1−3 Automatic Follow-up Control System for Agricultural Vehicles

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1. Introduction

Many types of agricultural operations use two or more farm vehicles, such as a forage harvester with a farm wagon. If one operator can drive two or more farm vehicles simultaneously, the work efficiency will be increased greatly, even when using two same machines for the same field operation. Recent years, several studies on the automatic follow-up control system for agricultural vehicles have been reported (Iida et al., 2001; Sutiarso et al., 2002; Noguchi et al., 2004; Abe et al., 2005). However, most of the follow-up control systems have dealt with the follow-up motion for straight lanes and thus only the relative position was measured. Even though some systems could be used for curvous paths, there was a big lateral error. The objective of this study is to develop an automatic follow-up control system for agricultural vehicles, which dealt with follow-up motion for both straight and curvous paths. Limiting to the test tractor, the velocity could not be adjusted during experiment. Therefore, the velocity was set constant and the steering angle was the single control variable.

2. Materials and methods

2.1. Overview of automatic follow-up control system

Figure 1 shows the follow-up control system for agricultural vehicles, which was composed of a leading tractor and a following tractor. The equipment used to measure the positions of the leading vehicle was a Total Station (TS) of Leica TCA1105 model. A prism, as a pair of TS, was mounted on the tractor rear and was placed at a height of 2.15 m from the ground. The position of the following vehicle was measured by a global positioning system (GPS) with a model of NovAtel RT-20 in a real-time kinematic (RTK) mode.

2.2. Trajectory acquisition

Due to vehicle vibration and uneven ground, there was some noise in the recorded trajectory of the leading vehicle. For acquiring more precise and smooth trajectory, the method of least squares and curve fitting were applied. In this research, a third-order polynomial was used to determine the curve for every 17 conjoint data points. In terms of this polynomial and the vehicle kinematic equations, the co-ordinates of the leading vehicle together with the heading angle and steering angle were identified.

Figure 2 shows that a reference course for the following vehicle was generated from a trajectory of the leading vehicle. P_{Fi} is on the normal of curve γ_L at point P_{Li} with lateral offset of d from the point P_{Li}. The sign of d was defined as a positive when the following vehicle followed the leading vehicle on left side, and a negative when on right side. The information attaching to the point P_{Li} could be expressed by a state vector: $x_{PLi}=[x_{PLi}, y_{PLi}, \theta_{PLi}, \alpha_{PLi}]^T$, and that for the point P_{Fi} by $x_{PFi}=[x_{PFi}, y_{PFi}, \theta_{PFi}, \alpha_{PFi}]^T$. According to the relationship between curve γ_L and γ_F, the state vector $\boldsymbol{x}_{PFi}$ could be calculated.

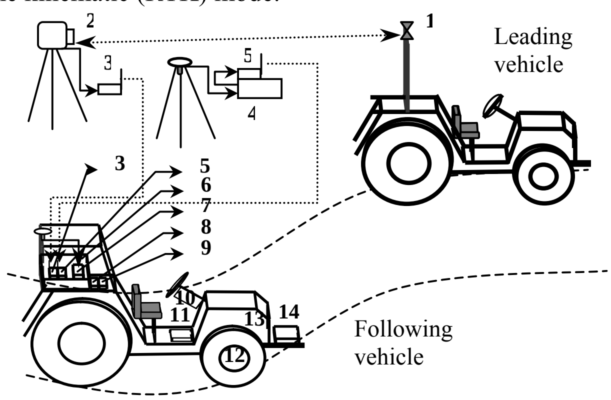
2.3. Optimal steering controller

The linear vehicle kinematic equations could be expressed as follow:

$$\delta\dot{\boldsymbol{x}} = \boldsymbol{A}(t)\delta\boldsymbol{x} + \boldsymbol{B}(t)\delta u \qquad (1)$$

where:

$$\boldsymbol{A}(t) = \begin{bmatrix} 0 & 0 & -v\sin\theta_{PFi} & 0 \\ 0 & 0 & v\cos\theta_{PFi} & 0 \\ 0 & 0 & 0 & \dfrac{v}{L\cos^2\alpha_{PFi}} \\ 0 & 0 & 0 & 0 \end{bmatrix}; \boldsymbol{B}(t) = [0,0,0,1]^T.$$



1: Prism 2: Total station 3: Wireless modem
4: GPS reference station receiver 5: Wireless modem
6: PC 7: GPS remote station receiver 8: AD/DA board
9: DC motor driver 10: DC motor 11: FOG
12: Potentiometer 13: Magnetic sensor 14: AC generator

Fig. 1. Composition of system

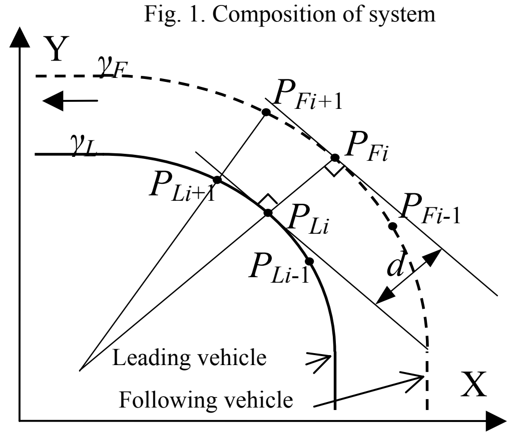


Fig. 2. Generation of the reference course for the following vehicle.

A linear and quadratic optimal regulator (LQR) with infinite time was designed. Subjecting to the constraint equation (Eq. (1)), the LQR calculated the optimal feedback gain matrix $\boldsymbol{K}$ such that the feedback control law

$$u = -\boldsymbol{K}\delta\boldsymbol{x} \quad (2)$$

minimized the performance index

$$J = \int_0^{\infty} (\delta\boldsymbol{x}^{\mathrm{T}}\boldsymbol{Q}\delta\boldsymbol{x} + \delta u^2)dt \quad (3)$$

where $\boldsymbol{Q} = q\boldsymbol{I} \in \boldsymbol{R}^{4\times 4}$ (q>0).

According to the optimal regulator theory, it was known that the optimal control for the Eqs. (1) and (2) may have formula (Eq. (4)), which was called Riccati algebraic equation.

$$\boldsymbol{PA} + \boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} - \boldsymbol{PBR}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{Q} = \boldsymbol{0} \quad (4)$$

By solving Eq. (4), the optimal feedback gain matrix could be obtained as below:

$$\boldsymbol{K} = -\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} \quad (5)$$

2.4. Experiments

Tests on automatic follow-up control system were conducted at a meadow. In order to evaluate the performance of the automatic follow-up control system, tests on both straight and curvous paths were conducted. For both tests, the velocities of leading and following vehicles were set constant at 0.5 m/s. The travelling distance between the leading and following vehicles was about 5 m.

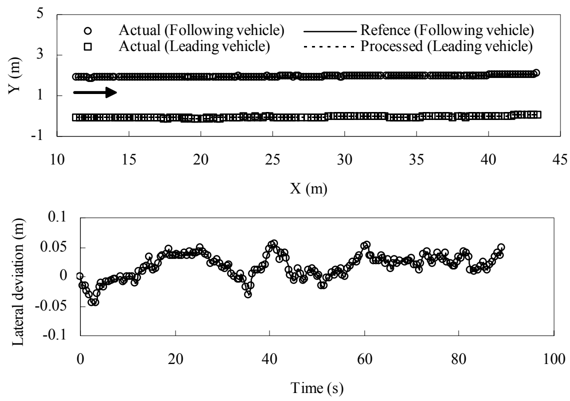


Fig. 3. Test on straight path

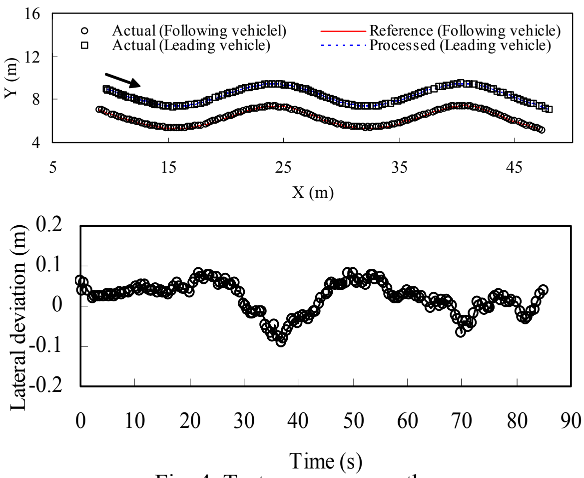


Fig. 4. Test on curvous path

3. Results and discussion

The dashed curve (Fig. 3) means the trajectory of the leading vehicle after being processed by the least squares fitting. It is found that the least squares fitting procedure filtered some noise caused by vehicle vibration and undulant ground. The time history of the lateral deviation is also illustrated in Fig. 3. The average and RMS errors of the lateral deviation are 0.02 and 0.02 m, respectively. These results indicate that the following vehicle could follow the leading vehicle precisely when the leading vehicle traveled along a straight path.

On the curvous path test (Fig. 4), the following vehicle could also follow the leading one successfully with the average and RMS lateral deviations of 0.02 and 0.04 m, respectively. At the same time, the results validate that the designed optimal controller was available for both straight and curvous paths.

4. Conclusions

An automatic follow-up control system for agricultural vehicles was developed, which dealt with follow-up motion for both straight and curvous paths. The absolute positions of a leading vehicle and following vehicle were measured in real-time. Simultaneously, a third-order polynomial was used to smooth the trajectory of the leading vehicle by the method of least squares. According to a given lateral offset, a reference course for the following vehicle to track was determined. An optimal path-tracking controller was designed for the following vehicle to follow the leading vehicle along the reference course. The test results indicated that the following vehicle followed the leading vehicle successfully.

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