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Following Performance Evaluation of a Mechanically Coupled Platoon

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Abstract

Coupling some trucks with the same destination is called a truck platoon system. The leading truck is driven manually and the following trucks are driven automatically by using sensors on the mechanical link. Mechanical links does not only restrict the movability of the following trucks, but also are used for sensors. We evaluate the manipulability and the following performance on the linked platoon system. The relation between the measure of manipulability and the following performance is also explained. Finally, the optimized link formation is proposed in this paper.

1 Introduction

These days, most of the freight transportation is transacted by trucks, and this situation is expected not to be changed in the near future. However, there are a lot of problems caused by trucks, air pollution, traffic congestion, increase of energy consumption and so on. In order to overcome these problems, truck platoon is now under investigation[1]. Since the trucks are driven by a very short distance in a platoon, the road capacity will be increased and the energy consumption will be reduced.
In CHAUFFEUR project, an electronically coupled truck platoon has been proposed[2][3]. The following truck is driven automatically by using a CCD camera and the so-called VVC (Vehicle to Vehicle Communication). The electronical coupling has a few problems with respect to the reliability in the emergent situations.
We proposed a mechanically coupled truck platoon that has the advantage of reliable measurement, wired communication and high safety[4][5]. In this paper, we give the design strategy of mechanical link for mechanically coupled truck platoon based on the measure of manipulability and the following performance by using three types of mechanical links. And based on the optimization problem, we give the appropriate link formation.

2 Measure of Manipulability Evaluation

2.1 Configuration of the 3 D.O.F link

A vehicle has three degree-of-freedom on the horizontal plane, two D.O.F on the position and one D.O.F. on the orientation. If the mechanical link has the same number of freedom, trucks in a platoon could run with small restriction from the mechanical link. We design three types of 3 D.O.F mechanical links, which have the same formation, as shown in Fig.1. All links have to have two rota-

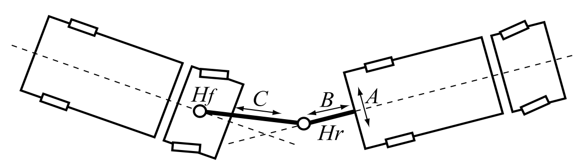

Fig. 1: Link formation

tion joints at H_f and H_r, which are used as sensors for steering control. These two joints could measure the relative yaw angle between two trucks. The remaining D.O.F is set on the prismatic joint, whose position is different for each link as shown in Fig.2. Link$A$'s prismatic joint is set at the leading truck's rear bumper, Link$B$'s is set between the tail of the leading truck and H_r, Link$C$'s is set between H_f and H_r.

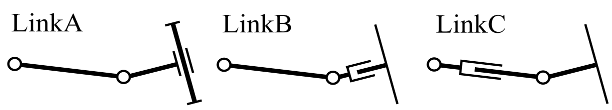

Fig. 2: Arragement of prismatic joint

2.2 Measure of Manipulability

Measure of manipulability (M.O.M.) is applied to evaluate the movability of truck platoon coupled with mechanical links. M.O.M. is often used in the evaluation of the robotic arm's manipulability performance[6]. In this section, M.O.M. of each link are compared.
We set the platoon's coordinate system as Fig.3. The kinematics of Link$A$ is given by the following

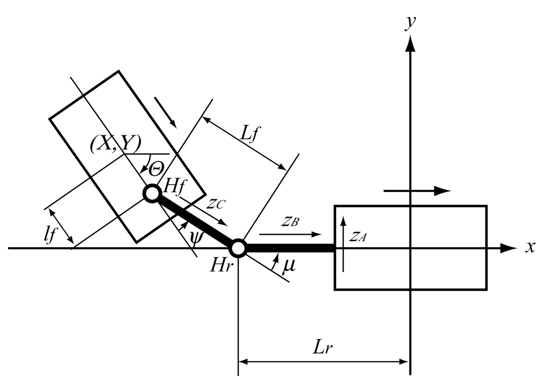

Fig. 3: Platoon's coordinate system

equations:

$$\begin{array}{l} X = -L_r - L_f\cos(\mu) - l_f\cos(\psi+\mu) \\ Y = L_f\sin(\mu) + l_f\sin(\psi+\mu) + z_A \\ \Theta = -\psi - \mu \end{array} \tag{1}$$

Each parameters are set as shown in Fig.3. By partial differentiation of Eq.1, we get the jacobian matrix $\boldsymbol{J}_A$ as:

$$\boldsymbol{J}_A = \begin{pmatrix} l_f\sin(\psi+\mu) & J_{A(12)} & 0 \\ l_f\cos(\psi+\mu) & J_{A(22)} & 1 \\ -1 & -1 & 0 \end{pmatrix} \tag{2}$$

$$J_{A(12)} = L_f\sin(\mu) + l_f\sin(\psi+\mu) \tag{3}$$

$$J_{A(22)} = L_f\cos(\mu) + l_f\cos(\psi+\mu) \tag{4}$$

In the same way, the jacobian matrix $\boldsymbol{J}_B$, $\boldsymbol{J}_C$ are obtained.

$$\boldsymbol{J}_B = \begin{pmatrix} l_f\sin(\psi+\mu) & J_{B(12)} & 1 \\ l_f\cos(\psi+\mu) & J_{B(22)} & 0 \\ -1 & -1 & 0 \end{pmatrix} \tag{5}$$

$$J_{B(12)} = L_f\sin(\mu) + l_f\sin(\psi+\mu) \tag{6}$$

$$J_{B(22)} = L_f\cos(\mu) + l_f\cos(\psi+\mu) \tag{7}$$

$$\boldsymbol{J}_C = \begin{pmatrix} l_f\sin(\psi+\mu) & J_{C(12)} & \cos(\mu) \\ l_f\cos(\psi+\mu) & J_{C(22)} & -\sin(\mu) \\ -1 & -1 & 0 \end{pmatrix} \tag{8}$$

$$J_{C(12)} = (L_f - z_C)\sin(\mu) + l_f\sin(\psi+\mu) \tag{9}$$

$$J_{C(22)} = (L_f - z_C)\cos(\mu) + l_f\cos(\psi+\mu) \tag{10}$$

By using the jacobian matrix J_i, M.O.M. is defined as:

$$w_i = \sqrt{\det(\boldsymbol{J_i}\boldsymbol{J_i}^T)}, i = A, B, C \tag{11}$$

M.O.M. is depended on the angle of the rotation joint. For the comparison of M.O.M. of each link, M.O.M. is calculated in two situations as follows.

Situation 1 Both trucks run along one curved road. The radius of the curve is set to $R = 100$[m]. ψ and μ are set as $\psi = 0.03$[rad], $\mu = 0.09$[rad] respectively.

Situation 2 Both trucks run along straight road. ψ and μ are set as $\psi = 0$[rad], $\mu = 0$[rad] respectively.

The M.O.M. of each link in each situation is shown in Table.1. Link$C$'s M.O.M. is the highest in each situation, which means that trucks in a platoon using Link$C$ have the best movability.

Table 1: Measure of Manipulability of each Link

	Link$A$	Link$B$	Link$C$
Situation1	0.38388	4.2428	4.26
Situation2	4.08419×10^{-16}	4.26	4.26

3 Following Performance Evaluation

3.1 Problem Formulation

In this section, we evaluate the following performance of the truck in a platoon by comparing with the optimized trajectory. The optimized trajectory is designed as follows.

1. Two trucks are not connected by link.
2. The first truck runs with velocity V.
3. The second truck is controlled so that it follows the same trajectory as the first truck.
4. The controller is designed based on the forward error correction algorithm by linear prediction[7] which is explained in the following section.

By the restriction of the link, the trajectory has perturbation by which the following performance index is evaluated quantatively. Because of the nonlinearity of the vehicle dynamics or link kinematics, the following performance index depends on the path of truck. We set one model, in which the leading truck is going straight and the second truck is going to follow the leading truck as shown in Fig.4. The initial condition of the rotation angle is $\mu_0 = 0.09$[rad], $\psi_0 = 0.03$[rad].

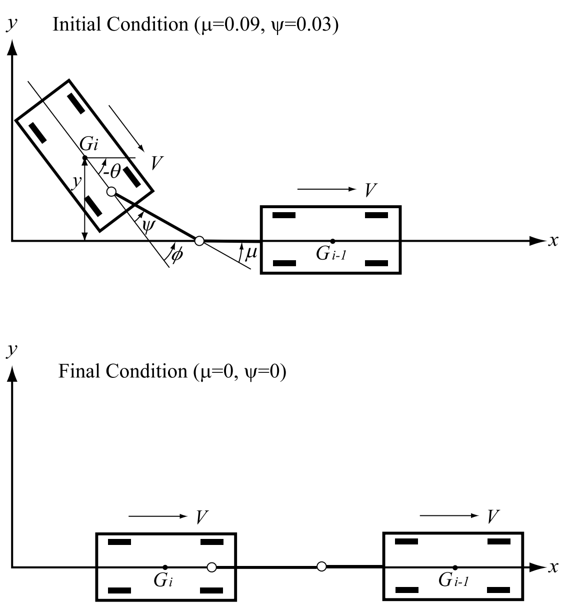

Fig. 4: Platoon model

3.2 Vehicle Dynamics

For the evaluation, we design the vehicle model. We use the two-wheeled model because the dynamic equations of the truck in a platoon are same as an uncoupled truck. The dynamic equations of the platoon system are as follows:

$$
\begin{aligned}
a_1 \frac{d\beta}{dt} + a_2\beta + a_3\gamma &= \delta \\
a_4\beta + a_5 \frac{d\gamma}{dt} + a_6\gamma &= \delta
\end{aligned}
\tag{12}
$$

Here, δ is the front steering angle, β is the slip angle, γ is the yawing rate and coefficient $a_i (i = 1, 2, \ldots, 6)$ are constants defined by configuration and velocity of the vehicle. When the vehicle is driven almost straight, $\beta \ll 1$ and $\gamma \ll 1$ are satisfied. Approximately in the model of Fig.4, Eq.12 can be converted into Eq.13:

$$
\begin{aligned}
b_1 \frac{d^2y}{dt^2} + b_2 \frac{dy}{dt} + b_3 \frac{d\theta}{dt} + b_4\theta &= \delta \\
b_5 \frac{dy}{dt} + b_6 \frac{d^2\theta}{dt^2} + b_7 \frac{d\theta}{dt} + b_8\theta &= \delta
\end{aligned}
\tag{13}
$$

Here, y is the lateral position of the center of gravity, θ is the yawing angle and coefficient $b_i (i = 1, 2, \ldots, 8)$ are constants.

3.3 Controller design

We design a controller based on the forward error correction algorithm by linear prediction[7]. The steering angle δ of the following truck is determined by the rotation angle μ and ψ which are measured by sensors on the mechanical link, and can be formulated as:

$$\delta = \boldsymbol{k}\boldsymbol{z} = k_1\mu + k_2\frac{d\mu}{dt} + k_3\psi + k_4\frac{d\psi}{dt} \tag{14}$$

Coefficients $k_i (i = 1, 2, 3, 4)$ are design parameters and determined by the linear quadratic regulator method. The state space equation of Eq.13 is written as:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\delta \tag{15}$$

Here, $\boldsymbol{A}$ and $\boldsymbol{B}$ are constant matrices. $\boldsymbol{x}$ is a state vector given by:

$$\boldsymbol{x} = \begin{pmatrix} y & \dot{y} & \theta & \dot{\theta} \end{pmatrix}^T \tag{16}$$

In the model of Fig.4, the leading truck is driven straight at constant velocity V, the second truck is going to follow the leading truck from the initial condition y_0, ϕ_0. Here, $y \ll 1$ and $|\phi| \ll 1$

are satisfied. By using linear quadratic regulator method, the steering angle δ is given as follows:

$$\delta = -\boldsymbol{K}\boldsymbol{x} = -K_1 y - K_2 \frac{dy}{dt} - K_3 \theta - K_4 \frac{d\theta}{dt} \quad (17)$$

Considering the steering angle δ and the following performance y, θ to the leading truck, we set the cost function as follows:

$$J = \int_0^\infty (y^2 + 100\theta^2 + 20\delta^2) dt \quad (18)$$

Here, we need to convert the feedback coefficient $\boldsymbol{K}$ in Eq.17 into the gain coefficient $\boldsymbol{k}$ in Eq.14 to use in the simulation with each mechanical link. Approximately in the model of Fig.4, y and θ are written as:

$$\begin{aligned} y &= L_f \mu + l_f(\mu + \psi) \\ -\theta &= \psi + \mu \end{aligned} \quad (19)$$

From Eq.14, Eq.17 and Eq.19, $\boldsymbol{k}$ is given as follows:

$$\boldsymbol{k} = \begin{pmatrix} -(L_f + l_f) & 0 & 1 & 0 \\ 0 & -(L_f + l_f) & 0 & 1 \\ -l_f & 0 & 1 & 0 \\ 0 & -l_f & 0 & 1 \end{pmatrix} \boldsymbol{K} \quad (20)$$

3.4 Simulation Result

First, we simulate the non-linked platoon model to obtain the optimized trajectory. This simulation is done based on Eq.21, which is substituted Eq.17 into Eq.15.

$$\dot{\boldsymbol{x}} = (\boldsymbol{A} - \boldsymbol{B}\boldsymbol{K})\,\boldsymbol{x} \quad (21)$$

The trajectory of the following truck is shown in Fig.5. To evaluate the following performance, we simulate three systems with different links. In these simulations, the following truck is controlled by the same algorithm as before. The simulation course is the same as the non-linked platoon model simulation. The result with Link$A$ is shown in Fig.6, Link$B$ is in Fig.7, Link$C$ is in Fig.8 respectively. The upper part shows the trajectory of the following truck and the lower part shows the slide length of the prismatic joint. The trajectories using Link$B$ and Link$C$ are similar to that of Fig.5, however the case with Link$A$ is different. Therefore, it seems to be difficult to realize the high following performance with Link$A$.

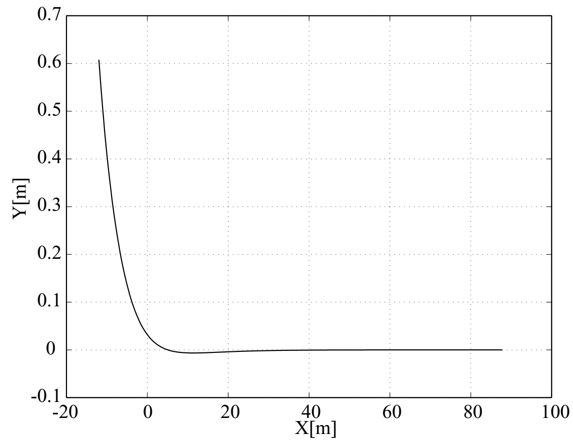

Fig. 5: Optimized trajectory

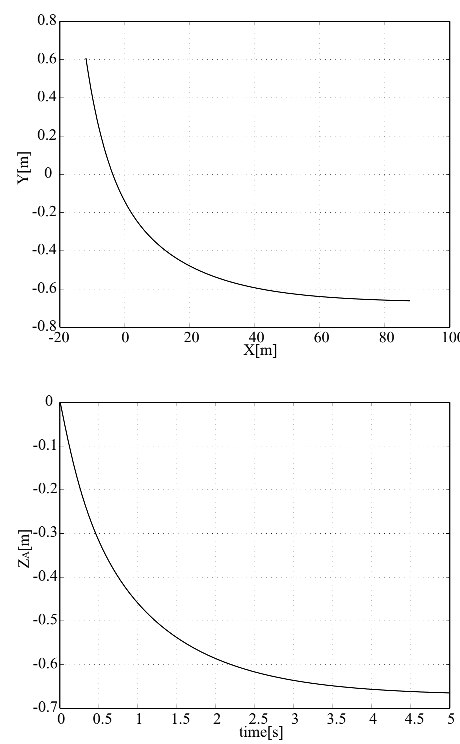

Fig. 6: Simulation result with Link$A$

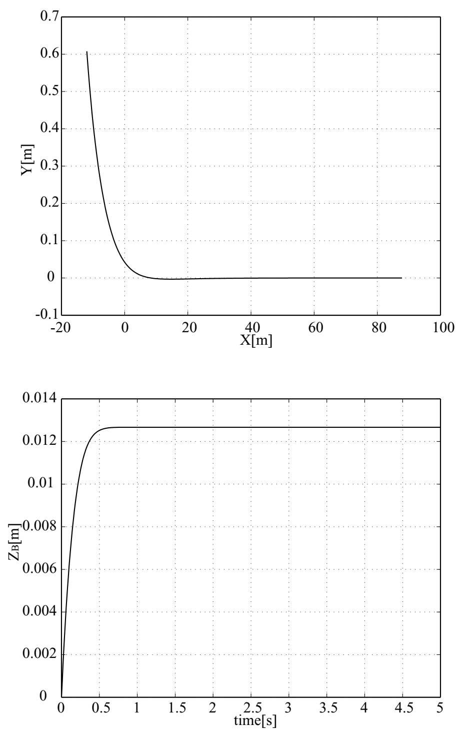

Fig. 7: Simulation result with Link$B$

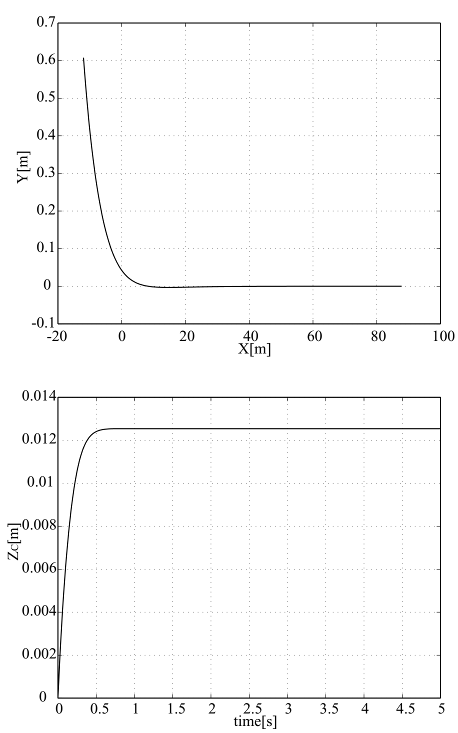

Fig. 8: Simulation result with Link$C$

3.5 Following Performance Evaluation

For the evaluation of the following performance, we set the performance index I_1, I_2 as follows:

$$I_1 = \int_0^{x(5)} (\Delta y) dx \tag{22}$$

$$I_2 = \int_0^{5} (\Delta z)^2 dt \tag{23}$$

I_1 means the square measure of error of trajectory and I_2 means the motion index of the prismatic joint. The result are shown in Table.2. The result of the following performance evaluation is that the most efficient link is Link$C$. Combining this result with that of Sect.2, we conclude that the following performance becomes better by using a link with a higher M.O.M.

Table 2: Following performance evaluation with Link$A$, Link$B$ and Link$C$

	$I_1[\mathrm{m}^2]$	$I_2[\mathrm{m}^2]$
Link$A$	4.7961×10	1.6207
Link$B$	1.0475×10^{-1}	7.7047×10^{-4}
Link$C$	9.2418×10^{-2}	7.5506×10^{-4}

4 Improvement of the Following Performance

4.1 Following Performance with Spring and Damper

Since the platoon runs at a constant speed, the link has a bias at the prismatic joint. In this section, a spring and damper are set to make the prismatic quantity smaller and improve the following performance. We simulate about four cases with different spring and damper parameter and the result is shown in Table.3. S is a spring constant and C means the coefficient of viscosity of the damper.

Case 1 $S = 0[\mathrm{N/m}], C = 0[\mathrm{Ns/m}]$

Case 2 $S = 5 \times 10^3[\mathrm{N/m}], C = 0[\mathrm{Ns/m}]$

Case 3 $S = 1 \times 10^5[\mathrm{N/m}], C = 0[\mathrm{Ns/m}]$

Case 4 $S = 1 \times 10^5[\mathrm{N/m}], C = 1 \times 10^5[\mathrm{Ns/m}]$

Table 3: Comparison of spring constant and damper constant

	$I_1[\mathrm{m}^2]$	$I_2[\mathrm{m}^2]$
case 1	9.2418×10^{-2}	7.5506×10^{-4}
case 2	9.2564×10^{-2}	8.0061×10^{-4}
case 3	9.3004×10^{-2}	5.2012×10^{-4}
case 4	9.5322×10^{-2}	7.0896×10^{-7}

These results show that spring and damper made the error area bigger because the restriction of the link intensifies.

4.2 Optimization of the spring constant and coefficient of viscosity

We set a cost function to optimize the trade-off relation between the error area and the prismatic quantity. The cost function J is set as follows:

$$J = \int_0^{x(5)} (\Delta y) dx + 2 \int_0^5 (\Delta z)^2 dt \qquad (24)$$

Here, Δy is the error of the trajectory and Δz is the slide of the prismatic joint. We find the optimized S and C which minimize the cost function J in Eq.24 The result of calculating the cost function J is shown in Fig.9. The minimum of the cost

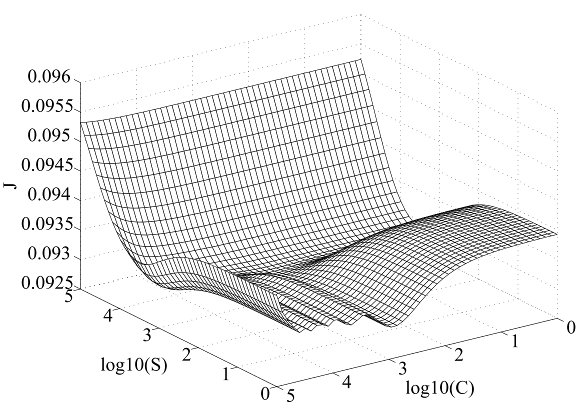

Fig. 9: Cost function

function occurs in the case of $S = 568.99$[N/m] and $C = 2330.0$[Ns/m]. By using this spring and damper, the performance index I_2 becomes smaller with less increase of the performance index I_1.

5 Conclusion

In this paper, we give the design strategy of mechanical link for mechanically coupled platoon system. The result of this paper is as follows.

1. The movability of trucks in mechanically coupled platoon is evaluated by the measure of manipulability (M.O.M.). Link$C$'s M.O.M. is the highest of the three links.
2. The following performance is evaluated by using the performance index I_1 and I_2. Link$C$'s I_1 and I_2 are the lowest of the three links.
3. The following performance becomes better when a link with a higher M.O.M is used.
4. The following performance is improved by setting the spring and damper at the prismatic joint. Spring and damper constants are determined by minimizing the cost function.

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