DEVELOPMENT AND SIMULATION OF THE PATH TRACKING CONTROL SYSTEM FOR COMBINE HARVESTERS BASED ON MPC

Xiaolian LÜ [1], Jialong TANG [2], Qian LI [2], Ruijuan SU [1], Xiaorong LÜ [2, *]

To improve the path tracking accuracy and stability of the harvester, a method based on Model Predictive Control (MPC) was proposed and simulation tests were carried out. The overall framework of the system was designed, the kinematic modeling was completed, the control constraints were determined, and the MPC controller was designed. The simulation test results show that under the optimal time-domain parameters N_p=15 and N_c=4, the minimum tracking deviation of the circular path is 3.81 cm, and the deviation of the double-shift path is less than 0.5 cm after stabilization. Under the same row spacing, the tracking deviation increases with the increase of speed, and the error of the arc segment is relatively large and concentrated at the exit position. Increasing the row spacing can significantly optimize the operation effect, the maximum position deviation of the arc segment is reduced to 0.24 m, and the maximum heading angle is reduced to 9.23°. The controller has an average position deviation of less than 2 cm in straight-line tracking and an average heading angle deviation of less than 2° in arc tracking, which can meet the requirements of precise operation of the harvester.

Keywords: Path Tracking; Model Predictive Control (MPC); Control System; Simulation Analysis

1. Introduction

As a core equipment in agricultural production, the accuracy and automation level of the combined harvester determine the harvesting quality and efficiency [1], [2]. Path tracking is a key technology for the autonomous operation of harvesters. With the development of precision agriculture, it has put forward higher requirements for the control accuracy, operational stability, and anti-interference ability [3], [4]. Many scholars have carried out extensive research on path tracking control technology for agricultural machinery [5], [6], [7]. Proportional-Integral-Derivative (PID) control is widely used in agricultural machinery path tracking control due to its simple structure and easy engineering

* Corresponding author, E-mail: lvxiaorong01212@126.com
[1] College of Mechanical and Electrical Engineering, Chuzhou University, Chuzhou, Anhui, 239000, China
[2] College of Machinery & Electronics, Sichuan Agricultural University, Yaan, Sichuan, 625014, China

implementation [8], [9], [10], [11]. However, it has poor adaptability to the nonlinear characteristics and external field disturbances, resulting in insufficient tracking accuracy and stability under complex working conditions. Model Predictive Control (MPC) has the advantages of handling multiple constraints and predicting the future behaviour of systems, so that it has been widely applied [12], [13], [14]. Riikka Soitinaho et al. [15] proposed a nonlinear model predictive control (NMPC)-based path tracking and obstacle avoidance approach for agricultural front-wheel-steered tractors, and can be achieves a cross-track error (XTE) of less than 0.05m on straight sections of the reference path. Wang et al. [16] proposed a parameter adaptive MPC method, which realizes adaptive parameter adjustment through Fuzzy Control (FC) and optimizes parameters using the Particle Swarm Optimization (PSO) algorithm to determine the optimal parameter combination. Yang et al. [17] proposed an MPC control strategy based on T-S fuzzy variable weights, and the strategy has good tracking effect on 80-120 km/h double lane change, wet road and docking road. Due to the complex field operation environment of harvesters, existing research on MPC-based path tracking for agricultural machinery mostly remains in the experimental stage, and its adaptability, reliability and operation accuracy in complex working environments are difficult to meet the actual operation requirements. Therefore, conducting research on MPC-based path tracking control technology adapted to the operational characteristics of harvesters is of great engineering and practical significance for improving the accuracy and stability of autonomous driving path tracking of harvesters. This study focuses on solving problems such as the insufficient adaptability of control decisions to operational characteristics in the actual operation of harvesters. Taking the self-developed harvester as the research object and combining its actual operation conditions, a prediction model adapted to the dynamic characteristics of the harvester is constructed, the MPC constraint conditions are optimized, and a suitable optimal control strategy is established to realize path tracking control that balances tracking accuracy, stability and adaptability, thus providing technical support for the engineering application of autonomous navigation of harvesters.

2. Materials and Methods

2.1 Overall Framework and Operating Principle

The designed path tracking control system mainly consists of an embedded controller, a perception module, an electric steering wheel assembly, a serial screen host computer, a storage module, a communication module, and a power supply module, as shown in Fig. 1.

The embedded controller uses the serial port of the development board to realize communication between multiple modules, integrates multi-module data, calculates the optimal steering command, drives the actuator, and achieves closed-loop control and exception handling. The host computer establishes serial communication with the controller to monitor the real-time operation status of the harvester, modify and issue the system's path commands online, and adjust the system's working parameters. The power supply module comprises a vehicle-mounted power supply and a step-down module, supplies power to the host computer and the electric steering wheel assembly and converts the 12V vehicle-mounted power supply into 5V DC to power the controller, sensors. During the operation of the control system, the path tracking controller calculates the position deviation based on the real-time pose information provided by the perception module and the reference path provided by the host computer. Then, the position deviation is used as the input of the path tracking algorithm to output the target heading angle of the harvester. The target heading angle is transmitted to the steering controller of the electric steering wheel assembly. According to the difference between the actual heading angle and the target heading angle, the steering controller adjusts the steering angle of the steering wheel, thereby changing the real-time heading and enabling them to travel along the given reference path.

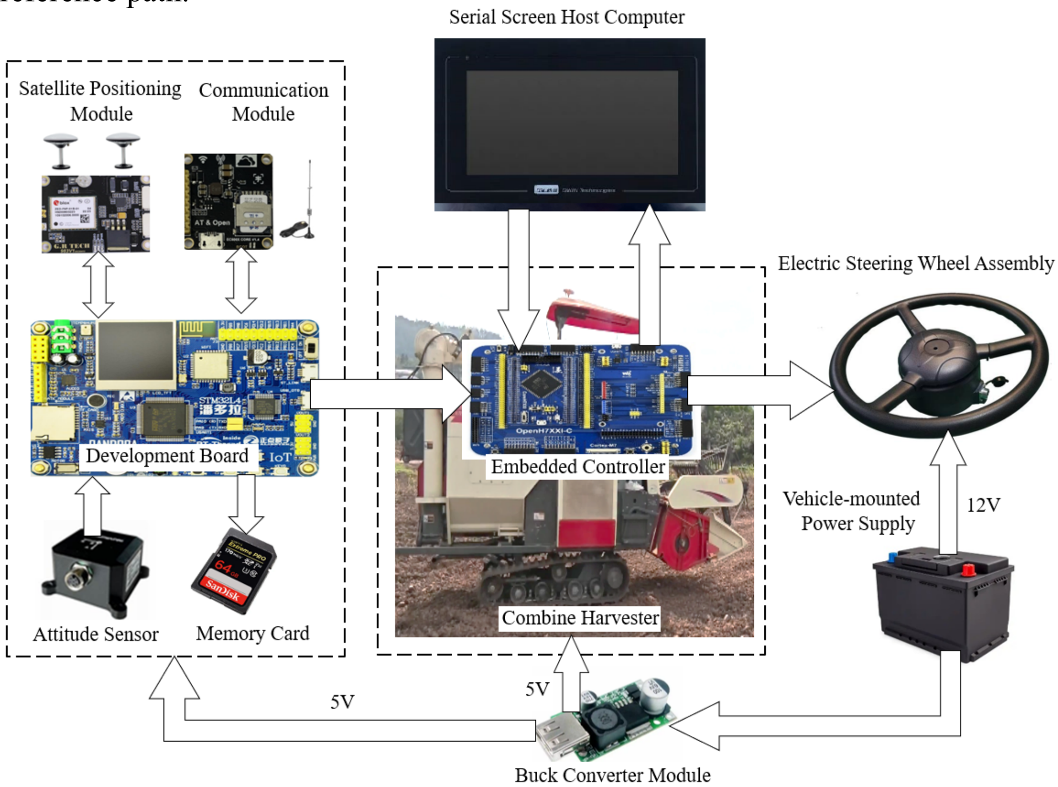


Fig. 1. Overall design framework of path tracking control system

2.2 Motion Prediction Model for the Harvester

To simplify the modeling process, the following assumptions are proposed: (1) The vehicle steadily travels at a low speed (≤5 km/h), and the slip and skid phenomena between the tracks and the ground are neglected. (2) The dynamic change of the vehicle's longitudinal speed is ignored. The engine output power remains stable during operation without frequent acceleration or deceleration. (3) The center of mass of the harvester coincides with its geometric center, and the machine is symmetrical about the center. The models of the harvester are mainly divided into two categories: dynamic models and kinematic models. Dynamic models focus on characterizing the coupling relationship between vehicle motion and applied forces, making them suitable for high-speed driving scenarios. In contrast, kinematic models are more applicable to low-speed operation scenarios. Considering the characteristics and real-time performance requirements of the harvester, kinematic model is adopted, which is shown in Fig. 2.

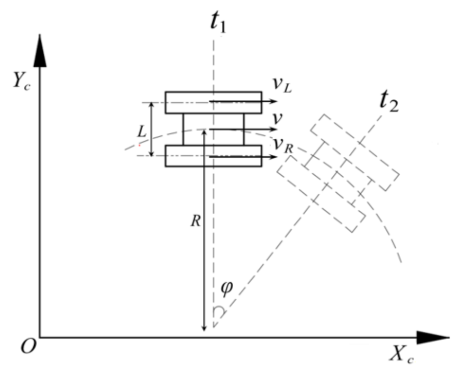


Fig. 2. Schematic diagram of kinematic model for tracked harvester

The vehicle coordinate system was established. When the attitude sensor is powered on, the forward direction of the harvester is set as the horizontal *Xc*-axis; the direction perpendicular to the forward direction of the harvester at the moment of power-on is set as the vertical *Yc*-axis. Taking the vehicle coordinate system as the reference frame, the kinematic model of the harvester is as follows:

$$\begin{bmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \frac{\cos\varphi}{2} & \frac{\cos\varphi}{2} \\ \frac{\sin\varphi}{2} & \frac{\sin\varphi}{2} \\ -\frac{1}{L} & \frac{1}{L} \end{bmatrix} \begin{bmatrix} v_L \\ v_R \end{bmatrix} \tag{1}$$

Where: v—Travel speed, m/s; v_L—Speed of the left track, m/s; v_R—Speed of the right track, m/s; R—Turning radius, m; L—Track gauge, m; φ—Heading angle, °.

The kinematic model is a nonlinear continuous system. To simplify the calculation process of the MPC controller and improve the real-time response performance and control efficiency of the system, linearization and discretization are performed on the nonlinear system. By abstracting the harvester kinematic model into a general control system with the input variable $u=[v_L, v_R]^T$ and the state variable $\chi=[x_c, y_c, \varphi_c]^T$, the following can be obtained:

$$\dot{\chi}=f(\chi, u) \tag{2}$$

The parameters expression related to the reference path is as follows:

$$\dot{\chi}_r=f(\chi_r, u_r) \tag{3}$$

Where: χ_r—reference state variable, $\chi_r=[x_r \quad y_r \quad \varphi_r]^T$; u_r— reference input variable, $u_r=[v_L \quad v_R]^T$.

To ensure the accuracy of the kinematic model after linearization, it is necessary to perform Taylor series expansion and ignore the high-order terms in the expansion, the expression is as follows:

$$\dot{\chi}=f(\chi,u)=f(\chi_r,u_r)+\frac{\partial f(\chi,u)}{\partial \chi}(\chi-\chi_r)+\frac{\partial f(\chi,u)}{\partial u}(u-u_r) \tag{4}$$

The linearized error model equation of the harvester is as follows:

$$\dot{\tilde{\chi}}=A\tilde{\chi}+B\tilde{u} \tag{5}$$

Its state-space expression is as follows:

$$\begin{aligned}\xi(k+1)&=\begin{bmatrix}A_k & B_k\\ 0_{m\times n} & I_m\end{bmatrix}\begin{bmatrix}\tilde{\chi}(k)\\ \tilde{u}(k-1)\end{bmatrix}+\begin{bmatrix}B_k\\ I_m\end{bmatrix}\Delta u(k)\\ \eta(k)&=[I_n \quad 0]\begin{bmatrix}\tilde{\chi}(k)\\ \tilde{u}(k-1)\end{bmatrix}\end{aligned} \tag{6}$$

Where: I—identity matrix; n—state dimension, n=3； m—control variable dimension, m=2.

When the prediction horizon of the MPC controller is N_p, the control horizon is N_c, and $N_p \geq N_c$, the system prediction model can be obtained as follows:

$$\begin{bmatrix}\eta(k+1)\\ \eta(k+2)\\ \vdots\\ \eta(k+N_c)\\ \vdots\\ \eta(k+N_p)\end{bmatrix}=\begin{bmatrix}\tilde{C}_k\tilde{A}_k\\ \tilde{C}_k\tilde{A}_k^2\\ \vdots\\ \tilde{C}_k\tilde{A}_k^{N_c}\\ \vdots\\ \tilde{C}_k\tilde{A}_k^{N_p}\end{bmatrix}\begin{bmatrix}\tilde{\chi}(k)\\ \tilde{u}(k-1)\end{bmatrix}+\begin{bmatrix}\tilde{C}_k\tilde{B}_k & 0 & 0 & 0\\ \tilde{C}_k\tilde{A}_k^1\tilde{B}_k & \tilde{C}_k\tilde{B}_k & 0 & 0\\ \cdots & \cdots & \ddots & \cdots\\ \tilde{C}_k\tilde{A}_k^{N_c-1}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_c-2}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{B}_k\\ \tilde{C}_k\tilde{A}_k^{N_c}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_c-1}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{A}_k\tilde{B}_k\\ \vdots & \vdots & \ddots & \vdots\\ \tilde{C}_k\tilde{A}_k^{N_p-1}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_p-2}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{A}_k^{N_p-N_c-1}\tilde{B}_k\end{bmatrix}\begin{bmatrix}\Delta u(k)\\ \Delta u(k+1)\\ \vdots\\ \Delta u(k+N_c-1)\end{bmatrix} \tag{7}$$

2.3 Design of MPC Path Tracking Controller

To ensure that the predicted output of the system is consistent with the actual output and that the combined harvester rapidly and stably tracks the reference path, it is necessary to construct an objective function and convert it into a quadratic programming problem. Referring to the relevant literature [18], the designed objective function in this study is as follows:

$$J(k)=\sum_{i=1}^{N_p}\|\eta(k+i)-\eta_{ref}(k+i)\|_Q^2+\sum_{i=0}^{N_c-1}\|\Delta U(k+i)\|_R^2+\rho\varepsilon^2 \tag{8}$$

Where: η_{ref}—reference output; Q, R—weight matrices; ρ— weight coefficient; ε—slack variable.

Three types of constraints need to be incorporated comprehensively: the upper and lower limit constraints of control variables, the upper and lower limit constraints of control variable increments, and the actual speed matching constraints. The expression for the upper limit constraint is as follows:

$$u_{\min}(k+i)\leqslant u(k+i)\leqslant u_{\max}(k+i),\quad i=0,1,\cdots,N_c-1 \tag{9}$$

Where: $u_{min}(k+i)$—Minimum value of the control variable, $u_{min}(k+i)=0$; $u_{max}(k+i)$—Maximum value of the control variable, $u_{max}(k+i)=2$.

The expression for the upper and lower limit constraints of control variable increments is as follows:

$$\Delta u_{\min}(k+i)\leqslant \Delta u(k+i)\leqslant \Delta u_{\max}(k+i),\quad i=0,1,\cdots,N_c-1 \tag{10}$$

Where:$\Delta u_{min}(k+i)$—Minimum value of the control variable increments, $\Delta u_{min}(k+i)=-0.25$;$\Delta u_{max}(k+i)$—Maximum value of the control variable increments, $\Delta u_{max}(k+i)=0.25$.

The expression for the actual speed matching constraints is as follows:

$$-0.1\leqslant\begin{bmatrix}\frac{1}{2} & \frac{1}{2}\end{bmatrix}\times u(k+i)-v_{ture}\leqslant 0.1,\quad i=0,1,\cdots,N_c-1 \tag{11}$$

Where: v_{ture}—Actual speed of the harvester.

By expanding the objective function of Equation (8) into a standard quadratic form and incorporating the constraint conditions, the optimization solution of the original objective function can be converted into the following quadratic programming problem:

$$\min\ J(\xi(k),u(k-1),\Delta U(k))=[\Delta U(k)^T,\varepsilon]^T H_k[\Delta U(k)^T,\varepsilon]+G_k[\Delta U(k)^T,\varepsilon] \tag{12}$$

Where: $H_k=\begin{bmatrix}\Theta^T Q\Theta+R & 0\\ 0 & \rho\end{bmatrix}$, $G_k=[2E(k)^T Q\Theta\ \ 0]$,

$$\Theta=\begin{bmatrix}\tilde{C}_k\tilde{B}_k & 0 & 0 & 0\\ \tilde{C}_k\tilde{A}_k^1\tilde{B}_k & \tilde{C}_k\tilde{B}_k & 0 & 0\\ \cdots & \cdots & \ddots & \cdots\\ \tilde{C}_k\tilde{A}_k^{N_c-1}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_c-2}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{B}_k\\ \tilde{C}_k\tilde{A}_k^{N_c}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_c-1}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{A}_k\tilde{B}_k\\ \vdots & \vdots & \ddots & \vdots\\ \tilde{C}_k\tilde{A}_k^{N_p-1}\tilde{B}_k & \tilde{C}_k\tilde{A}_k^{N_p-2}\tilde{B}_k & \cdots & \tilde{C}_k\tilde{A}_k^{N_p-N_c-1}\tilde{B}_k\end{bmatrix}$$

$$E(k)=\psi\xi(k)-Y_{ref}(k),Y_{ref}(k)=\left[\eta_{ref}(k),\eta_{ref}(k+1),\cdots,\eta_{ref}\left(k+N_p\right)\right]^T。$$

3. Results and Analysis

3.1 Construction of Simulation Platform

The path tracking simulation platform for the harvester was built based on MATLAB/Simulink. The platform consists of four modules: the reference path generation module, the combine harvester model, the MPC controller module and the data acquisition module, as shown in Fig.3. Reference Path Generation Module: It is used to provide a reference path for the simulation system. Ideally, the harvester's travel path should coincide with the reference path. The design of the reference path draws on several commonly used paths in the field of agricultural machinery autonomous driving for testing tracking accuracy and performance, including straight lines, circular paths, and double-shift paths. Combine Harvester Model: It implements the established kinematic model and error model. The input is the output of the MPC controller, and the output of the harvester model includes the real-time coordinate and heading angle of the harvester, which serve as the input parameters of the MPC controller. MPC Controller Module: It integrates the objective function, constraint conditions and algorithms. The input parameters of the controller are the coordinate values and heading angles of both the harvester and the reference path, while the output is the linear speed of the left and right tracks of the harvester. Data Acquisition Module: It records key indicators such as the reference path for path tracking, actual travel path and control variables.

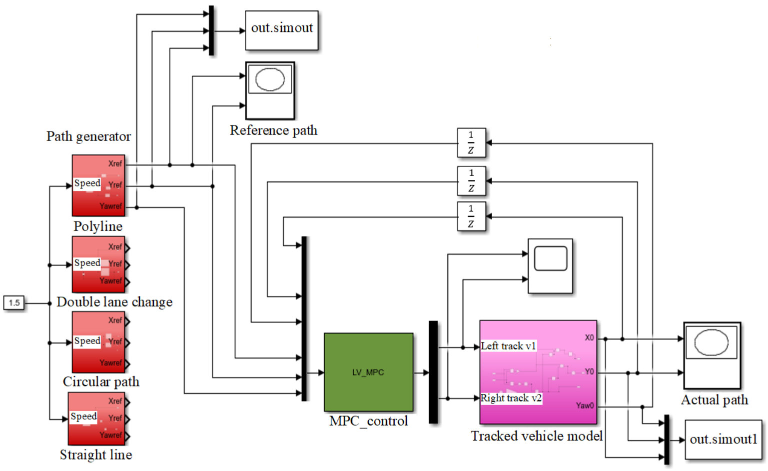


Fig. 3. Simulation model of MPC controller

3.2 Design of Test Scheme

(1) Effects of prediction horizon N_p and control horizon N_c: The circular and double lane change paths was generated. During the simulation, the initial

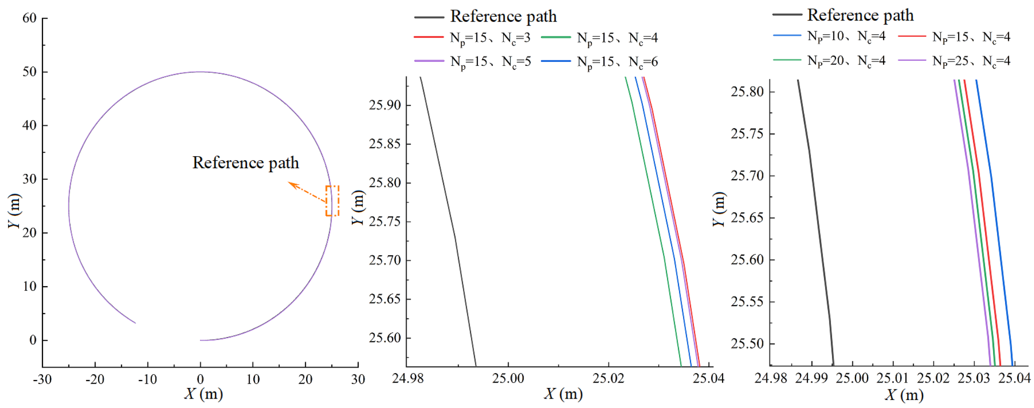
position was set to (0,0), the initial heading angle was 0°. Combining the conventional operating speed range of the harvester with the motion characteristics of low-speed field operations, the vehicle speed is fixed at 0.8 m/s, and the simulation step size was 0.2 s. To balance prediction effectiveness and the computational load of the controller, the N_p is initially set to 15. Through variable parameter testing, the optimal N_c is determined. Using this optimal N_c as a fixed value, N_p is further optimized to finalize the best parameter combination for configuring the MPC path tracking controller.

(2) Performance test of the path tracking controller under different conditions: The typical "S-shaped path" of the harvester were respectively designed for different row spacing. The initial position of the harvester was (0,0), the initial heading angle was 0°, and the control cycle was 200ms. Referring to the conventional planting row spacing and width operation row spacing of field crops with reference harvesters, two typical row spacing parameters of 2.4m and 4.4m were selected for operation path simulation. In the performance testing of path tracking controllers under different operating conditions, composite paths combining straight lines and arcs were designed under the above row spacing to compare and analyze the adaptability of the controller in path tracking under different operating widths. Based on the actual operating speed range of the harvester in the field, three speeds of 0.4m/s, 0.8m/s, and 1.2m/s were set respectively, corresponding to three typical working conditions of low speed, medium speed, and high speed. The tracking effect of the controller was tested under different motion states

3.3 Analysis Results

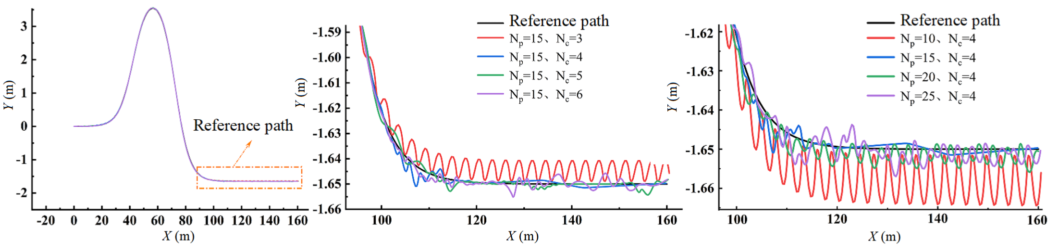
(1) When the N_p was fixed, the simulation tracking performance in different N_c was recorded to determine the optimal value. Under the optimal value of N_c, N_p was adjusted to obtain the optimal parameter combination of N_p and N_c . The simulation results are shown in Fig. 4 and Fig. 5.

The simulation results demonstrate that the designed path tracking controller can achieve stable tracking of circular paths and double lane change paths, but its control performance is significantly affected by the parameters of N_p and N_c. For circular paths, when N_p is fixed at 10, the tracking performance is optimal when N_c=4, with a position deviation of 4.1 cm, while it is the worst when N_c=3. When N_c is fixed at 4, the optimal tracking effect is achieved at N_p=25 with a position deviation of 3.81 cm, whereas the poorest performance is observed at N_p=10. For double lane change paths, slight oscillations tend to occur at the end of the path if the parameters are mismatched, with a maximum amplitude of 1.5 cm. The results of local amplification show that the optimal tracking performance is obtained at N_p=15 and N_c=4, where the system quickly stabilizes after slight oscillations with the deviation maintained below 0.5cm after stabilization. In contrast, cases with N_p=15 and N_c=3, as well as N_p=10 and N_c=4, suffer from non-convergence or oscillations with large amplitudes. The analysis indicates that an excessively small N_c leads to insufficient degrees of freedom for controller adjustment, making it difficult to rapidly correct tracking deviations and thus resulting in oscillations or non-convergence. An excessively small N_p limits the predictive horizon of the controller, preventing it from fully predicting path variations. Although an excessively large N_p can improve prediction accuracy, it leads to diminishing marginal benefits and increased computational load. Based on the comprehensive consideration of simulation results, processor performance, memory resources, and the impact of constraint matching on control accuracy, the optimal parameters of the controller are determined as N_p=15 and N_c=4.



(a) Preset path (b) N_p fixed (c) N_c fixed

Fig. 4. Simulation Results of Circular Path Tracking in Different Time Domains

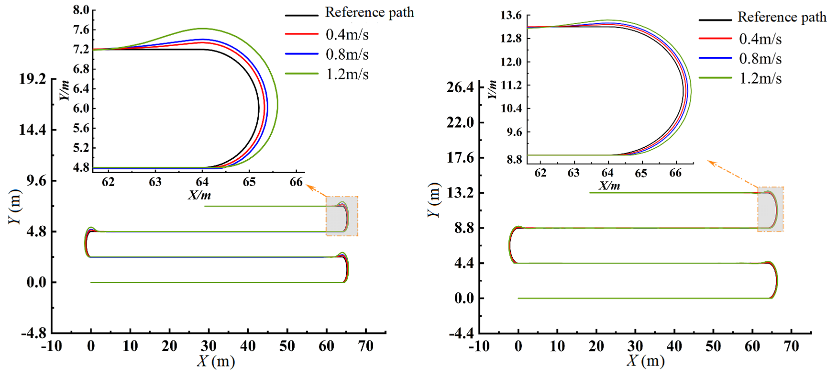


(a) Preset path (b) N_p fixed (c) N_c fixed

Fig. 5. Simulation Results of Double-Shift Path Tracking in Different Time Domains

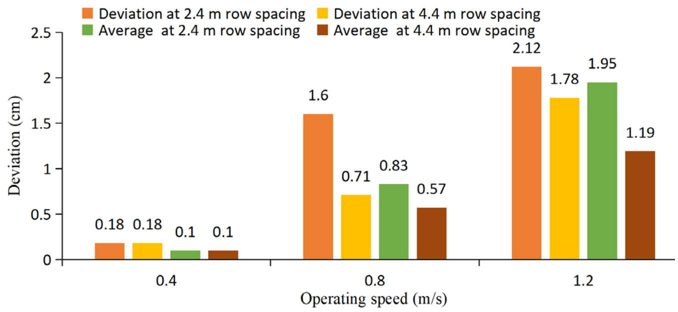
(2) The N_p=15 and N_c=4 are set, and the position deviation and heading angle deviation were taken as the testing indicators. the reference path is composed of straight-line segments and circular-arc segments. The indicators for straight-line segments include position deviation, average position deviation, heading angle deviation and average heading angle deviation. The indicators for circular-arc segments include position deviation, average position deviation,

heading angle deviation and average heading angle deviation at different positions. Under different row spacing, the tracking effects at different speeds are shown in Fig. 6, and the position and heading angle deviation results are shown in Fig. 7.

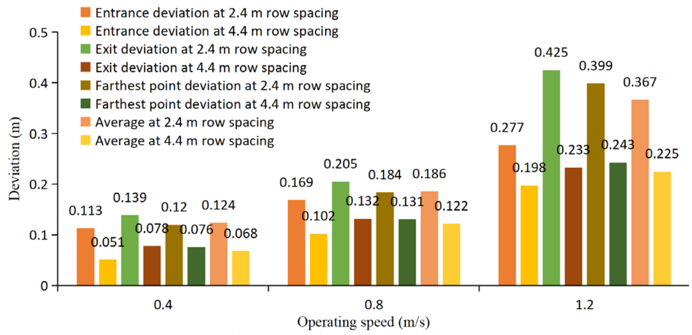


(a) 2.4 m Row Spacing (b) 4.4 m Row Spacing

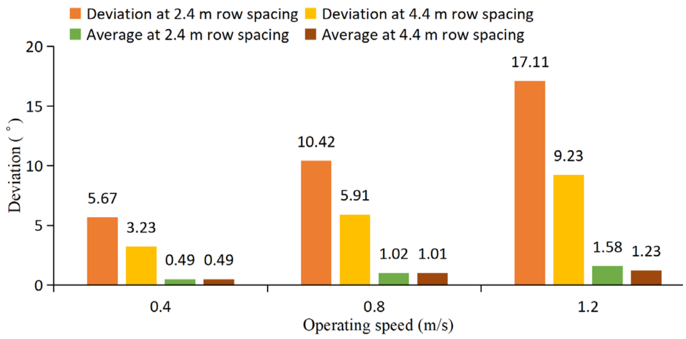
Fig. 6. Path Tracking Results at Different Row Spacing



(a) Straight-section driving



(b) Curved-section driving



(c) Heading angle deviation

Fig. 7. Harvester Position Deviation Under Different Test Conditions

The simulation results show that the designed MPC controller enables the combine harvester to achieve stable tracking of the reference path, with relatively large tracking errors in the circular arc segments and error peaks concentrated at the exit positions. When the speed increases from 0.4 m/s to 1.2 m/s, the maximum position deviation of straight-line path tracking increases from 0.18 cm to 2.12 cm, and the average position deviation increases from 0.1 cm to 1.95 cm; the maximum position deviation of circular arc path tracking increases from 0.139 m to 0.425 m, and the average position deviation increases from 0.124 m to 0.367 m. The maximum heading angle deviations in the circular arc segments, rising from 5.67° to 17.11°, while the average heading angle deviations increased from 0.49° to 1.58°. An increase in row spacing corresponds to a larger turning radius, which can significantly improve the tracking performance of circular arc segments. At a constant speed, as the radius of the circular arc segment increases, the tracking effect of the harvester is significantly enhanced. After the turning radius is increased, the maximum position deviation of the circular arc segment is reduced to 0.243 m, and the maximum heading angle deviation is reduced to 9.23°. The analysis is as follows: the increase in the traveling speed of the harvester will aggravate the lag of the system's dynamic response. Under high-speed conditions, the traveling distance per unit time increases, which relatively shortens the prediction window for the controller to respond to the steering demand of circular arc segments. It is difficult for the controller to make sufficient adjustments in advance, and errors tend to accumulate to peaks at the exit positions of the curves. Meanwhile, the ground adhesion of the track's changes significantly during high-speed travel, and the response speed of the steering actuator is difficult to match the command output of the controller. An increase in row spacing corresponds to a larger turning radius, which can effectively reduce the constraints on the steering movement of the harvester. When turning with a large radius, the steering angular velocity decreases, the movement posture of the harvester body becomes more stable, the stress state between the tracks and the ground is optimized, and the steering actuator can follow the controller commands more accurately. The simulation results indicate that average position deviation is less than 2 cm in straight-line path tracking, an average position deviation is less than 0.367 m in circular arc path tracking, and an average heading angle deviation is less than 2°, all of which meet the basic requirements for precision operations.

4. Conclusions

The designed path tracking system for the combine harvester exhibits excellent operational performance. The system kinematics model constructed on this basis can precisely characterize the motion state of the harvester during path tracking. The MPC controller demonstrates favorable path tracking performance and can realize stable tracking of the circular paths and double lane change paths. The optimal parameter combination of the prediction horizon is N_p=15 and N_c=4. The tracking accuracy decreases with the increase of traveling speed and improves with the enlargement of the row spacing. When the speed increases from 0.4 m/s to 1.2 m/s, the maximum position deviation of the straight-line segment increases from 0.18 cm to 2.12 cm, and the maximum heading angle deviation of the circular arc segment increases from 5.67° to 17.11°. The average position deviation of the controller is less than 2 cm in straight-line tracking, and the average heading angle deviation is less than 2° in circular arc tracking, which meet the technical requirements for the precision operation of the combine harvester. On the basis of this study, the research boundary can be further expanded in the future to enhance the adaptability of the entire path tracking control system to complex field conditions and variable operating conditions, continuously optimize the comprehensive performance of control algorithms, and gradually complete the transition from simulation experiments to actual field experiments. The gradual promotion of intelligent harvester path tracking technology from theoretical verification to practical application.

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