Proceeding of the 14th International Forum of Automotive Traffic Safety, 2017, pp 213-219
No.ATS.2017.308

Model Predictive Control of U-Turn Path Tracking for Autonomous Agricultural Vehicle

Yiheng Lin[1], Guodong Yin[1*], Zongchao Ma[2], Ji Wang[2], Xiangrui Wang[2]

[1]*School of Mechanical Engineering, Southeast University, Nanjing China 211189*

[2] *75660 Troop of the PLA, Hengyang China 421008*

**Corresponding author e-mail: ygd@seu.edu.cn*

Abstract:

Background: Intelligent technique can greatly promote the rapid development of agricultural industry and enhance the market competition of agricultural machinery products of China, however, the current domestic agricultural machinery intelligence level is still lacking, thus improving the intelligent level of agricultural machinery is imminent.

Objective**:** This paper is aimed to study the automatic driving technology of agricultural vehicle, this paper studies the reasonable driving control method of agricultural vehicle, and achieve the automatic driving with higher accuracy under the straight and curve driving conditions.

Method and Material: In this paper, path tracking based on model predictive control (MPC) for the intelligent agricultural vehicle is investigated. The motion of the vehicle was simulated based on the path tracking error dynamics and vehicle lateral dynamics. Simulink-CarSim joint simulation platform was used to validate the proposed path tracking controller.

Results**:** the simulation results show that the control method is feasible. the mean values of the error of the vehicle for the straight lines are 1.8 cm. Besides, the mean values of the error of the vehicle for the curved lines are 5.44 cm.

Conclusions: The fast MPC framework has been elaborated for the control of an intelligent agricultural vehicle system by U-turn method in a standard orchard. Simulation results based on Simulink-CarSim platform verify the effectiveness of the proposed control approach. The simulation results show that the proposed MPC framework is able to control the agricultural vehicle system with a reasonable accuracy.

Keywords: MPC, standard orchard, path tracking, agricultural vehicle, Simulink-CarSim

1 Introduction

Agricultural vehicle automatic navigation technology is one of the important support technologies of modern agricultural machinery and equipment. Realizing the intelligent navigation of agricultural machinery can effectively reduce the labor intensity of the driver and improve the quality of farmland work, which has important theoretical research significance and practical application value.

While develop autonomous navigation is all over the world, especially in Japan and America [1][2]. Takai et al. used RTK-GPS and IMU published an autonomous guidance for Crawler-Type robot tractor [3], they obtained enough accurate for the tractor. Some researchers used Low-Cost GPS based on Kalman Filter (KF) to position a tractor, which results that the proposed filter can satisfactorily preprocess the low-cost GPS receiver data when used in an assistance guidance GPS system for tractors [4][5]. Researchers of China improved a tuning method of fractional order proportional differentiation (FOPD) controller to track the path of a tractor, the simulation results demonstrate the optimal FOPD controller enables the closed-loop system to have smaller IAE value [6]. Xiwen Luo et al. Developed an automatic navigation control system based on RTK-DGPS on Dongfanghong X-804 tractor and conducted field experiment. The experimental results show that the maximum error of linear tracking is less than 0.15m [7]. Xing Wu et al. investigated the tractors kinematics and dynamics properties of the vehicle actuated, the experiment results show the tractor can actuate the heavy-duty vehicle with low power consumption [8]. Ramezani et al. proposed a new DSWTS algorithm for real-time pedestrian detection in autonomous agricultural tractors. The results show that the DSWTS algorithm has good accuracy at 8-20m [9]. Middle East countries are also devoted to studying the automatic driving of agricultural machinery and have achieved many successes [10] [11].

This paper is organized as follows: in section 2 the modeling the vehicle lateral dynamics and the path tracking error dynamics is given. The MPC approach is shown in section 3. In section 4, the path tracking simulations results are given. At last, the conclusions are addressed in section 5.

2 Modeling

2.1 The vehicle lateral dynamic model

As the operation speed of the agricultural vehicle is rather limited, it is reasonable to assume that the lateral forces on the left and right wheels are equal to each other and can be summed. Therefore, the vehicle is modeled as a well-known bicycle model. The forces on the vehicle are schematically illustrated in Fig.1.

The dynamics equation for 2 DoF model of agricultural vehicle can be given as follows:

$$\begin{cases} I_z\dot{\gamma} = l_f F_{yf} - l_r F_{yr} \\ m v_x \dot{\beta} = F_{yf} + F_{yr} - m v_x \gamma \end{cases} \tag{1}$$

Where F_{yf} and F_{yr} stand for front and rear lateral forces which are related with the front and rear slip angles α_f and α_r, respectively. which can be modeled as

$$F_{yf} = C_f \alpha_f,\ \ F_{yr} = C_r \alpha_r \tag{2}$$

Where C_f and C_r stand for the cornering stiffness of the front and rear tires, respectively. The slip angles of front and rear tires are represented by α_f and α_r, which can be defined using the following equations [12]:

$$\alpha_f = \delta_f - \frac{l_f \gamma}{v_x} - \beta,\ \ \alpha_r = \frac{l_r \gamma}{v_x} - \beta \tag{3}$$

We assume that the sideslip angle is sufficiently small, so β can be defined as

$$\beta = \frac{v_y}{v_x} \tag{4}$$

Supposing v_x is a constant or with a slow changing rate. Solving equation (1) by substituting equations (2) to (4), the following 2 DoF linear dynamic model can be derived:

$$\begin{cases} \dot{\gamma} = a_{11}\gamma + a_{12}\beta + b_{11}\delta_f \\ \dot{\beta} = a_{21}\gamma + a_{22}\beta + b_{21}\delta_f \end{cases} \tag{5}$$

the model parameters in (5) are given as:

$$\begin{aligned} & a_{11} = -\frac{l_f{}^2 C_f + l_r{}^2 C_r}{I_z v_x}, a_{12} = \frac{l_r C_r - l_f C_f}{I_z} \\ & a_{21} = \frac{l_r C_r - l_f C_f}{m v_x{}^2} - 1, a_{22} = -\frac{C_f + C_r}{m v_x} \\ & b_{11} = \frac{l_f C_f}{I_z}, b_{21} = \frac{C_f}{m v_x} \end{aligned} \tag{6}$$

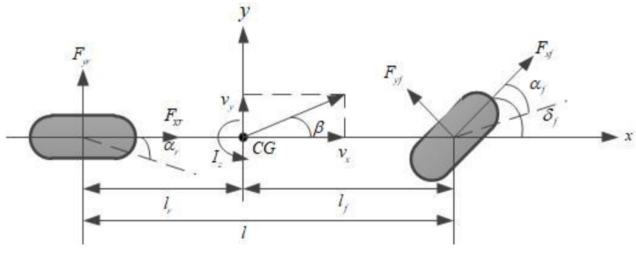

Fig.1. 2 DoF vehicle dynamic model

2.2 The path tracking error dynamics

Fig.2 shows the path following error dynamics model. τ represents the distance from the CG of the vehicle to the closest point *M* on the desired path, i.e., the orthogonal projection point of CG on the desired path. Which is stand for lateral offset. ψ presents the heading error between actual heading angle of the agricultural vehicle ψ_r and tangential direction of the desired path ψ_d, then we can get:

$$\psi = \psi_r - \psi_d, \dot{\psi}_r = \gamma \tag{7}$$

And where *s* is defined as the curvilinear coordinate (arc-length) of point *M* along the path from an initial position predetermined, and $\dot{s} = ds/dt, s \geq 0$, $\rho(s)$ stands for the curvature of the desired path at the point *M*, and is related with *s*. where v_x and v_y stand for the vehicle longitudinal and lateral velocities, respectively.

The curvilinear coordinate of point *M* along the path *s* is given as:

$$\dot{s} = \frac{1}{1 - \tau \cdot \rho(s)}(v_x \cos\psi - v_y \sin\psi) \tag{8}$$

The path following error dynamics based on the Serret-Frenet equation is introduced in [13] was showed as follows:

$$\begin{cases} \dot{\tau} = v_x \sin\psi + v_y \cos\psi \\ \dot{\psi} = \gamma - v_x \rho(s) \end{cases} \tag{9}$$

Combined (5) with (9), we can get:

$$\begin{cases} \dot{\gamma} = a_{11}\gamma + a_{12}\beta + b_{11}\delta_f \\ \dot{\beta} = a_{21}\gamma + a_{22}\beta + b_{21}\delta_f \\ \dot{\tau} = v_x \sin\psi + v_y \cos\psi \\ \dot{\psi} = \gamma - v_x \rho(s) \end{cases} \tag{10}$$

The state variable is selected as $\xi(t) = \begin{bmatrix} \gamma & \beta & \tau & \psi \end{bmatrix}^T$,the control input is selected as $u(t) = \delta_f$,The vehicle dynamics can be described by the following compact differential equation:

$$\begin{cases} \dot{\xi}(t) = f(\xi(t), u(t)) \\ \eta(t) = y(\xi(t)) \end{cases} \tag{11}$$

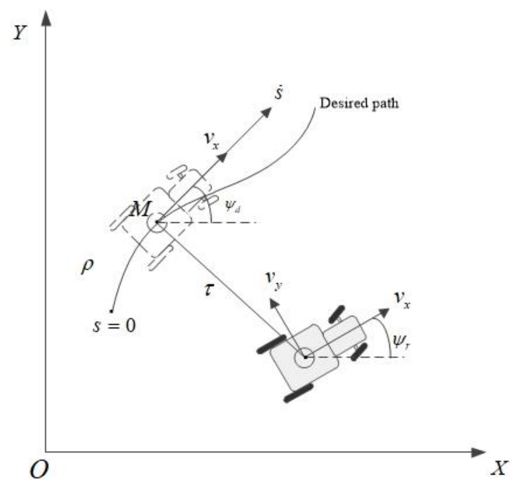

Fig.2. Path tracking error dynamics model

3 Model predictive controller

3.1 Problem description

Considering a non-linear system, the general form of discrete-time model as follows:

$$\begin{cases} \xi(t+1) = f(\xi(t), u(t)) \\ \xi(t) \in \chi, u(t) \in \Gamma \end{cases} \tag{12}$$

Where $f(\bullet,\bullet)$ is system state transfer function, $\xi \in R^n$ is the state vector, $u \in R^m$ is the control vector, χ is state variable constraint, Γ is control variable constraint. Let $f(0,0)=0$ is a stable point of the system, which is also system control objective, for any time horizon *N*, consider the follow cost function [14]:

$$J_N(\xi(t), U(t)) = \sum_{k=t}^{t+N-1} g(\xi(k), u(k)) + l(\xi(t+N)) \tag{13}$$

Where $U(t) = [u(t), \cdots, u(t+N\text{-}1)]^T$,i.e. the control input sequence in the time horizon *N*.

Combined (12) with (13), MPC is to solve the following constrained optimization problem at each step in the time horizon: respectively.

$$\begin{aligned} &\min_{U_t, \xi_{t+1}, \cdots, \xi_{t+N,t}} J_N(\xi_t, U_t) \\ s.t. \quad &\xi_{k+1,t} = f(\xi_{k,t}, u_{k,t}), k = t, \cdots, N-1 \\ &\xi_{k,t} \in \chi, k = t+1, \cdots, t+N-1 \\ &u_{k,t} \in \Gamma, k = t, \cdots, t+N-1 \\ &\xi_{t,t} = \xi(t) \\ &\xi_{N,t} \in \chi_{fi} \end{aligned} \tag{14}$$

In (14), $\xi_{k+1,t} = f(\xi_{k,t}, u_{k,t})$ is state constraint of the system, $\xi_{k,t}$ and $u_{k,t}$ stand for state vector constraint and control input vector constraint, respectively. $\xi_{t,t}$ and $\xi_{N,t}$ is starting state constraint and final state constraint,Once the solution $U_t^*(t) = [u_t^*, \cdots, u_{t+N\text{-}1,t}^*]$ to problem (14) has been computed, the first sample of U_t^*

$$u(\xi(t)) = u_{t,t}^* \tag{15}$$

is applied to the plant (12). And the optimization problem is solved over a shifted horizon for the next sampling time.

3.2 MPC controller design

Using Euler method to take the model (11) approximation into a discrete-time linear invariant state-space model as follows:

$$\begin{aligned} &\xi(k+1) = A\xi(k) + Bu(k) \\ &u(k) = u(k-1) + \Delta u(k) \\ &\eta(k) = C\xi(k) \end{aligned} \tag{16}$$

Where $\xi(k) \in R^n, y(k) \in R^p$ and $u \in R^m$ are the state vector, output vector and input vector, respectively. The matrices *A*, *B* and *C* are obtained by discrete equation (10). Considering the follow cost function:

$$\begin{aligned} J(\xi, u, \Delta U) = &\sum_{i=1}^{N_P} \left\| \eta(t+i \mid t) - \eta_{ref}(t+i \mid t) \right\|_Q^2 \\ &+ \sum_{i=1}^{N_c-1} \left\| \Delta u(t+i \mid t) \right\|_R^2 + \sigma\varepsilon^2 \end{aligned} \tag{17}$$

Where N_p and N_c represent the prediction and control horizons, respectively. As in standard MPC schemes, we use $N_P > N_c$ and the control signal is assumed constant for all $N_c \le t \le N_P$,i.e., $\Delta u(t+i|t) = 0, \forall i \ge N_c$, *Q* and *R* are the weight matrices, η_{ref} stand for the desired outputs , σ and ε relaxation factors. The constraints are given as follows:

$$\begin{aligned}
&\Delta U_{\min} \le \Delta U_t \le \Delta U_{\max} \\
&U_{\min} \le A\Delta U_t + U_t \le U_{\max} \\
&y_{hc,\min} \le y_{hc} \le y_{hc,\max} \\
&y_{sc,\min} - \varepsilon \le y_{sc} \le y_{sc,\max} + \varepsilon \\
&\varepsilon > 0
\end{aligned} \tag{18}$$

Where y_{hc}, y_{sc} is hard and soft constraints, respectively. The solution to get (17) subject to the model equation (16) is the base of the MPC scheme presented in [15], [16].

4 Simulation results

This paper we use Simulink-CarSim joint simulation platform to simulate, the parameters of agricultural vehicle were selected from CarSim. Vehicle mass m=3000 kg, moment of inertia about yaw axis I_z =1765 kg ㎡, Distance of front wheel axle from CG l_f =1.05 m, distance of rear wheel axle from CG l_r=1.0 m, cornering stiffness of the front tires C_f=90000 N/rad, cornering stiffness of the rear tires C_r=85000N/rad.

We set the vehicle moves at 18km/h, all initial value of vehicle state is zero, set the parameters of the MPC controller as follows:

- Sample time $T = 0.02s$,
- Prediction horizon $N_p = 15$, control horizon $N_c = 5$,
- Constraints on inputs and input rates: $-45^\circ \le \delta_f \le 45^\circ, -55^\circ / s \le \Delta\delta_f \le 55^\circ / s$
- Weight matrices: $Q = \begin{pmatrix} 10^3 & 0 \\ 0 & 10^2 \end{pmatrix}, R = 10, \sigma = 10$

The system outputs lateral offset and heeding error $[\tau, \ \psi]$ results change over time are address in Fig.3 and Fig.4 respectively, the average error of the whole simulation of the lateral offset is 2.09cm, the mean values of the error of the vehicle for the straight lines are 1.8 cm. Besides, the mean values of the error of the vehicle for the curved lines are 5.44 cm, the maximum error occur at the moment that the vehicle turns straight to curve, the maximum error is about 7.0cm, but it soon converged, fluctuating up and down within a certain little range.

The heading errors are fluctuating up and down are not converged to zero that is caused by the nonzero sideslip angle in steady state of path following. The little mean error of lateral offset is indicated that the MPC controller can satisfy orchard work for agricultural vehicle.

Yaw rate and the path tracking results are shown in Fig.5. From the figure one can observe that the yaw rate is maintained in reasonable region. The overshoot occurred at each straight line turn into the curve or the curve turn into the straight line. The other values are converging to a certain value and maintain in a reasonable region. The result indicated that the agricultural vehicle simulation process is very smooth.

The trajectory of the path following are shown in Fig. 6. Where the blue line stand for the desire path, and the red dotted line stand for the real path of the vehicle. In the path tracking trajectory result, one can clearly see that the path tracking objective is completed satisfactorily by MPC technique, which indicates the possibility of vehicle transgressing the fruit trees line is considerably reduced. The mean error of the path tracking was maintained so small that can ensure the agricultural vehicle work in the orchard safe and reduce the possibility of destroying fruit trees.

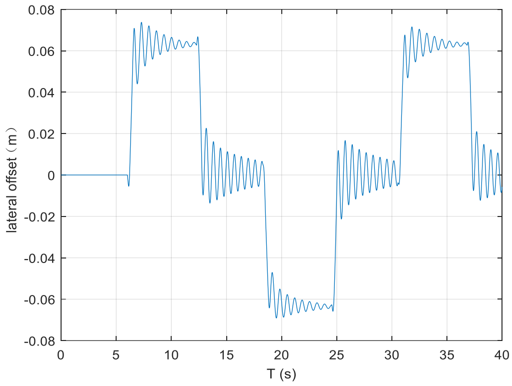

Fig. 3 Lateral offset results

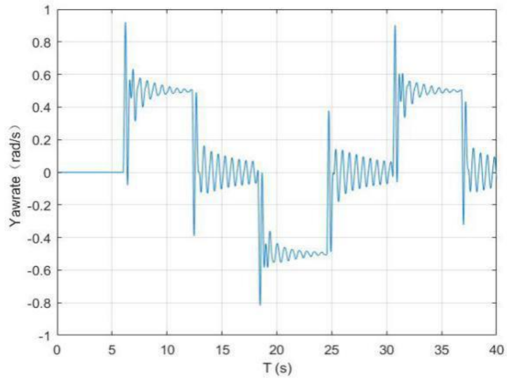

Fig.4 Heading error results

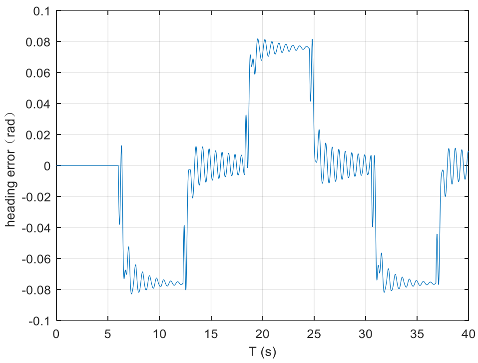

Fig. 5 Lateral offset results

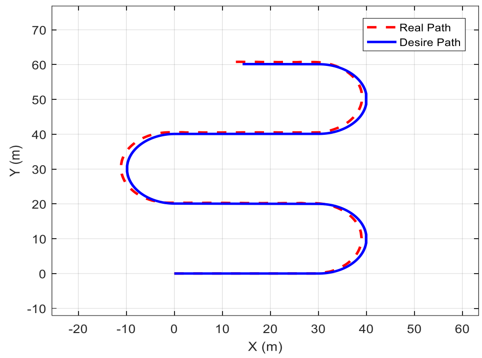

Fig. 6 U-turn path tracking results

5 Conclusions

In this study, a fast MPC framework has been elaborated for the control of an intelligent agricultural vehicle system by U-turn method in a standard orchard. Simulation results based on Simulink-CarSim platform verify the effectiveness of the proposed control approach. The simulation results show that the proposed MPC framework is able to control the agricultural vehicle system with a reasonable accuracy. The mean value of the error to the straight lines trajectory is 1.8cm and 5.44 cm for the curve line, respectively. So, it is an efficient control strategy for intelligent agricultural vehicle path tracking. However, since the soil in the orchard always been soft, the coupling between the tire and the soft road is not considered in the dynamic model of the vehicle, the state variable, sideslip angle, is difficult to obtain, output feedback control has real significance, which is left for our future works.

Acknowledgement

This work is supported by National Science Foundation of China (U1664258, 51575103), National Key R\&D Program in China with grant 2016YFB0100906, 2016YFD0700905, the Fundamental Research Funds for the Central Universities and the Research Innovation Program for Postgraduates of Jiangsu Province under Grant SJLX16_0035.

References

[1] Torii .T, *Reseach in autonomous agriculture vehicles in Japan*, Computers and Electronics in Agriculture, 2000 ,p.133-153.
[2] O'Cormor M. *Carrier-phase Differential GPS for automatic control ofland vehicles*[D]. CA:Stanford University.1997.
[3] R. TAKAI, O. BARAWID, N. NOGUCHI, *Autonomous navigation sysytem of crawler-type robot tractor*. in the 18th International federation of automatic control. 2011. Milano, Italy.
[4] J. G. Gil, R.R. Gonzalez, S.A. Garcia, F.J.G. Gil, *A Kalman filter implementation for precision improvement in Low-cost GPS position of tractors*, Sensors, 15307-15323, 2013.

[5] Noguchi.N, Oscar C.B.J, *Robot farming system using multiple robot tractors in Japan agriculture*, in the 18th International federation of automatic control. 2011. Milano, Italy.
[6] Zhang M., Lin X, Yin W., *An improved tuning method of fractional order proportional differentiation(FOPD) controller for the path tracking control of tractors,* Biosystems engineering （116）2013.p.478-486..
[7] X.W. Luo, Z.G. Zhang, Z.X. Zhao, B. Chen, L. Hu, X.P. Wu, *Design of DGPS navigation control system for Dongfanghong X-804 tractor*, Transactions of the CSAE. Vol.25(11), 139-145, 2009.
[8] Wu X, Shen W, Lou P., Wu B, *An automated guided mechatronic tractor for path tracking of heavy-duty robotic vehicles*, Mechatromics, 2016,p.23-31.
[9] Ramezani H, Zakidizaji H, Masoudi H, *A new DSWTS algorithm for real-time pedestrian detection in autonomous agricultural tractors as a computer vision system*, Measurement, 2016,p.126-134.
[10] G.F.Botta, A.Tolon-Becerra, M. Tourn, X.Lastra-Bravo, D.Rivero, *Agricultural traffic:Motion resistance and soil compaction in relation to tractor design and different soil conditions*, Soil & Tillage research, 2012, p.92-98.
[11] G.Zaidner and A.Shapiro, *A novel data fusion algorithm for low-cost localisation and navigation of autonomous vineyard sprayer robots*, Biosystems engineering，2016.p.133-148.
[12] J. Y. Wong, N.Y. John, *Theory of ground vehicles*, New York ,1993.
[13] R. Skjetne and T. I. Fossen, *Nonlinear maneuvering and control of ships*, in Proc. MTS/IEEE OCEANS, Honolulu, HI, USA, 2001, p. 1808–1815.
[14] F. Kuhne, W.F. Lages, *Model predictive control of a mobile robot using linearization*. Proceedings of the IEEE international conference on robots and system, 2011，p.298-304.
[15] J.Backman, T.Oksanen and A.Visala, *Nolinear model predictive trajectory control in tractor-trailer system for parallel guidance in agricultural field operations.* Safety Science, 2007. **46**(7): p. 133-138.
[16] E.Kayacan, E.Kayacan, H.Romon, *Nonlinear modeling and identification of an autonomous tractor-trailer system.* Computers and Electronics in agricultrure (106) 2014, p. 1-10.