Abstract

In Japan, a new project for reducing CO$_2$, called "Energy ITS project" has started since 2008 by New Energy and Industrial Technology Development Organization (NEDO) for reducing CO$_2$ emissions. This project aims to develop techniques for the autonomous platooning of heavy-duty trucks to reduce their air resistance in expressway driving. Platooning needs lateral and longitudinal control. This paper describes novel lateral and longitudinal control. Lateral control method is based on path following. Longitudinal control method uses information acquired from the front and rear trucks by inter-vehicle communication. And a steering control methods using feedforward control to deal with a road cant and a deviation from a target course by a disturbance are proposed. The experimental results of autonomous platooning are provided to evaluate the effectiveness of the method. In this experiment, the platoon is composed of four trucks, and two kind trucks are used.

1. INTRODUCTION

In Japan, the realization of a low-carbon society using Intelligent Transport Systems (ITS) is advocated. The achievement of the automatic transport system by ITS technology with high effect of energy conservation is required as the energy and environmental measures on the transportation field. For this realization, a new project for reducing CO$_2$, called "Energy ITS project" has started in Japan since 2008 by New Energy and Industrial Technology Development Organization (NEDO). This project is based on the concept that an autonomous platooning system does not essentially depend on road infrastructure. Platooning can improve driving efficiency and reduce CO$_2$ emissions\(^1\). Many studies on autonomous driving and platooning have been conducted\(^2\). Although most methods require specialized road infrastructures, the techniques developed in recent years have been using the existing infrastructure in Japan, Europe\(^3\) and the United States\(^4\). A maneuver of practical factor is not proposed in the existing studies.

In this paper, we describe novel control methods of autonomous driving in the lateral direction and platooning in the longitudinal direction. The knowledge that the road cant and a disturbance influence the performance of the controller is acquired. Then, we propose the control method using feedforward control to deal with a road cant and the method to deal with a deviation from a target course by a disturbance using path regeneration. The effectiveness of the proposed methods is evaluated by the experimental results. In existing study\(^5\), we used three trucks and same kind truck. In this experiment, the platoon is composed of four trucks. We use two kind trucks: one is a large-size truck and the other is a small size truck.
2. LATERAL CONTROL

2.1 Lateral vehicle model

Single-track model shown in Fig. 1 is used as a truck model to design a lateral controller. Single-track model is the motion model of vehicle where the right and left wheels in the front and rear is concentrated on the intersection of the longitudinal axis and the axel tree equivalently. In this model, the motion in a horizontal plane of the vehicle which runs in high speed and constant velocity is assumed.

Considering that the velocity is high and the turning radius is large, the vehicle dynamics is represented by the single-track model which is regarded that right and left tires exist on the center of each axle like Fig. 1. Its dynamics is described as follows\(7\):

\[
\begin{align*}
\frac{d}{dt} \begin{bmatrix} \gamma \\ \beta \end{bmatrix} &= A \begin{bmatrix} \gamma \\ \beta \end{bmatrix} + B \delta, \\
A &= \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} -\frac{2}{M} (Kf l_f^2 + Kr l_r^2) - \frac{2}{J} (Kf l_f - Kr l_r) \\ -\frac{2}{MV^2} (Kf l_f - Kr l_r) - 1 - \frac{2}{MV} (Kf + Kr) \end{bmatrix}, \\
B &= \begin{bmatrix} h_{11} \\ b_{11} \end{bmatrix} = \begin{bmatrix} \frac{2}{MV} Kf l_f \\ \frac{2}{MV} 2Kf l_f \end{bmatrix},
\end{align*}
\]

where \(K_f\) and \(K_r\) are the cornering stiffness of the front and rear tires, \(l_f\) and \(l_r\) are the distance from the vehicle's center of gravity to the front and rear tire axles, \(M\) is the mass of the vehicle, \(\beta\) is the side slip angle of the center of gravity, \(\gamma\) is the yaw rate, \(V\) is vehicle velocity, \(J\) is the moment of inertia.

2.2 Path following control

The control system\(8\) is designed so that a real vehicle follows to the reference path in the framework of path following where a virtual reference vehicle runs as shown in Fig. 2.\(9\).

We define the origin of the coordinate system on the reference vehicle's center of gravity like Fig. 2, and take relative errors toward the real vehicle. Then the relative errors \(e_1, e_2, e_3\) are defined by

\[
\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos(\theta_r + \beta_r) & \sin(\theta_r + \beta_r) & 0 \\ -\sin(\theta_r + \beta_r) & \cos(\theta_r + \beta_r) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - x_r \\ y - y_r \\ (\theta + \beta) - (\theta_r + \beta_r) \end{bmatrix},
\]

where \((x, y)\) is the vehicle's center of gravity, and the subscript \(r\) means the parameters of the reference vehicle. The derivative of \(e_1, e_2, e_3\) is represented by

\[
\frac{d}{dt} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} V \cos e_3 - V' + e_3 \omega_r \\ V \sin e_3 + e_3 \omega_r \\ \omega - \omega_r \end{bmatrix},
\]

We assume that the reference vehicle always runs according to the speed of a real vehicle. It is easy to derive a path following controller. It is necessary to satisfy that \(e_1 = 0\) and \(e_1 = 0\). Therefore, the time derivative of errors is represented by

\[
\frac{d}{dt} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} V \sin e_3 \\ \omega - \omega_r \end{bmatrix}.
\]

We select the control input as follows:

\[
\omega_c = \omega_r - K_r e_3 V' - K_f \sin e_3,
\]

where \(K_r\) is a positive constant and \(\omega_r = \dot{\theta}_r + \dot{\beta}_r\). The stability is guaranteed by Lyapunov stability theorem\(10\). However, \(\omega_c\) cannot be input directly to a real vehicle. Therefore, the control input is expressed by (1) as follows:

\[
\delta_c = \frac{MV}{2K_f} \gamma + \frac{2(Kf l_f - Kr l_r)}{MV} \beta + \omega_r - K_r e_3 V - K_f \sin e_3.
\]
2.3 Feedforward control for cant

Generally, an expressway is designed at a speed over 100 km/h. When a vehicle runs at a speed lower than design speed, a vehicle falls in a slant direction of a cant by the influence of gravity. As the limit speed of heavy-duty trucks is 80 km/h in Japan, a cant becomes a disturbance in steering control. Then, we propose the method to deal with an influence of a gravity ingredient of a vehicle as shown in Fig. 3 by feedforward control.

Its dynamics including a cant is described as follows:\(^{(8)}\):

\[
\dot{\gamma} = \frac{C_i, \delta + Mg \sin(\sigma)}{V} , \quad \beta = \alpha + \frac{C_i, \delta}{l_i, C_i},
\]

where \(C_i = 2*K_l, C' = 2*K_r\), \(g\) is gravity and \(\sigma\) is an angle of a cant. As \(\dot{\gamma} = 0, \beta = 0\) in steady state, \(\delta\) of an ingredient of a cant is represented by

\[
\delta_{\text{can}} = \frac{-Mg(l_i, C_i - l_i, C_i)}{IC_i, C_i} \sin(\sigma).
\]

\(\delta_{\text{can}}\) is added to (7) as feedfoward.

2.4 Path regeneration

There are various disturbances on real expressway: rut on a road and difference from the plan information in construction and so on. The disturbance becomes a factor of a deviation in lateral direction. Then, we propose the method to deal with the deviation by path regeneration. When a deviation in lateral direction occurs by disturbances, path regeneration controls the increase of the error, and makes the error converge rapidly.

A path for a modification of a course is generated by combining a clothoid curve so that the rate of change of curvature \(\rho\) becomes constant each classification to distance \(p\) as shown in Fig. 4. The classification is composed of four divisions.

As a curvature radius is \(R\) and \(V\) is constant, the relations are represented as follows:

\[
\frac{\rho}{R} = \frac{1}{\omega} = \frac{\Delta \theta}{\theta} , \quad \Delta \theta = \int_0^t \omega dt = \int_0^t \rho dp, \quad \rho = \frac{dp}{Vdt}, \quad \Delta \theta = \int_0^t \omega dt = \int_0^t \rho dp.
\]

where \(dp=Vdt\) is a distance of movement in minimum time. The area of Fig. 4 equals to the amount of change of \(\theta\) from (10). A path for a modification is generated from a height and a length of \(p-\rho\) curve according to \(e_2\) and \(e_3\). The shape of \(p-\rho\) curve is changed as follows:

\[
\frac{dp}{dt} = \frac{-e_2(t_i)}{\rho}, \quad \frac{\Delta \theta}{\theta} = \int_0^t \sin \frac{\rho dt}{\theta} = \int_0^t \sin \frac{\rho dt}{\theta} = \int_0^t \sin \frac{\rho dt}{\theta} = \int_0^t \sin \frac{\rho dt}{\theta} = \int_0^t \sin \frac{\rho dt}{\theta}.
\]

And \((\Delta X, \Delta Y)\) is represented as follows:

\[
\Delta X = \int_0^t \cos \frac{1}{2} \rho dp, \Delta Y = \int_0^t \sin \frac{1}{2} \rho dp.
\]

As it is impossible to integrate (14) directly, Maclaurin’s expansion is used as follows:

\[
\sin x = \sum_{n=0}^\infty (-1)^n \frac{x^{2n+1}}{(2n+1)!} , \quad \cos x = \sum_{n=0}^\infty (-1)^n \frac{x^{2n}}{(2n)!}.
\]

\((\Delta X, \Delta Y)\) are represented as follows:

\[
\Delta X = \sum_{n=0}^\infty (-1)^n \frac{\alpha}{(2n)!} \frac{1}{4n+1} \rho^{4n+1},
\]

\[
\Delta Y = \sum_{n=0}^\infty (-1)^n \frac{\alpha}{(2n)!} \frac{1}{4n+3} \rho^{4n+3}.
\]
3. LONGITUDINAL CONTROL

3.1 Longitudinal vehicle model

The heavy-duty truck model to design a control system is represented as follows:

\[ x_i = v_i , \quad (17) \]

\[ \dot{v}_i = -\frac{1}{T} v_i + \frac{1}{T} u_i , \quad (18) \]

where \( x_i \), \( v_i \), and \( u_i \) are the position, the velocity and the input of the truck. \( K \) is the gain of acceleration or braking. \( T \) is the time constant. The subscript \( i \), \( 1 \leq i \leq n \), \( i \) shows the number of vehicle. \( i=1 \) is the first vehicle and \( i=n \) is the last one.

3.2 Platooning with front and rear information

To make the distance between controlled vehicles in platoon and their velocity follow the constant target spacing and velocity, we proposed the control method\(^6\) which uses the relative velocity and spacing information of a front and rear truck. The platoon stability in both the backward and forward directions is guaranteed based on Lyapunov stability theory. This controller is designed as follows:

\[ d_i = x_i - x_{i+1} - d_r - L , \quad (19) \]

\[ w_i = v_i - v_r , \quad (20) \]

where \( d_i \) and \( w_i \) are the error of the distance between controlled vehicles and the velocity.

\( d_s \) and \( v_s \) are the constant desired spacing and velocity. \( L \) is the length of vehicle. Input \( u_i \) is represented by

\[
u_i = \frac{T}{K} \left( \frac{1}{T} v_i + v_r - c_0 w_i + k_1 d_{i-1} - k_2 d_i + c_1 (v_i-1 - v_i) - c_2 (v_i - v_{i+1}) \right) , \quad (21)\]

where \( c_i \), \( c_s \), \( k_1 \) and \( k_2 \) are the positive constant (\( c_i = c_2 \) and \( k_1 = k_3 \)). In the case of the lead truck, \( k_i = 0 \) and \( c_i = 0 \). In the case of the last truck, \( k_i = 0 \) and \( c_i = 0 \). The stability is guaranteed by Lyapunov direct method\(^6\).

4. EXPERIMENTS

4.1 Experimental truck

In this experiment, we use two kinds of trucks as shown in Fig. 5. One is HINO Profia which is 25t class. The other is ISUZU Elf which is 2t class. The test course is an oval course which consists of 750m straight line and 180m radius curve. The width of the road is 3.75m. A cant on radius curve is about 6%.

4.2 System architecture

The truck has on-board sensors: two cameras and lasers on the truck’s left front and rear, a wheel speed sensor and a yaw rate sensor. The lateral deviation \( e_2 \) and the heading angle \( e_3 \) are calculated by the cameras and lasers. The information from the sensors is processed and sent to dSPACE Autobox. The control input is calculated from the information which is measured by the sensors. Autobox sends the control input to the steering ECU and the engine ECU through the CAN. The steering ECU operates a motor which is installed on the steering wheel. And the control cycle of the truck is 20msec.

4.3 System parameters and variables

The system parameters and variables in these experiments are shown in Table 1, Table 2 and Table 3. The system parameters of trucks are shown in Table 1. The control gains of lateral controller are shown in Table 2. The gains between the shown velocities are given by interpolation. The gains of the

<table>
<thead>
<tr>
<th>Table 1. System parameters</th>
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<tr>
<td>( M ) [kg]</td>
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<td>( l_r ) [m]</td>
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<td>( l_l ) [m]</td>
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<td>( K_r ) [N/rad]</td>
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<td>( K_c ) [N/rad]</td>
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longitudinal controller are shown in Table 3.

### 4.4 Experimental results of platooning

In this experiment, the operation of acceleration and steering is controlled. The platoon is composed of three Profia and an Elf. A target velocity of platoon is controlled at 80km/h, \( a = 0 \), and a target distance is 10m. The results of the lateral control are shown in Fig. 6. The results of the longitudinal control are shown in Fig. 7 and Fig. 8. The lateral error was less than \( \pm 0.1 \text{m} \) on a straight and curve. The heading angle was less than \( \pm 0.5 \text{deg} \) on a straight curve. The error of the inter truck distance was kept to be less than \( \pm 0.2 \text{m} \). The error of the velocity of the...
controlled truck was kept to be less than ±0.1 m/s. Therefore, we could confirm the precise performance of the proposed method.

4.5 Experimental results of path regeneration

In this experiment, the operation of acceleration and steering is controlled. We set the initial error as 8 m to evaluate the method of path regeneration. The result is shown in Fig. 9. As the Fig. 9, the shift to the stable steering control is realized without an overshoot. Therefore, the generation of a smooth path and precise following were confirmed.

5. Conclusions

In this paper, we considered a practical factor, and proposed two control methods. One was the method using feedforward control. The other was the method to deal with a deviation from a target course by a disturbance using path regeneration. And we confirmed that the proposed methods had a precise performance for autonomous platooning by experimental results.

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REFERENCES


4) C. Bergenhem, Q. Hung, A. Benmimoun, and T. Robinson, "Challenges of platooning on public motorways", 17th World Congress on Intelligent Transport Systems, 2010


