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Robot Vehicle Platoon Experiment Based on Multi-Leader Vehicle Following Model

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***Abstract*—The velocity control algorithm of vehicles in vehicle platoon is applied for the platoon experience of the vehicle robots. Stability analysis of the models is performed to determine the parameters and then, the summation of sensitivities for all leader vehicles is maximized. The results show that the velocity control can be performed by the velocities of only one or two leader vehicles; the nearest leader vehicle and the lead vehicle of the platoon. The model is applied for the velocity control of the vehicle robots in the vehicle platoon. The experimental result is compared with the numerical simulation in order to confirm the validity of the model. The experimental result qualitatively agrees with the computer simulation.**

***Keywords*-Vehicle Platoon, Chandler Model, Multi-Leader Model, Simulation**

I. Introduction

Vehicle platoon is one of the promising systems in Intelligent Transportation Systems (ITS) [1]. Vehicle platoon system allows many vehicles to drive at the same velocity and to accelerate or brake simultaneously. Since vehicle platoon decreases the distances between vehicles using electronic and mechanical systems, the traffic capacity can be increased safely. In this study, the velocity control algorithm of vehicles in vehicle platoon is presented and applied for the platoon experience of the vehicle robots.

The velocity control algorithm is defined by means of the vehicle following model[2], [3], [4], [5], [6]. In the vehicle following model, the vehicle velocity or acceleration is defined as the function of the information from the nearest forehand vehicle such as the velocity difference, the distance and so on. The velocity control model in this study is based on the multi-leader Chandler model[2], [3]. The vehicle acceleration is defined as the function of the velocity differences from the leader vehicles. Stability analysis of the model is performed to determine the parameters. The model is applied for the velocity control of the vehicle robots in the vehicle platoon[7]. The experimental results are compared with the computer simulation in order to discuss the validity of the model.

The remaining part of this paper is organized as follows. In section II, the stability analysis of the mathematical model is given. The experiment results of the robot vehicle platoon are shown in section III. The results are summarized again in section IV.

II. Velocity Control Model

A. Chandler Model

Chandler model is given as follows[2].

$$\ddot{x}_n(t+\Delta t) = a_1(\dot{x}_{n-1}(t) - \dot{x}_n(t)) \tag{1}$$

The variable $x_n(t)$ is the position vector of the vehicle i at time t, the variable Δt is delay time of the control and the parameter a_1 is the sensitivity of the vehicle n to the vehicle $n-1$. The notation $(\ddot{\ })$ and $(\dot{\ })$ denote the first and second derivatives with respect to the time t, respectively. Equation (1) controls the acceleration rate $\ddot{x}_n(t)$ according to the difference between $\dot{x}_{n-1}(t)$ and $\dot{x}_n(t)$. In this model, the vehicle $n-1$ is the nearest leader vehicle of the vehicle n.

When the vehicle n takes the vehicle $n-1$ to vehicle $n-m$ as the leader vehicles, the original Chandler model is extended as follows[3], [8].

$$\ddot{x}_n(t+\Delta t) = \sum_{j=1}^{m} a_j(\dot{x}_{n-j}(t) - \dot{x}_n(t)) \tag{2}$$

Parameter m is the total number of leader vehicles.

B. Four Vehicle Platoon Model

The platoon is composed of four vehicles. Vehicles are named as a lead, a first follower, a second follower and a third follower vehicles from the head of the platoon (Fig.1).

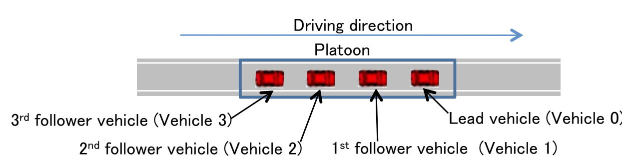

Figure 1. Vehicle platoon

C. Stability Analysis

Assume a small deviation y_n from the state velocity v_0 as follows.

$$\dot{x}_n = v_0 + y_n \tag{3}$$

Substituting equation (3) to equation (2), we have

$$\ddot{y}_n(t+\Delta t) = \sum_{j=1}^{m} a_j(\dot{y}_{n-j}(t) - \dot{y}_n(t)) \tag{4}$$

Applying Fourier transform to the variable y_n, we have

$$\begin{aligned} y_k(n,t) &= \exp(i\alpha_k n + zt) \\ \alpha_k &= \frac{2\pi}{N}k, \quad k = 0,1,2,\ldots,N-1 \end{aligned} \tag{5}$$

The parameter N and the notation i denote the total number of vehicles and the imaginary unit, respectively.

Substituting equation (5) to equation (4), we have

$$\mathrm{e}^{\Delta tz}z - \sum_{j=1}^{m} a_j \mathrm{e}^{ji\alpha_k} - 1 = 0 \tag{6}$$

Applying Taylor expansion

$$\mathrm{e}^{\Delta tz} \cong 1 + \Delta tz \tag{7}$$

to equation (6), we have

$$\Delta tz^2 + z - \sum_{j=1}^{m} a_j \mathrm{e}^{ji\alpha_k} - 1 = 0 \tag{8}$$

Finally, we have

$$\Delta t = \frac{\sigma_c}{\sigma_c^2} \tag{9}$$

The variable σ_c and σ_c^2 are defined as follows.

$$\sigma_c = \sum_{j=1}^{m} a_j(1-\cos(j\alpha_k)) \tag{10}$$

$$\sigma_s = \sum_{j=1}^{m} a_j \sin(j\alpha_k) \tag{11}$$

1) First Follower Vehicle: Since a first follower vehicle has one leader vehicle, $m = 1$. From equation (9), we have

$$a_1 \leq \frac{1}{2\Delta t} \tag{12}$$

When the delay time is given as $\Delta t = 1$,

$$0 \leq a_1 \leq \frac{1}{2} \tag{13}$$

Maximum sensitivity is as follows.

$$(a_1)_{\max} = 0.5 \tag{14}$$

2) Second Follower Vehicle: Since a second follower vehicle has two leader vehicles, $m = 2$. From equation (9), we have

$$\frac{(a_1+2a_2)^2}{a_1+4a_2} \leq \frac{1}{2\Delta t} \tag{15}$$

When the delay time is given as $\Delta t = 1$,

$$8a_2^2 + 4(2a_1-1)a_2 + (2a_1^2 - a_1) \leq 0 \tag{16}$$

The sensitivity a_1 and a_2 have to satisfy the following conditions.

$$0 \leq a_1 \leq \frac{1}{2} \tag{17}$$

$$0 \leq a_2 \leq \frac{(1-2a_1)+\sqrt{1-2a_1}}{4} \tag{18}$$

The total sensitivity b_2 is defined as follows.

$$b_2 \equiv a_1 + a_2 \leq \frac{(1+2a_1)+\sqrt{1-2a_1}}{4} \tag{19}$$

The total sensitivity b_2 is maximized to the value $(b_2)_{\max} = 9/16$ at $a_1 = 3/8$ and $a_2 = 3/16$.

3) Third Follower Vehicle: Since a second follower vehicle has two leader vehicles, $m = 3$. From equation (9), we have

$$\Delta t = \frac{\begin{array}{c} a_1 + 2a_2(1+\cos\alpha_k) \\ + a_3(4\cos^2(\alpha_k) + 4\cos\alpha_k + 1) \end{array}}{\begin{array}{r} 2(a_1 + 2a_2\cos\alpha_k + a_3(4\cos^2(\alpha_k) - 1))^2 \\ \times \cos^2(\alpha_k/2) \end{array}} \tag{20}$$

When the delay time is given as $\Delta t = 1$,

$$\begin{aligned} &18a_3^2 + (12a_1 + 24a_2 - 9)a_3 \\ &\quad + (2a_1^2 + 8a_2^2 + 8a_1a_2 - a_1 - 4a_2) \leq 0 \end{aligned} \tag{21}$$

The sensitivity a_1, a_2 and a_3 have to satisfy the following conditions.

$$0 \leq a_1 + a_2 \equiv b_2 \leq \frac{9}{16} \tag{22}$$

$$0 \leq a_3 \leq \frac{(3-4a_1-8a_2)+\sqrt{9-16(a_1+a_2)}}{12} \tag{23}$$

The total sensitivity b_3 is defined as follows.

$$\begin{aligned} b_3 &\equiv a_1 + a_2 + a_3 \\ &\leq \frac{(3-4a_1-8a_2)+\sqrt{9-16(a_1+a_2)}}{12} \end{aligned} \tag{24}$$

The total sensitivity b_3 is maximized to the value $(b_3)_{\max} = 2/3$ at $a_1 = 1/2$, $a_2 = 0$ and $a_3 = 1/6$.

Figure 2. Experimental landscape

III. Experiment

A. Velocity Control Model

Assume the positions of the lead, the first follower, the second follower and the third follower vehicles as x_0, x_1, x_2 and x_3, respectively.

Since the first follower vehicle has only one leader vehicle, it is considered that the first follower vehicle follows the single-leader vehicle following model:

$$\ddot{x}_1(t+\Delta t) = \frac{1}{2}(\dot{x}_0(t) - \dot{x}_1(t)) \tag{25}$$

According to the above results, the velocity control models of the second and the third follower vehicles are respectively given as follows.

$$\begin{aligned} \ddot{x}_2(t+\Delta t) &= \frac{3}{8}(\dot{x}_1(t) - \dot{x}_2(t)) \\ &\quad + \frac{3}{16}(\dot{x}_0(t) - \dot{x}_2(t)) \qquad (26) \\ \ddot{x}_3(t+\Delta t) &= \frac{1}{2}(\dot{x}_2(t) - \dot{x}_3(t)) \\ &\quad + \frac{3}{16}(\dot{x}_0(t) - \dot{x}_3(t)) \qquad (27) \end{aligned}$$

The velocity differences to far leader vehicles are approximated with the finite difference as follows

$$\dot{x}_{j-1}(t) - \dot{x}_j(t) \equiv \Delta\dot{x}_j \simeq \frac{\Delta x_j(t) - \Delta x_j(t-\Delta t)}{\Delta t} \tag{28}$$

where $\Delta x_j = x_{j-1}(t) - x_j(t)$ and $j = 1, 2$.

LEGO Mindstorm NXT[7] is designed to a vehicle robot. The vehicle platoon is composed of four vehicle robots. A vehicle has the ultrasonic sensor and the Bluetooth communication. The distance Δx_j is estimated by the ultrasonic sensor. The lead vehicle velocity $\dot{x}_0(t)$ is obtained from the lead vehicle through the Bluetooth.

B. Vehicle Platoon Simulation

Velocity control process of the first follower vehicle is summarized as follows.

1) Initialize time-step as follows. $t = 0$.
2) Estimate the vehicle head distance from the nearest leader vehicle $\Delta x_1(t)$ by ultrasonic sensor.

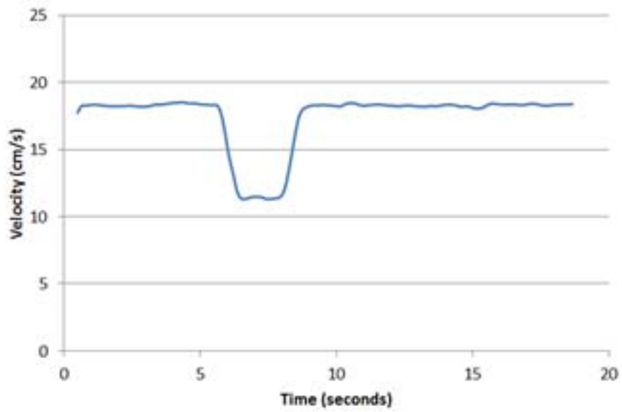

Figure 3. Velocity fluctuation of lead vehicle

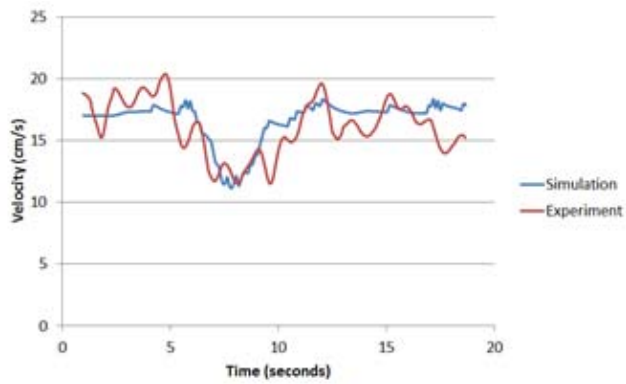

Figure 4. Velocity fluctuation of third follower vehicle

3) Increment time-step as follows $t = t + \Delta t$.
4) Estimate the vehicle head distance from the nearest leader vehicle $\Delta x_j(t)$ by ultrasonic sensor.
5) Calculate the acceleration by equation (25).
6) Update the velocity by

$$\dot{x}_j(t+\Delta t) = \dot{x}_i(t) + \ddot{x}_2(t+\Delta t)\Delta t \tag{29}$$

7) Return step 3.

Velocity control process of the second and the third follower vehicles is summarized as follows.

1) Initialize time-step as follows $t = 0$.
2) Estimate the vehicle head distance from the nearest leader vehicle $\Delta x_j(t)$ by ultrasonic sensor.
3) Increment time-step as follows $t = t + \Delta t$.
4) Estimate the vehicle head distance from the nearest leader vehicle $\Delta x_j(t)$ by ultrasonic sensor.
5) Obtain the lead vehicle velocity $\dot{x}_0(t)$ by Bluetooth communication.
6) Calculate the acceleration by equation (26) or (27).
7) Update the velocity by

$$\dot{x}_j(t+\Delta t) = \dot{x}_i(t) + \ddot{x}_2(t+\Delta t)\Delta t \tag{30}$$

8) Return step 3.

C. Experimental Result

Four vehicles of LEGO MINDSTORMS NXT moves as a platoon along a black line (Fig.2). Initial vehicle head distance is 10 cm.

Velocity fluctuations of the lead vehicle and the third follower vehicle are shown in Figs.3 and 4, respectively. In Fig.4, the computer simulation is also shown. Although the velocity fluctuation in the experimental result vibrates more violently than that in the computer simulation, it can be concluded that they agree qualitatively.

IV. Conclusion

The velocity control model was defined and applied for the vehicle velocity control in the vehicle platoon. The model was based on the multi-leader Chandler model. The model parameters are determined from the stability analysis. When the summation of the sensitivities for all leader vehicles was maximized, only one or two vehicle velocity information was necessary for velocity control. The control model was applied for the robot vehicle platoon simulation. Although the velocity fluctuation in the experimental result vibrates more violently than that in the computer simulation, it can be concluded that they agree qualitatively. In the future study, we would like to apply the model to the other platoon experiments.

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