Research on Lateral Motion Control Strategy of Automatic Transport Vehicle based on Model Predictive Control Algorithm of Spatial Domain

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Abstract: Aiming at the lateral motion control of the automatic transport vehicle designed, a model predictive control algorithm based on space domain is proposed based on the kinematics model. Firstly, the deviation model of automatic transport vehicle based on spatial domain is established and used as the prediction model. Then an objective function is designed to optimize the lateral displacement deviation and the change of the steering curvature of the automatic transport vehicle, to ensure the minimum lateral displacement deviation between the automatic transport vehicle and the reference path during the working process. Finally, to solve the optimal curvature, the objective function is converted into a quadratic programming problem. The joint simulation experiment is carried out with double line shifting as the reference path. The results show that the designed lateral motion control strategy can accurately and stably track the reference path under different speed, load, and has good robustness.

Keywords: *Automatic Transport Vehicle, Model Predictive Control Algorithm, Spatial Domain, Kinematics Model*

I. INTRODUCTION

In the process of coal mining, production, and transportation, having efficient, safe, and reliable mining and transportation capabilities as the basis for working in coal mines can not only improve production efficiency, but also reduce human casualties. However, the actual working conditions of coal mines are harsh and dangerous, and manual mining and transportation are not only inefficient, but also have more casualties. According to data, compared with manual driving, autonomous vehicles can greatly reduce fuel consumption and maintenance costs, improve production efficiency, and improve the service life of tires and reduce the number of casualties. Therefore, to ensure efficiency and safety in the mining and transportation process, it is important to automate coal mining and transportation.

The key to intelligent transportation is the design of lateral motion control strategy.At present, many control algorithms have been produced under the efforts of scholars, mainly including fuzzy control algorithm, model predictive control algorithm and neural network algorithm. Hongtao Xue et al. [1] of Jiangsu University proposed a horizontal fuzzy control strategy based on rough sets, which is mainly used to intelligently identify the driving environment and avoid obstacles and implemented the proposed method on a model vehicle named "RoboCar".Seo Ji Hwan et al. [2] designed a lateral motion control strategy based on the model predictive control algorithm in order to overcome the disadvantage that traditional motion planning would lead to passenger discomfort Samuel Oludare Bamgbose et al. [3] proposed a new design method combining neural network with traditional control system.Because the traditional motion control strategy may have the disadvantages of unsmooth steering and reduced security, this paper designs a lateral motion control strategy based on the spatial domain model predictive control algorithm to ensure accurate tracking of the reference path and smooth steering and establishes a joint simulation for verification.

II. INTELLIGENTMOBILEVEHICLEMODEL

A. *Kinematic model*

Generally, when the vehicle is at low speed and the sampling period is 200ms, the performance of the kinematics model is like that of the dynamics model, and its dynamics characteristics can be ignored. It is convenient to design the motion control strategy based on the kinematics model. When the intelligent mobile vehicle works in the coal mine, to avoid the unsafe accidents that may occur during its driving as far as possible, the intelligent mobile vehicle is required to run at a low speed, with the maximum speed not exceeding 1m/s. Therefore, it is better to study the lateral motion control based on the kinematics model of intelligent mobile vehible by comprehensively considering the operational efficiency, real-time and other factors. The kinematics model in Cartesian coordinate system is[4]：

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} \cos\varphi \\ \sin\varphi \\ 2\tan\delta_f / l \end{bmatrix} V \tag{1}$$

In the formula:
X -Abscissa in rectangular coordinate system.
Y -Vertical coordinate under rectangular coordinate system.
φ -Heading angle.
δ_f -Front wheel angle.
l -wheel base.

B. *Deviation model based on spatial domain*

First, a smooth reference path is planned according to the actual working conditions, and then the position of the intelligent mobile vehicle at the current moment and the information of each motion state are projected onto the reference path, thus realizing the decomposition of the intelligent mobile vehicle motion state information in the Cartesian coordinate system in the Frenet coordinate system[5]. The decomposed state information and the corresponding relationship between the state information in the global coordinate system and the Frenet coordinate system can be obtained from Figure 1.

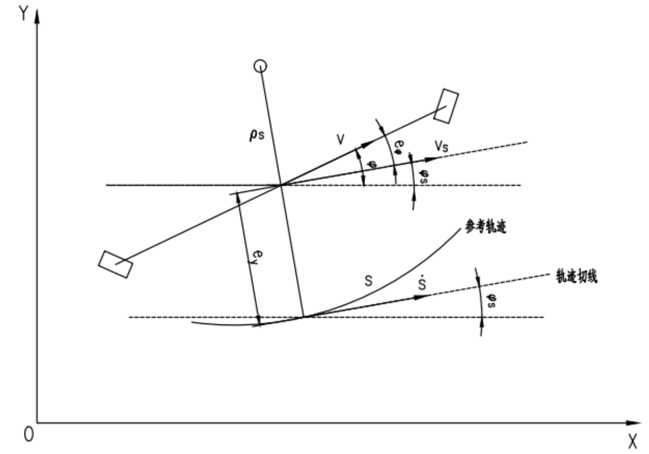


Fig.1Kinematic model in Frenet coordinate system

Assuming that the position of the intelligent mobile vehicle in the Cartesian coordinate system at the current moment is [X,Y,φ], and the corresponding tracking position on the reference path is[Xref,Yref,φref], then the curvature radius of the road at the current corresponding tracking position is:

$$\rho_s = \frac{\left(\left(X'_{\text{ref}}(s) \right)^2 + \left(Y'_{\text{ref}}(s) \right)^2 \right)^{3/2}}{\left| X'_{\text{ref}}(s) Y''_{\text{ref}}(s) - X''_{\text{ref}}(s) Y'_{\text{ref}}(s) \right|} \tag{2}$$

The lateral displacement deviation between the current position of the intelligent mobile vehicle and the corresponding tracking position is:

$$e_y = k_e \sqrt{\left(X - X_{\text{ref}} \right)^2 + \left(Y - Y_{\text{ref}} \right)^2} \tag{3}$$

Where, when the lateral displacement deviation is positive, k_e=1; When the lateral displacement deviation is negative, k_e=-1, the yaw angle deviation is:

$$e_\varphi = \varphi - \varphi_{\text{ref}} \tag{4}$$

The projection speed along the tangent direction of the reference path is:

$$V_s = \left(\rho_s - e_y \right) \dot{\varphi}_s = V \cos e_\varphi \tag{5}$$

The heading angle of the reference path is:

$$\dot{\varphi}_s = \frac{V \cos e_\varphi}{\rho_s - e_y} \tag{6}$$

Travel speed along the reference path is:

$$\dot{s} = \frac{\rho_s V \cos e_\varphi}{\rho_s - e_y} \tag{7}$$

The lateral displacement deviation and yaw angle deviation with respect to time derivatives can be expressed as:

$$\begin{aligned} \dot{e}_y &= V \sin e_\varphi \\ \dot{e}_\varphi &= \dot{\varphi} - \dot{\varphi}_s \end{aligned} \tag{8}$$

Assuming that the speed of the intelligent mobile machine at any corresponding tracking position is not zero during its movement, the deviation model of the intelligent mobile machine based on the time domain can be converted into the deviation model based on the space domain:

$$\begin{aligned} \frac{de_y}{ds} &= \frac{de_y}{dt}\frac{dt}{ds} = \frac{\dot{e}_y}{\dot{s}} = \frac{\rho_s - e_y}{\rho_s} \tan e_\varphi \\ \frac{de_\varphi}{ds} &= \frac{de_\varphi}{dt}\frac{dt}{ds} = \frac{\dot{e}_\varphi}{\dot{s}} = \frac{\rho_s - e_y}{\rho_s \cos e_\varphi}\kappa - \frac{1}{\rho_s} \end{aligned} \tag{9}$$

III. DESIGN OF MODEL PREDICTIVE CONTROLLER

A. Linearization and discretization

Assume any point on the reference track(ξref,uref) meet the above kinematic equations. At point(ξref,uref), equation (9) is linearized using the first-order Taylor approximation of the reference trajectory, and discretized using Euler formula.Set the distance from walking to

$$\Delta s = \frac{\rho_s(k) \cos e_\varphi(k)}{\rho_s(k) - e_y(k)} VT \tag{10}$$

The linear discrete spatial deviation model is:

$$\tilde{\xi}(k+1) = A_{k,t}\tilde{\xi}(k) + B_{k,t}\tilde{u}(k) \tag{11}$$

In the formula:

$$A_{k,t} = \begin{bmatrix} 1 - \dfrac{\tan e_{\varphi,r}}{\rho_s}\Delta s & \dfrac{\rho_s - e_{y,r}}{\rho_s \cos^2 e_{\varphi,r}}\Delta s \\ -\dfrac{\kappa_r}{\rho_s \cos e_{\varphi,r}}\Delta s & 1 + \dfrac{\left(\rho_s - e_{y,r}\right)\sin e_{\varphi,r}\kappa_r}{\rho_s \cos^2 e_{\varphi,r}}\Delta s \end{bmatrix}$$

$$B_{k,t} = \begin{bmatrix} 0 \\ \dfrac{\rho_s - e_{y,r}}{\rho_s \cos e_{\varphi,r}}\Delta s \end{bmatrix}$$

B. Design of model predictive controller

To prevent the occurrence of sudden change of control quantity, control increment is used to replace the control quantity, which is converted as follows:

$$\chi(k|t) = \begin{bmatrix} \tilde{\xi}(k|t) \\ \tilde{u}(k-1|t) \end{bmatrix} \tag{12}$$

Select the lateral displacement deviation as the output, and establish the prediction model as:

$$E(t) = \Psi_t \chi(t|t) + \Theta_t \Delta U(t) \tag{13}$$

When designing the objective function, it is necessary to add the optimization of the deviation of the system state and the control increment to ensure that the intelligent mobile vehicle can track the desired path safelyand accurately. According to the control object and control objective studied, the objective function selected here needs to optimize the lateral displacement deviation and steering curvature variation of the intelligent mobile vehicle, to ensure the minimum lateral displacement deviation between the intelligent mobile vehicle and the reference path during the working process, and at the same time to avoid sudden changes in steering curvature. Therefore, the objective function can be designed as follows:

$$J\left(\chi(t),u(t-1),\Delta U(t)\right)=\sum_{i=1}^{N_p}\left\|e\left(t+i\left|t\right.\right)\right\|_Q^2+\sum_{i=1}^{N_c-1}\left\|\Delta U\left(t+i\left|t\right.\right)\right\|_R^2+\rho\varepsilon^2 \tag{14}$$

In the formula:

Q -Weight coefficient of tracking lateral displacement deviation.

R -Steering curvature control increment weight coefficient.

ρ -Relaxation factor weight coefficient.

ε -Relaxation factor.

Convert the objective function into the standard quadratic form and combine the constraint conditions to solve the optimization problem, which can be converted into a quadratic programming problem:

$$J\left(\chi(t),u(t-1),\Delta U(t)\right)=\frac{1}{2}\begin{bmatrix}\Delta U(t)\\ \varepsilon\end{bmatrix}^{\mathrm{T}}H_t\begin{bmatrix}\Delta U(t)\\ \varepsilon\end{bmatrix}+G_t^{\mathrm{T}}\begin{bmatrix}\Delta U(t)\\ \varepsilon\end{bmatrix} \tag{15}$$

$$s.t.\begin{cases}\Delta U_{\min}\le\Delta U_t\le\Delta U_{\max}\\ U_{\min}\le A\Delta U_t+U_t\le\Delta U_{\max}\\ E_{\min}\le E_t\le E_{\max}\end{cases}$$

Because the final output of the designed lateral motion controller is the steering curvature, which cannot be directly applied to the intelligent mobile vehicle, it is also necessary to convert the output steering curvature into the wheel angle through formula (16).

$$\kappa=\frac{1}{R}=\frac{2\tan\delta_f}{l} \tag{16}$$

IV. SIMULATION TEST VERIFICATION

In order to verify the control performance of the designed lateral motion control strategy, the joint simulation is conducted on the Trucksim and MATLAB/Simulink simulation platform, and the simulation system is established according to the above control strategy, as shown in Figure 2.

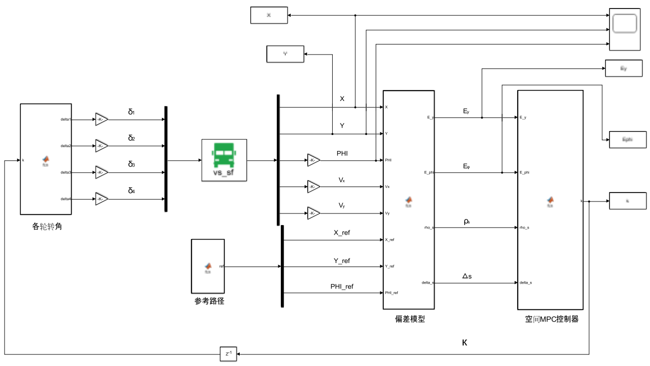


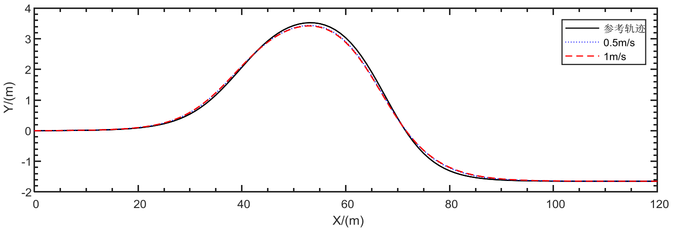
Fig.2 Co-simulation of lateral motion control strategy

In the actual movement process of intelligent mobile vehicle, it will face various working conditions, and the designed controller may also show different control performance under different working conditions. To better understand and analyze the control performance of the control strategy under different conditions, twe different simulation conditions are designed to verify the control performance of the controller.

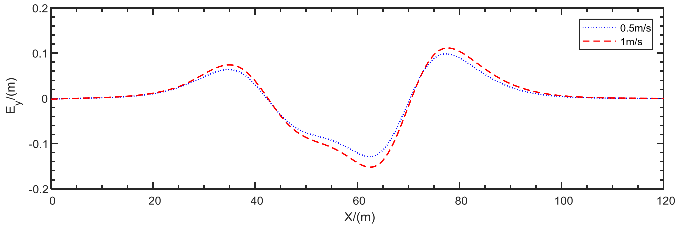
A. Robustness of control strategy at different speeds

Although the established lateral motion control strategy eliminates the impact of the speed of intelligent mobile vehicles on the state variables, there is still an impact on space variables, which may cause changes in the final control performance. Therefore, to verify the robustness of the designed control strategy to the speed, simulation tests are carried out for the lateral motion control at different speeds. The intelligent mobile vehicle is selected to drive at the speed of 0.5m/s and 1m/s respectively when it is unloaded.

The simulation test results are shown in Figure 3. The dotted line and dotted line represent the simulation results of the intelligent mobile machine at the speed of 0.5m/s and 1m/s. Figure (a) shows the comparison between the actual motion path and the reference path of the intelligent mobile machine at different speeds. It can be seen from the figure that the intelligent mobile machine has a faster and better tracking effect on the reference path under the control of the transverse motion controller, although the speed is different. Figure (b) shows the variation of the lateral displacement deviation of the intelligent mobile machine at different speeds. From the figure, it can be found that when the speed of the intelligent mobile machine is 0.5m/s, the maximum lateral displacement deviation during the movement of the intelligent mobile machine is -0.129m, and the steady-state lateral displacement deviation is 0.003m; The maximum lateral displacement deviation of the intelligent mobile machine at the speed of 1m/s is -0.152 m, and the steady-state lateral displacement deviation is 0.004 m. It can be concluded that with the increase of the speed of the intelligent mobile machine, the lateral displacement deviation will also increase, but the deviation values are in a very small range. When reaching the steady state, the lateral displacement deviation at different speeds basically does not change, indicating that the intelligent mobile machine can maintain good control effect at different speeds. Figure (c) shows the variation diagram of the yaw angle deviation value of the intelligent mobile machine at different speeds. From the variation curve in the figure, although the movement speed of the intelligent mobile machine is different, the variation of the yaw angle deviation value is basically consistent, so it can be explained that the controller can make the intelligent mobile machine have better stability in the path tracking process at different speeds. Figure (d) shows the change curve of the steering curvature of the intelligent mobile machine. At different speeds, the change curve of the steering curvature of the intelligent mobile machine basically does not change, and is within the constraint range, and there is no obvious fluctuation and mutation, with good smoothness. To sum up, the lateral motion controller has good tracking effect on intelligent mobile machines at different speeds, that is, it has strong robustness to speed.



(a)



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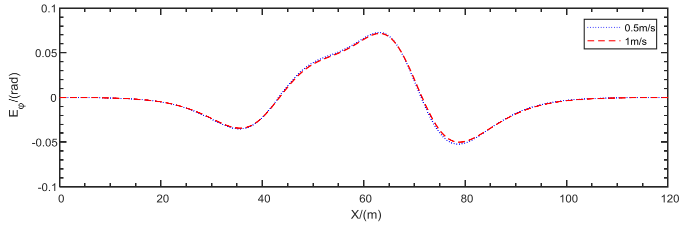

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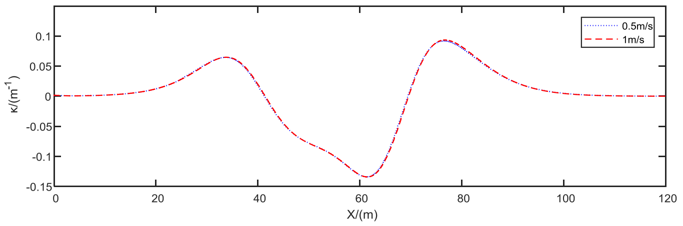


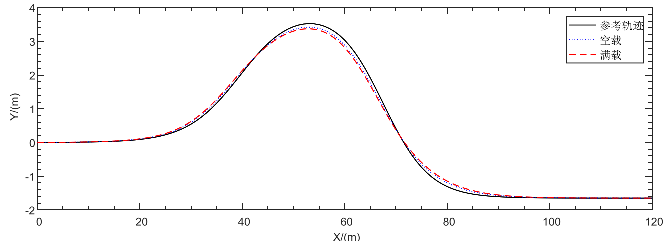
(d)

Fig.3 Simulation results of lateral control at different speeds

B. Robustness of control strategy under different loads

Intelligent mobile vehicles are mainly used to transport heavy objects such as belts, and their mass changes greatly under no-load and full-load conditions. However, since the designed lateral motion control strategy is mainly based on the kinematics model, ignoring the mass of intelligent mobile machines and loads, it is necessary to consider the control performance of the control strategy under different loads. Here, it is assumed that the intelligent mobile machine will travel along the reference path at a constant speed of 1m/s when it is under no load and full load respectively.

The simulation test results are shown in Figure 4. Figure (a) shows the comparison between the actual motion path and the reference path of the intelligent mobile vehicle under no-load and full load respectively. From the simulation results, the intelligent mobile vehicle can accurately track the desired path under the control of the lateral motion controller, whether it is empty or full. Figure (b) shows the variation of lateral displacement deviation of intelligent mobile vehicles under different loads. From the figure, it can be found that the lateral displacement deviation under full load condition has increased compared with that under no-load condition, with the maximum of -0.233m, indicating that with the increase of load, the lateral displacement deviation may also increase, but it is within the safe range. Figure (c) shows the change of yaw angle deviation value under different loads, and Figure (d) shows the change of steering curvature. From the change curve in the figure, there is no significant change in yaw angle deviation and steering curvature under different loads, and there is no obvious sudden change at the corner, and it remains flat, indicating that intelligent mobile vehicles can have good stability under different loads. the lateral motion controller has good robustness under different loads.



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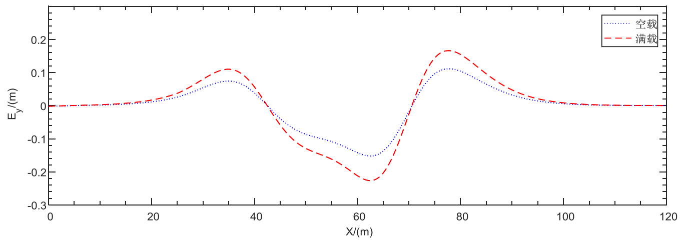

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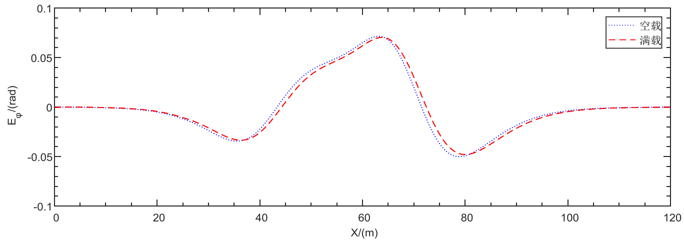

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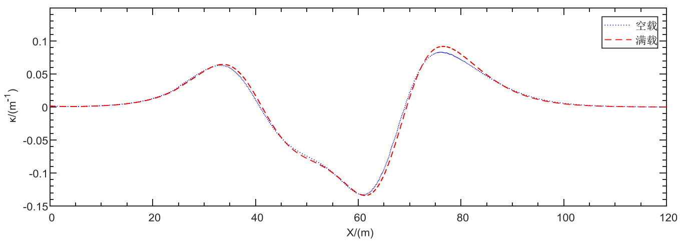

(d)

Fig.4 Simulation results of lateral control under different loads

CONCLUSION

By analyzing the kinematics conversion relationship between Cartesian coordinate system and Frenet coordinate system, the kinematics model of intelligent mobile vehicle in Frenet coordinate system is established based on the derived kinematics model of Cartesian coordinate system, and the deviation model of intelligent mobile vehicle in space domain is established on this basis. Then the lateral motion control strategy is designed based on the model predictive control algorithm. In the design process of lateral motion control strategy, the prediction model is selected as the linearized and discretized space domain deviation model. The selected objective function is mainly used to optimize the lateral displacement deviation and the change of steering curvature of the intelligent mobile machine, to ensure the minimum lateral displacement deviation between the intelligent mobile machine and the reference path during the working process, and to avoid sudden changes in steering curvature. In addition, considering the requirements of the steering actuator and the safety during operation, the change of the steering curvature, the steering curvature and the lateral displacement deviation of the intelligent mobile machine are limited. Finally, to solve the optimal curvature, the objective function is converted into a quadratic programming problem. Through joint simulation, taking double line shifting as the reference path, it is verified that the designed lateral motion control strategy has good robustness at different speeds and loads.

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