

Soft-Link Control for Electric Light Vehicle

Manabu Omae*, Takeki Ogitsu**, Hiroshi Shimizu**

This study developed a soft-link control system for electric light vehicles. The meaning of the soft-link control is that a vehicle automatically follows the preceding vehicle with a very short inter-vehicle distance as if the both vehicles were mechanically connected. The soft-link control is expected to stretch the limitation of the light vehicles, because small capacity of the light vehicle is timely enlarged, resulting in giving a potential to apply them to more various purposes. In this study, the experimental vehicles are developed based on small electric vehicles and control algorithms are designed. Stability and reliability of control and accurate tracking are realized by using information of the preceding vehicle sent via wireless LAN communication. The experimental results show that the controlled vehicle can follow the preceding vehicle with an inter-vehicle distance of less than 1[m].

Keywords: Light Vehicle, Passenger Cars, Transportation Systems(ITS, etc.), Intelligent Vehicle

1. INTRODUCTION

There has been a great interest in the development of intelligent or automated highway systems. Such intelligent transportation systems are expected to improve safety, efficiency, and accessibility of transit and quality of highway travel. This paper focuses on the soft-link control, one of types of automatic driving control, where a vehicle automatically follows the preceding vehicle with a very short inter-vehicle distance as if the both vehicles were mechanically connected. The automatic driving systems in which a vehicle follows a preceding vehicle or in which vehicles travel as one group called as the platoon have been reported in the field of passenger vehicle for enlarging traffic capacity and in the field of heavy-duty vehicles for laborsaving[1-12]. The soft-link system for a passenger vehicle will be also important considering incoming aging society. As to light vehicles, the soft-link control is expected to stretch the limitation of the light vehicles, because small capacity of the light vehicle is timely enlarged by soft-link control. Moreover the soft-link control is realized relatively easily if it is applied to electric light vehicles because of the following reasons: 1) Inter-vehicle distance can be accurately controlled because traction and braking forces are quickly and accurately generated by electric motors. 2) Energy of collision is small resulting in vehicles are not damaged if the following vehicle collides with the preceding vehicle for some reasons.

This study developed the soft-link control system for electric light vehicles, as shown in Fig.1. The

experimental vehicles are developed and control algorithms are designed. The experimental results show that the controlled vehicle can follow the preceding vehicle with an inter-distance of less than 1[m].

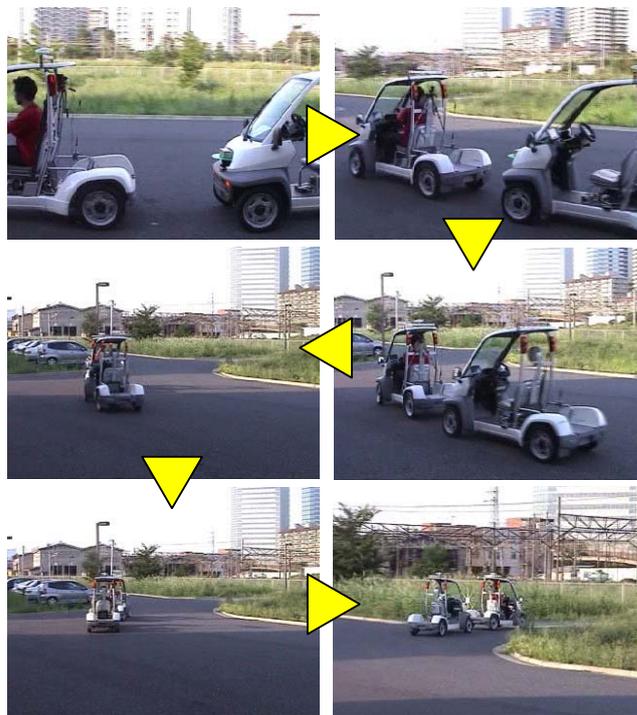


Fig. 1 Soft-link control

2. EXPERIMENTAL VEHICLE

This chapter describes the experimental vehicles for the soft-link control. In the following sections, the configuration of experimental vehicles and measurement of relative positions of the vehicles are explained.

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2.1 Configuration of Experimental Vehicle

Figures 2 and 3 show the developed vehicles and their configuration, respectively. Two vehicles of the same configuration are developed so that one vehicle can follow the other.

An AC servo motor is fixed for controlling a steering angle from a computer. The AC servomotor turns the shaft of steering wheel through reduction gears. The maximum speed is 120[rpm] at the steering wheel.

Traction and braking forces of the vehicle can be controlled by the computer. Two DC brushless motors are fixed for driving rear wheels. The computer sends the desired torque commands to the inverter of the motors. Braking force is generated by sending torque command to the opposite direction of the motors' turning. The acceleration range of control is about $-2[m/s^2] \sim 2[m/s^2]$.

State variables of vehicle motion such as a velocity, acceleration and yaw rate are measured by sensors. A scanning laser radar is equipped for detecting obstacles in front of the vehicle and for measuring the relative position of the other vehicle. The laser radar's horizontal scan range is 180[deg] with resolution of 0.5[deg] and the maximum distance of detection is 80[m] with resolution of 1[cm]. An RTK-GPS is equipped for measuring vehicle position. Real-time information of vehicle position and yaw angle (vehicle's heading angle) is estimated by Kalman filter integrating the RTK-GPS information and the vehicle motion information[13,14]. A wireless modem is used for obtain differential correction information of RTK-GPS.

Communication between two vehicles is done by 2.4GHz wireless LAN system. The protocol of the communication is UDP. Information of a vehicle position, a yaw angle, yaw rate, velocity, torque command and steering angle is exchanged at a period of 50[ms].

A steering-wheel-shaped controller is used for an input device for a driver, so this vehicle has the steer-by-wire configuration.



Fig. 2 Experimental vehicle

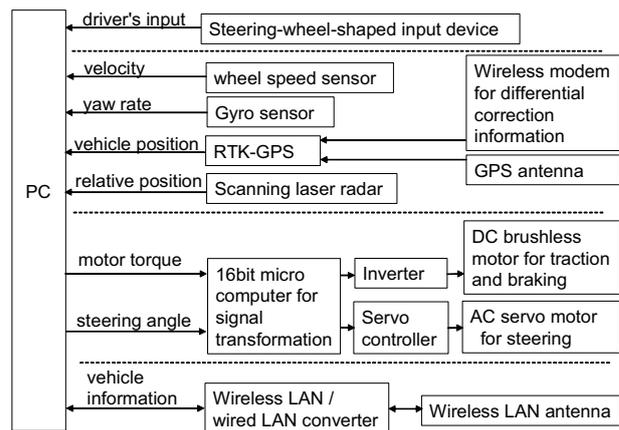


Fig. 3 Configuration of experimental vehicle

2.2 Measurement of Relative Position of Preceding Vehicle

In the soft-link control, the following vehicle is controlled according to the relative position of the preceding (or leading) vehicle. Thus it is important for the following vehicle to detect the relative position of the preceding vehicle accurately and reliably. In this study, the information of the relative position of the preceding vehicle is obtained by two methods. One is measurement by the scanning laser radar. The other is measurement by the RTK-GPS.

The scanning laser radar is fixed on the front of the vehicle as shown in the left part of Fig.4 and measures distances between the vehicle and all objects around it. To identify the preceding vehicle, a retro-reflector is attached on the preceding vehicle as shown in the right part of Fig.4. The intensity of the laser reflected by the retro-reflector is stronger than that reflected by other objects. Thus, by measuring the intensity of the reflected laser as well as the distance to the objects, the preceding vehicle's relative position is extracted efficiently. In addition to the measurement by the scanning laser radar, vehicle's position information based on the RTK-GPS is used. The preceding vehicle sends its position and yaw angle information to the following vehicle by wireless LAN communication. The relative position of the preceding vehicle is calculated using the positions and yaw angles of the preceding and following vehicles on the computer of the following vehicle. By using the relative position information obtained by two methods, reliable measurement is realized.



Fig. 4 Measurement of relative position of preceding vehicle

3. CONTROL ALGORITHM FOR SOFT-LINK CONTROL

This chapter describes two control algorithms for implementation of soft-link control. One is a longitudinal control algorithm for keeping an inter-vehicle distance, and the other is a lateral control algorithm for steering the front wheels to follow the preceding vehicle. In the following sections, those control algorithms are explained.

3.1 Longitudinal Control

This study designed a longitudinal control algorithm to keep the inter-vehicle distance very short and constant regardless of a vehicle speed. Considering that the soft-link control should be applied to more than two following vehicles, the control algorithm should guarantee the string stability, which means that spacing errors should not get amplified as they propagate upstream from vehicle to vehicle[5,6]. A lot of research results on longitudinal control have been reported in the fields of automatic driving systems and driver-assistance systems. Seeing those researches, complex control algorithms are necessary for accurate spacing control because of non-linear characters of engine and hydraulic brake systems. In this study, characteristics of vehicles are almost same, traction and braking forces can be control accurately and quickly by electric motors. Thus a simple control algorithm can realize accurate spacing control with grantee of the string stability. The proposed control algorithm enables the vehicle to follow the preceding vehicle with a fixed distance with guarantee of the string stability by using information of inter-vehicle distance as well as velocity and traction and braking forces command of the preceding vehicle. The information of the preceding vehicle is obtained via wireless LAN communication.

Figure 5 shows variables for the proposed longitudinal control. The control input is desired torque of motors for driving wheels. The control input of the leading vehicle (T_{des_1}) is as follows:

$$T_{des_1} = K_{pV}(V_{des} - V_1) + K_{iV} \int_0^T (V_{des} - V_1) dt + R(V_1), \quad (1)$$

where

V_{des} : desired velocity [m/s],

V_1 : velocity of the leading vehicle [m/s]

$R(V)$: estimated torque for compensating resistance forces (rolling resistance and aerodynamic drag) at V_1 [Nm]

K_{pV} , K_{iV} : feedback gains. The desired velocity (V_{des}) changes according to driver's input. The control input of the 1st-following vehicle (T_{des_1}) is as follows:

$$T_{des_1} = T_{des_1} + K_{pS}(L_1 - L_{des}) + K_{dS}(V_1 - V_1), \quad (2)$$

where

V_1 : velocity of the 1st-following vehicle [m/s],

L_1 : distance between the leading vehicle and the 1st-following vehicle [m],

K_{pS} and K_{dS} : control gains.

V_1 and T_{des_1} are sent from the leading vehicle via wireless LAN communication. The above algorithms

means the control input feed-backing spacing and velocity error between the leading vehicle and the first following vehicle with feed-forwarding of control input of the leading vehicle.

If the soft-link control is applied to more than three vehicles, control input of i -th following vehicle (T_{des_i}) is as follows:

$$T_{des_i} = T_{des_i-1} + K_{pS}(L_i - L_{des}) + K_{dS}(V_{i-1} - V_i), \quad (3)$$

where

V_i : velocity of the i -th following vehicle [m/s],

L_i : distance between the i -th following vehicle and ($i-1$)-th following vehicle [m].

The reason why the above algorithm guarantees the string stability is explained by calculating the transfer function from input of the leading vehicle to spacing error between first and second following vehicles. In the following explanation, a platoon of three vehicles is considered. The relationship between acceleration command and vehicle acceleration is assumed to be 1st-order delay system as follows:

$$\dot{V}_1(s) = \frac{1}{t_1 s + 1} u_1(s), \quad \dot{V}_1(s) = \frac{1}{t_1 s + 1} u_1(s), \quad \dot{V}_2(s) = \frac{1}{t_2 s + 1} u_2(s), \quad (4)$$

where t_1 , t_1 and t_2 are the time constants of the vehicles and s is the Laplace operator. It should be noted that acceleration commands are used in the explanation instead of torque commands used in the control algorithm for simplicity of the explanation. The platoon system is shown as follows:

$$\frac{d}{dt} \begin{pmatrix} V_1 \\ \dot{V}_1 \\ sp_1 \\ \dot{sp}_1 \\ \dot{V}_1 \\ sp_2 \\ \dot{sp}_2 \\ \dot{V}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ \frac{p_1}{t_1} & \frac{p_2}{t_1} & \frac{p_3}{t_1} & \frac{p_4}{t_1} & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \\ \frac{q_1}{t_2} & \frac{q_2}{t_2} & \frac{q_3}{t_2} & \frac{q_4}{t_2} & 0 & \frac{q_5}{t_2} & \frac{q_6}{t_2} & -1 \end{pmatrix} \begin{pmatrix} V_1 \\ \dot{V}_1 \\ sp_1 \\ \dot{sp}_1 \\ \dot{V}_1 \\ sp_2 \\ \dot{sp}_2 \\ \dot{V}_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \\ t_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} u_1 \quad (5)$$

where input is acceleration command of the leading vehicle (u_1), and state variables are velocity and acceleration of the leading vehicle (V_1 , \dot{V}_1), spacing error and velocity error between the leading and first following vehicles (sp_1 , \dot{sp}_1), acceleration of the first following vehicle (\dot{V}_1), spacing error and velocity error between the first and second following vehicles (sp_2 , \dot{sp}_2), and acceleration of the second following vehicle (\dot{V}_2). In Eq. 5, $p_1 \sim p_4$ are feedback coefficients of the first following vehicle. $q_1 \sim q_6$ are feedback coefficients of the second following vehicle. In the proposed control algorithm, the second following vehicle uses the torque command of the first following vehicle, which means $q_1 = p_1$, $q_2 = p_2$, $q_3 = p_3$ and $q_4 = p_4$. And In the platoon, the vehicles' specifications are assumed to be the same, which means $t_1 = t_1 = t_2$. Substituting $p_1 \sim p_4$ and t_1 for $q_1 \sim q_4$, t_1 and t_2 , the transfer function from u_1 to sp_2 ($G(s)$)

calculated by the following equation (Eq. 6) is zero regardless of values of $p_1 \sim p_4$, q_5 , q_6 , and t_l . This means that the input of the leading vehicle does not affect the spacing error between the first and second following vehicles and that spacing errors do not get amplified as they propagate upstream from vehicle to vehicle by the acceleration and deceleration of the leading vehicle.

$$G(s) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}^T \left[s\mathbf{I} - \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & t_l & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 \\ \frac{p_1}{t_l} & \frac{p_2}{t_l} & \frac{p_3}{t_l} & \frac{p_4}{t_l} & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \\ \frac{p_1}{t_l} & \frac{p_2}{t_l} & \frac{p_3}{t_l} & \frac{p_4}{t_l} & 0 & \frac{q_5}{t_l} & \frac{q_6}{t_l} & -1 \end{pmatrix} \right]^{-1} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} = 0 \tag{6}$$

Figure 6 shows simulation result of longitudinal control applied to four vehicles, where $L_{des}=1[m]$. The upper part of Fig. 6 shows the velocity of the leading vehicle. The lower part of Fig. 6 shows the spacing errors of each vehicle, where spacing errors are almost same and curves in the graph look like one curve. The result shows that accurate control is realized, and that spacing errors do not get amplified as they propagate upstream from vehicle to vehicle.



Fig. 5 Longitudinal control

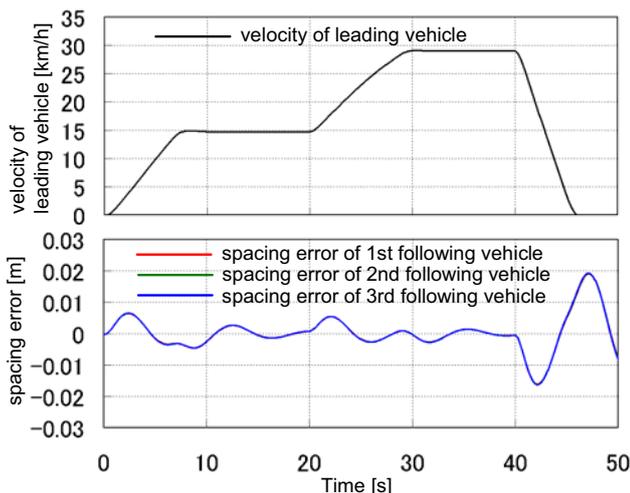


Fig. 6 Simulation result of longitudinal control

3.2 Lateral Control

This study designed control algorithms for determining a front steering angle of the following vehicle. To realize accurate tracking of the following vehicle on the trajectory of the leading vehicle, control

input should feed-back a lateral deviation of the following vehicle to the trajectory of the leading vehicle and dynamic information of vehicle such as yaw rate and lateral acceleration and should use feed-forward information such as future lateral deviation, curvature of the desired trajectory. The proposed soft-link system, however, an inter-vehicle distance is too short, that is preview time of feed-forward information is very short, and it is possible that vehicle behavior is unstable by the feed-back terms. Thus this study designed a control algorithm without feed-backing a lateral deviation or dynamic information of vehicle, considering the stability taking priority over the accuracy of tracking. Front steering angle of the 1st-following vehicle (δ) is determined as follows:

$$\delta = K_{st} \theta, \tag{7}$$

where

θ : angle of direction of the leading vehicle on the 1st-following-vehicle-coordinate system shown in Fig. 7 [rad],

K_{st} : control gain.

If the soft-link control is applied to more than three vehicles, the above control has the problem of accumulation of tracking errors as shown in Fig. 8. The accumulation of tracking error can be reduced in some degree by tuning the control gain. Elimination of the accumulation of tracking error can be realized by determining the front steering angle of the following vehicle based on the trajectory of the leading vehicle instead of the position of the adjacent preceding vehicle as shown in Fig. 9. The following vehicle can get the trajectory of the leading vehicle by receiving the position information of the leading vehicle via wireless LAN communication. The method for obtaining the real-time and accurate position information by using RTK-GPS and vehicle motion sensors is explained in the paper[13,14].

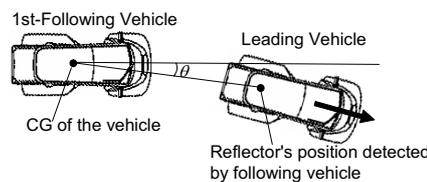


Fig. 7 Lateral control

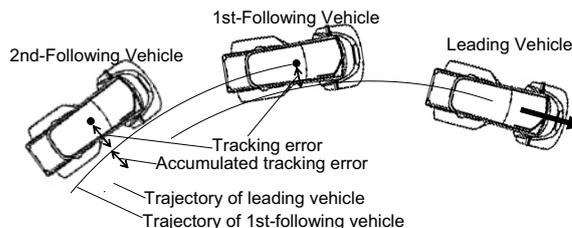


Fig. 8 Accumulation of tracking errors

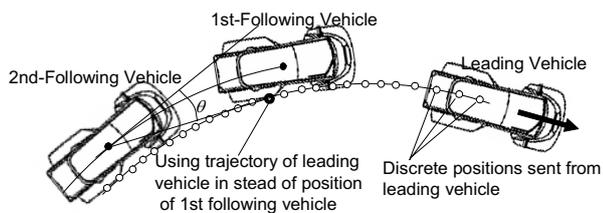


Fig. 9 Prevention of accumulation of tracking errors

4. EXPERIMENTAL VALIDATION

The proposed soft-link control system is validated by experiment. In the experiment, one vehicle is controlled to follow the leading vehicle driven by a human driver. The desired space between the leading and following vehicles is set to be 0.8[m].

Control parameters described in Chapter 3 is tuned by road tests. $K_{pV_s}=5.8 \times 10^1$ [Ns], $K_{iV_s}=9.7$ [N], $K_{pS}=1.1 \times 10^2$ [N], $K_{dS}=1.1 \times 10^2$ [Ns] and $K_{sI}=8.3 \times 10^{-1}$ are used as control parameters in the experiment. It should be noted that control parameters for determining the desired torque of motors are shown as total torque around the wheels' axles and that the desired torques of the leading and following vehicles are limited to the ranges of $-8.1 \times 10^1 \sim 8.1 \times 10^1$ [Nm] and $-1.3 \times 10^2 \sim 1.3 \times 10^2$ [Nm], respectively.

Figure 10 shows the experimental result. The upper and middle parts show velocities and trajectories of the leading and following vehicles. The velocities of the vehicles are measured by wheel speeds of the vehicles. The trajectories are measured by the histories of real-time positions of the vehicles calculated by using RTK-GPS and vehicle motion information. The lower parts of Fig. 10 show the inter-vehicle distance and the steering angles of front wheels of the leading and following vehicles. The inter-vehicle distance is measured by the scanning laser radar on the following vehicle.

The experimental result shows that the developed soft-link system enables the following vehicle to follow the preceding vehicle with a short inter-vehicle distance from start to stop.

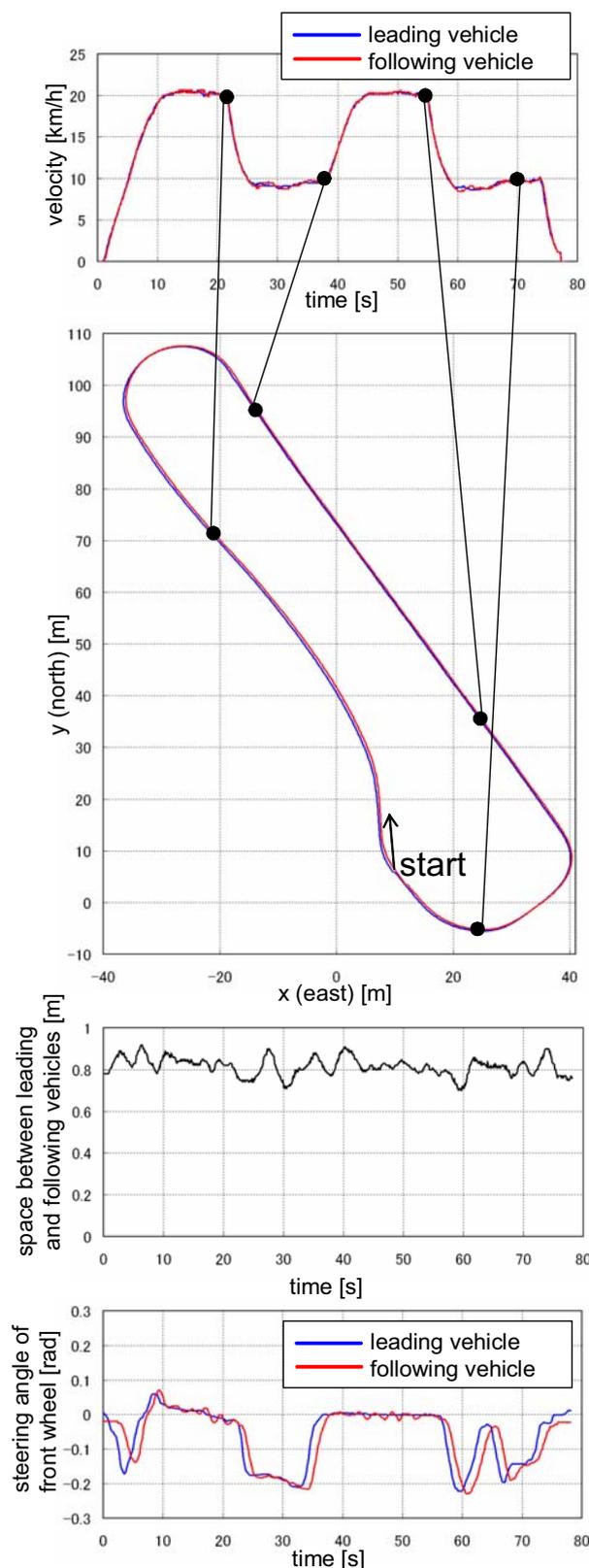


Fig. 10 Experimental result

5. CONCLUSIONS

This study developed the soft-link control system of electric light vehicles. The experimental vehicles are developed and control algorithms are designed. Stability and reliability of control and accurate tracking are realized by using information of the preceding vehicle sent via wireless LAN communication. The experimental results show that the vehicle can follow the preceding vehicle with an inter-vehicle distance of less than 1[m]. The fruit of this study will stretch the limitation of capacity of electric light vehicles and will give a potential to apply electric light vehicles to more various purposes.

REFERENCES

- [1] S. E. Shladover: Review of the State of Development of Advanced Vehicle Control Systems(AVCS), *Vehicle System Dynamics*, Vol.24, No6-7, (1995), pp.551-595.
- [2] T. Fujioka, K. Suzuki: Control of Longitudinal and Lateral Platoon Using Sliding Control, *Vehicle System Dynamics*, Vol.23, No.8, (1994), pp.647-664.
- [3] T. Fujioka, M. Omae: Vehicle Following Control in Lateral Direction for Platooning, *Vehicle System Dynamics Supplement*, Vol. 28, (1998), pp.422-437.
- [4] R. Rajamani, S. B. Choi, J. K. Hedrick, B. Law, R. Prohaska, P. Kretz: Design and Experimental Implementation of Control for a Platoon of Automated Vehicles, *Proceedings of the ASME Dynamic Systems and Control Division 1998*, DSC-Vol.64, (1998), pp.681-690.
- [5] D. Swaroop, J. K. Hedrick, C. C. Chien, P. Ioannou: A Comparison of Spacing and Headway Control Laws for Automatically Controlled Vehicles, *Vehicle System Dynamics*, Vol.23, No.8, (1994), pp.597-625.
- [6] H. Raza, P. Ioannou: Macroscopic Analysis of Traffic Flow of Automated Vehicle, *Advances in Intelligent Transportation System Design*, SAE Sp-1285, Paper No.972655, (1997), pp.25-34.
- [7] D. Yanakiev, I. Kanellakopoulos: Speed Tracking and Vehicle Follower Control Design for Heavy-Duty Vehicles, *Vehicle System Dynamics*, Vol.25, No.4, (1996), pp.251-276.
- [8] J. Seuss, J. Richert: Control Structures for Vehicle Convoy Driving, *Proceeding of the International Symposium on Advanced Vehicle Control 1996*, Vol.2, (1996), pp.1277-1292.
- [9] S. Seshagiri, H. K. Khalil: Longitudinal Adaptive Control of a Platoon of Vehicles, *Proceedings of 1999 American Control Conference*,(1999).
- [10] L. Alvarez, R. Horowitz: Safe Platooning in Automated Highway Systems Part I: Safety Regions Design, *Vehicle System Dynamics*, Vol.32, No.1, (1999), pp.23-55.
- [11] L. Alvarez, R. Horowitz: Safe Platooning in Automated Highway Systems Part II: Velocity Tracking Controller, *Vehicle System Dynamics*, Vol.32, No.1, (1999), pp.57-84.
- [12] U. N. Petersen, A. Ruckgauer, W. O. Schiehlen: Lateral Control of a Convoy Vehicle System, *Proceedings of the IAVSD Symposium*, (1996).
- [13] M. Omae, T. Fujioka: DGPS-Based Position Measurement and Steering Control for Automatic Driving, *Proceedings of 1999 American Control Conference*, (1999), pp. 3686-3690.
- [14] M. Omae, N. Hashimoto, H. Shimizu: Automatic Driving System for Light Vehicle with Easy Setup Feature, *Proceedings of the 21st International Electric Vehicle Symposium*(2005).

BIOGRAPHIES



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