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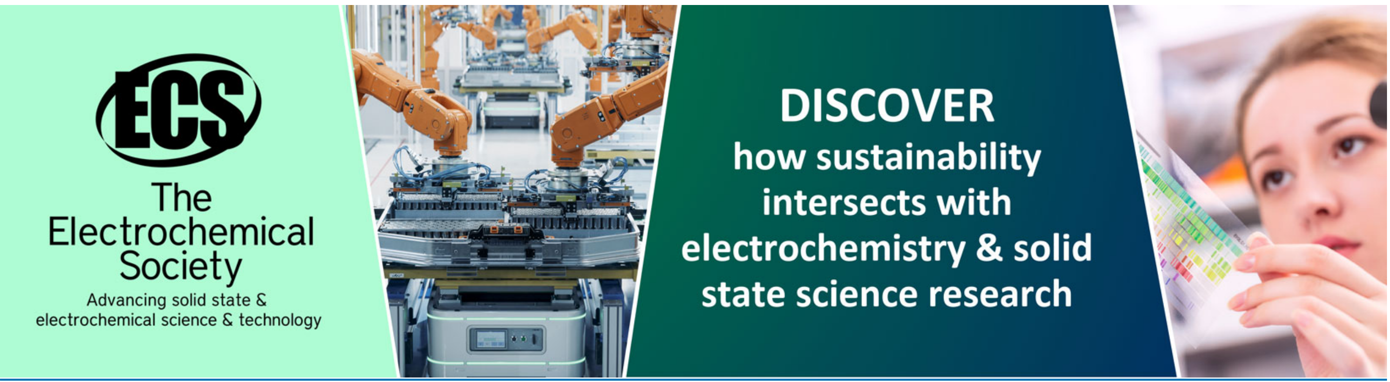

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High clearance four-wheel independent electric drive sprayer path tracking control based on self-correction controller

Guohai Liu [1], He Zhang [2,*], Duo Zhang [3], Yue Shen [4], Zijie Wang [5], Yandong Xu [6]

[1]Jiangsu University, Zhenjiang China

[2]Jiangsu University, Zhenjiang China

[3]Jiangsu University, Zhenjiang China

[4]Jiangsu University, Zhenjiang China

[5]Jiangsu University, Zhenjiang China

[6]Jiangsu University, Zhenjiang China

*Corresponding author's email: 253829891@qq.com

Abstract: Most traditional agricultural machines use traditional mechanical transmission with fuel drive and front wheel steering, and most of them are manned, with low transmission efficiency, poor flexibility and low level of intelligence. This paper proposes a new high ground clearance sprayer with four-wheel independent drive (4WID) with dual front and rear steering axles. This sprayer is an oil-electric hybrid that not only saves energy, but also reduces the pollution to crops. In this study, a path tracking controller and a self-correcting controller are constructed based on the kinematic model of the sprayer, respectively. The model prediction controller is used as the main controller, and it outputs the desired steering angle and speed of the sprayer based on the current state of the sprayer and the desired path to achieve path tracking control. The self-correcting controller, as an auxiliary controller, adopts fuzzy control method and designs fuzzy control rules based on the driver's experience to correct the wheel turning angle at the current moment, which not only retains the advantages of model prediction control in linear path tracking, but also improves the control effect in curved path tracking and enhances the path tracking accuracy in large curvature roads. The simulation shows that the maximum lateral deviation of 0.03 m can be achieved by the model predictive control alone, and the maximum lateral deviation is reduced to 0.0141 m after adding the self-correcting controller.

1. Introduction

Most of the traditional agricultural equipment is fuel-driven and mostly manned, which has low transmission efficiency, single control form, large turning radius, difficult attitude control and other problems, and low fuel utilization efficiency, which can cause serious pollution to the environment. In order to improve the efficiency of fuel utilization as well as productivity, the group has developed a four-wheel independent electric drive (4WID) high ground clearance sprayer as shown in Figure 2. In this paper, we design a model predictive controller for path tracking and a self-correcting controller for path tracking control to improve the path tracking accuracy of the sprayer. The accuracy problem of path tracking of unmanned agricultural machine is the focus of this paper, where there are various control algorithms such as model predictive control algorithm, pure tracking algorithm, linear quadratic regulator (LQR) algorithm, Stanley algorithm, etc. in path tracking control [1]. K Yang [2] et al.

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proposed an adaptive NMPC that changes the control level according to the path curvature contour, and his proposed control algorithm can track the reference path more accurately. Chao L I [3] et al. proposed an improved pure tracking algorithm based on differential GPS positioning navigation system, which greatly reduces the lateral deviation compared with the pure tracking algorithm. Fan [4] et al. proposed an initial planning path optimization method based on the three-point path geometry relationship. The method can improve the accuracy of path tracking. Gong Y [5] et al. proposed a parameter self-tuning path tracking controller, which combines the advantages of pure tracking model and parameter self-tuning fuzzy controller, and the control method has a small lateral deviation and improves the path tracking performance. In this study, the model predictive control has good tracking accuracy in the tracking straight line part, and the self-correcting controller is introduced in the tracking turn part to make it have higher tracking accuracy. The control block diagram of the whole vehicle is as follows:

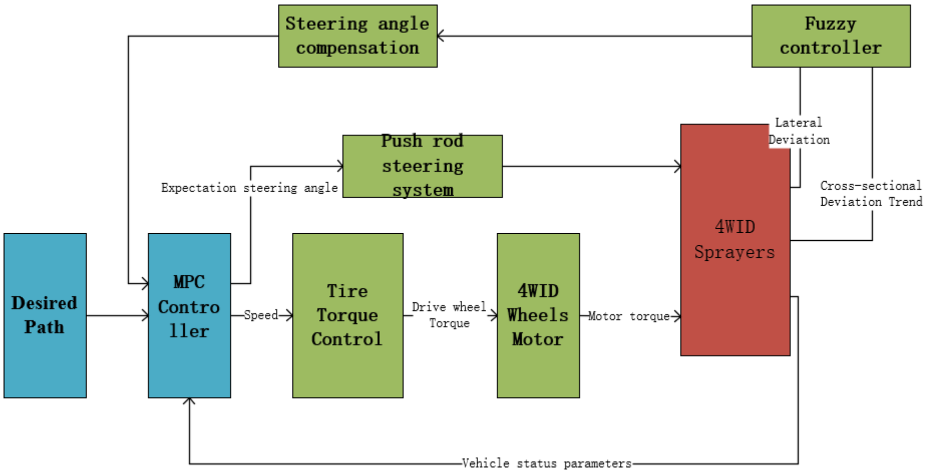

Figure 1 . Block diagram of the whole vehicle control system

2. Kinematic model of 4WID electric drive sprayer

The kinematic model of the sprayer is based on the special geometry structure of the sprayer, and describes the motion law of the sprayer in terms of the spatial position attitude and the change of vehicle speed, which can describe the motion state of the sprayer in the low speed condition more accurately. The kinematic model can make the model not affected by the uncertainty of the vehicle, so that the model prediction controller has better control accuracy. According to the chassis structure of the sprayer, the kinematic relationships of the sprayer can be obtained as shown in Figure 3. Where θ is the heading angle of the body, R1 and R2 are the steering radius of the front and rear suspensions, and the vertical foot is S.


Figure 2 Unmanned high ground clearance sprayer

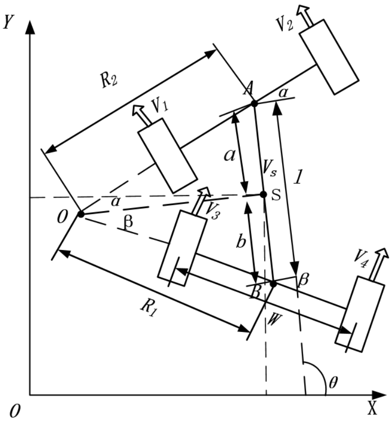

Figure 3. Kinematic relationships of sprayer

According to the Ackermann-Jeantand steering principle [6], the relationship between the four wheel speeds of the sprayer and the steering angle can be obtained as follows:

$$V_1 = V \left(\frac{1}{\cos\alpha} - \frac{W\tan\alpha}{2b} \right) \tag{1}$$

$$V_2 = V \left(\frac{1}{\cos\alpha} + \frac{W\tan\alpha}{2a} \right) \tag{2}$$

$$V_3 = V \left(\frac{1}{\cos\beta} - \frac{W\tan\beta}{2b} \right) \tag{3}$$

$$V_4 = V \left(\frac{1}{\cos\beta} + \frac{W\tan\beta}{2b} \right) \tag{4}$$

where α and β are the steering angles of the front and rear axes of the sprayer. a, b is the distance from the front and rear steering axles to the center of mass of the vehicle, which is equal in the ideal steering situation. W is the left and right wheelbase, and V is the longitudinal speed of the sprayer. The analysis of the kinematic model of the sprayer leads to the state-space equations of the sprayer in the global coordinate system.

$$\dot{X} = V\cos\phi \tag{5}$$

$$\dot{Y} = \mathrm{V}\sin\phi \tag{6}$$

$$\dot{\phi} = \frac{2Vtan\delta_f}{l} \tag{7}$$

where X, Y is the position of the sprayer on the global coordinate system, ϕ is the heading angle of the sprayer, V is the longitudinal velocity, and δ_f is the front wheel steering angle.

3. Design of Model Predictive Controller (MPC)

MPC control uses the kinematic model developed above, it predicts the future output of the system based on the current state quantities and the expected output of the system in the model [7]. Select the state quantity of the sprayer $x = [X, Y, \phi]^T$, the control quantity $u = \left[V, \delta_f\right]^T$, and the state space equation of the sprayer can be written as:

$$\dot{x} = f(x, u) \tag{8}$$

In order to simplify the model, select a reference state x_{ref}, which is expanded at x_{ref} by Taylor's formula. The equation for the state space with respect to the state quantity x error can be obtained:

$$\dot{\tilde{x}} = \dot{x} - \dot{x}_{ref} = \frac{\partial f}{\partial x}(x - x_{ref}) + \frac{\partial f}{\partial u}(u - u_{ref}) \tag{9}$$

$$\dot{\tilde{x}} = A\tilde{x} + B\tilde{u} \tag{10}$$

where A and B are Jacobi matrices of f with respect to x and u.The above equation is discretized by Forward-Euler method by adding the sampling time. The discretized state space equation is as follows:

$$\dot{\tilde{x}} = \frac{\tilde{x}(k+1)-\tilde{x}(k)}{\tau} = A\tilde{x}(k) + B\tilde{u}(k) \tag{11}$$

The following equations can be obtained:

$$\tilde{x}(k+1)=(I+TA)\tilde{x}(k) + TB\tilde{u}(k) \tag{12}$$

$$\tilde{x}(k+1)=A_{k,t}\tilde{x}(k)+B_{k,t}\tilde{u}(k) \tag{13}$$

According to the state space equations after discretization, combined with the actual situation of spraying machine control, the prediction equation is written. The prediction equation is expressed as follows:

$$Y = \Psi\tilde{x}(k) + \theta\tilde{u}(k) \tag{14}$$

Where Y is the output quantity matrix of the system; Ψ and $\theta$are the iteration matrices of the equation.

In the solution process, the control sequence in the control time domain is finally obtained by setting a suitable optimization objective and solving it since the increment of the control quantity is introduced. The selected optimization objectives are as follows:

$$J(k) = (Y - Y_{ref})^T Q(Y - Y_{ref}) + \Delta u^T R\Delta u + \rho\varepsilon^2 \quad = (E + \theta\Delta u)^T Q(E + \theta\Delta u) + \Delta u^T R\Delta u + \rho\varepsilon^2$$
$$= \Delta u^T(\theta^T Q\theta + R)\Delta u + \rho\varepsilon^2 + 2E^T Q\theta\Delta u \tag{15}$$

Q, R is the weight matrix. In the actual control system, the relaxation factor ε and some constraints are added to prevent the situation of no feasible solution. The constraints are as follows：

$$u_{min}(t+k) \le u(t+k) \le u_{max}(t+k) \tag{16}$$

$$\Delta u_{min}(t+k) \le \Delta u(t+k) \le \Delta u_{max}(t+k) \tag{17}$$

$$k = 0,1,2,\ldots,N_c - 1$$

At the end of each control cycle, a series of control input increments are obtained as in equation (18) to get the current control amount of the system. At the next moment, the output of the next time domain is predicted based on the current amount of state of the sprayer, which in turn gives a new control increment. The control system is cycled through until the entire control process is completed.

$$u(t) = u(t-1) + \Delta u_t \tag{18}$$

4.Design of Self-correcting controller

4.1 Design principle of Self-correcting controller

The design idea of the self-correcting controller is to introduce the trend of lateral deviation over a period of time to monitor the control effect of the model predictive control controller, and to calculate the desired compensation angle of the steering wheel δ_c in real time, which is used to reduce the lateral deviation and the steering angle output from the model predictive controller in ADAMS. The model predictive controller has better tracking effect in straight path and small curvature path tracking process, while the tracking effect in larger curvature path tracking process may differ greatly from the desired tracking effect. Therefore, the change in lateral deviation at a certain time can be used to measure the fit of the tracking path of the sprayer, i.e.: the trend of lateral deviation. If the trend of lateral deviation is large, the compensation angle of the desired steering angle should be output to adjust the body attitude to reduce the lateral deviation, and if the trend of lateral deviation is constant and the lateral deviation is small at this moment, the compensation of steering angle should not be increased, or increase a small angle compensation. The trend of the lateral deviation can be expressed as follows:

$$ec = \frac{y_t - y_{t-\Delta t}}{\Delta t} \tag{19}$$

where y_t is the lateral deviation value at the moment and $y_{t-\Delta t}$ is the lateral deviation value at the moment t-Δt. Since fuzzy control does not depend on the exact mathematical model of the controlled object and can use the control law to describe the relationship between the system variables, fuzzy control is used to design the Self-correcting controller.

4.2 Design of the fuzzy controller

The fuzzy controller takes the trend of lateral deviation and lateral deviation as input and the compensation angle of steering angle as output. The compensation angle is added to the sprayer steering angle output from the MPC and used to change the sprayer driving attitude, which in turn improves the accuracy of sprayer path tracking. Fuzzy control uses operational experience to create a library of fuzzy control rules to output the desired control quantities. The fuzzy quantities corresponding to the input variables e, ec and output variable u are E, EC and U. The fuzzy subsets of E EC and U are {NB, NM, NS, ZO, PS, PM, PB}, The affiliation functions for both input and output are Gaussian functions.

According to the actual driving experience of the driver, the design principle of the fuzzy controller is: when driving in a straight line, the tracking effect of the model prediction controller is better, the lateral deviation is smaller, and its change trend is also smaller, considering the problem of system stability, the control amount of the self-correcting controller output should be small angle compensation or no compensation. At the turn, the lateral deviation is relatively large, and if the absolute value of the trend amount of deviation increases, the self-correcting controller should output the compensation angle to make the sprayer move in the direction of deviation reduction. According to the above design principles, the fuzzy control rules table can be obtained as in Table 1. The Mamdani method is used to establish the fuzzy control rule base. The MIN-MAX-center of gravity method is used to defuzzify and transform the output into an accurate quantity.

Table 1：Fuzzy control rule table

E \ EC	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PB	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	ZO	ZO	NS
NS	PM	PM	PS	PS	ZO	NS	NM
ZO	PM	PS	PS	ZO	NS	NS	NM
PS	PM	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	ZO	NS	NM	NB	NB
PB	ZO	ZO	NS	NM	NB	NB	NB

5. Simulation results and analysis

The MPC controller and the self-correcting controller are built in MATLAB/Simulink, and the parameters used for the model prediction controller and their values are shown in Table 2. The sprayer model is built in ADAMS View, and the MPC-based path tracking and self-correcting control scheme is analyzed by joint simulation with Matlab and Adams. The continuous U-bend condition is selected for simulation verification of the control system.

Table 2：Parameters and their values used by MPC

Parameters	value
Sampling time	0.05s
Control time domain N_c	45
Predicted time domain N_p	90

Weight matrix Q	210
Weight matrix R	35
Extreme value of wheel turning angle	10°
Extreme value of wheel turning angle increment	0.8°
Relaxation factor	100

5.1 Comparison of simulated working conditions based on MPC path tracking controller

Figure 4 shows the path tracking of the sprayer when based on the MPC path tracking controller. The blue solid line is the actual running trajectory and the red dashed line is the expected reference trajectory. The two curves overlap highly at the straight line and the lateral deviation is almost 0. There is a slight error at the turn, but it is still within the acceptable range, which shows that the path tracking control has a good control effect under MPC control. Figure 5 shows the running speed of the sprayer, the speed of the sprayer is always maintained at 1m/s in the straight line driving part, and the speed fluctuates slightly at the turn, but the speed can be adjusted to 1m/s quickly because the model prediction control has better dynamic control performance.

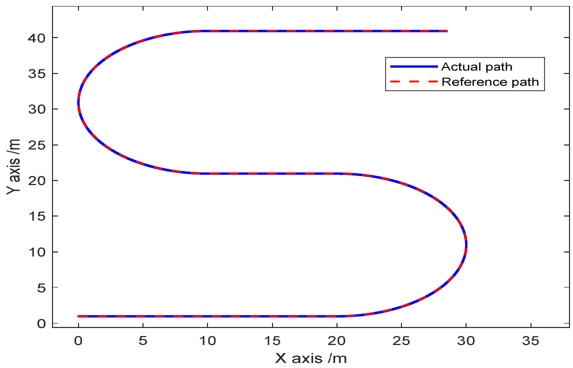

Figure 4.Comparison of reference path and actual path

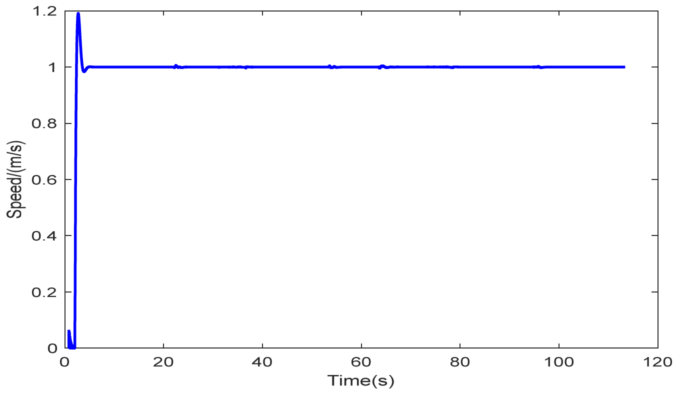

Figure 5. Spraying machine speed

Figure 6 shows the lateral deviation of the sprayer. In the straight driving part, the MPC controller has good tracking effect in path tracking, and in the curved driving, during the turning of the sprayer, the MPC controller produces certain deviation in path tracking due to the large curvature of the curves, and the maximum lateral deviation reaches 0.03 m, which verifies that the model prediction controller has high control accuracy. Figure 7 shows the steering angle waveform of the sprayer, where the steering angle is 0°in the straight part and 4.866° in the turn and remains constant.

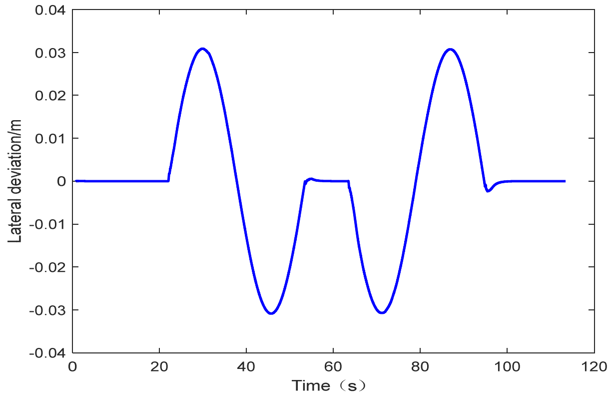

Figure 6 . Lateral deviation of the sprayer

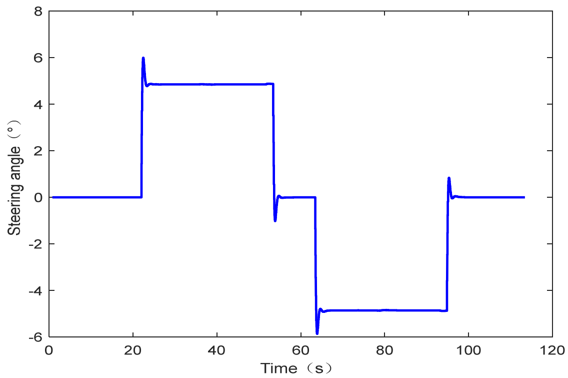

Figure 7. the steering angle waveform of the sprayer

5.2 Simulation conditions when adding the Self-correcting controller

The model predicts that the controller tracks better in tracking straight parts and small curvature paths, but the tracking effect may differ significantly from the desired tracking effect during tracking of larger curvature paths at turns. In order to improve the tracking accuracy of the controller, the self-correcting controller is designed to have higher path tracking accuracy in large curvature paths. Figure 8 shows the machine path tracking of the sprayer with the introduction of the self-correcting controller. Both curves are highly overlapping in the straight driving part as well as in the turns, and the lateral deviation is reduced in the turns. It can be verified that the system still has good applicability after adding the self-calibration controller. Figure 9 shows the speed waveform of the sprayer when the Self-correcting controller is introduced. The speed of the sprayer is always maintained at 1m/s in the straight driving part, and the speed fluctuates slightly at the turns, which is basically consistent with the effect of the model prediction control alone.

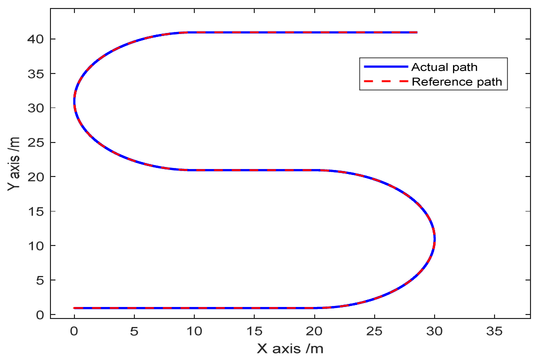

Figure 8.Comparison of reference path and actual path

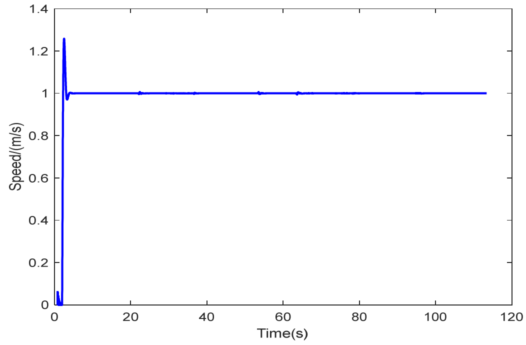

Figure 9. Spraying machine speed

Figure 10 shows the lateral deviation of the sprayer, and in the straight line part, the lateral deviation is always controlled at 0. In the curved driving, due to the addition of the self-correcting controller, the lateral deviation is greatly reduced compared with the model prediction control alone, and the maximum lateral deviation reaches 0.0141 m, which verifies the feasibility of the self-correcting controller. Figure 11 shows the comparison of the steering angle of the sprayer before and after the addition of the self-correcting controller. In the straight line part, the self-correcting controller does not produce a control effect due to the small lateral deviation, and the steering angle remains 0°. At the turn, the lateral deviation increases, and the Self-correcting controller produces the corresponding control effect and outputs the corresponding compensation angle to the model prediction controller, resulting in a slight fluctuation of the steering angle.

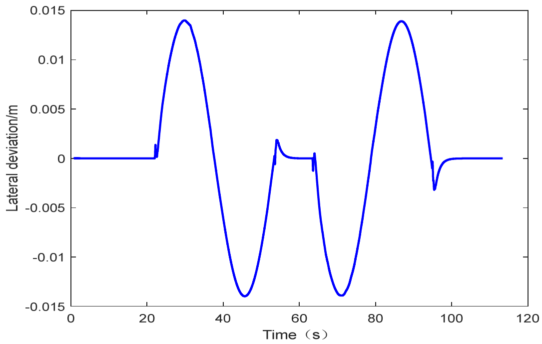

Figure 10. Lateral deviation of the sprayer

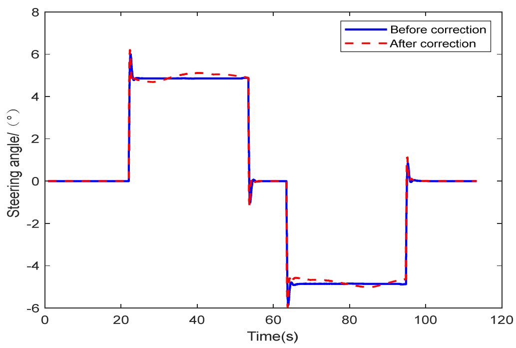

Figure 11. Comparison of steering angle before and after correction

6. Conclusion

In this paper, we develop a new front-rear dual steering axle 4WID electric drive chassis structure of high ground clearance sprayer to address the shortcomings of the traditional high ground clearance sprayer, and establish the kinematic model of the sprayer, and construct the path tracking controller and self-correcting controller based on the kinematic model of the sprayer respectively. The joint ADAMS/MATLAB simulation results show that the lateral deviation of the model predictive control alone is controlled within 0.03m. After adding the self-correcting controller, the lateral deviation of the sprayer can be controlled within 0.0141 m, which verifies the feasibility of the self-correcting controller.

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