Fault-Tolerant Controller Design for Vehicles Platooning

Gyeong-Hwan Yoon*, Jae Weon Choi**

*School of Mechanical Engineering, Pusan National University, Pusan 609-735, Korea
(Tel: +82-51-510-3203; Fax: +82-51-514-0685; Email: khyoon@pusan.ac.kr)
**School of Mechanical Engineering and Research Institute of Mechanical Technology
Pusan National University, Pusan 609-735, Korea
(Tel: +82-51-510-2470; Fax: +82-51-514-0685; Email: choijw@pusan.ac.kr)

Abstract: This paper considers the problem of longitudinal control of a platoon of automotive vehicles on a straight lane of a highway and proposes control laws in the event of loss of communication between the lead vehicle and the other vehicles in the platoon. Since safety plays a key role in the development of an Automated Highway System, fault-tolerant control is vital. In this paper, we develop a control algorithm in vehicle platooning and prove that this control algorithm is stable for certain class of faults such as parameter uncertainties. The performance of the controller is demonstrated through a series of simulations incorporating various vehicles and AHS faults. Results of simulation shows that the vehicles have good performance in spite of simple automotive and AHS failure, such as actuator failure,that is to say, engine input failure, communication failure between lead vehicle and the another vehicles.

Keywords: automated highway system, vehicle platooning control, fault-tolerant control, expected spacing error, sliding mode controller, time-to-go

1. Introduction

In company with safeties of each vehicles in platoon, safeties of the whole platoon must be guaranteed in vehicles platooning which is for more than two cars to drive at high speed as maintaining a constant distance of each vehicles. Generally, the safety of vehicles platooning is guaranteed by communication of much information for driving between each vehicles. Researches for vehicles platooning have been advanced in many kinds of fields for several decades.

The research of longitudinal control in vehicles platooning has much advanced in precedent researching works. Representatively controller of PID type have been proposed[1-2], and sliding mode type controller have been proposed[5-6]. What is more over,it has been proposed that a controller which guarantees stable vehicles platooning using information of precedent vehicles without lead vehicle information [3-4]. Controller that proposed in reference [3] uses only precedent vehicles driving information, but it has demerits, that is to say, which is processes solving complex differential equation to search optimal controller parameters. In [4], a controller that proposed has used control input information of precedent vehicles without using lead vehicle driving information. In this paper, we proposed controller for vehicles platooning not using velocity, position and acceleration of lead vehicle proceeding but using velocity, position and acceleration of precedent vehicle driving information. And it doesn't use the contol input information of precedent vehicle.

The method that proposed in this paper is so simple in computational process, and it has good performance in using lead vehicle information. And also it has good performances at not using lead vehicle driving information because of faults in communication network for vehicles platooning. Moreover it has fault tolerant performance in faulty situation of actuator owing to disturbance of outer surroundings. We showed that it has good performance not only in the situation of cessation in communication between lead vehicle and following vehicles,but also actuator faults in following vehicle's engine the proposed controller good performances by numerical simulations in using MATLAB.

2. Design for vehicles platooning

2.1. Dynamic model for vehicles platooning

Many vehicle dynamic models have been used for vehicles platooning. In this paper, we used the vehicle dynamics model for constant headway driving that used in[4, 7-8].

$$\dot{x}_i = v_i \tag{1}$$

$$\dot{v}_i = a_i \tag{2}$$

$$\dot{a}_i = \frac{1}{\tau_i}(a_i^c - a_i) \tag{3}$$

where τ_i means the time constant that includes inner systems, for example, vehicle tire, wheels, engine, transmission

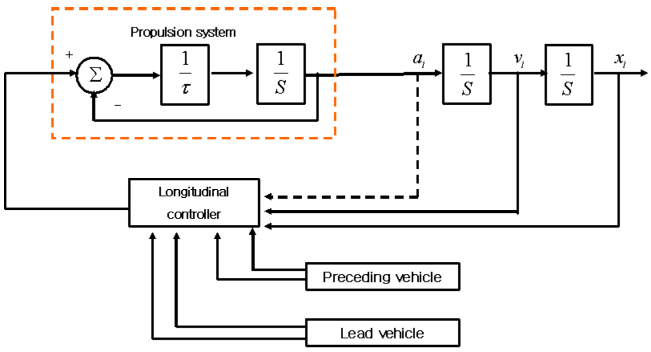

Fig. 1. Complete vehicle dynamic model

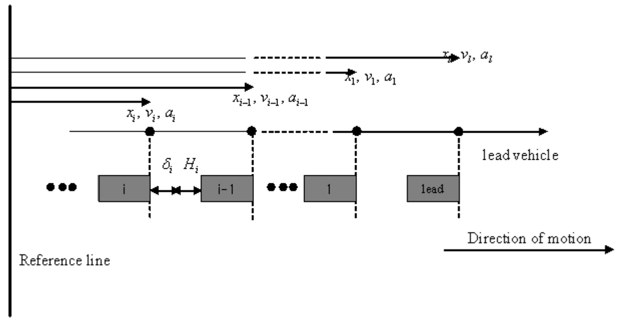

Fig. 2. Vehicle platooning dynamic model

etc. In Fig. 2 the i-th spacing deviation of each vehicles is like this

$$\delta_i = x_{i-1} - x_i - H_i \tag{4}$$

H_i means distance of each vehicle that is determined to consider vehicle velocity, vehicle lengths.

2.2. Design of the controller for vehicles platooning

In vehicles platooning, the objective of the control is to take velocity errors and acceleration errors between vehicles zeros, that is as follows

$$\lim_{t\to\infty} |\delta_i(t)| = 0 \tag{5}$$

$$\lim_{t\to\infty} \left|\dot{\delta}_i(t)\right| = 0 \tag{6}$$

In references [1, 2] a control input of the i-th vehilcle, namely a_i^c , is as follows

$$a_i^c = f\left(x_{i-1},\ \ v_{i-1},\ \ a_{i-1},\ \ x_i,\ \ v_i,\ \ a_i,\ \ v_l,\ \ a_l\right) \tag{7}$$

where $(x_i,\ v_i\ , a_i)$ means velocity and acceleration of the i-th vehicle. Above mentioned controller use velocity and acceleration of a precedent vehicle, in reference [7] controller use control inputs of precedent vehicles instead of lead vehicle informations.

In this paper, a proposed controller is as follows

$$a_c^i = u_d + u_s \tag{8}$$

$$u_d = -k_v \dot{\delta}_{*i} - k_a \ddot{\delta}_{*i} \tag{9}$$

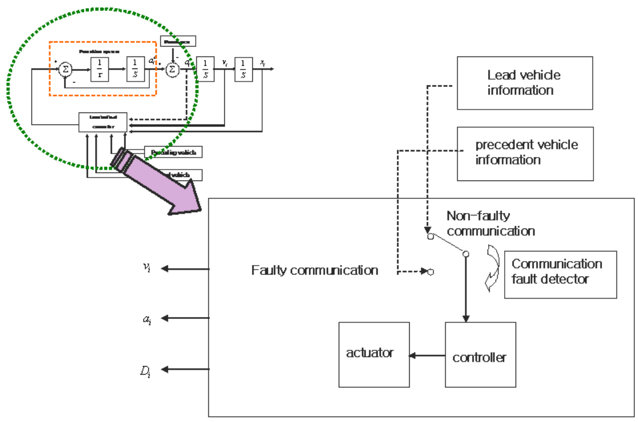

Fig. 3. Structure of vehicle platooning controller

$$u_s = -k_D \left\{\frac{D_i}{t_{go}}\right\}^2 sat\left(D_i/\gamma_D\right) - k_a s \left\{\ddot{\delta}_i\right\}^2 sat\left(\ddot{\delta}_i/\gamma_a\right) \tag{10}$$

where $\dot{\delta}_{*i}$, $\ddot{\delta}_{*i}$ are switched by two cases.

Case 1: it is possible to communicate the lead vehicle with following vehicles

$$\begin{aligned}\dot{\delta}_{*i} &= v_l - v_i \\ \ddot{\delta}_{*i} &= a_l - a_i\end{aligned} \tag{11}$$

Case 2 : it is impossible to communicate the lead vehicle with following vehicles

$$\begin{aligned}\dot{\delta}_{*i} &= v_{i-1} - v_i \\ \ddot{\delta}_{*i} &= a_{i-1} - a_i\end{aligned} \tag{12}$$

where δ_i, $\dot{\delta}_i$, $\ddot{\delta}_i$, k_v,k_a, k_{as}, k_D mean vehicle distance deviations, firsr oder differentials and second order differentials of each vehicles, design parameters. and $sat(D_i/\gamma)$ is as follows

$$sat(D_i/\gamma) = \begin{cases} 1 & if \quad D_i > \gamma \\ D_i & if \quad |D_i| > \gamma \\ -1 & if \quad D_i < -\gamma \end{cases} \tag{13}$$

where γ is design parameter, D_i is expected spacing error to be defined as follows

$$D_i = (x_{i-1} - x_i) + (v_{i-1} - v_i)\, t_{go} + \frac{1}{2}\,(a_{i-1} - a_i)\, t_{go}^2 \tag{14}$$

where t_{go} is the time-to-go until the futute time t_f and may be written as

$$t_{go} = t_f - t \tag{15}$$

And, we assume that the boundary of D_i exists. For the sake of brevity, we assume that H_i is zero.as one may easily understand, D_i is the expected spacing error at the future time t_f if both the predecessor and following vehicles keep their respective current accelerations constant for t_{go} In this paper, the controller for vehicle platooning only uses informations of the precdent vehicle. Also, in not faulty communication of lead vehicle it uses informations of the lead vehicle And, it consits of simple PID controllers, Sliding mode controllers. It is in Fig. 2.

2.3. Stability problem

A Lyapunov candidate function is defined to consider the stabiliy of the system as follows

$$V = \frac{1}{2} D_i^2 \tag{16}$$

A differentiated equation(16) is as follows

$$\begin{aligned}\dot{V} &= D_i \dot{D}_i \\ &= D_i \left[\frac{1}{2}\left\{\frac{1}{\tau_{i-1}}\left(a_{i-1}^c - a_{i-1}\right) - \frac{1}{\tau_i}\left(a_i^c - a_i\right)\right\}\right] t_{go}^2 \\ &= D_i \frac{1}{2\tau} t_{go}^2 \left[-k_a \left(\ddot{\delta}_{*i-1} - \ddot{\delta}_{*i}\right) - k_v \left(\dot{\delta}_{*i-1} - \dot{\delta}_{*i}\right)\right. \\ &\quad -k_D \left\{\frac{D_{i-1}}{t_{go}}\right\}^2 sat\left(D_{i-1}/\gamma_D\right)\end{aligned}$$

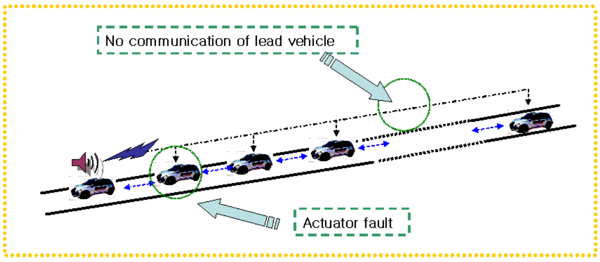

Fig. 4. Model of faults in vehicles platooning

$$
\begin{aligned}
&+k_D \left\{ \frac{D_i}{t_{go}} \right\}^2 sat\left(D_i/\gamma_D\right) \\
&-k_a \left\{ \ddot{\delta}_{i-1} \right\}^2 sat\left(\ddot{\delta}_{i-1}/\gamma_a\right) \\
&+k_a \left\{ \ddot{\delta}_{i} \right\}^2 sat\left(\ddot{\delta}_{i}/\gamma_a\right) - \dot{\delta}_{*i} \Big] \qquad (17)
\end{aligned}
$$

In equation(17), we assume that a term of the relative accelerations between each vehicles is smaller than other terms , that is to say as follows.

$$
\begin{aligned}
&-k_a \left(\ddot{\delta}_{*i-1} - \ddot{\delta}_{*i}\right) - k_v \left(\dot{\delta}_{*i-1} - \dot{\delta}_{*i}\right) \\
&-k_D \left\{ \frac{D_{i-1}}{t_{go}} \right\}^2 sat\left(D_{i-1}/\gamma_D\right) \\
&+k_D \left\{ \frac{D_i}{t_{go}} \right\}^2 sat\left(D_i/\gamma_D\right) - k_a \left\{ \ddot{\delta}_{i-1} \right\}^2 sat\left(\ddot{\delta}_{i-1}/\gamma_a\right) \\
&+k_a \left\{ \ddot{\delta}_{i} \right\}^2 sat\left(\ddot{\delta}_{i}/\gamma_a\right) >> \dot{\delta}_{*i} \qquad (18)
\end{aligned}
$$

and rest temrs are assumed that as follows

$$
\begin{aligned}
\dot{\delta}_{*i-1} - \dot{\delta}_{*i} \approx 0 \ , \quad \ddot{\delta}_{*i-1} - \ddot{\delta}_{*i} \approx 0 \\
|D_{i-1}| > |D_i| \ , \quad D_i D_{i-1} > 0 \qquad (19)
\end{aligned}
$$

And finally we have obtained as follows

$$
\dot{V} < 0 \qquad (20)
$$

So, the proposed controller is string stable.

3. Simulations and results

3.1. Situation of a vehicle faults

In vehicles platooning, there are two main faults situations. First, communication between lead vehilce and following vehicles was abruptly cut off. Second, actuator faults of individual vehicles. Two faulty cases are seen in Fig. 4

3.2. Scinarioes of the vehicle faults and results

Scinarioes of the vehicle faults are as following in Fig. 5 and 6. First, we consider the situation when following vehicles only uses relative driving informations due to the communication-cut-off of the lead vehicle and second we consider the situation in which the efficiency of actuator is 30actuator faults in a following vehicle. Parameters used in each situatuions are as follows
$k_v = 0.9\,/\,\sec^2$, $k_a = 0.2\,/\,\sec$, $k_{as} = 10\sec^3/m^3$,
$H = 0m$,$t_{go} = 1\sec, \gamma_D = 0.1$, $\gamma_a = 0.1$, $\tau = 0.25$ sec
As seen in Fig. 7, and 8althogh the dirving informations are switched because of the communication-cut-off of the lead

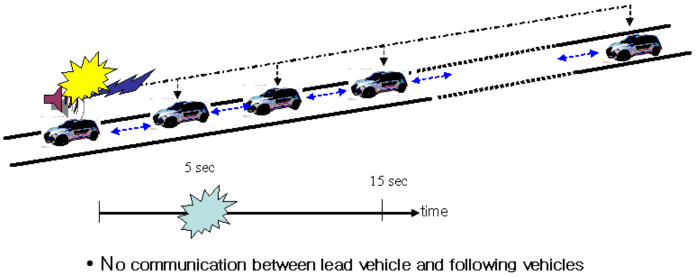

Fig. 5. Scinario of cut-off communication in a lead vehicle

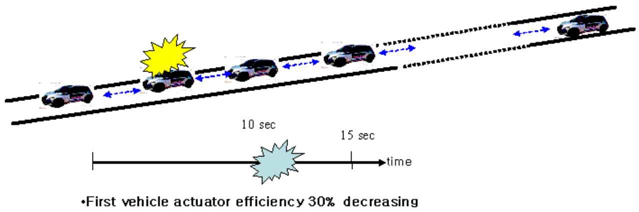

Fig. 6. Scenario of an actuator fault in an first following vehicle

vehicle , following vehicles have keep up with velocity command of the lead vehicle. And as seen in Fig. 8, following vehicles have chattering, but its magnitude is so small. Also,as seen in Fig. 9 and 10, although following vehicles have actuator faults, relative spacing deviations converge to zero rapidly in 3 seconds.
Here, since the controller uses relative driving informations of each following vehicles. each relative driving information has the property of transient response, the small deviation value brings about chattering in the vicinity of zero. It has chattering to use driving informations of precedent vehicles,

4. Conclusions

In this paper, the contoller is proposed that guarantees the string stability in vehicles platooning, the distance deviation and the velocity deviation are convergenced to zero. And without the driving information of lead vehicle it has good performance in vehicles platooning. Besides it has fault-tolerant performance in actuator faults following vehicles, using only informations of precedent vehicles. Also, necessary informations to computate control input for vehicles platooning are fewer than precedent researches.

References

[1] D. N. Godhole, J. Lygeros, "Longitudinal control of the lead car of platoon," *IEEE Transactions on Vehicular Technology*, Vol. 43, No. 4, pp. 1125-1135, 1994.

[2] S. Sheikholeslam, and C. A. Desoer, R. A. Singer, "Longitudinal control of a platoon of vehicles," *Proceedings of the American Control Conference*, pp. 291-297, 1990.

[3] S. Sheikholeslam, and C. A. Desoer, "Longitudinal control of a platoon of vehicles with no communication of lead vehicle information: A system level study," *IEEE Transactions on Vehicular Technology*, Vol. 42, No. 4, pp. 546-554, 1997.

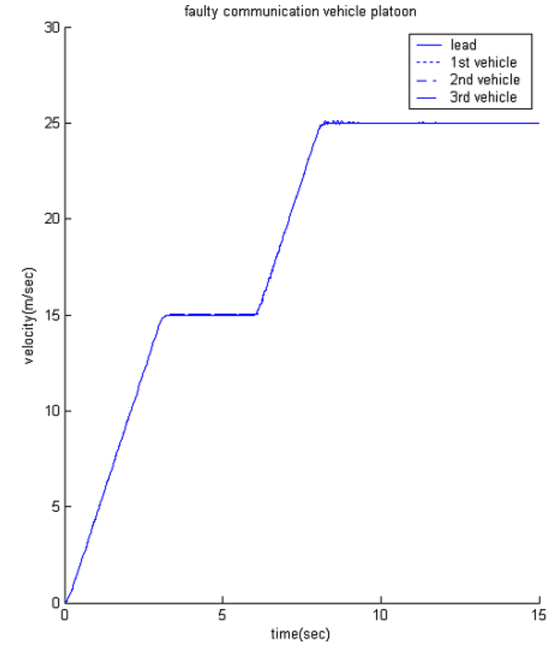

Fig. 7. Responses of velocicties in the faulty communication situation for lead vehicle

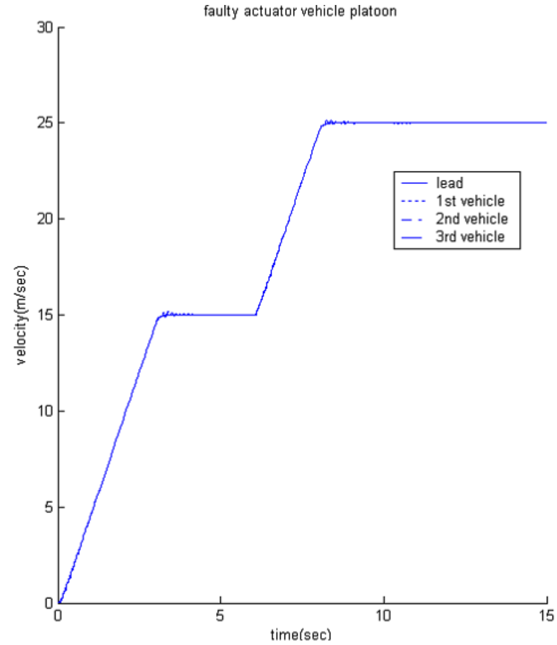

Fig. 9. Responses of velocities in the actuator-faulty situation for 1st vehicle

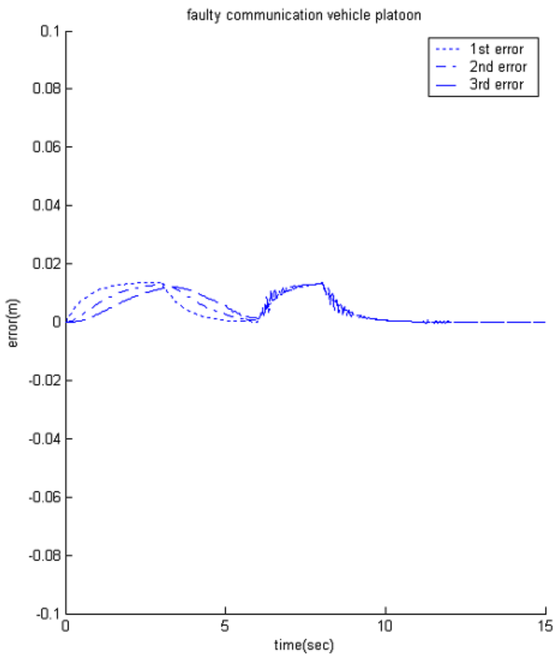

Fig. 8. Responses of distance deviations in the faulty communication situation for lead vehicle

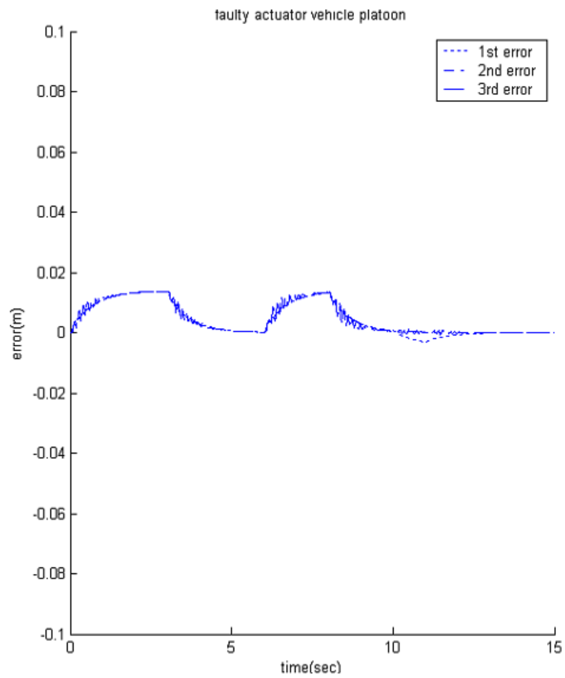

Fig. 10. Responses of distance deviations in the actuator-faulty situation for 1st vehicle

[4] T. S. No, K. Chong, and D. Roh, “A lyapunov function approach to longitudinal control of vehicles in a platoon,” *IEEE Transactions on Vehicular Technology*, Vol. 50, pp. 116-124, 2001.

[5] T. S. Jeffrey and K. M. Passino, “Fault-tolerant control for automated highway systems,” *IEEE Transactions on Vehicular Technology,*, Vol. 46, No. 3, pp. 770-785, 1997.

[6] A. Stotsky, C. C. Chien, and P. Ioannou, “Robustt platoon-stable controller design for autonous intelligent vehicles,” *Proceedings of Conference on Decision and Control,*, July 1994.

[7] S. E. Shladover, “Longitudinal control of automated guideway transit vehicles within platoons,” *ASME Transactions on Journal of Dynamic Systems, Measurement, and Control*, Vol. 100, pp. 302-310, 1978

[8] S. E. Shladover, “Longitudinal control of automative vehicles in clode-formation platoons” *ASME Transactions on Journal of Dynamic Systems, Measurement, and Control*, Vol. 113, pp. 231-241, 1991.