the actual hardware circuit, the noise interference of various sensor signals can easily lead to the problem of large tracking error and low accuracy. The Kalman filter method has the optimality of state estimation and the performance of reducing the disturbance of the system. In addition, the fuzzy rules based on the driver's experience are closer to the actual parking operation. Therefore, this paper based on the fuzzy control, the Kalman filter method is introduced into the feedback channel of the closed-loop control of the system to reduce the measurement noise of the sensor detection data and improve the tracking accuracy of the parking path.

2. Kinematics Equation of Vehicle Parking at Low Speed

The vehicle's vehicle speed is relatively low in the parking process, generally 3-5km/h. According to Ackerman's steering principle, the influence of lateral force can be ignored, that is, the wheel only rolls and turns, but does not slide in the parking process. As shown in Figure 1, the vehicle under parking motion is approximately simplified into a rigid body. Since the direction of rear wheel movement is always consistent with the direction of body movement during parking, the center point r of rear wheel axis is taken as the center of mass of the vehicle, that is, the motion state of r is approximately substituted for the motion state of the vehicle. Vehicle positions are denoted by center of mass $r(x, y)$ in this paper.

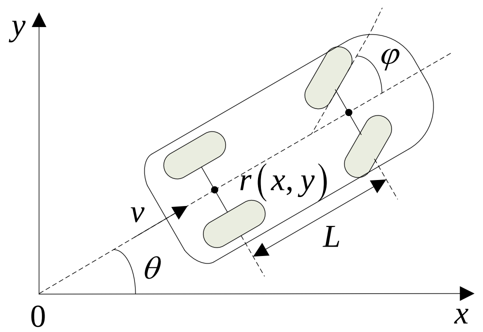

Figure 1. Vehicle kinematics model

According to Ackerman's steering principle and vehicle kinematics characteristics, the vehicle kinematics equation with vehicle speed v and wheel angle φ as input is expressed as:

$$\begin{cases} \dot{x} = v \cdot \cos\theta \\ \dot{y} = v \cdot \sin\theta \\ \dot{\theta} = v \cdot \tan\varphi / L \end{cases} \tag{1}$$

where θ refers to the orientation angle, that is, the angle between body direction and horizontal direction. In practical applications, equation (1) is usually converted into the following discrete form:

$$\begin{cases} x(k+1) = x(k) + Tv\cos(\theta(k)) \\ y(k+1) = y(k) + Tv\sin(\theta(k)) \\ \theta(k+1) = \theta(k) + \dfrac{Tv\tan(\varphi(k))}{L} \end{cases} \tag{2}$$

where T is the sampling period and k is the sampling time.

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3. Parking Path Tracking Control Method Based on Kalman Filter and Fuzzy Control

According to the state-space equation of four-wheel vehicles, in the low-speed parking process of vehicles, the position coordinate (x, y) of vehicles changes with the slight change of the direction angle θ. Therefore, the control goal of the automatic parking system is to control the vehicle heading angle θ by controlling the steering angle φ to ensure that the vehicle's position coordinates coincide with the target parking path. The vehicle's speed is very low and fluctuates very little in the parking process, so it can be assumed that the vehicle moves at a constant speed and its speed is set as v.

Given the characteristic parameter (x, y, θ) corresponding to the off-line parking path curve, after the fuzzy controller processes, the steering wheel angle φ corresponding to the vehicle parking is output, which will be used as the input signal of the vehicle model to output the position gesture of the vehicle under the current steering wheel angle (x_o, y_o, θ_o). Since the vehicle can be located only by using the vehicle position coordinate (x_o, y_o), the measurement of θ_o can be ignored to improve the response speed of the system. The measurement module generates the position measurement value (x^*, y^*) with measurement noise. At the same time, the measured value is filtered by Kalman filter to obtain the filtered position coordinate (x^*_{ekf}, y^*_{ekf}), which is further compared with the reference vehicle position and posture coordinates. After processing by fuzzy controller, the front wheel angle at the next moment is output to control the vehicle to track the parking path in real time. And so on, keep updating the position and angle of the front wheel until the vehicle is safely parked in the parking space.

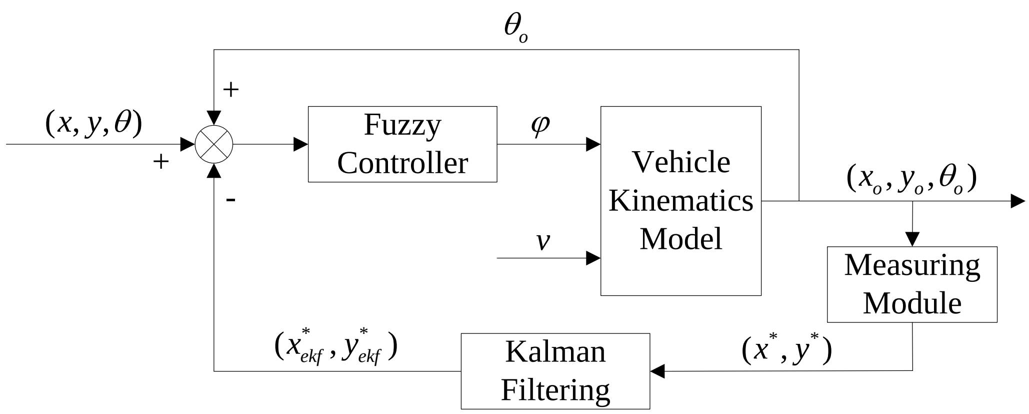

Figure 2. Fuzzy Kalman filter control block diagram

Assume that the pose coordinate r of the vehicle tracking parking track curve at time k is (x^*_k, y^*_k), after feeding back to Kalman filter for prediction, the prediction coordinate at time $k+1$ is (x^*_{k+1}, y^*_{k+1}). By analogy, the pose coordinates of the vehicle at each moment and every step are fed back to the Kalman filter for noise removal and updating. This not only has the real-time tracking feedback, but also the tracking effect is more accurate.

3.1 Parking Path Tracking Fuzzy Control

The selection and number of input and output variables of the fuzzy controller will affect the response speed of the controller[8]. Since the position coordinate and heading angle of a vehicle reflect the position of the vehicle and the rate of change of the vehicle position respectively, they can well represent the vehicle's motion state. Therefore, in the automatic parking path tracking, it is necessary to track the position and heading angle of the vehicle in real time, and strictly control their error as minimum as possible.

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Based on the above analysis, under the premise of ensuring the control precision and the controller response speed, the position error and the heading angle error are selected as the input signals of the fuzzy controller. The Kalman filter feedback is used to continuously update the vehicle position and heading angle data in real time, according to the fuzzy rules. The steering angle φ is derived to control the vehicle to steer along the planned path. The fuzzy controller is designed from three aspects: input/output variable domain and membership function, fuzzy rule and anti-fuzzification.

3.1.1 Input/Output Variable Discussion Domain and Membership Function

The fuzzy controller is adopted as a two-dimensional input and one-dimensional output mode. The position error of the input of the fuzzy controller is set as D, the heading error D1, and the steering angle φ of the front wheel. Considering the actual situation of parallel parking, the range of vehicle direction angle (-180°, 180°). The length and width of the parking spaces used in this paper are 2.5m and 1.8m, the range of position error D is set as (-250mm, 250mm), the range of course angle error D1 is (-30°, 30°), and the output value of front wheel steering angle φ is (-40°, 40°).

The number of fuzzy sets of the input position error D and the heading angle error D1 are both set to 5, which are NB (negative large), NS (negative small), ZO (zero), PS (positive small) and PB (large), respectively. The fuzzy set number of the output steering Angle is 7, namely NB (negative large), NM (negative medium), NS (negative small), ZO (zero), PS (positive small), PM (middle) and PB (large). Meanwhile, the robustness of the automatic parking trajectory tracking controller is improved by reducing the tunable parameters. Gaussian, s-type and z-type membership functions are used in this paper. To improve the stability and robustness of the system, each membership function has an appropriate overlap area, as shown in Figure 3 and Figure 4.

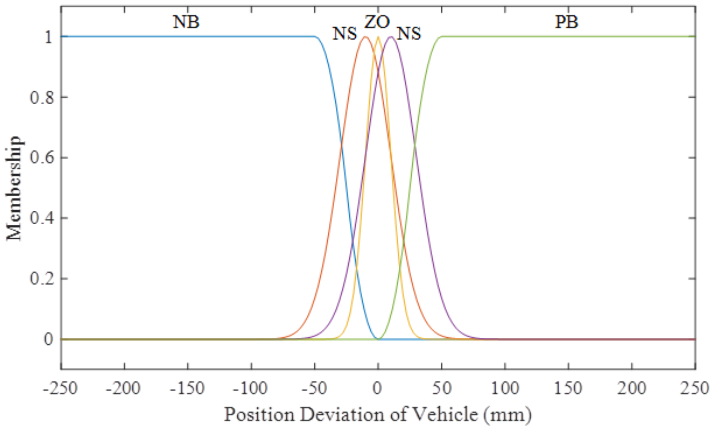

Figure 3. Vehicle position error D membership function

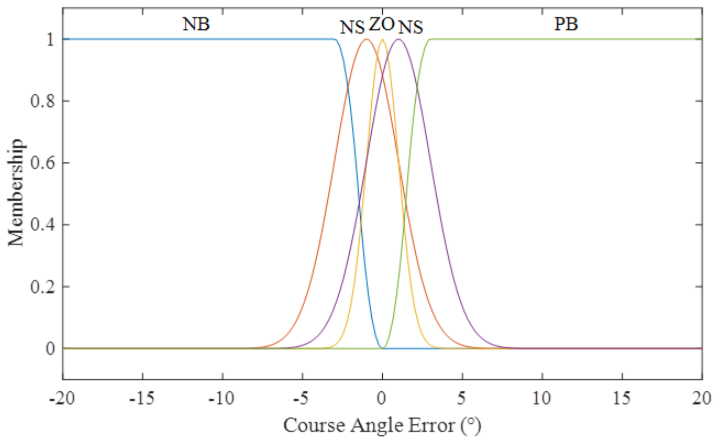

Figure 4. Membership function of course angle error D1

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3.1.2 Fuzzy Rules

The fuzzy rules reflect the fuzzy relationship between the input and output, which is obtained by summarizing the actual parking experience of the driver. If the position error of the vehicle is positive, when the heading angle error is positive, the adjustment position error should be dominant, and the front wheel steering angle output is negatively small or negative; when the heading angle error is negative, the position error is still mainly adjusted, and the front wheel steering angle output is negative. Similarly, the same is true when the position error is negative. If the position error of the vehicle is small or even zero, then the heading angle of the vehicle should be mainly adjusted at this time. Meanwhile, in order to avoid overshoot, the front wheel steering angle is not too large and should be reduced as the heading angle error decreases[9-10]. If there is no error in the position and heading angle of the vehicle, it is not necessary to adjust the steering angle of the front wheel, and the front wheel should be returned to positive at this time. The fuzzy control rules formulated based on the above parking experience are shown in Table 1, and the generated fuzzy control surface is shown in Figure 5.

Table 1. Fuzzy control rules

The front wheel steering angle φ		The vehicle position error D				
		NB	NS	ZO	PS	PB
The course angle error D1	NB	PS	NM	NB	NB	NB
	NS	PM	NM	NM	NB	NB
	ZO	PB	PS	ZO	NS	NB
	PS	PB	PB	PM	PM	NM
	PB	PB	PB	PB	PM	NS

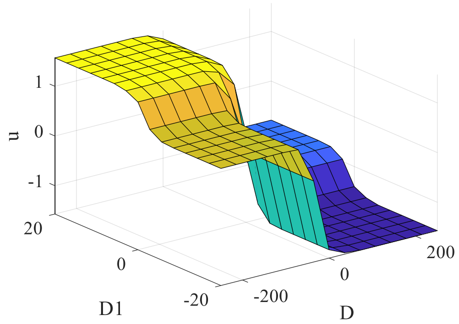

Figure 5. Fuzzy relationship between vehicle position error D and course angle error D1

3.1.3 Anti-fuzzification

According to the above fuzzy rules, the output is still a fuzzy subset, which needs to be de-fuzzified to control the controlled object. Currently, commonly used anti-fuzzification methods include barycenter method, weighted average method, area barycenter method, maximum membership average method, etc[11]. The principle of barycenter is applied to the fuzzy controller, and the fuzzy subset of the output is subjected to fuzzy decision to obtain the steering angle of the front wheel.

3.2 Prediction of Vehicle Status Based on Kalman Filter

The observation signal is used to filter the feedback signal from the fuzzy controller, and the statistical characteristics of the measurement noise are continuously estimated and corrected, and the online adjustment of the filter parameters is realized to reduce the actual filtering error and improve the tracking accuracy of the parking path[12-13]. This paper mainly designs the Kalman filter module by observing the error variance.

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The pose coordinate of the vehicle tracking parking trajectory curve at moment k is (x_k^*, y_k^*), then the speed of the vehicle in the x-axis direction and the speed in the y-axis direction at moment k can be expressed as the ordered number pair $(\dot{x}_k^*, \dot{y}_k^*)$. Thus, the state vector of the vehicle position and posture at moment k can be obtained as $X(k) = (x_k^*, y_k^*, \dot{x}_k^*, \dot{y}_k^*)$. Then the state model of the system can be expressed as:

$$X_{k+1} = A_{(k+1,k)} \cdot X_k + W_k \tag{3}$$

where $A_{(k+1,k)}$ is the state transition matrix, W_k is the white noise whose mean value is 0 and the covariance is Q.

Since vehicle parking is a slow process that requires precise steering wheel operation, the sampling time for a Kalman filter is extremely small, If T_s is set here, the state transition matrix can be expressed as:

$$A_{(k+1)} = \begin{bmatrix} 1 & 0 & T_s & 0 \\ 0 & 1 & 0 & T_s \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Observation quantity $z_k = (\hat{x}_k^*, \hat{y}_k^*)$, the observation model of the system can be expressed as:

$$Z_k = H_k \cdot X_k + V_k \tag{5}$$

where V_k is the white noise whose mean value is 0 and the covariance is R.

Since the observations are only position dependent, the observation matrix is set to:

$$H_k = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

Thus, the state equation and observation equation of the system can be obtained as follows:

$$\begin{bmatrix} x_{k+1}^* \\ y_{k+1}^* \\ \dot{x}_{k+1}^* \\ \dot{y}_{k+1}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & T_s & 0 \\ 0 & 1 & 0 & T_s \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_k^* \\ y_k^* \\ \dot{x}_k^* \\ \dot{y}_k^* \end{bmatrix} + W_k \tag{7}$$

$$\begin{bmatrix} \hat{x}_k^* \\ \hat{y}_k^* \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_k^* \\ y_k^* \\ \dot{x}_k^* \\ \dot{y}_k^* \end{bmatrix} + V_k \tag{8}$$

where W_k and V_k are randomly set during the experiment.

The prediction equation of the Kalman filter and the update equation can be obtained from the equations (3) to (6).

The prediction equation is:

$$\hat{X}_{(k+1,\ t)} = A_{(k+1,\ t)} \cdot \hat{X}_k \tag{9}$$

$$P_{(k+1,k)} = A_{(k+1,k)} \cdot P_t \cdot A_{(k+1,k)}^T + Q \tag{10}$$

The update equation is:

$$K_{k+1} = P_{(k+1,t)} \cdot H_k^T \cdot \left[H_k \cdot P_{(k+1,k)} \cdot H_k^T + R \right]^{-1} \tag{11}$$

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$$\hat{X}_{k+1} = \hat{X}_{(k+1,k)} + K_{k+1} \cdot (Z_k - H_k \cdot \hat{X}_{(k+1,k)}) \quad (12)$$

$$P_{k+1} = (I - K_{k+1} \cdot H_k) \cdot P_{(k+1,k)} \quad (13)$$

$\hat{X}_{(k+1,k)}$ and $\hat{X}_{k+1}$ are the prior estimates and posterior estimates respectively. According to equation (11), when the measurement error covariance R tends to 0, K_{k+1} tends to 1, indicating that the measured value is more real. On the contrary, when $P_{(k+1,t)}$ approaches 0, K_{k+1} approaches 0, indicating that the predicted value is more reliable.

Based on the fuzzy logic control parking path tracking algorithm, the distance from the target parking path is calculated, and the observed value is obtained accordingly. Kalman filter is used to predict the state of the system at the next moment, and the state and error equation of the system are continuously updated according to the observation value, so as to control the position error and pose error of vehicles in a small range, making the parking path tracking of vehicles more accurate.

4. Simulation Comparison and Verification

In order to verify the effectiveness of the proposed algorithm, the fuzzy control algorithm is used as the control, and the simulation is carried out in MATLAB/Simulink environment. The vehicle model parameters set in the simulation experiment are shown in Table 2.

Table 2 Vehicle parameters

Parameter	Value（mm）
Vehicle length	4428
Vehicle width	1765
Front overhang	1043
Rear overhang	825
Wheel base	2560

During the simulation, noise is artificially added to the vehicle wheel speed signal to simulate the measurement noise of the actual sensor detection data. The following is compared with the fuzzy control from the tracking effect, tracking error and x, y axis tracking error.

4.1 Parking Path Tracking Effect

The proposed algorithm and the fuzzy control algorithm are compared and demonstrated under the parking reference speed of 4.5km/h. In terms of simulation conditions, the initial coordinate of the vehicle is (0,1), the initial heading angle is $\theta = 0$, and the control frequency of the path tracking algorithm is 10Hz.

Figure 6 shows the tracking effect of the proposed algorithm and fuzzy control algorithm on a given reference parking path. It can be seen from the figure that there is no significant difference in the tracking effect between the two algorithms in the initial reversing phase. And the steering wheel is continuously adjusted in the middle stage, compared with the fuzzy control algorithm, the article proposed algorithm has smaller tracking error and is closer to the reference parking path. In the final reversing phase, the two algorithms have the same tracking effect.

4.2 Tracking Error

Through the above analysis, the proposed algorithm is obviously superior to the fuzzy control algorithm. To quantitatively analyze the parking trajectory tracking error of the two algorithms, the error curves of the two are placed in the same coordinate system, as shown in Figure 7.

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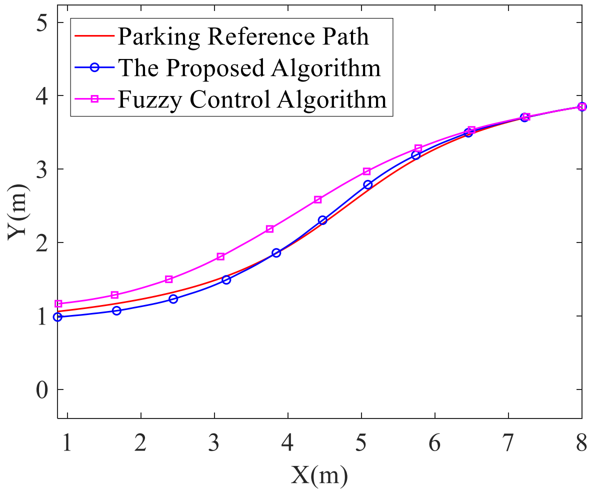

Figure 6 Parking path tracking effect comparison figure

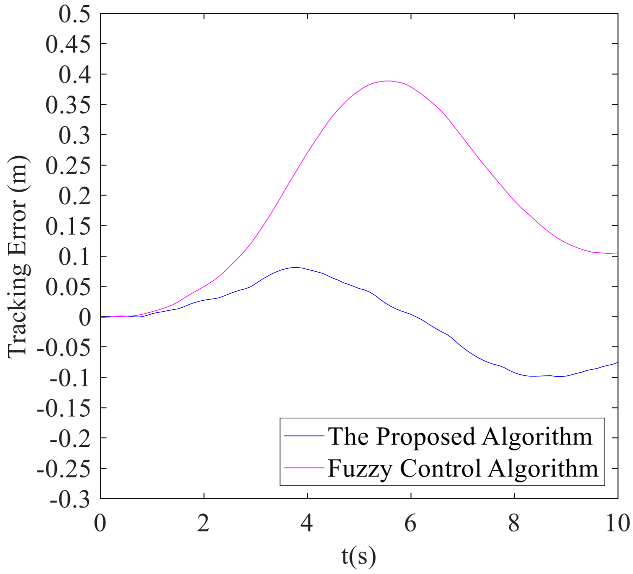

Figure 7 Comparison of tracking error

It can be seen from Figure 7 that in the middle stage of parking trajectory tracking, the tracking error of the fuzzy control algorithm reaches up to 0.38m, which is may cause the vehicle and the surrounding obstacles to smash in the actual parking, causing traffic accidents; However, the tracking error of the algorithm in this paper changes smoothly throughout the parking stage, and its error fluctuates between -0.12m and 0.075m and fluctuates less and less, which is in line with the actual parking demand.

Figure 8 is a comparison of the tracking errors of the two algorithms on the x and y axes. From another perspective, it is further verified that the proposed algorithm has less tracking error than the fuzzy control algorithm. It can be seen that the tracking error of the fuzzy control algorithm on the x and y axes is not only large but also has a large fluctuation frequency and has strong instability. Compared with the fuzzy control algorithm, the proposed algorithm has small tracking error fluctuation amplitude and frequency for the x and y axes, therefore, the algorithm proposed in this paper is more practical.

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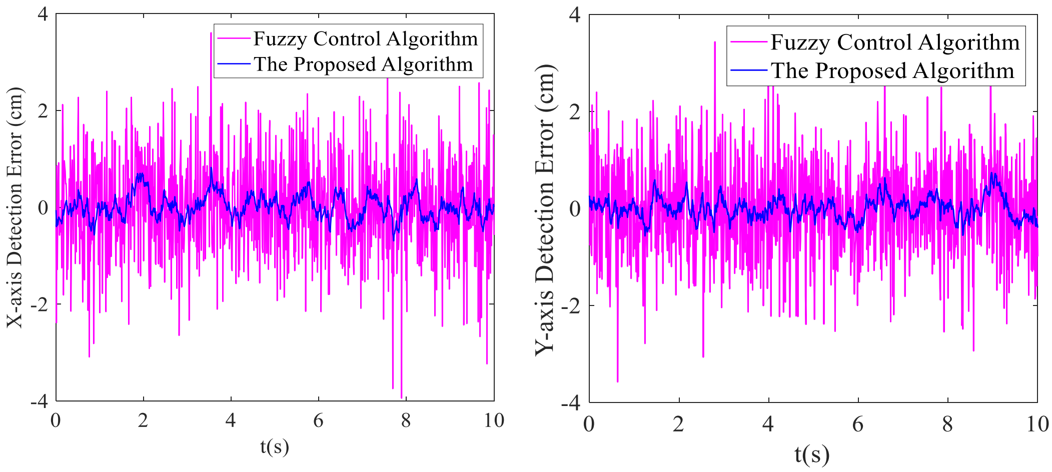

Figure 8 Tracking errors of x and y axes

5. Conclusion

Aiming at the problem of large error and low accuracy of parking path tracking in automatic parking technology, this paper proposes a tracking algorithm combining fuzzy control and Kalman filtering. Starting from the angle of reducing the measurement noise interfered by sensors in the system, the Kalman filtering method is introduced into the fuzzy control to reduce the position deviation and course angle deviation of the vehicle, so as to improve the accuracy of the angular output of the front wheel and thus improve the parking path tracking accuracy. Compared with the fuzzy control algorithm, the algorithm proposed in this paper is more accurate and precise.

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