Cascaded navigation control for agricultural vehicles tracking straight paths

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Abstract: In precision agriculture (PA), an agricultural vehicle navigation system is essential and the navigation control accuracy is important in this system. As straight path tracking is the major operating mode of agricultural vehicles on large fields, a cascaded navigation control method for straight path tracking is proposed in this study. Firstly, a cascaded navigation control structure for the agricultural vehicle was discussed. Based on this structure, the navigation control task was decomposed into two cascaded control tasks, namely, the path tracking control task and the steering control task. Secondly, a relative kinematics model of agricultural vehicles was deduced, and an optimal Proportional-Derivative (PD) method based on the deduced model was developed in the path tracking control task. Then, an improved PD method based on a transition process was proposed in the steering control task to enhance the performance of the steering control subsystem. Finally, the effectiveness and the superiority of the proposed method were verified by a series of experiments. Results of the experimental data analysis show that mean value of the lateral position deviation is 0.02 m and standard deviation of the lateral position deviation is 0.04 m, which proves that the proposed method has achieved satisfactory effects on the straight path tracking of agricultural vehicles.

Keywords: agricultural vehicle, navigation control, relative kinematics model, optimal PD controller, improved PD controller
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1 Introduction

In the context of precision agriculture (PA), automatic navigation for agricultural vehicles is one of the key technologies to realize precision farming operations, such as planting, fertilization, spraying, tillage, cultivation. Research on agricultural vehicles navigation control has become very popular in the last ten years and they could be affordable for farmers, dependable autonomous vehicles for agricultural applications in the near future.

For most of the farming operations mentioned above, the navigation control accuracy of an agricultural vehicle navigation system is essential. From the perspective of control, there is a long history in dealing with the navigation control problem of agricultural vehicles[1,2]. Generally, there are mainly two types of control methods for an agricultural vehicle navigation system, which are model-based methods and model-free methods.

Model-based method can be further divided into the kinematics model-based method and dynamics model-based method. Luo et al.[3] developed a navigation control system for Dongfanghong X-804 tractors and designed a navigation controller based on Ellis kinematics model. Zhang et al.[4] constructed the kinematics of the cucumber harvesting robot manipulator using D-H coordinate frame model. The inverse kinematics which provided a foundation for trajectory planning was solved with inverse transform technique. Zhu et al.[5] created a suboptimal reference course and

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launched a path-tracking controller based on a vehicle kinematics model for headland turning of a tractor. Since the kinematics model-based control method did not consider the effect of the dynamics parameters, some researchers also developed the dynamics model-based methods. Qiu[6] and Zhang et al.[7] developed a dynamic path search algorithm for tractor automatic navigation and used on-board RTK−DGPS (Real time kinematic differential GPS) and FOG (Fiber optic gyroscope) sensors to provide real-time tractor posture measurements. Shamshiri and Ismail[8] applied the nonlinear Lyapunov function based control method to joint angles tracking of a two-link oil palm harvesting robot manipulator with uncertain system parameters. Derrick et al.[9-11] proposed a model reference adaptive control method based on a yaw dynamics model to compensate yaw rate variations caused by the load changes of implements attached to the tractor. Zhou et al.[12] deduced the kinematic and dynamic models of off-road mobile robots with slipping parameters, and then solved the problems of slippage modeling and tracking control for the off-road mobile robot. In addition, Zhou et al.[13] also studied the real-time terrain modeling problem of off-road mobile robots and achieved the 3D localization of the robot in outdoor environment.

As for the model-free methods, Huang et al.[14] used the BP neutral network to determine look-ahead distance in a pure pursuit method and then obtained a desired steering angle based on the pure pursuit method. Ding and Wang[15] constructed a fuzzy Proportional-Derivative (PD) controller in a vision-based navigation system. Antonelli et al.[16] proposed a path following approach based on a fuzzy-logic set of rules. The input to the fuzzy system was represented by approximate information concerning the next bend ahead the vehicle and the corresponding output was the cruise velocity[16]. Chen et al.[17] applied the neural network, which enabled the controller with self-learning ability, into the control of autonomous agricultural vehicles. Lian et al.[18] developed a fuzzy controller for an agricultural vehicle navigation system. The input parameters of the controller were the orientation deviation and the steering angle of the front wheel, and the output parameter was the rate of the steering actuator motor[18]. Zhang et al.[19] developed a fuzzy-adaptive control method for off-road vehicle guidance system, and the designed control method could effectively weaken the control process overshoot.

In a word, to meet the growing high precision demands in an agricultural vehicle navigation control system, many control methods have been proposed and satisfactory results have been reported. However, there exist some strict application constraints in these methods. For example, dynamic model parameters are hard to obtain in the dynamics model-based methods; performance index of navigation control system is not optimal, or the design of the model-free method requires experience knowledge and complex training process.

In view of the above problems, this study proposes a cascaded navigation control method that consists of the path tracking control method and the steering control method. In the path tracking control subsystem, an optimal PD method is to be designed as the path tracking control method to ensure that the vehicle optimally tracks the path. In the steering control subsystem, an improved PD method is to be developed as the steering control method to enhance the performance of the steering control subsystem.

The cascaded navigation control structure, the path tracking control method, the steering control method, and the effectiveness and the superiority of the proposed method are introduced below.

2 Cascaded navigation control structure

The control diagram of the agricultural vehicle navigation system based on the cascaded navigation control structure is shown in Figure 1. The cascaded navigation control structure is advantageous because the two control tasks, which are the path tracking control task and the steering control task, can be individually controlled by using different control techniques.

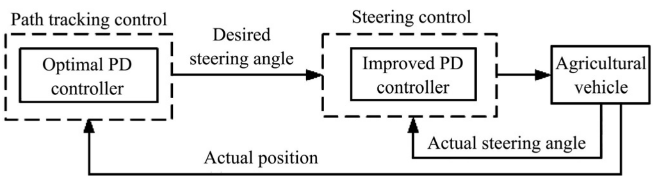


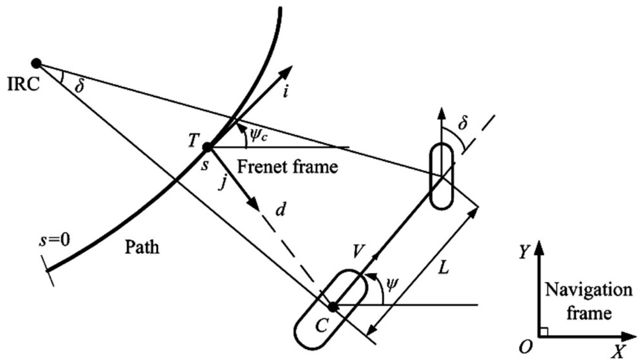
Figure 1 Diagram of the agricultural vehicle navigation control system

Since the kinematics model of agricultural vehicles can be deduced easily, we can utilize the model-based method to optimize the parameters of the PD controller in the path tracking control task. The path tracking controller based on the optimal PD control method determines the desired steering angles optimally. Then, the steering controller regulates the steering subsystem to track the desired steering angles quickly and without overshooting by using the transient process-based PD method (the improved PD method). The method does not need the steering subsystem model which is difficulty to obtain.

3 Path tracking control method

3.1 Relative kinematics model

As it is shown in Figure 2, we defined the navigation frame and the Frenet frame. Suppose that the vehicle mass is totally carried on the rear axle, we can choose point C as the control point of the vehicle. The point C orthogonally projects to the point T on the path.



Note: V is the longitudinal speed of the vehicle; Ψ is the orientation of the vehicle centerline with respect to the X axis of the navigation frame; δ is the front wheel steering angle; L is the wheelbase of the vehicle; d is the lateral deviation of the agricultural vehicle with respect to the reference path. When the vehicle locates on the left side of the path, the value of d is negative, otherwise it is positive; s is the curvilinear coordinate of point T along the reference path; Ψ_c denotes the tangent orientation at point T on the reference path in the navigation frame; θ_e stands for the heading angle deviation of the vehicle with respect to the reference path.

Figure 2 Correlation between the vehicle and the path

We can easily deduce the agricultural vehicle kinematics model, which indicates the relative position and attitude relation between the agricultural vehicle and the straight path, in the Frenet frame as follows.

$$\begin{cases} \dot{d} = V\sin\theta_e \\ \dot{\theta}_e = \dfrac{V\tan\delta}{L} \end{cases} \tag{1}$$

We can employ first-order Taylor series to approximate Equation (1) if both θ_e and δ are small. The small angle hypothesis is reasonable for agricultural vehicles tracking a straight path. Consequently, we rewrite the model by the state equation as follows.

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\delta \tag{2}$$

where

$$\boldsymbol{x} = [d, \theta_e]^{\mathrm{T}},\quad \boldsymbol{A} = \begin{bmatrix} 0 & V \\ 0 & 0 \end{bmatrix} \text{ and } \boldsymbol{B} = \begin{bmatrix} 0 \\ \dfrac{V}{L} \end{bmatrix}$$

Then, the transfer function of the agricultural vehicle can be defined as:

$$G(s) = \frac{d(s)}{\delta(s)} = \frac{V^2}{Ls^2} \tag{3}$$

3.2 Path tracking control method based on optimal PD

The Equation (3) is not the agricultural vehicle itself but its model and is used only for the purpose of the controller design. The controller, once designed, should be applied to the vehicle but not the model. According to classic control theory, a PD controller is adequate for such kind of model. Therefore, an optimal PD controller based on the deduced model was proposed in this study and it guaranteed that the vehicle tracked the desired path optimally. The optimal parameters of the PD controller were determined by the methodology of linear quadric regulator (LQR). The control diagram is shown in Figure 3, where $G_c^*(s)$ is the transfer function of the optimal PD controller, e is control error, r and d are command signal and output respectively.

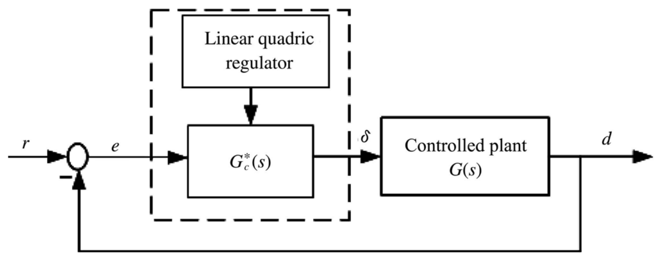


Figure 3 The control diagram with the optimal PD controller

In this study, our control objective is to ensure d equals zero, so the command signal r is zero. Hence, the path tracking control subsystem is described by equations as follows.

$$\begin{cases} \delta(s) = G_c^*(s)e(s) \\ G_c^*(s) = k_p^* + k_d^* s \\ e(s) = -d(s) \\ d(s) = G(s)\delta(s) \end{cases} \tag{4}$$

In order to find the optimal controller parameters k^*_p and k^*_d by using LQR, we introduced the state vector $\boldsymbol{z} = [e \quad \dot{e}]^{\mathrm{T}}$. According to Equation (4), we can deduce:

$$\ddot{e} = -\frac{V^2}{L}\delta \tag{5}$$

So the differential equation of $\boldsymbol{z}$ is

$$\begin{aligned} \dot{\boldsymbol{z}} &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \boldsymbol{z} + \begin{bmatrix} 0 \\ -\frac{V^2}{L} \end{bmatrix} \delta \\ &= A'\boldsymbol{z} + B'\delta \end{aligned} \tag{6}$$

Considering that the speed of the agricultural vehicle is relatively slow and stable, we can assume that the speed of the agricultural vehicle is constant. Hence, the system demonstrated by the state Equation (6) is linear time-invariant. According to LQR theory, we used the performance index function (7) and obtained the desired steering angle expression as Equation (8).

$$\mathrm{J} = \frac{1}{2}\int_0^\infty (\boldsymbol{z}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{z} + \delta^{\mathrm{T}}\boldsymbol{R}\delta)dt \tag{7}$$

Where $\boldsymbol{Q} = \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix} \geq 0$ and $\boldsymbol{R} = r > 0$ are the state weighting matrix and the control weighting matrix respectively.

$$\begin{aligned} \delta &= -\boldsymbol{R}^{-1}\boldsymbol{B}'^{\mathrm{T}}\boldsymbol{P}\boldsymbol{z} \\ &= \frac{V^2}{rL}[p_{12}, p_{22}]\boldsymbol{z} \end{aligned} \tag{8}$$

where, P_{12} and P_{22} are the elements of symmetric positive-definite solution matrix $\boldsymbol{P} = \begin{bmatrix} p_{11} & p_{12} \\ p_{12} & p_{22} \end{bmatrix}$ of the algebraic Riccati equation.

Solving the algebraic Riccati Equation (9), we can obtain Equation (10).

$$\boldsymbol{P}\boldsymbol{A}' + \boldsymbol{A}'^{\mathrm{T}}\boldsymbol{P} - \boldsymbol{P}\boldsymbol{B}'\boldsymbol{R}^{-1}\boldsymbol{B}'^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{Q} = 0 \tag{9}$$

$$\begin{cases} p_{12} = \frac{L}{V^2}\sqrt{ar} \\ p_{22} = \frac{L}{V^2}\sqrt{br + \frac{2Lr\sqrt{ar}}{V^2}} \end{cases} \tag{10}$$

According to Equations (8) and (10), the desired steering angles can be further described as:

$$\begin{aligned} \delta &= [\frac{\sqrt{ar}}{r}, \frac{\sqrt{br + \frac{2Lr\sqrt{ar}}{V^2}}}{r}]\boldsymbol{z} \\ &= [\frac{\sqrt{ar}}{r}, \frac{\sqrt{br + \frac{2Lr\sqrt{ar}}{V^2}}}{r}]\begin{bmatrix} e \\ \dot{e} \end{bmatrix} \end{aligned} \tag{11}$$

Thus, we can obtain that explicit expressions of the optimal PD controller parameters k^*_p and k^*_d are:

$$\begin{cases} k_p^* = \frac{\sqrt{ar}}{r} \\ k_d^* = \frac{\sqrt{br + \frac{2Lr\sqrt{ar}}{V^2}}}{r} \end{cases} \tag{12}$$

So far, the optimal PD controller parameters are obtained according to Equation (12), which meets the optimal performance index (7).

Furthermore, in order to verify the closed-loop stability of the control system, the closed-loop system characteristic equation is deduced as follows:

$$D(s) = Ls^2 + k_d^* V^2 s + k_p^* V^2 = 0$$

Since

$$\begin{aligned} a_0 &= L > 0 \\ a_1 &= k_d^* V^2 > 0 \\ a_2 &= k_p^* V^2 > 0 \end{aligned} \tag{13}$$

the closed-loop system is stable according to Hurwitz criterion. However, there exists a delay in the actuator response with respect to the desired steering angle input. Due to the delay effect, the path tacking control subsystem may be unstable. So the speed of the agricultural vehicle should not be too fast in practical application. Fortunately, the speed ranges from 0.5 m/s to 2 m/s in most precision farming applications. Therefore, we can neglect the delay impact within the speed range.

4 Steering control method

As for the steering control subsystem, we hope that it can track the desired steering angle quickly and without overshooting. In addition, we cannot utilize model-based control methods to control the steering subsystem because it is difficult to obtain accurate steering subsystem model. Therefore, an improved PD steering control method based on a transition process was proposed in the study.

First, we arranged a proper transition process according to the control objective. Then, we adopted the transition process rather than the desired constant steering angle as the command value of the steering subsystem in each control period. The benefits to do this are that we can decrease the initial error of the subsystem and choose bigger feedback gains to fasten the system response without producing big initial shock force to the steering subsystem. Finally, the PD control structure was used as the control structure of the steering control method.

The transition process must meet two requirements: the executive capacity of the actuator and reaching the command value of the desired steering angle smoothly during the transient process time.

According to these two requirements, we may utilize the following function (14) to arrange the transition process of the steering control subsystem.

$$\mathrm{h}(T,t)=\begin{cases}\dfrac{\delta-\delta_{pre}}{2}(1+\sin(\pi(\dfrac{t}{T}-\dfrac{1}{2})))+\delta_{pre} & t\le T\\ \delta & t>T\end{cases} \tag{14}$$

where, T is the transition process time; δ is the desired steering angle; δ_{pre} is the previous desired steering angle.

The function, rather than the desired constant steering angle from the upper level path tracking control, determines the desired reference input trajectory of the steering control subsystem, which starts from δ_{pre} (initial time) to δ (T time).

According to the arranged transition process determined by the function $\mathrm{h}(T,t)$, we can easily obtain the differential expression of the function as follows.

$$d\,\mathrm{h}(T,t)=\begin{cases}\dfrac{(\delta-\delta_{pre})\pi}{2T}\cos(\pi(\dfrac{t}{T}-\dfrac{1}{2})) & t\le T\\ 0 & t>T\end{cases} \tag{15}$$

If the current actual steering angle is δ_a, the error derivative is defined as $d\,\mathrm{h}(T,t)-\dot{\delta}_a$ between the desired steering angle output and the actual steering angle output.

Subsequently, we utilized the popular PD controller structure to control the steering subsystem. Therefore, the algorithm of the improved PD controller is given as follows.

$$u=k_{pi}(\mathrm{h}(T,t)-\delta_a)+k_{di}(d\,\mathrm{h}(T,t)-\dot{\delta}_a) \tag{16}$$

where, u is the control input of the steering actuator; k_{pi} and k_{di} are the proportional gain and differential gain of the improved PD controller, respectively.

5 Experimental verification

5.1 Experimental platform

The developed control method was verified by a series of experiments on a tractor as shown in Figure 4. The 59 kW and rear-wheel drive tractor was modified and equipped with the navigation system. The geometric and inertial parameters of the tractor are shown in Table 1.

Figure 4 Tractor equipped with navigation system for experimental verification

Table 1 Main specifications of the experimental tractor

Parameter	Value
Mass, kg	3 115
Wheelbase, mm	2 188
Turning radius, mm	3 800
Front track width, mm	1 600
Rear track width, mm	1 730

5.2 Description of the experiments

The experimental platform described above was equipped with the data acquisition system and the navigation system based on the navigation control method proposed in the study. In the navigation system, we selected the NovAtel RTK GPS receiver as the position sensor and its accuracy of location measurement is 1 cm + 1 ppm (circular error probability). The steering actuator uses the electronic proportional valve SP08-47C.

Experiments of straight path tracking were performed at different speeds (0.8 m/s and 1.2 m/s). In order to compare with the other methods, we also carried out the straight path tracking experiments by using the pure pursuit method (PPM).

In the experiments, we chose $a = 0.01$, $b = 0.2$ and $r = 1$, and determined the optimal PD (OPD) controller parameters k^*_p and k^*_d according to Equation (12). However, since it is difficult to obtain accurate steering subsystem model, the trial-and-error method is used to set the proportional gain k_{pi} and the differential gain k_{di} of the improved PD (IPD) controller as 20 and 0.5, respectively. The transition process time T is 0.3 s according to the executive capacity of the steering subsystem.

5.3 Experimental results and discussion

The proposed steering control method (IPD method) was first tested when the agricultural vehicle automatically tracked the path at the speeds of 0.8 m/s and 1.2 m/s respectively. Figures 5 and 6 show the tracking effects of desired steering angles by using the IPD method. As it can be seen, the steering control subsystem has good tracking accuracy and tracking speediness. Since we arranged and adopted the transition process rather than the desired constant steering angle as the command value of the steering control subsystem in every control period, the initial error of the subsystem decreased mostly. Therefore, we can choose a bigger proportional gain to fasten the system response without producing big initial shock force to the steering subsystem. During the process of the steering control experiment, we set the proportional gain of IPD method as k_{pi}=20 by using trial and error method. However, if the traditional PID method is used in the steering control subsystem, since the desired steering angle is constant, it will cause the set point jump of steering control subsystem. Consequently, the initial error is large. So, in order to avoid the initial shock force as well as to weaken the response overshoot, the proportional gain of the traditional PID method should be set smaller than that of the IPD method. However, the smaller proportional gain of traditional PID method will slow down the response speed of steering control subsystem for the agricultural vehicle. From the perspective, using the transition process in the IPD method will quicken the response speed of the steering control subsystem. In addition, data analysis results of the IPD method also reveal that mean value of steering angle tracking errors is 0.5° and the mean delay time of tracking is 0.3 s.

In order to verify the consistency of the control performance of the proposed optimal PD method (OPD method), two different experiments were conducted. In the first experiment, the OPD method was tested on the agricultural vehicle whose travel speed was set at 0.8 m/s to verify the consistency of control performance at the same speed. For this experiment, two runs were made with the proposed OPD method. In each run, the agricultural vehicle was started off the path by approximately 0.3 m. Figure 7 indicates the path tracking

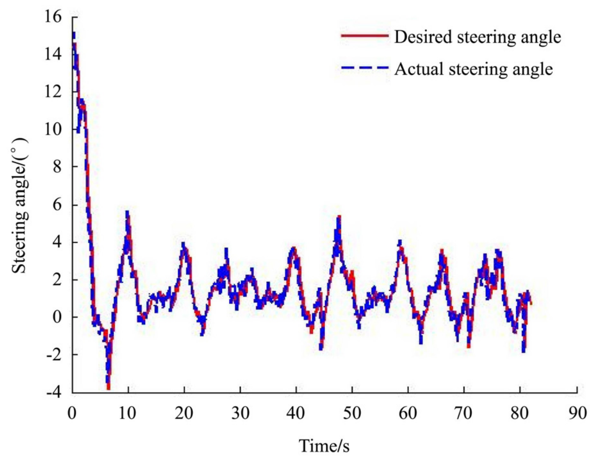


Figure 5 Steering angles tracking at the speed of 0.8 m/s

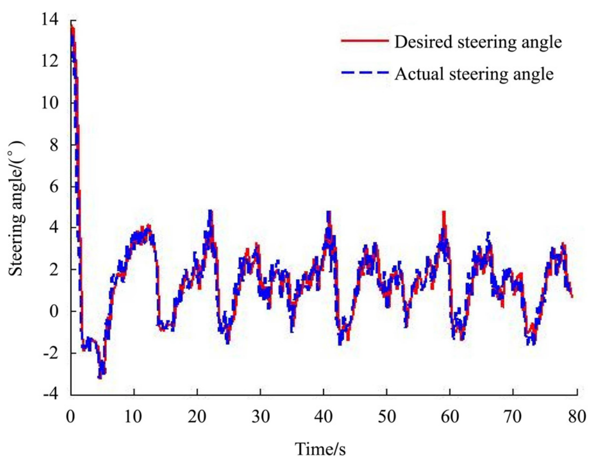


Figure 6 Steering angles tracking at the speed of 1.2 m/s

errors of the automatic navigation. From the figure, we concluded that the automatic navigation control system with the OPD method has very good response speed. Moreover, the control process overshoot can be effectively weakened and the overshoot is less than 0.08 m. Only the steady-state portion of the runs was used in the analysis of the deviation data. The statistical results from the experiments showed that, in the two runs, the good path tracking performance was obtained, and mean value of the lateral position deviation was 0.02 m and standard deviation of lateral position deviation was 0.04 m. Therefore, it is found that the proposed OPD method has the consistency of the control performance at the same speed. In the second experiment, we tested the proposed OPD method at different travel speeds of the agricultural vehicle. For this experiment, the agricultural vehicle realized automatic navigation control at speeds of 1.2 m/s and 0.8 m/s, respectively. Similarly, the experiment was performed at an initial lateral deviation value of about 0.3 m/s. Figure 8 shows the lateral position error response of the agricultural vehicle at different speeds. The steady-state portion of the runs was also used in the analysis of experiment results, the statistical results show that the path tracking effects of the proposed OPD method are basically the same when the agricultural vehicle automatically tracks the straight path at speeds of 0.8 m/s and 1.2 m/s. Therefore, we can conclude that the navigation control system with the OPD method has the consistency with respect to the path tracking performance.

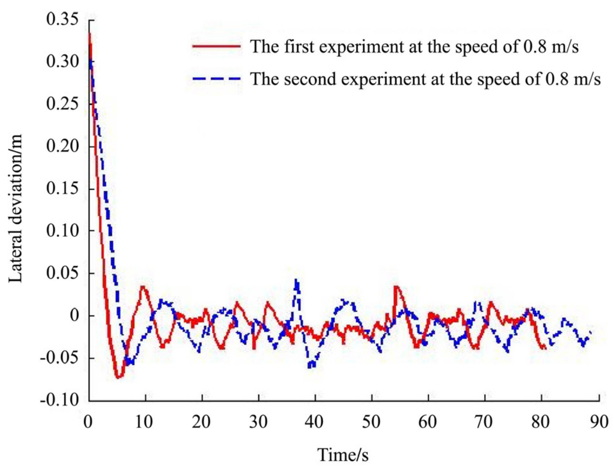


Figure 7 Lateral position deviation at the speed of 0.8 m/s

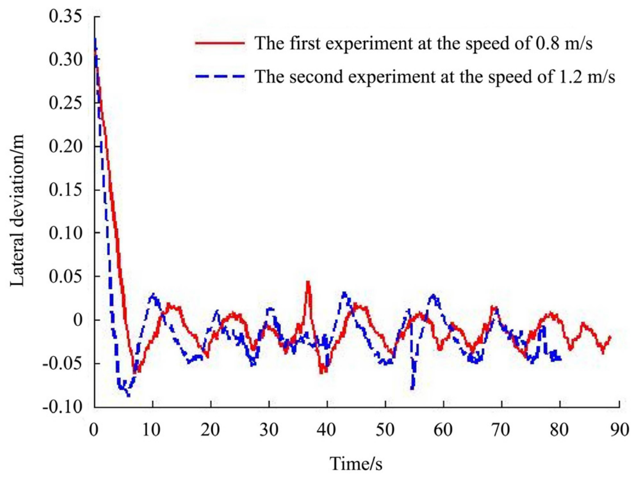


Figure 8 Lateral position deviation at different speeds of 0.8 m/s and 1.2 m/s

Further, in order to verify the effectiveness and superiority of the proposed OPD method, we also carried out the comparison experiment. For this experiment, we respectively utilized the proposed OPD method and the commonly used pure pursuit model method (PPM method) as the path tracking control method in the navigation control system. The steering control method in the comparison experiment was the proposed steering control method (IPD method). Figure 9 indicates the comparison results of the experiments using the proposed OPD method and the PPM method. From the figure, we can obviously conclude that the proposed OPD method has better performance than the PPM method. From the experiment, it is found that the control parameter (look-ahead distance) in the PPM method is sensitive to the speed and initial error. Therefore, the control parameter of the PPM method is difficult to determine. However, the control parameters of the OPD method can be uniquely determined with respect to a certain performance index by choosing the weighting matrix, as shown in section 5.2. In addition, the data statistical results of the experiments with the OPD method also show that mean value of the lateral position deviation is less than 0.02 m and standard deviation of lateral position deviation is less than 0.04 m. They are better than those of the PPM method. Therefore, the effectiveness and the superiority of the proposed OPD method were obviously verified by agricultural vehicle navigation experiments.

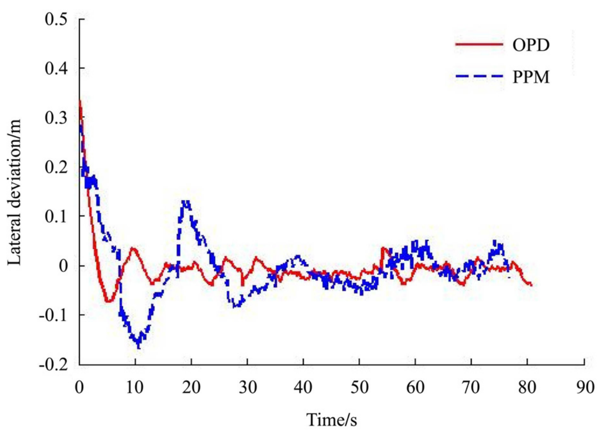


Figure 9 Lateral position deviation of the OPD method and the PPM method

6 Conclusions and future work

In this study, a cascaded navigation control method for straight path tracking was presented. Firstly, the study deduced a relative kinematics model of agricultural vehicles in the Frenet frame. Secondly, the study developed the optimal PD method as the path tracking control method to control the agricultural vehicle to track straight paths optimally. The optimal parameters of the optimal PD method were obtained by the LQR method based on the deduced relative kinematics model. Then, because of the difficulty to obtain the accurate model of the steering subsystem, the study proposed the improved PD control method based on the transition process as the steering control method, which guaranteed that the steering control subsystem tracked the desired steering angle quickly and without producing big initial shock force to the steering subsystem. Finally, in order to test and verify the proposed method, the study carried out automatic navigation experiments of the agriculture vehicle. From the experiment results, the effectiveness and the superiority of the proposed navigation control method were verified. The analysis results of experimental data demonstrate that mean value of the lateral position deviation is 0.02 m and standard deviation of lateral position deviation is less than 0.04 m. The results also reveal that mean value of steering angle tracking errors is 0.5° and the mean delay time of tacking is 0.3 s.

Some improvements can be expected in the future. For example, we may extend the navigation control method proposed in this study to track curve paths and design a robust or an adaptive control method to compensate yaw dynamics disturbances.

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