HILS-Based Development of a Relative Position and Orientation Measurement System for Platooning Vehicles with Coupling Devices

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Abstract: We propose a new platooning vehicle that uses a coupling device not for the traction of following vehicles but for the measurement of relative position and orientation between leading and following vehicles. The following vehicles are driven by their own motors. This paper reports development of the relative position and orientation measurement system. In the coupling device, multiple distance sensors are equipped around the pin. These sensors acquire the distance between the pin and a hexagonal ring. The array of distance values is converted to the relative position and orientation of vehicles using two methods: (1) Geometric method and (2) Data look-up method. After a prototype of the proposed measurement system is implemented, it is evaluated using hardware in the loop simulation (HILS) that simulates multiple vehicles' platooning drive. Therefore, the system capabilities have been evaluated not only by the measurement precision but also by the platooning performance. The experimentally obtained results demonstrate that the proposed measurement system is sufficiently valid and feasible. The data look-up method exhibits especially superior performance because it uses no geometric conditions explicitly.

Key Words: automobile, self-driving car, hardware in the loop simulation, data-driven approach.

1. Introduction

Ultra-small mobility is receiving attention recently as a form of electric vehicle [1]–[5]. It is suitable for daily life travel and for short distance transfer in urban areas and tourist spots. It is anticipated for use in one-way car-sharing. In a one-way car-sharing service, several lending and returning spots (“ports”) are prepared. One may return a vehicle at a different spot from where it was borrowed. Because such a service might substantially enhance the convenience of users, it is regarded as accelerating the use of car-sharing [6]. Uneven availability of vehicles among spots is a severe difficulty that must be resolved for smooth operation of the service. The optimization of spot placement has been studied [7]. Nevertheless, the complete elimination of vehicle repositioning processes is impossible. Therefore, reducing the number of workers and working hours necessary for repositioning are expected to become increasingly urgent issues along with expansion of services.

Although auto-driving vehicles represent a good choice for the service described above and much R & D has been devoted to realization of auto-driving vehicles [8]–[10], many technological challenges [11],[12] and regulatory challenges have arisen [13],[14]. Therefore, this study assesses the proposed method of the platooning of vehicles connected by coupling devices, as presented in Fig. 1. Here, a driver is on board only in the leading vehicle: no driver is on board any following vehicles. Although they have coupling devices, the following vehicles are self-propelled. They follow the path of the leading vehicle while avoiding mechanical contact in the coupling device to the greatest extent possible. During platooning operations, one driver can reposition more than one vehicle in more than one spot, thereby achieving great reduction of worker numbers and working hours necessary for repositioning.

We collected information related to the relative position and orientation between vehicles for cruise control of platooning operations, making use of a measurement system mounted on the coupling device. Because the coupling device is covered completely, it is less affected by climate or environmental light than laser range finders and other sensors, which are mainly used in recent studies. In addition, the coupling device works as a safeguard against irregularity in platooning operations and therefore prevents runaway vehicles. As explained above, the coupling device connecting vehicles functions as a sensor housing of a relative position and orientation measurement device, working as a safeguard against possible irregular platooning operations while making almost no mechanical contact. It does not pull the following vehicle. Therefore, compared to mechanical traction by a trailer and column operation [15],[16], the proposed operation can make a turn with a small turning radius. It is able to proceed with a long connection, even in a
This paper reports our development of the relative position and orientation measurement system, which is the core technology of platooning vehicles equipped with our proposed coupling device. The targets of this study are (1) a proposal of a method to take measurements and to process data collected by such measurements for sensors favorably mounted on the coupling device and (2) the validation of that proposal, examining the effects of related factors on performance in platooning operations. Because implementation of the whole system of our targeted project was difficult at the time we started this study, we implemented only the relative position and orientation movement measurement system and applied “Hardware In the Loop Simulation” (HILS) software for the remainder of our system.

This paper is structured as follows. Section 2 outlines the relative position and orientation measurement system for platooning vehicles and describes the framework of cruise control of platooning vehicles using information obtained with the measurement system and HILS. Then Section 3 explains the actual implementation of the measurement system we developed and the method used to estimate the relative position and orientation of the vehicle. Section 4 introduces our experiment, assessing platooning operation assisted by HILS. Finally, Section 5 presents conclusions.

2. Relative Position and Orientation Measurement System for Platooning Vehicles Connected by Coupling Device

2.1 Relative Position and Orientation Measurement at Coupling Devices

Figure 2 depicts a schematic diagram of the platooning vehicles and the coupling device we propose. The coupling device comprises a pin fixed to the leading vehicle and a ring attached to the following vehicle. The pin moves freely in the domain inside of the ring; it is not constrained at all. We measure the relative position and orientation between two vehicles, indirectly estimating the relative position \((x, y)\) and orientation \(\theta\) between the pin and the ring. The platooning operation is executed based on control signal for the velocity and angular velocity, generated from the measured data described above. Although displacement in the \(z\) direction and the orientations (attitudes) of pitching and rolling must be considered in the final design of platooning vehicle for practical use, we first exclusively examined planar displacement \((x, y)\) and orientation \(\theta\) to simplify the assessment. In addition, as a first step of the project, this study assumes that the road surface is sufficiently flat in the area where the proposed vehicles drive. The concavity and convexity of road surface will be considered in the next step of this study.

By attaching sensors around the pin, as depicted in Fig. 3 and by measuring the distance between the pin and ring, we estimate the relative position and orientation between two vehicles. In actual implementation, the sensor information will be used for the following vehicle. Therefore, the pin mounting sensors are not connected directly to the leading vehicle; rather, the leading vehicle is connected to the packaged pin and ring fixed on the following vehicle. The coupling device is retracted when it is not connected to another vehicle.

We tried two approaches as methods to estimate the relative position and orientation from the arrayed data of measured pin-ring distances. The first method of estimation uses geometric positioning between the pin and ring. We formulate simultaneous equations describing geometric positioning between the pin and ring and solve them using the arrayed data of measured pin-ring distances to estimate the relative position and orientation. We designate this method hereinafter as the geometric method of estimation.

The second method of estimation uses no direct geometric positioning between the pin and ring. To apply this method, we collect arrayed data of measured pin-ring distance for main possible pin positioning in the ring in advance. Furthermore, we generate datasets including the associated information of the relative position and orientation of the pin with arrayed data of measured pin-ring distance. Then, in platooning operation, we compare obtained arrayed data of measured pin-ring distances with the datasets described above to estimate the relative position and orientation of the pin in that operation. We designate this method hereinafter as the data look-up method of estimation.

We conducted experiments to examine how the difference between these two estimation methods of relative position and orientation influence the platooning operation performance. Because the size of the dataset prepared beforehand in the data look-up method of estimation would influence the accuracy of the estimated relative position and orientation, we also tested the effects of differences in the datasets on the platooning operation performance.

2.2 Cruise Control of Platooning Operation of Vehicles with Coupling Device

The following vehicles performing platooning operation in this study must trace a trajectory resembling that of the leading vehicle, while maintaining the connected state with the neighboring vehicles. Although earlier studies have investigated the cruise control of platooning operation [17]–[19], not all were for cruise control of the platooning operation of vehicles with a coupling device that has no function of traction at all. There-
Our cruise controller for platooning operation has two targets. The first is to maintain the distance and orientation between vehicles. Therefore, we tried to make the controller mounted on the following vehicle orient the center of the coupling device in front of the following vehicle to that of the coupling device behind the leading vehicle (Fig. 4). We designated this function as tracking control of the coupling device.

The second target is to make the following vehicle run on the same trajectory with that of the leading vehicle. Therefore, we tried to make the controller mounted on the following vehicle orient point \( x_{ref} \) away from the center of the following vehicle to the trajectory of the leading vehicle (Fig. 5). We designated this function as trajectory tracking control. The trajectory of the leading vehicle was calculated by integration of the measured relative position and orientation.

Combining these two methods of control, we developed a cruise controller for platooning operation described above. Equations (1) and (2) are the control expressions of our cruise controller for platooning operation:

\[
\omega = K_{\text{out}} \theta_{\text{path}} + K_{\text{add}} \theta_{\text{path}} + K_{\text{out}} \int \theta_{\text{path}} dt, \tag{1}
\]

\[
v = K_{v} v_{\text{lead}} + K_{p x} x_{p} + K_{d x} x_{p} + K_{i x} \int x_{p} dt, \tag{2}
\]

\[
v_{\text{lead}} = \sqrt{(v_{\text{pre}} + \dot{x}_{p})^2 + \dot{y}_{p}^2}. \tag{3}
\]

This controller used the trajectory tracking control explained above for control signal of angular velocity \( \omega \) and the tracking control of coupling device described above for control signal of translational velocity \( v \). Both of these two equations describe PID control. For the translational velocity, we used coupling device tracking control to follow the leading vehicle. For the angular velocity, however, we had to use both control methods because the angular velocity determines the direction of movement. However, if the platooning operation is executed properly \(^1\), the trajectory tracking control works similarly with the tracking control of the coupling device. Therefore, we decided to control the angular velocity solely by the trajectory tracking control. Figures 4 and 5 describe \( \theta_{\text{path}}, x_{p}, \) and \( y_{p} \) in these equations. All of \( K_{\text{out}}, K_{\text{add}}, K_{\text{out}}, K_{v}, K_{p x}, K_{d x}, K_{i x} \) are PID coefficients. Furthermore, \( v_{\text{lead}} \) in Eq. (2) is the estimated translational velocity of the leading vehicle calculated using Eq. (3); \( v_{\text{pre}} \) is the output of the translational velocity for the following vehicle at the previous step of control.

In addition, our simulation of vehicle movement exclusively incorporates the kinematics calculated using Eq. (4). Therefore, we must evaluate the effects of dynamic factors such as the weight of the vehicles and the friction between the vehicle wheel and road surface in future studies. Symboles \( v_{R} \) and \( v_{L} \) in Eq. (4) respectively denote the translational velocities of left and right wheels; also, \( d \) is the distance from the axis of rotation to wheel. Symbole \( \rho \) stands for the turning radius. In addition, using the translational and angular velocities, the behavior of the vehicle in global coordinate system is described as Eq. (5) [20].

\[
\begin{align*}
\omega &= \frac{v_{R} - v_{L}}{2d}, \\
v &= \frac{v_{R} + v_{L}}{2}, \\
\rho &= \frac{d(v_{R} + v_{L})}{v_{R} - v_{L}}, \tag{4}
\end{align*}
\]

\[
\begin{align*}
\dot{x} &= v \cos \theta, \\
\dot{y} &= v \sin \theta, \\
\dot{\theta} &= \omega. \tag{5}
\end{align*}
\]

2.3 HILS-Assisted Simulation of Platooning Operation

We evaluated our relative position and orientation measurement system using HILS. HILS can simulate the behavior of a developing object without its hardware. Moreover, the use of software simulation can help us examine the developed object in conditions closer to its actual use. As Fig. 6 shows, our HILS comprises a measurement system equipped with a sensor mounted pin and ring, a PC (personal computer) functioning as a simulator, and the test bed with electric stages.

HILS follows the steps shown below. Step 1: Range sensors mounted on the pin in the measuring system measure the distance to the inner wall of the ring. Step 2: The relative position and orientation are estimated from the arrayed data of measured pin-ring distances. Step 3: Using that estimation, the cruise controller for platooning operation calculates the target values of the translational and angular velocities. Step 4: Using those target values of the translational and angular velocities, the vehicle movement simulator (based only on kinematics) renews the relative position and orientation between vehicles. Step 5: Making use of this renewed relative position and orientation between vehicles, the test bed mounting electric stages moves to renew the pin position and orientation in the measurement system. Then we return to Step 1.

\(^1\) We assumed that the distances from the axis of rotation to the head and tail of a vehicle were equal.
3. Measurement of Relative Position and Orientation Movement between Vehicles

3.1 Basic Design of Measurement System

The measurement system is made of the pin mounted on the leading vehicle and the ring fixed to the following vehicle (Fig. 3). The pin has sensors mounted on it. Infrared range sensors are attached around the pin, which were selected because of their contactless nature and durability for repeated measurements. The pin must be mounted by sensors much sufficient compared to the minimum for estimating the three variables of position \((x, y)\) and orientation \((\theta)\) and must have a simple geometry in fabrication work and in geometric calculation. Therefore, we prepared a regular octagonal pin and attached eight sensors on the faces of octagon: one on each face as depicted in Fig. 3.

A regular polygonal ring geometry was preferred for easy fabrication and for simple geometric calculation. With the increasing number of apices of polygons, the number of points which are rotationally symmetric to the center of the ring increases as well. When the pin is on one of these points, range outputs are mutually equal, causing confusion in data processing. The minimum radius of rotation in platooning operation was set to 6 m, the same as that of a microbus. The vehicle length was set to 3 m, which represents the maximum orientation of \(\pm 30^\circ\) between two successive vehicles. By these settings, if the polygonal ring has not more than six vertices, then a symmetric point described above appears for rotation more than \(60^\circ\), practically eliminating the possible chance of confusion said above. However, if the polygonal ring has approximately three vertices (included), then the movable area of the pin becomes narrow and such a configuration requires a quite large ring. Based on these considerations, we selected the regular hexagon as the shape of inner wall surface of the ring.

To find the movable area of the pin in the coupling device in determining the rough dimensions of the coupling device, we performed a preliminary simulation experiment of the behavior of vehicles in platooning operations incorporating the method of our cruise control, the errors in relative position and orientation measurement of the pin, and the delay in signal transmission in measuring devices. Based on results of this preliminary experiment, we determined the movable area of the pin as the interior of a hexagon circumscribing a circle with a 230 mm radius. Figure 7 presents an overview of the measuring device and the electric movable stage.

3.2 Estimation of the Relative Position and Orientation by Geometric Method

In this method, estimation of the relative position and orientation is done by solution of simultaneous equations describing the geometric relation between the pin and ring. Figure 9 shows a schematic model of the measuring device. The procedures are presented below.

3.2.1 Step 1: Exhaustive listing of wall (measured object)-sensor combinations

In this step, we solve the simultaneous equations presented above using the arrayed data of measured pin-ring distances \(L_i = (L_1, \ldots, L_8)\) to obtain many candidates of estimated orientation \(\hat{\theta}_j (j = 1, \ldots, N_{all})\). Not knowing the side of the wall which a sensor is facing to at this stage, we solve the simultaneous equations for all possible combinations of the pin and side of the inner wall of ring to get multiple candidates of estimated orientation \(\hat{\theta}_j\). Equations (6)-(11) show the geometric relation for arrayed data of measured pin-ring distances \(L_i(i = 1, \ldots, 8)\)
when sensor \( i \) faces each six side of the inner wall. Here, \( R \) stands for the radius of the circle inscribing the regular hexagonal inner wall of the ring, \( r \) signifies the distance between the pin center and the window of the range sensor, and \( \phi_i \) denotes the angle given by Eq. (12).

As these equations show, measurement errors are not explicitly considered in the geometric method. The measurement value depends not only on the distance between the sensor and the target surface but also on the angle of the target surface. This characteristic makes it difficult to consider the effect of measurement errors explicitly.

These equations are non-linear and a solution cannot be obtained analytically. To obtain a solution numerically, the proposed multiple steps are required. These steps find and evaluate multiple candidates of a solution and select the most probable solution. To solve the simultaneous equations, we assume that the neighboring two sensors face the same side of the inner wall. Consequently, for sensor 1 facing side 1, for example, we calculate a candidate of the estimated orientation \( \hat{\theta}_j \) substituting \( L_1 \) and \( L_2 \) into Eq. (6).

Actually, for eight range sensors and six sides of the inner wall, \( N_{all} \) is 48 by the calculation of 8 \( \times \) 6 = 48.

\[
2R + x = \sqrt{3}y = (L_i + r) |2 \sin(\phi_i - \pi/6)|, \quad (6)
\]
\[
R + x = (L_i + r) |\cos \phi_i|, \quad (7)
\]
\[
2R + x + \sqrt{3}y = (L_i + r) |2 \sin(\phi_i + \pi/6)|, \quad (8)
\]
\[
2R - x + \sqrt{3}y = (L_i + r) |2 \sin(\phi_i - \pi/6)|, \quad (9)
\]
\[
R - x = (L_i + r) |\cos \phi_i|, \quad (10)
\]
\[
2R - x - \sqrt{3}y = (L_i + r) |2 \sin(\phi_i + \pi/6)|, \quad (11)
\]
\[
\phi_i = \pi/4(i + 1) + \theta. \quad (12)
\]

3.2.2 Step 2: Calculation of candidates of estimated position from candidates of estimated orientation

We calculate candidates of the estimated positions \( \hat{x}_j, \hat{y}_j \) from corresponding candidate of the estimated orientation \( \hat{\theta}_j \). For each \( \hat{\theta}_j \), we obtain more than one solution of \( x \) and \( y \) coordinates from the equations described above and name them \( x_{jk}, y_{jk} \). To find \( \hat{x}_j, \hat{y}_j \) for each \( \hat{\theta}_j \), we cluster points \( (x_{jk}, y_{jk}) \) using the agglomerative method [21] based on the single linkage method. Then we take averages of \( x_{jk} \) and \( y_{jk} \) in the most crowded cluster containing the largest number of elements to select as \( \hat{x}_j \) and \( \hat{y}_j \).

3.2.3 Step 3: Probability-based weighted average of candidates of estimated position and orientation

Substituting candidates of the estimated position and orientation \( \hat{x}_j, \hat{y}_j \) and \( \hat{\theta}_j \) into the equations above provides distance \( \hat{L}_j = (\hat{L}_{j1}, \ldots, \hat{L}_{j8}) \). Using the deviation of calculated distance \( \bar{L}_j \) from the measured one \( L \) as weight, we find the weighted average of the candidates of the estimated position and orientation \( \hat{x}_j = (\hat{x}_j, \hat{y}_j, \hat{\theta}_j) \) as shown by Eqs. (13) and (14) to determine the estimated \( \hat{x} \):

\[
\hat{x} = \frac{\sum_{j=1}^{N_{all}} k_j \hat{x}_j}{\sum_{j=1}^{N_{all}} k_j}, \quad (13)
\]
\[
k_j = \frac{1}{\sum_{i=1}^{8} (L_i - \bar{L}_j)^2}. \quad (14)
\]

3.3 Estimation of the Relative Position and Orientation between Pin and Ring by Data Look-Up Method

Our data look-up method of estimation uses no geometrical relation between the pin and ring and estimates the relative position and orientation using a data-driven method. To be specific, the k-nearest neighbor method (k-NN method) [21] is used. The data look-up method of estimation is explained below.

1. In advance, we prepare datasets that associate the reference value of the measured distances \( L_{ref} = (L_{ref,1}, \ldots, L_{ref,8}) \) for each relative position and orientation of the pin as the learning data (template). To deal with the problem of measurement uncertainty, multiple samples are acquired in this step.

2. Then we collect arrayed data of the measured distance \( L \) for the relative position and orientation of the pin (measured object). This \( L \) works as the test data.

3. Furthermore, then we search for learning data close to the test data. There we scale the closeness of two data by the square of the Euclid distance in the feature space of the measured distance as in Eq. (15):

\[
D = \sum_{i=1}^{8} (L_{ref,i} - L_i)^2. \quad (15)
\]

4. Finally, we define the estimated position and orientation of the pin as the average of position and orientation associated to k learning data close to the test data.

The number \( k \) in the k-NN method we used is 15 that we selected in our preliminary examination.

4. Experiments

We conducted HILS-assisted experimental simulation of platooning operation to find the effect of the two different methods measuring the relative position and orientation of vehicles on the operational performance.

4.1 Setting of Experiments

Figure 10 presents a schematic diagram of our vehicle. The number of vehicles in our platooning was five, the maximum speed of vehicle 60 km/h, and the maximum acceleration 2.44 m/s\(^2\). We selected the PID coefficients in Eqs. (1) and (2) as shown in Eq. (16) to elucidate the effect of experimental configurations on platooning operation. In addition, the period of calculation for the simulation was 0.01 s.

\[
\begin{align*}
K_{pp} &= 10, K_{pd} = 0, K_{dd} = 0, \\
K_v &= 1, K_{vp} = 10, K_{vd} = 0, K_{dd} = 0.
\end{align*}
\]
We selected four courses of platooning operations after consulting the literature [22]. Then we added to them a course of the accelerated start.

1. Course for making circular operation: The vehicle runs at translational speed of 30 km/h and angular velocity of 0.28 rad/s on a circle of 30 m radius for 120°.

2. Course for lane changing: The vehicle runs at 50 km/h and makes a 3.6 m lane change within 40 m distance.

3. Course for slaloming operation: The vehicle runs at translational speed of 50 km/h and makes slaloming operation for 6 pylons placed at 30 m intervals.

4. Course for making pulsed steering: The vehicle runs at translational speed of 50 km/h. It is subjected to a pulse response test.

5. Course for accelerated start: The stationary vehicle starts at one-half of the maximum acceleration and accelerate to the maximum speed.

Because the results of vehicle operation were mutually similar, below we introduce just the result for the second, the course for changing lane, as a typical result.

As the index for evaluating platooning operations, we used the displacement of trajectories between the leading and following vehicles. The displacement is defined as illustrated in Fig. 11. By this definition, the displacement at a point of trajectory of the leading vehicle is the normal distance from that point to the point where the normal line intersects the trajectory of the following vehicle. We designate this displacement as the trajectory error below. When the pin moved crossing the boundary of the allowed area, we halted HILS after recognizing a failure of platooning operations. Under the setting of the experiment described above, we examined the effects of the two different methods for measuring the relative position and orientation of vehicles on the operation. The experiment for each condition was repeated five times.

4.2 Preliminary Experiment: Results of Experiments to Evaluate the Accuracy of Estimating the Relative Position and Orientation of Pin

Using both the geometric method of estimation and data look-up method of estimation, we performed a preliminary experiment to evaluate the accuracy of estimating the relative position and orientation of the pin. The learning data for the data look-up method were obtained through 11 times of sensor output collections for 329,751 relative positions and pin orientations in the allowed area.

| Method         | x (mm) | y (mm) | θ (°) |
|----------------|--------|--------|-------|
| Geometric      | 16.7   | 13.1   | 8.1   |
| Data look-up   | 2.9    | 3.1    | 1.7   |

Table 1 presents the results of experimentally found root mean square error (RMSE error) of the relative position and orientation estimation defined by Eq. (17). Here, xi, yi, ai, and ni in Eq. (17) respectively denote the true x, estimated x, and the number of points measured:

\[
RMS\ E = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \hat{x}_i)^2}. \tag{17}
\]

The setting interval of the relative position and orientation of the pin was 5 mm for x and y and 1° for θ. Table 1 shows the accuracy of the data look-up method of estimation is superior to that of the geometric method of estimation in each respect of x, y, and θ. This result is considered to be caused by the difference of output characteristics of the range sensor depending on the angle between the sensor and the measured surface, as presented in Fig. 12. Figure 12 shows that the sensor value changes depending not only on the distance but also the angle between the sensor and the measured surface. These characteristics hindered accurate calculation of the distance data and brought about failure of maintaining geometric relation.

4.3 Results of HILS-Assisted Experimental Simulation of Platooning Operation

Figures 13 and 14 present the results of experimental platooning operations. In these figures, the vehicle trajectory is shown at the top, the trajectory error in the middle, and the distribution of pin positions in the coupling device on bottom.

One can recognize failure of the platooning operations using the geometric method in the vehicle behind the second (Fig. 13). The trajectory error of operation based on the data look-up method was less than that by the geometric method, suggesting good performance of platooning operation using the data look-up method (Fig. 14). Similarly, the pin distribution was more crowded stably around the center of the ring in operation based on the data look-up method compared to that in operation based on the geometric method. Furthermore, it is noteworthy that all the operations conducted using the data look-up method were successful, but all those conducted using the geometric method produced failure.

This is thought to have occurred because of the non-zero time average of estimation error in operation based on the geometric method. Figure 15, which depicts a time-series graph of the estimation error of pin orientation, indicates that the error had
in the allowed movable area in the ring. Figure 16 presents the positional distribution of estimation error of pin orientation for a typical orientation of $\theta = 0$ in the lane change course operation. This figure represents the greater positional bias (dependence on position) of the estimation error of pin orientation in the geometric method compared to the data look-up method. Because, as explained earlier, the correct distance is not output depending on the angle of the side surface of the ring (object of measurement), the geometric method of estimation is thought to have generated similar error in the neighboring domain. If the pin moves into the positional domain of estimation error with the same sign in the course operation, it generates estimation error for which the time average is not zero.

4.4 Experiment to Assess Effects of Conditions Used to Prepare Learning Data

In the data look-up method of estimation, the number of elements in datasets and others affect the accuracy of the relative position and orientation estimation. Therefore, we evaluated the effects of different datasets on the platooning operation performance.

As shown in Table 2, we prepared three datasets to perform experiment of platooning operation using them. The intervals of $x$ and $y$ and pitches of $\theta$ for collecting data elements for learning data are listed in the table. Dataset A (Ref.) are the reference learning data used in the experiment described in the previous section. In Dataset B ($\theta$ sparse), points of data collection were sparse on the $\theta$ axis compared to Dataset A (Ref.). In Dataset C ($xy$ sparse), points of data collection were sparse on the $x-y$ plane compared to Dataset A (Ref.).

Table 2 Details of three training datasets.

| Dataset  | $x$ (mm) | $y$ (mm) | $\theta$ (°) | number of data   |
|----------|----------|----------|--------------|-----------------|
| A (Ref.) | 5        | 3.13     | 1.71         | $3.6 \times 10^6$ |
| B ($\theta$ sparse) | 5 | 5 | 9 | $4.3 \times 10^5$ |
| C ($xy$ sparse) | 15 | 15 | 1 | $4.0 \times 10^5$ |

Accuracy of Relative Position and Orientation Estimation of Pin

We conducted a preliminary experiment to confirm the accuracy of the relative position and orientation estimation of the pin using the three learning data explained above. The coordinates for the relative position and orientation estimation were all selected from the coordinates where we collected data for Dataset A (Ref.). Table 3 presents the accuracy (RMSE) of the relative position and orientation estimation of the pins. We recognize that Dataset B ($\theta$ sparse) and Dataset C ($xy$ sparse) yielded similar accuracy of estimation. Dataset A (Ref.), with the largest number of learning data, yielded the best estimation accuracy. In addition, estimations using both of Datasets B and C had different RMSE of $x$, $y$, and $\theta$ compared to the estimation produced using Dataset A (Ref.). This result proves that all of intervals in $x$ and $y$ and pitch in $\theta$ for generation of learning data affected the estimation performance.

Table 3 Estimation accuracy (RMSE) of three datasets.

| Data set  | $x$ (mm) | $y$ (mm) | $\theta$ (°) |
|-----------|----------|----------|--------------|
| A (Ref.)  | 2.92     | 3.13     | 1.71         |
| B ($\theta$ sparse) | 7.29 | 7.32 | 4.25 |
| C ($xy$ sparse) | 7.35 | 6.96 | 3.64 |
Results of Experimental Platooning Operation  Figures 17 and 18 present the results. In these figures, the top is the trajectory of the vehicles, the middle is the trajectory error, and the bottom is the distribution of pin positions in the coupling device. We can ascertain from these figures that the platooning operation based on Dataset B (θ sparse) failed at the fourth vehicle. The trajectory error in operation based on Dataset C (xy sparse) was smaller than that based on Dataset B (θ sparse). Operation based on Dataset C (xy sparse) showed better platooning performance. Actually, all the platooning operations based on Dataset C (xy sparse) were successful, but all the platooning operations based on Dataset B (θ sparse) failed.

One reason is the variation of the estimation accuracy over pin orientations. Table 4 presents the RMSE of estimation of pin position in operation. In contrast to the preliminary experiment, there is, in the course operation, a great difference of estimation RMSE between operation based on Dataset B (θ sparse) and that based on Dataset C (xy sparse). Figures 19 and 20 respectively present time-series graphs of RMSE of estimation of y and θ in the course operation. Figure 20 shows a
large RMSE of orientation estimation in platooning operation based on Dataset B (θ sparse).

To help find reasons for the result described above, we show the RMSE of estimation of ϒ and θ in Figs. 21 and 22. The variation ranges of ϒ and θ are indicated in the figures, as well.

Although the RMSEs are small for the conditions when the learning data obtained, those seem large for conditions when the learning data are not obtained. In particular for orientation estimation in Fig. 22, the variation range for operation are small compared with the whole range of measurement. Consequently, when the θ pitch of data collection is large, the effect of variation of estimation accuracy becomes substantial. Therefore it is suspected that the performance of the operation based on Dataset B (θ sparse) for learning data might have become worse. These suggest that in collecting learning data, one must consider the way the data are used for operation.

5. Conclusion

In this paper, we proposed a platooning operation connected by coupling devices and described the fundamental construction of the measuring system for relative position and orientation mounted on the coupling device. Then we introduced the basic design of the relative position and orientation measurement system composed of a pin mounted with several range sensors and a ring, of which the inner wall was the measured object of the sensor. We also demonstrated two methods of the relative position and orientation measurement to process the arrayed range data obtained there: the geometric method of estimation, and the data look-up method of estimation. Finally, using the measurement system we designed and built, we conducted a HILS-assisted experiment to examine the effects of the two different methods of the relative position and orientation measurement on the performance of platooning operation of vehicles and to demonstrate the effectiveness of the relative position and orientation measurement system we proposed.

Results show that the measurement accuracy of the data look-up method of estimation is better than that of the geometric method in estimating the relative position and orientation of the pin. These results are considered to be caused by the different characteristics of range sensor output dependent on the angle of the inner wall of ring, and by the importance of the accuracy of range data in the geometric method relying on the geometric relation.

Our HILS-assisted experiment of platooning operation demonstrated the superiority of the data look-up method of estimation over the geometric method of estimation. The geometric method includes positional variation of the estimation error in the area of pin movement, which generated estimation error that gave a non-zero time average in the operation time and which caused inferiority of this method. Based on the consideration presented above, we concluded that we must use a method of estimation that does not depend on the geometric relation between the pin and ring in the measurement system of the relative position and orientation of the pin for the proposed coupling device of platooning operations.

The data look-up method of estimation requires acquisition of learning data in advance. The size and nature of collected data seem to affect the platooning operation performance. Therefore, we performed experimental platooning operations using three learning data to conclude that we need to select ϒ and θ intervals and θ pitch for data collection in view of the way the learning data are used.

In addition, our simulation of platooning operation of vehicles exclusively incorporated their kinematics. For that reason, we must evaluate the effects of dynamical factors such as the inertia of vehicles and the friction between the vehicle wheels and the road surface, which are not small in actual vehicles. However, these points are left as subjects for our future study.

References

[1] Ministry of Land, Infrastructure, Transport and Tourism: Guidelines Introducing Personal Mobility, 2013.
[2] Toyota Motor Corporation: Smart mobility society, http://www.toyota.co.jp/jpn/tech/smart_mobility_society/, Access: 29 Aug. 2017.
[3] Toyota Motor Corporation: Ha:mo, http://www.toyota.co.jp/jpn/hamo/, Access: 29 Aug. 2017.
[4] Nissan Motor Corporation: One-way style large scale car sharing service using personal mobility, http://www.nissan-global.com/JP/NEWS/2014/STORY/140919-01-j.html, Access: 29 Aug. 2017.
[5] Honda Motor Co Ltd.: Honda Smart Community MC-β, http://www.honda.co.jp/mc-beta/, Access: 29 Aug. 2017.
[6] Y. Yasue, R. Kanamori, T. Yamamoto, and T. Morikawa: Analysis on characteristics of carsharing members and use intention, Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management), Vol. 69, No. 5, pp. L761–L770, 2013 (in Japanese).
[7] Gonçalo Homem de Almeida Correia and Antunes, António Paix: Optimization approach to depot location and trip selection in one-way carsharing systems, Transportation Research Part E: Logistics and Transportation Review, Vol. 48, No. 1, pp. 233–247, 2012.
[8] U. Özgüner and K. Redmill: Sensing, control, and system integration for autonomous vehicles: A series of challenges, SICE Journal of Control, Measurement, and System Integration, Vol. 1, No. 2, pp. 129–136, 2008.
[9] M. Mukai, J. Murata, T. Kawabe, H. Nishira, Y. Takagi, and Y. Deguchi: Optimal path generation for automotive collision avoidance using mixed integer programming, SICE Journal of
Control, Measurement, and System Integration, Vol. 1, No. 3, pp. 222–226, 2008.
[10] S. Thrun, et al.: Stanley: The robot that won the darpa grand challenge, Journal of Field Robotics, Vol. 23, No. 9, pp. 661–692, 2006.
[11] S. Tsugawa: Survey on automated driving systems, JATSS review, Vol. 37, No. 3, pp. 199–207, 2013 (in Japanese).
[12] Y. Suda and K. Aoki: Current activities and some issues on the development of automated driving, Journal of Information Processing and Management, Vol. 57, No. 11, pp. 809–817, 2015 (in Japanese).
[13] Ministry of Foreign Affairs of Japan: Convention on Road Traffic, http://www.mofa.go.jp/mofaj/gaiko/treaty/pdfs/B-S39(2)-0533_1.pdf, Access: 29 Aug. 2017.
[14] California Department of Motor Vehicles: Summary of Draft Autonomous Vehicles Deployment Regulations, https://www.dmv.ca.gov/portal/wcm/connect/dbcf0f21-4085-47a1-889f-3b864ea11f/AVRegulationsSummary.pdf?MOD=AJPERES, Access: 29 Aug. 2017.
[15] J. David and P.V. Manivannan: Control of truck-trailer mobile robots: A survey, Intelligent Service Robotics, Vol. 7, No. 4, pp. 245–258, 2014.
[16] T. Ikegami, T. Ogitsu, and H. Mizoguchi: Distributed power control evaluation of hard-link-type mobility using velocity and load data, Proceedings of International Conference on Connected Vehicles and Expo (ICCVE), pp. 362–366, Oct 2015.
[17] R. Hoeger, A. Amditis, M. Kunert, A. Hoess, F. Flemisch, H.-P. Krueger, A. Bartels, A. Beatner, and K. Pagle: Highly automated vehicles for intelligent transport: Haveit approach, Proceedings of ITS World Congress, 2008.
[18] T. Robinson, E. Chan, and E. Coelingh: Operating platoons on public motorways: An introduction to the SARTRE platooning programme, Proceedings of 17th World Congress on Intelligent Transport Systems, Vol. 1, p. 12, 2010.
[19] R. Kunze, M. Haberstroh, R. Ramakers, K. Henning, and S. Jeschke: Automated truck platoons on motorways—a contribution to the safety on roads, Automation, Communication and Cybernetics in Science and Engineering 2009/2010, pp. 415–426, Springer, 2010.
[20] K. Yoneda, T. Tsubouchi, and H. Osumi: The First Time of the Robot Creative Design, 2nd Edition, Kodansha, 2013 (in Japanese).
[21] E. Alpaydin: Introduction to Machine Learning, pp. 158–159, MIT Press, 2004.
[22] K. Nasukawa, Y. Miyashita, and M. Shiokawa: Efficiency Tests for Running, Tokyo Denki University Press, 2008 (in Japanese).

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