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Multiobjective adaptive car-following control of an intelligent vehicle based on receding horizon optimization

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Dear editor,

Vehicle control is one of the key steps of intelligent driving [1]. Algorithms based on receding horizon optimization (RHO) can predict future trajectories and handle multiobjective constraint conditions; therefore, RHO-based methods have attracted considerable attention in the field of vehicle control. Although existing methods use RHO to design controllers, they do not simultaneously meet the multiobjective optimal control performance requirements on tracking, fuel economy, and ride comfort. The main reasons are (1) the deficiency of a single control target, (2) the difficulty to achieve global optimization in closed-loop systems, and (3) the high computational complexity and low computational efficiency that cannot meet the real-time requirements.

To solve the abovementioned problems, the main contributions of this study include the following aspects: (1) A multiobjective adaptive following control model is established. (2) According to the model, a cost function including tracking accuracy, fuel economy, and ride comfort is built. Therefore, the inequality constrained predictive optimization problem can be solved. (3) The RHO is adopted to guarantee computational efficiency and ensure the real-time requirements of the vehicle are met.

Modeling of control object. The inverse model is used to compensate for the longitudinal nonlinearity of a vehicle to establish a control system with linear input-output characteristics, named generalized vehicular longitudinal dynamics system (GVLDS) (Figure 1(a)). The input and output characteristics of GVLDS are described by the first-order inertial transfer function:

$$\alpha_f = \frac{K_G}{T_G s + 1}\alpha_{f\mathrm{des}}, \tag{1}$$

where a_f is the actual acceleration, K_G and T_G are the system gain and time constant of the transfer function model, respectively, and $a_{f\mathrm{des}}$ is the desired acceleration.

Integrated modeling of the dynamic characteristics. The coupling relationship between vehicles and the longitudinal dynamic characteristics between vehicles need to be considered. The integrated modeling idea is adopted to establish a continuous kinetic model of a multiobjective adaptive tracking control system (Figure 1(b)). Then, the model of an intervehicular longitudinal dynamics system is $\Delta\dot{d} = \Delta v - [\tau_h + r(2v_f - v_{f\mathrm{mean}})]a_f$, $\Delta\dot{v} = a_p - a_f$, where a_p is the acceleration of the preceding vehicle. The continuous dynamic model of the tracking system is established:

$$\begin{aligned} \dot{x} &= \begin{bmatrix} 0 & 1 & -\tau_h - r(2v_f - v_{\mathrm{mean}}) \\ 0 & 0 & -1 \\ 0 & 0 & -1/T_G \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \frac{K_G}{T_G} \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} v \\ &\hat{=} \phi x + \Pi u + \Gamma v, \\ x &= [\Delta d \;\; \Delta v \;\; a_f]^{\mathrm{T}},\ u = a_{f\mathrm{des}},\ v = a_p, \end{aligned} \tag{2}$$

where the system state $x \in \mathbb{R}^3$ is the vector comprising the vehicle distance error, relative speed, and intelligent vehicle acceleration. Eq. (2) is discretized by the zero-order invariant control input method:

$$x(k+1) = Ax(k) + Bu(k) + Gv(k). \tag{3}$$

Let T_s denote the control cycle, and then $A = \sum_{i=0}^{\infty} \frac{\phi^k T_s^k}{k!}$,

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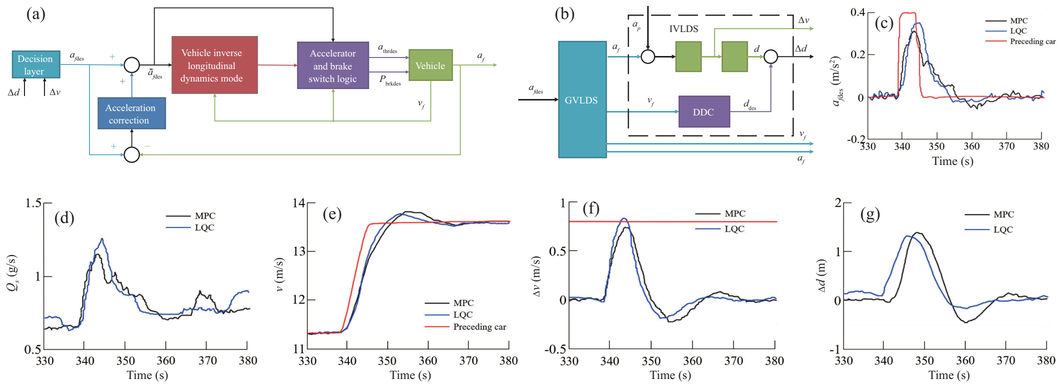

Figure 1 (Color online) (a) Generalized vehicular longitudinal dynamics system; (b) multiobjective adaptive tracking control system model; experimental results of (c) the desired acceleration, (d) the instantaneous fuel consumption, (e) the vehicle speed, (f) the relative speed, and (g) the distance error, respectively.

$B=\sum_{k=0}^{\infty}\frac{\phi^{k-1}T_s^k}{k!}\prod$, $C=\sum_{k=0}^{\infty}\frac{\phi^{k-1}T_s^k}{k!}\Gamma$.

Cost function. For the multiobjective optimal control, the cost function of the predicted time domain is as follows:

$$\begin{aligned}L(y,u,\Delta u) &= \textstyle\sum_{i=0}^{P}\|\omega_{\mathrm{CF}}y(k+i+1|k)\|^2\cdot w_y\\ &+\textstyle\sum_{i=0}^{P}\|u(k+i|k)\|^2\cdot w_u+\sum_{i=0}^{P}\|u(k+i|k)\|^2\cdot w_{\Delta u},\end{aligned}\tag{4}$$

where k is the current time, P is the predicted length, and $[k : k+P-1]$ is the predicted time domain of the multiobjective adaptive car-following control for the intelligent vehicle, $(k+i|k)$ represents the prediction of the $k+i$ time based on the time information of k, $\|\cdot\|$ is the 2-Norm of the matrix, and u is the control increment.

Constraint design. The predictive constraint for multiobjective adaptive car-following control is given by

$$\begin{cases}u_{\min}\leqslant u(k+i|k)\leqslant u_{\max},\\ \Delta u_{\min}\leqslant \Delta u(k+i|k)\leqslant \Delta u_{\max},\\ y_{\min}\leqslant y(k+i+1|k)\leqslant y_{\max},\\ a_{\mathrm{safe}}\cdot y(k+i+1)\leqslant d_{\mathrm{safe}}+\tau_{\mathrm{safe}}v(k+i+1|k),\\ i=0:(P-1),\end{cases}\tag{5}$$

where $u_{\min}=a_{f\min}$ and $u_{\max}=a_{f\max}$ are the lower and upper bounds of the control input, respectively; $\Delta u_{\min}=j_{f\min}\cdot T_s$ and $\Delta u_{\max}=j_{f\max}\cdot T_s$ are the lower and upper bounds of the control increment, respectively; $y_{\min}$ and $y_{\max}$ are the lower and upper bounds of the system output, respectively. Moreover, v is the inference of the acceleration of the preceding car, $y(k+i+1|k)$ represents the predicted value of the interference v, and $a_{\mathrm{safe}}\in\mathbb{R}^{n\times n}, d_{\mathrm{safe}}\in\mathbb{R}^n$ and $\tau_{\mathrm{safe}}\in\mathbb{R}^n$ are the coefficient matrices.

Multiobjective control algorithm. The RHO-based multiobjective adaptive car-following vehicle control model algorithm is given by

$$u^*(k)=u(k-1)+\Delta u^*(k+0|k),\tag{6}$$

where the control input is the desired acceleration; $u^*(k)$ is the optimal control input of k step; $u(k-1)$ is the control input of $k-1$ step; $u^*(k+0|k)$ is the first element of the optimal control increment. The optimal control increment $u^*(k+i|k)$ is the optimal solution for the prediction problem. The Dantzig-Wolfe's efficient set method is used to solve the problem [2], and the optimal control law is given. The cycle of the algorithm is 100 ms.

Experiments. The comparison method is linear quadratic control (LQC) [3], which is a type of multiobjective coordinated optimal control method and suitable for linear objects. The urban road experimental results (Figures 1(c)–(g)) prove the real-time performance of the control method and the acceleration can meet the longitudinal ride comfort standard. However, the RHO method is more accurate to track the preceding vehicle's acceleration, and its absolute value is lower than that of the LQC method. The instantaneous fuel consumption of the RHO method is lower than that of the LQC method in most periods, indicating that the fuel economy of the RHO method is better. The tracking speed and accuracy of the RHO method are higher. In addition, the relative vehicle speed and vehicle distance error are smaller than those of the LQC method. Therefore, the tracking performance of the RHO method is better than that of the LQC method. More details are included in Appendixes A–E.

Conclusion and future work. The RHO method proposed in this study effectively solves the three functional requirements of intelligent vehicle tracking accuracy, low fuel consumption, and ride comfort. The comparative experimental results show that the proposed method is superior to the existing LQC method in the three aspects. In the future, we will further improve the real-time performance of the algorithm based on the proposed method.

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Supporting information Appendixes A–E. 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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