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Regional path moving horizon tracking controller design for autonomous ground vehicles

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Abstract A novel regional path tracking description is presented in this manuscript, and the moving horizon control method that is model predictive control (MPC) is proposed to discuss the regional path tracking issue which could avoid colliding road boundary when tracking a more complex road effectively. The feasible region for autonomous ground vehicles (AGVs) running is determined first according to the detected road boundaries. Then, in order to keep the actual trajectory of AGVs in the region and satisfy the safety requirements, MPC method is employed to design the path tracking controller considering actuator and road boundary constraints. In order to verify the effectiveness of the proposed method, experiments based on Hongqi AGV HQ430 are carried out, and the results illustrate that the presented method could be successfully applied to Hongqi AGV vehicle HQ 430.

Keywords autonomous ground vehicles, regional path tracking, model predictive control, road boundaries, experimental validation

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1 Introduction

For autonomous ground vehicles (AGVs), one of the most important issues is path tracking. Conventionally, steering and velocity control are generally two typical aspects in path tracking problem [1]. Steering control is discussed in this manuscript because it is important to path tracking and related to vehicle lateral stability. Most of the exist algorithms are developed based on point-line vehicle-road model [2]. It regards vehicle as a rigid point, and employs a continuous curve or discrete points to describe the desired path [3]. Compared with practical situations, it may cause collisions when tracking a more complex road ignoring the size and shape of AGVs [4, 5]. In addition, ignoring the width of road may make AGVs deviate the feasible road region [6]. However, according to the corresponding literatures [2, 3], there are few discussions of path tracking considering the shape of vehicle and width of road.

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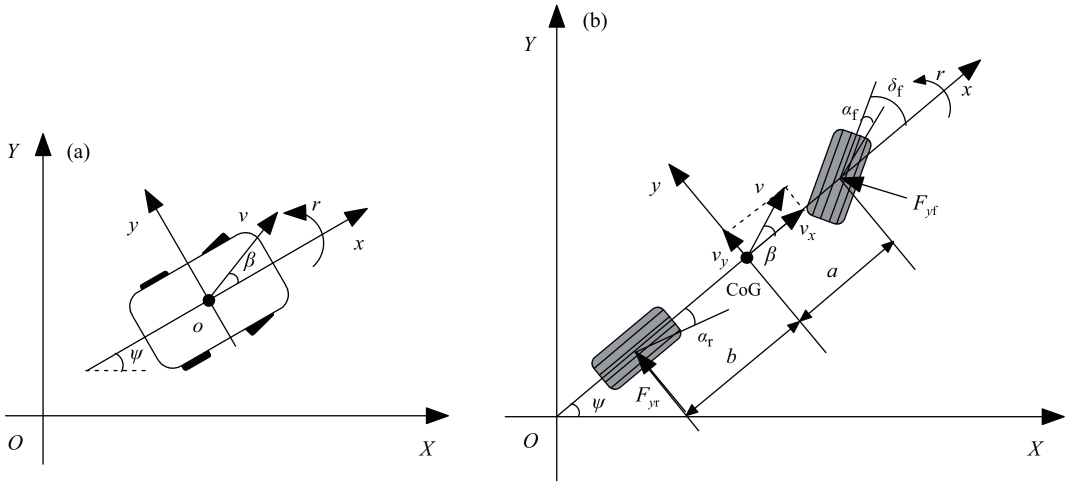


Figure 1 Vehicle model. (a) Vehicle kinematic relation; (b) 2-DOF linear bicycle model.

Based on the above discussions, suitably considering the shape of vehicle and repeatedly testing the width of road are the challenges in solving steering control problem. Besides it should make control decision repeatedly for AGVs according to the previewed traffic environment and road information. In this manuscript, it proposes a novel regional path tracking issue, in which the shape of vehicle is considered as a rectangle and the feasible road region that considers the width of road is described as feasible region. Then the road boundaries and actuator saturation are considered as constraints, and model predictive control (MPC) method is introduced to solve the regional path tracking problem. Moreover, the experiments based on Hongqi AGV HQ430 are carried out to verify the effectiveness of the presented regional path tracking moving horizon method.

The main contributions of this paper lie in two aspects. (1) The original description of regional path tracking issues for AGVs is presented which considers the shape of vehicle and feasible road region. (2) The moving horizon path tracking controller is proposed and it could be successfully applied to Hongqi AGV vehicle HQ430.

2 Regional path tracking problem

In this paper, only the steering control is studied, so the longitudinal dynamics of the vehicle is ignored. That is to say, the longitudinal velocity is assumed as constant which is commonly discussed in such problems [7]. Considering that path tracking performance is related to the position and dynamic characteristics of vehicle, the kinematic and dynamic relationships that are shown in Figure 1 are both employed here. The kinematic relationship is derived based on inertial coordinate system XOY as shown in Figure 1(a) with assumptions that the vehicle is considered as a rigid body with non-deformable wheels, being front wheels used for steering. Moreover, regarding the vehicle dynamics that is shown in Figure 1(b), the vehicle body coordinate system with the origin at center-of-gravity (CoG) is defined. The direction of longitudinal velocity points to forward and the lateral velocity points to the left. Based on the above description, the vehicle could be described as follows:

$$\dot{y} = v(\psi + \beta), \tag{1a}$$

$$\dot{\psi} = r, \tag{1b}$$

$$\dot{\beta} = \frac{(C_{\rm f} + C_{\rm r})}{mv}\beta + \left(\frac{(aC_{\rm f} - bC_{\rm r})}{mv^2} - 1\right) r - \frac{C_{\rm f}}{mv}\delta_{\rm f}, \tag{1c}$$

$$\dot{r} = \frac{(aC_{\rm f} - bC_{\rm r})}{I_z}\beta + \frac{(a^2C_{\rm f} + b^2C_{\rm r})}{I_z v}r - \frac{aC_{\rm f}}{I_z}\delta_{\rm f}, \tag{1d}$$

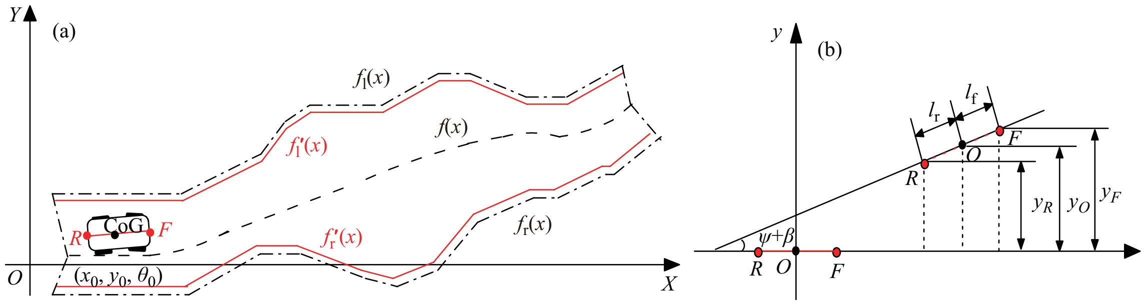


Figure 2 (Color online) Vehicle road model. (a) Feasible region for AGVs; (b) the relationship between CoG and front end F and rear end R.

$$y_{\text{out}} = y, \tag{1e}$$

where y is the lateral position of CoG in the inertial coordinate system, v is the longitudinal vehicle velocity, ψ is the yaw angle, r is the yaw rate, β is the vehicle sideslip angle, m is vehicle mass, I_z is the moment of inertia around z axis, δ_f is the front wheel steering angle, and C_f and C_r are the cornering stiffness of the front and rear tire, respectively. The longitudinal velocity is constant, vehicle mass m, cornering stiffness C_f and C_r and the moment of inertia around z axis I_z vary so slowly that could be assumed as constant. In addition, the CoG is considered as constant during vehicle running which makes a and b invariant. Based on above consideration, selecting lateral position y as output, front wheel steering angle δ_f as input, and $x = [y\ \phi\ \beta\ r]$ as states, then the vehicle model in Eq. (1) could be treated as linear-time-invariant system.

According to the actual situation of vehicle running on the road, as shown in Figure 2(a), the local feasible region for vehicle running is represented by three curves: the centerline $f(x)$, the left boundary $f_\text{l}(x)$ and the right boundary $f_\text{r}(x)$. Accordingly, the vehicle runs in this region could be described as a rectangle, where the width of vehicle is expressed as w and the length is described as l. Then the regional path tracking problem of AGVs could be described by searching and tracking the optimal path in the determined region.

Besides, it is essential to avoid crashing the road boundaries to ensure the safety of AGVs. Based on the relationship between vehicle described in Eq. (1) and road, the aim could be achieved by restricting the lateral positions of the front end F and the rear end R within the road boundaries. In addition, in order to make the regional path tracking problem more simple, the vehicle is simplified as a rigid bar, accordingly the boundary on each side of road is reduced by half of the vehicle to ensure the rationality of the simplification. Therefore, the simplified feasible road region could be described as $f_\text{l}'(x) = f_\text{l}(x) - \frac{w}{2}$, $f_\text{r}'(x) = f_\text{r}(x) - \frac{w}{2}$. Then the lateral positions of front and rear end of vehicle should be satisfied the following conditions:

$$f_\text{r}'(x) \leqslant y_i \leqslant f_\text{l}'(x), \quad i = F, R, \tag{2}$$

where $y_i, i = F, R$ represents the lateral positions of the front end and rear end, respectively.

The geometric relationships and the movement direction of vehicle are shown in Figure 2(b). Considering most roads are small-curvature, the simplification could be carried out, that is $\sin(\psi + \beta) \approx \psi + \beta$. Accordingly, the relationships between lateral position of CoG and front and rear end of the vehicle could be described as $y_F = y + l_\text{f}(\psi + \beta)$, $y_R = y - l_\text{r}(\psi + \beta)$, where y is the lateral position of CoG, ψ is yaw angle. Then the lateral position of CoG that is the output of the vehicle system is considered to satisfy the following constraints:

$$f_\text{r}'(x) - l_\text{f}(\psi + \beta) \leqslant y_{\text{out}} \leqslant f_\text{l}'(x) - l_\text{f}(\psi + \beta), \tag{3a}$$
$$f_\text{r}'(x) + l_\text{r}(\psi + \beta) \leqslant y_{\text{out}} \leqslant f_\text{l}'(x) + l_\text{r}(\psi + \beta). \tag{3b}$$

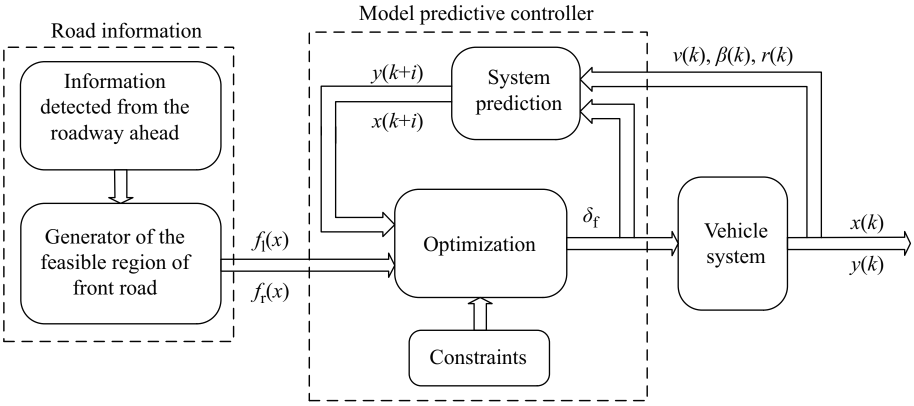


Figure 3 Block diagram of the path following control system.

3 Regional path tracking control

Considering the road and traffic are both varied instantaneously, it needs AGVs to make decision in each sample time according to the previewed roadway a distance ahead. In addition, the feasible region obtained from the above section restricts the vehicle lateral position, which is considered as constraints of system. Therefore, MPC approach is introduced to discuss path tracking controller design. The structure of the control scheme is shown in Figure 3 clearly.

The road information detected from the roadway ahead is a series of position points. In order to turn the previewed point of road information into the road boundary information, it introduces the quadratic search based three times Lagrange interpolation formula described in Eq. (4) in the module of generator of the feasible region of front road,

$$f_{\rm r}(x) = \sum \prod_{i \neq p} \frac{(x - x_{\rm r}(i))}{(x_{\rm r}(p) - x_{\rm r}(i))} y_{\rm r}(p), \quad p, i = j, n, m, k, \tag{4a}$$

$$f_{\rm l}(x) = \sum \prod_{i \neq p} \frac{(x - x_{\rm l}(i))}{(x_{\rm l}(p) - x_{\rm l}(i))} y_{\rm l}(p), \quad p, i = j, n, m, k, \tag{4b}$$

where, j, k, n and m represent the position of the four sets of interpolation points in the given road points sequence $(x_{\rm r}, y_{\rm r}, x_{\rm l}, y_{\rm l})$. Moreover, j is the start point and m is the end point, which are selected based on the quadratic search algorithm. While the other two sets of interpolation points can be obtained as $n = \lfloor \frac{k-j}{3} + j \rfloor$, $m = \lfloor \frac{k-j}{3} + n \rfloor$. When the feasible road boundary is determined, the road centerline could also be expressed as $f(x) = \frac{1}{2}\left(f_{\rm l}(x) + f_{\rm r}(x)\right)$.

By discretizing the continuous-time model in Eq. (1) with a sample time of $T_{\rm s}$ seconds, a discrete-time model described as follows is obtained,

$$x(k+1) = A_{\rm c}x(k) + B_{\rm c}u(k), \quad y_c(k) = C_{\rm c}x(k), \tag{5}$$

where $A_{\rm c} = e^{AT_{\rm s}}$, $B_{\rm c} = \int_0^{T_{\rm s}} e^{A\tau}{\rm d}\tau \cdot B$, $C_{\rm c} = C$, the matrices A, B, C could be obtained from Eq. (1).

In the following, the vehicle dynamic prediction shown in Figure 3 could be carried out. Suppose that the predictive horizon is P, the control horizon is N, and the control input keeps invariant beyond control horizon, that is $u(k+N-1) = u(k+N) = \cdots = u(k+P-1)$. Accordingly, based on Eq. (5), the predicted output of the system at time k can be computed. Then, define the control input sequence $U(k)$ and the predict output sequence $Y(k+1|k)$ at time k as

$$U(k) = \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+N-1) \end{bmatrix}, \quad Y(k+1|k) = \begin{bmatrix} y(k+1) \\ y(k+2) \\ \vdots \\ y(k+P) \end{bmatrix}. \tag{6}$$

Besides, centerline of feasible road region is selected as the reference input sequence,

$$R(k) = \begin{bmatrix} f(k) & f(k+1) & \cdots & f(k+P-1) \end{bmatrix}^{\mathrm{T}}. \tag{7}$$

In order to follow the centerline in the given feasible region, it requires to minimize the difference between the predicted output and road centerline, that is $J_1 = \|Y(k+1|k) - R(k)\|^2$. In addition, considering the saturation of mechanical system, the action of steering wheel motor is limited, which is formulated as minimizing $J_2 = \|U(k)\|^2$. Besides, it ensures that AGVs consume low energy by minimizing driving route as $J_3 = \sum_{i=1}^{P}(\|\Delta x_d(k+i)\|^2 + \|\Delta y_d(k+i)\|^2)$, where $\Delta x_d(k+i) = v(k)\cdot T_{\mathrm{s}}$, $\Delta y_d(k+i) = y_o(k+i) - y_o(k+i-1)$, $i = 1,\ldots,P$, are longitudinal and lateral distances in a sample time.

Considering minimizing all of those three objectives simultaneously is contradictive, weighting factors are introduced. Accordingly, the multi-objective cost function could be obtained as follows:

$$J = \|\Gamma_y(Y(k+1|k) - R(k))\|^2 + \|\Gamma_u U(k)\|^2 + \sum_{i=1}^{P}\Gamma_{d,i}(\|\Delta x_d(k+i)\|^2 + \|\Delta y_d(k+i)\|^2), \tag{8}$$

where $\Gamma_y = \mathrm{diag}(\Gamma_{y,1},\Gamma_{y,2},\ldots,\Gamma_{y,P}) > 0$, $\Gamma_{d,i} > 0$, $\Gamma_u = \mathrm{diag}(\Gamma_{u,1},\Gamma_{u,2},\ldots,\Gamma_{u,N}) > 0$ are weighting matrices, and the sample interval is $v(k)\cdot T_{\mathrm{s}}$.

Considering the mechanical characteristic of steering actuator, it bounds the steering variation and steering rate. In order to ensure an applicable control variable, the following constraints of control input and variation of control input are also considered,

$$u_{\min} \leqslant u(k+i) \leqslant u_{\max}, \tag{9a}$$

$$\Delta u_{\min} \leqslant \Delta u(k+i) \leqslant \Delta u_{\max}, \tag{9b}$$

where $\Delta u(k+i) = u(k+i+1) - u(k+i)$, $i = 0,\ldots,N-1$ is the control increment, $u_{\max}$ is the maximum wheel steering angle and $u_{\min}$ is the minimum wheel steering angle.

Moreover, the output of the vehicle system is considered to satisfy the following constraints in discrete form obtained from Eq. (3):

$$f_{\mathrm{r}}'(k+i) - l_{\mathrm{f}}(\psi(k+i) + \beta(k+i)) \leqslant y_{\mathrm{out}}(k+i) \leqslant f_{\mathrm{l}}'(k+i) - l_{\mathrm{f}}(\psi(k+i) + \beta(k+i)), \tag{10a}$$

$$f_{\mathrm{r}}'(k+i) + l_{\mathrm{r}}(\psi(k+i) + \beta(k+i)) \leqslant y_{\mathrm{out}}(k+i) \leqslant f_{\mathrm{l}}'(k+i) + l_{\mathrm{r}}(\psi(k+i) + \beta(k+i)), \tag{10b}$$

where $i = 1,\ldots,P$, $\psi(k+i) = [0\ 1\ 0\ 0]x(k+i)$, $\beta(k+i) = [0\ 0\ 1\ 0]x(k+i)$, $f_{\mathrm{l}}'(k+i)$ and $f_{\mathrm{r}}'(k+i)$ are discrete values of the left and right boundaries of the given feasible region, respectively.

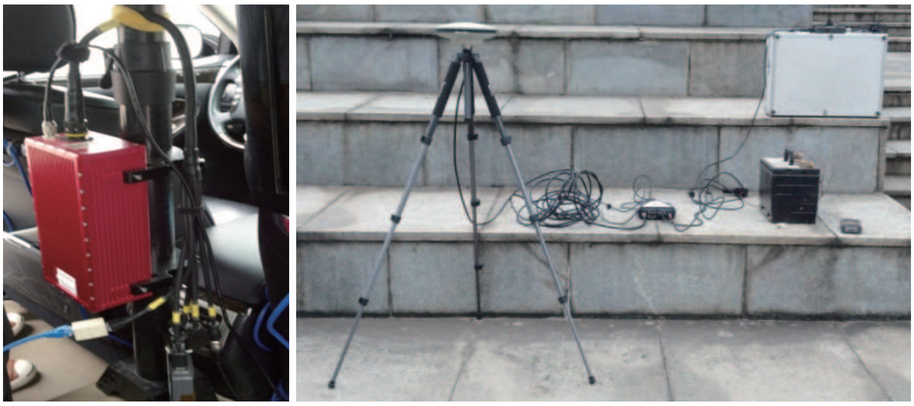
In conclusion, the regional path tracking problem can be transformed into the moving horizon control problem presented in the following optimization problem:

$$\min_{U(k)} \quad J(y(k), U(k), N, P), \quad \text{s.t. Eqs.(5), (9), and(10).} \tag{11}$$

After successfully solving the MPC problem described by Eq. (11), only the first element of the optimal control sequence $U(k)$ is applied to the controlled vehicle. In the next sample time, the optimization problem is solved again.

4 Implementation and experiments

In order to demonstrate the effectiveness of the proposed regional path tracking method, the presented MPC algorithm is implemented based on C language and differential evolution algorithm is employed to solve the optimization issue considering computational efficiency and hardware resources consumption. Then the validation experiments are carried out on the Hongqi AGV HQ430 at a square. The AGV Hongqi vehicle HQ430 is composed of two parts which are environment perception system and driving control system. Driving control system runs in a single board computer which includes three parts that



(a) (b)

Figure 4 (Color online) Additional sensors used in the experiment and data acquisition system. (a) RT3002; (b) GPS.

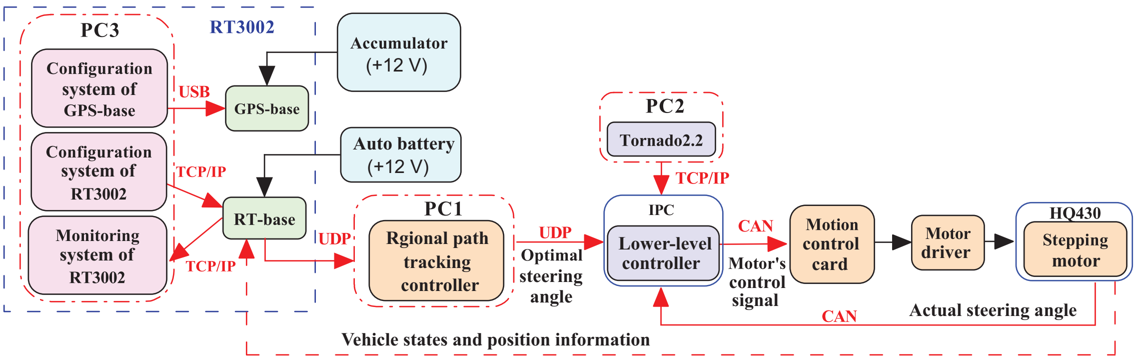


Figure 5 (Color online) Data acquisition system.

are decision-making, planning and control. Environment perception system includes two parts which are lane marking detection and preceding vehicle recognition that running in two different computers, respectively. The sensors used for perception are right-and-left wheel odometer, braking pressure sensor and throttle valve position, gyroscope and two cameras. Besides, in order to obtain vehicle velocity and sideslip angle, RT3002 developed by Oxford Technical Solutions is employed and the installed location on the vehicle seen in Figure 4(a). Moreover, in order to obtain vehicle position information, GPS Integrated Navigation system seen in Figure 4(b) is adopted. There are two additional computers used in the experiments, where the regional path moving horizon tracking controller runs in the Thinkpad T420, and the other Thinkpad T420 is used to configure RT3002.

In the experiments, the front steering angle obtained from the proposed MPC method replaces the original front steering angle computed by driving control system. The communication between sensors and steering motor, and driving control system is shown in Figure 5. The regional path moving horizon tracking controller needs to exchange information with other systems, and the user datagram protocol (UDP) is used to communicate with RT3002 and driving control system. In addition, the CAN bus is employed to exchange information from driving control system to steering motor, and vehicle system. The additional sensor equipped on the experiment vehicle communicates information with other systems employed by UDP.

5 Conclusion

A novel regional path tracking description for autonomous ground vehicles (AGVs) is presented in this manuscript, and then regional path moving horizon tracking controller is proposed using model predictive control (MPC) method, where the front wheel steering angle was selected as the control variable. In order to validate the performance of the proposed method, experiments are carried out based on Hongqi autonomous ground vehicle HQ430. Experimental results demonstrate the effectiveness of the proposed regional path tracking method.

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Conflict of interest The authors declare that they have no conflict of interest.

Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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