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Accurate Vehicle Localization using DTW between Range Data Map and Laser Scanner Data Sequences

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Abstract— **We propose a method for accurate vehicle localization. The proposed method detects a vehicle's location and traveling lane by matching between a pre-constructed $Range\ Data\ Map$ and laser scanner data sequences measured while the vehicle runs. The Range Data Map consists of an absolute position on the road and range data at the position. We use Dynamic Time Warping (DTW) to align multiple range data sequences. Experiments using 40 data sequences collected while a vehicle ran on the same route with multiple traffic lanes were conducted. The results demonstrated the effectiveness of vehicle localization and traveling lane classification.**

I. INTRODUCTION

In recent years, the development of advanced driver assistance and vehicle navigation systems has been seen. In order to improve these systems, it is important to accurately locate a vehicle's position. We can obtain vehicle locations within a few centimeters margin of error or less using highly precise devices such as RTK-GPS (Real Time Kinematic GPS). However, they are very expensive and unstable in urban areas. Thus we make use of a commonly used GPS in a general vehicle navigation system. However such a navigation GPS contains a positional error of about a few meters, which sometimes becomes 30 meters because of multipath effects. Therefore, it is difficult to rely only on a navigation GPS to accurately locate vehicles.

We have developed a method for change detection in streetscapes from GPS coordinated omni-directional image sequences [1]. This method aligns image sequences acquired while cars are running on the same route on different days by DTW and detects changes by calculating differences between images taken at the same location. In addition, we have improved the accuracy of position information by averaging coordinates associated to the aligned images. GPS signals contain two types of error. One is random error that changes on every observation, and the other is the biased error due to satellite constellation, ionosphere delay and troposphere delay [2]. The method attempts to reduce both of these errors by averaging GPS coordinates obtained at the same location on different days. However, this method is sensitive to insolation conditions and it also does not consider lane shifting. In these cases, it is difficult to accurately locate the vehicle.

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Hence, this paper proposes a method of accurate vehicle localization that is independent of insolation conditions and could deal with lane shifting. In order to solve these problems, we propose a method that makes use of a laser scanner instead of a camera. This device can acquire depth distribution in front of a vehicle as range data. Generally, laser scanners are mounted near the bumper on the front of a vehicle as shown in Fig. 1. They have been put into practical use for adaptive cruise control or preventive safety purposes. Fig. 2 shows two different expressions of range data: (a) shows the plotted range data on the scan plane, while (b) shows the range data and in-vehicle camera image taken at the same location. We use a laser scanner that scans range data along a single horizontal line at a certain height from the road surface.

The proposed method accurately locates a running vehicle and recognizes the traveling lane by matching between a $Range\ Data\ Map$ and range data sequences measured while a car is running. A Range Data Map consists of an absolute position on the road map and corresponding range data at the position. This is constructed before vehicle localization.

The rest of this paper is organized as follows. In Section II, we introduce some works related to vehicle localization. We then describe the proposed method and the construction method of a Range Data Map in Section III and report experimental results in Section IV. Finally we discuss the results in Section V and summarize the paper in Section VI.

II. RELATED WORKS

Many works have been presented which are considered useful for the enhancement of vehicle navigation systems in terms of offering better information [3][4]. In these systems,

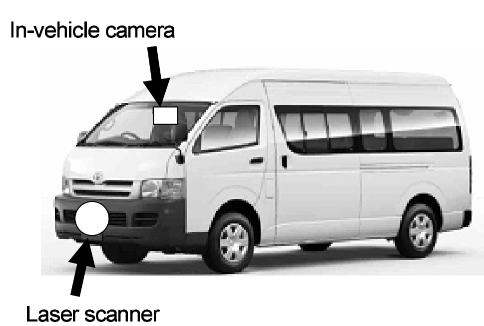
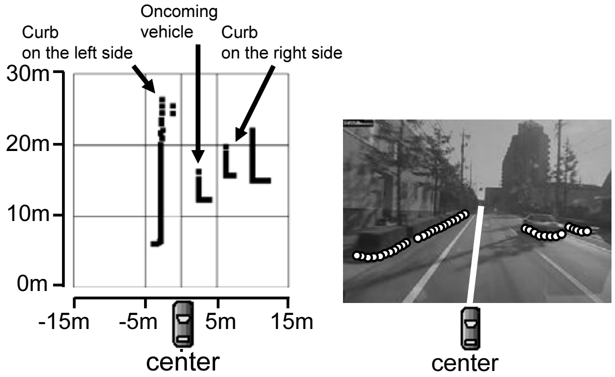


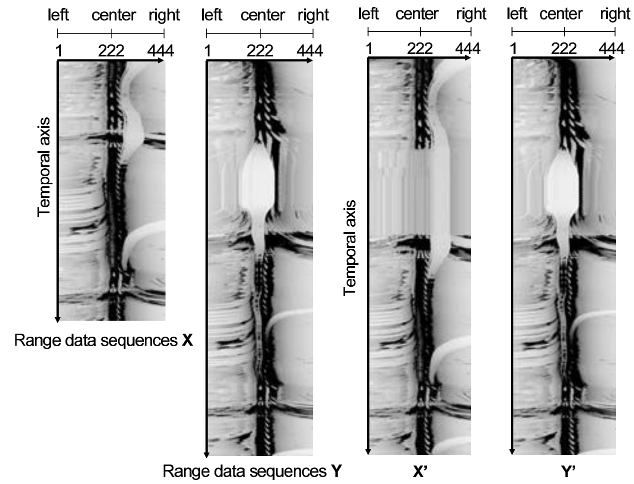
Fig. 1. Position of laser scanner and in-vehicle camera mounted on vehicle used in experiments.



(a) Range data plotted on scan plane (bird's-eye view). Each axis represents distance from vehicle. Origin point (both axis 0 meter) is vehicle position

(b) In-vehicle camera image plotted with corresponding range data

Fig. 2. Range data and in-vehicle camera image at same location: curbs and an oncoming vehicle are observed. Since the mounted positions of the devices are different, the plotted range data in (b) do not form horizontal lines.



(a) Before alignment

(b) After alignment

Fig. 3. Examples of range data sequences aligned by DTW. The range data are represented as pixel brightness. A horizontal line represents range data measured by one scan (444 points). Brighter pixels are nearer. The vertical axis is the temporal axis. Two data sequences shown in (a) are before alignment. Although these were taken along the same route, temporal expansion was caused by differences in car speed and waiting time for traffic signals. Two data sequences shown in (b) are those after alignment.

it is important to accurately locate a vehicle's position. However, existing methods have made use of only GPS coordinates to accomplish this. Thus, we focus on using not only a GPS but also a laser scanner.

Some methods of vehicle localization using a laser scanner have been developed [5][6]. Ono et al. proposed an ego-motion estimation method by analyzing distortion of time sequences of range data without using a GPS [4]. Weiss et al. proposed an ego-localization algorithm, which creates a map with information about landmarks such as posts of traffic lights and traffic signs and their accurate positions on the map [6]. Vehicle locations are obtained by matching between the map and the laser scanner data measured from a running vehicle. This method needs to detect accurate positions of the landmarks. In contrast, our method captures beforehand the entire range data along a road in a city without detecting the landmarks. Then we accurately locate a running vehicle by matching between the database and the laser scanner data.

III. Proposed Method

A. Overview

Our system consists of the following two processes:

- Construction of a Range Data Map (in advance)
- Vehicle Localization (in real-time).

First, we describe the construction of a Range Data Map in Section III-B and then describe the method for vehicle localization in Section III-C.

We realize vehicle localization by matching between range data in a Range Data Map and range data taken by a running vehicle. For the matching of data sequences, Dynamic Time Warping (DTW) is used to absorb temporal expansion and contraction caused by differences in car speed in each run. Fig. 3 shows the temporal expansion of the two data sequences absorbed by DTW.

B. Construction of Range Data Map

A Range Data Map consists of an absolute position on a road map and corresponding range data at each position (Fig. 4). In order to construct a Range Data Map, we need range data and accurate vehicle locations where the range data were measured. It is possible to construct this by running a vehicle mounted with a laser scanner and an RTK-GPS along all the roads in both directions at least once. However, an RTK-GPS is expensive and, moreover, sometimes cannot obtain a location when a vehicle is surrounded by high buildings. Consequently, a navigation GPS is used in the proposed method in order to obtain a location with a low-cost system.

As for the accuracy of positioning, a navigation GPS has less than a 30m margin of error. Due to this fact, the accuracy of navigation GPS coordinates must be improved. Generally, it is known that the average of GPS coordinates obtained at the same location for a long time converges to the ground truth (Fig. 5). Thus, the proposed method expects to obtain a large amount of GPS coordinated range data from many vehicles running freely with a laser scanner and a navigation GPS. Data sequences taken along the same traveling lane are extracted from the collected data. Then the extracted sequences are aligned.

Fig. 6 shows the flow of the construction of a Range Data Map. A Range Data Map has information about $\mathbf{m} = (\mathbf{p}, \mathbf{r}, l)$ at each point on the map shown in Fig. 4. Here, $\mathbf{p}$ represents a location vector with latitude and longitude as its elements, and $\mathbf{r} = (r_1, \ldots, r_S)$ represents range data at the location. S represents the number of data taken by a laser scanner in one scan, and l represents the lane of a running vehicle.

First, we apply DTW between range data sequences taken along the same route, in the same lane and in the same direction of travel. Secondly, position information is improved by averaging GPS coordinates corresponding to the aligned range data, and the improved position information and the range data are stored to the Range Data Map. Details of the process are as follows.

Step 1 Range data sequences $\{\mathbf{A}_1, \ldots, \mathbf{A}_N\}$ taken along the same route from a collection of GPS coordinated range data sequences are extracted referring to navigation GPS coordinates. N represents the number of data sequences, which is the number of runs along the route. Each $\mathbf{A}$ is represented as $\mathbf{A} = (\mathbf{a}_1, \ldots, \mathbf{a}_I)$, where I is the number of scans. Then, supposing that we construct a Range Data Map for a particular lane l', each $\mathbf{a}$ is represented as $\mathbf{a} = (\mathbf{p}, \mathbf{r}, l')$.

Step 2 Assuming that $\mathbf{A}_1$ was taken first, $\mathbf{A}_1$ is aligned with each of the rest of the $N-1$ data sequences $\{\mathbf{A}_n | n = 2, \ldots, N\}$ by DTW. In DTW, each pair of range data sequences is applied to (1) and (2) recursively:

$$D_n(i,j) = \min \begin{cases} D_n(i-1, \quad j \quad) + d_n(i,j) \\ D_n(i-1, j-1) + d_n(i,j) \\ D_n(\quad i \quad , j-1) + d_n(i,j) \end{cases}, \qquad (1)$$

$$d_n(i,j) = d_{L1}(\mathbf{r}_{1,i}, \mathbf{r}_{n,j}). \qquad (2)$$

Here, $D_n(1,1) = d_n(1,1)$, $i = 1, \ldots, I_1$, $j = 1, \ldots, I_n$, and $d_n(i,j)$ represents the dissimilarity between two range data. $\mathbf{r}_{1,i}$ is the i-th range data of $\mathbf{A}_1$, and $\mathbf{r}_{n,j}$ is the j-th range data of $\mathbf{A}_n$. The dissimilarity is defined by L1 distance, that is to say, when $\mathbf{r}_{1,i}$ is represented as $\mathbf{x} = (x_1, \ldots, x_S)$, $\mathbf{r}_{n,j}$ is represented as $\mathbf{y} = (y_1, \ldots, y_S)$. Thus, (2) is substituted by

$$d_{L1}(\mathbf{x}, \mathbf{y}) = \sum_{s=1}^{S} |x_s - y_s|. \qquad (3)$$

Until $D_n(I_1, I_n)$ is obtained, the alignment (i,j) is stored; here j is aligned to i by (1). As a result, sequences $\mathbf{A}_1$ and $\mathbf{A}_n$ are aligned.

Step 3 To improve position information of the Range Data Map, GPS coordinates associated to the aligned range data that are considered to be observed at the same location are averaged as follows:

$$\mathbf{p}'_i = \frac{1}{N} \sum_{j \in \mathbf{J}_i} \mathbf{p}_j. \qquad (4)$$

Here, $\mathbf{J}_i = \{i, j |$ each j aligned to i by (1) $\}$.

Step 4 Range data of $\mathbf{A}_1$, $\mathbf{r}'_i (= \mathbf{r}_{1,i})$, an averaged position information $\mathbf{p}'_i$ and the traveling lane l' are stored to the Range Data Map at each $i = 1, \ldots, I_1$. The process described above is applied to each traffic lane $l \ (= 1, \ldots, L)$. As for the range data on the map, at this moment, we store only the range data sequences of $\mathbf{A}_1$. However, all range data sequences of $\mathbf{A}_n \ (n = 1, \ldots, N)$ can be stored, if we have a sufficiently storage space. This is expected to improve the accuracy of vehicle localization.

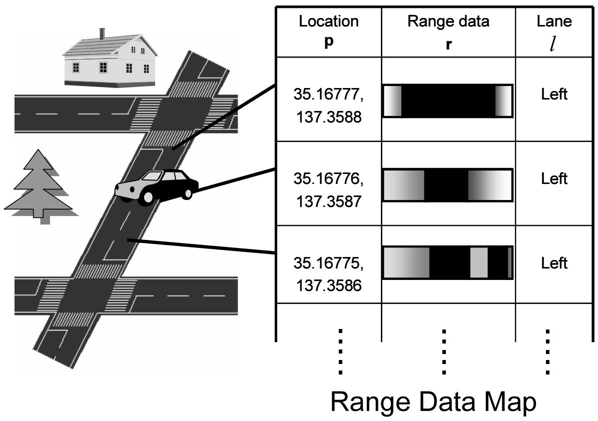


Fig. 4. Part of Range Data Map. $\mathbf{p}$ represents location vector with latitude and longitude. $\mathbf{r}$ represents range image at location, where intensity is inversely proportional to depth. l represents lane.

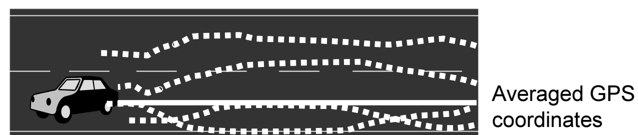


Fig. 5. Improving position information of Range Data Map by averaging vehicle locations. Continuous line represents averaged positions. Broken lines represent positions obtained by GPS.

Finally, range data taken in different traffic lanes are aligned by making use of the improved position information. This enables vehicle localization considering lane shifts.

C. *Vehicle localization*

It is the most important in this method to align a Range Data Map and range data sequences. To obtain an accurate vehicle location and to recognize the traveling lane, we use DTW in the same manner as the construction of a Range Data Map, but here we consider lane shifts.

Fig. 7 shows the flow of vehicle localization. In vehicle localization, we accurately align the range data sequences obtained from a running vehicle with a Range Data Map by DTW and then accurately locate vehicle position from the Range Data Map. First, we extract range data sequences taken along the same route from the Range Data Map constructed beforehand referring to GPS coordinates. In the case that the route has multiple lanes, we extract range data sequences for each lane. Secondly, DTW is used to align range data sequences extracted from a Range Data Map with range data sequences measured from a running vehicle. Details are as follows.

Step 1 Define range data sequences measured from a running vehicle as $\mathbf{X} = (\mathbf{x}_1, \ldots, \mathbf{x}_J)$, where $\mathbf{x}_J$ is the latest measured range data. Vehicle location is given from the information of the point on the Range Data Map aligned with $\mathbf{x}_J$. Range data sequences taken along the same route as $\mathbf{X}$ are extracted from a Range Data Map using GPS coordinates obtained by the vehicle. In the case that the route has multiple lanes, range data sequences are extracted along

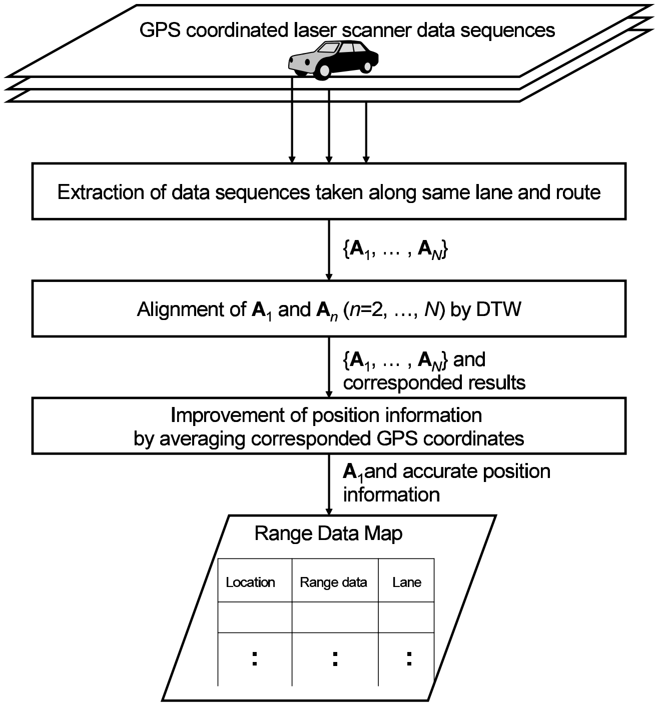


Fig. 6. Flow chart of construction of Range Data Map.

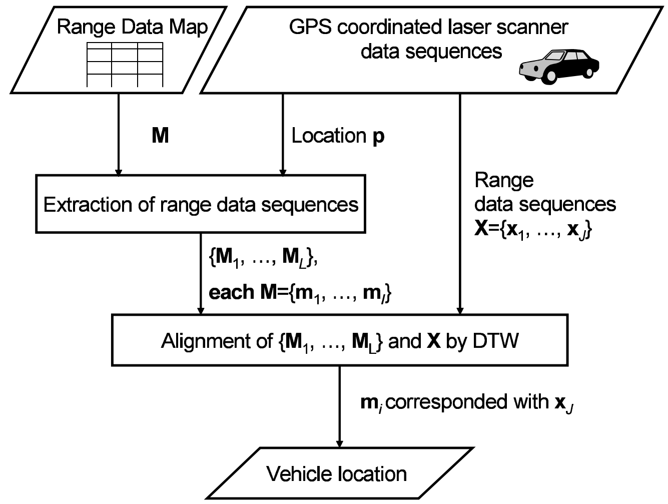


Fig. 7. Flow chart of vehicle localization scheme.

the same route for each lane. we define range data sequences extracted from a Range Data Map as $\{\mathbf{M}_1, \ldots, \mathbf{M}_L\}$, where L is the number of lanes. Each $\mathbf{M}$ is represented as $\mathbf{M} = (\mathbf{m}_1, \ldots, \mathbf{m}_I)$, where $\mathbf{m} = (\mathbf{p}, \mathbf{r}, l)$. Here, $\mathbf{p}$ represents the location vector with latitude and longitude, $\mathbf{r}$ the range data at that location represented as $\mathbf{r} = (r_1, \ldots, r_S)$, and l the lane information.

Step 2 $\mathbf{X}$ is aligned with $\{\mathbf{M}_1, \ldots, \mathbf{M}_L\}$ by DTW. In DTW, an equation that is similar to (1) only without the suffix n is used. Thus, two data sequences are applied to (5) and (6) recursively:

$$D(i,j) = \min \begin{cases} D(i-1, \quad j \ ) + d(i,j) \\ D(i-1, j-1) + d(i,j) \\ D(\quad i \ \ , j-1) + d(i,j) \end{cases}, \qquad (5)$$

$$d(i,j) = \min_l d_{L1}(\mathbf{r}_{l,i}, \mathbf{x}_j). \qquad (6)$$

Here, $D(1,1) = d(1,1)$, $i = 1, \ldots, I$, $j = 1, \ldots, J$, and $d(i,j)$ represents the dissimilarity between the range data. $\mathbf{r}_{l,i}$ is the i-th scan point of range data $\mathbf{M}_l$, and $\mathbf{x}_j$ is the j-th scan point of $\mathbf{X}$. The dissimilarity is defined by L1 distance shown in (3).

Step 3 From (7) and (8), the traveling lane $\hat{l}$ is obtained. Then, vehicle location is given as $\mathbf{p}_{\hat{i}}$ in the data sequences of the $\hat{l}$-th lane $\mathbf{M}_{\hat{l}}$:

$$\hat{i} = arg \min_i D(i, J), \qquad (7)$$

$$\hat{l} = arg \min_l d_{L1}(\mathbf{r}_{l,\hat{i}}, X_J). \qquad (8)$$

IV. Experiments

In order to demonstrate the effectiveness of the proposed method, we conducted experiments using actual data. Additionally, in order to evaluate the accuracy of the construction of a Range Data Map, we examined the performance of the alignment of data sequences taken along the same lane. We describe this in the following section.

A. Mounted sensor

In order to collect range data with navigation GPS coordinates, an experimental vehicle mounted with the following two sensors was prepared:

- Laser scanner
- Navigation GPS (Standalone positioning) [7].

Table I shows the specifications of the laser scanner. In order to evaluate experimental results, we additionally equipped the experimental vehicle with the following two sensors:

- In-vehicle camera (Panasonic WV-CP650)
- RTK-GPS [7].

The in-vehicle camera was used for judging the experimental results by manual checking. The RTK-GPS was used as the ground truth to evaluate the improvement of position information by averaging the navigation GPS coordinates at the same location.

Sampling rates of the mounted sensors are as follows:

TABLE I

SPECIFICATIONS OF LASER SCANNER (LMS-Q140I)

Rangefinder	
Measurement range y	up to 150m (for natural targets, $\rho \geq 10\%$)
Measurement accuracy	¶ 25 mm
Laser wavelength	0.9μm (near infrared)
Eye safety	Class 1 for scanned beam
Scanner	
Scanning range	¶ 40 deg = 80 deg total
Scanning rate	20 scans per second
Angle readout resolution	0.036 deg

- laser scanner: 20 scans per second
- In-vehicle camera: 10 frames per second
- Navigation GPS: 1 Hz
- RTK-GPS: 1 Hz.

B. Experimental condition

The proposed method was evaluated in the following terms:

- Performance of vehicle localization
  - Accuracy of traveling lane classification
  - Alignment accuracy in the direction of travel.

In experiments, a total of 40 data sequences collected along two different routes with two lanes on one side of a road were used. They consist of 10 sequences taken at each lane and along each route. Table II shows the details of routes A and B. Note that route A has two intersections en route.

TABLE II
EXPERIMENTAL DATA SET

Route	Length[m]	Traveling lane (number of data sequences)
A y	917	left-hand lane (10), right-hand lane (10)
B y	717	left-hand lane (10), right-hand lane (10)

The number of range data points measured in one scan was 444, that is to say, $S = 444$ in (3). Since the number of traffic lanes L was 2, we defined $l = 1$ as the left-hand lane and $l = 2$ as the right-hand lane. The number of runs N was 10 for each lane.

In construction of a Range Data Map, we aligned data sequences collected in the first run with each data sequence of the remaining nine runs in the same lane by using DTW. Considering lane shifts, range data sequences in different lanes on the Range Data Map have to be aligned, which is achieved by shifting the range data in a perpendicular direction of travel in (3).

C. Results

In order to evaluate the accuracy of vehicle localization, we examined the success rate of traveling lane classification and alignment performance of DTW in the direction of travel.

- The success rate per scan of traveling lane classification was 89.3% on average. If a lane classification result is identical to the actually traveled lane, we judged it to be correct. Table III shows the success rate in detail by routes and lanes.

TABLE III
SUCCESS RATES OF TRAVELING LANE CLASSIFICATION

Route	Success rate [%]	Number of samples
route A (left-hand lane) y	92.4	20951
route A (right-hand lane) y	88.6	26281
route B (left-hand lane) y	94.8	15797
route B (right-hand lane) y	81.2	14256
average y	89.3	

- The success rate per scan of range data alignment was 92.7% on average. In other words, if we have an accurate Range Data Map, the probability of obtaining an accurate vehicle location is 92.7%. Table IV shows the success rates in detail by routes and lanes. To evaluate this, we randomly chose 300 images from in-vehicle camera images that were captured in synchronization with a laser scanner and a GPS. Here, we selectively used only range data whose traveling lane classification succeeded and judged the results manually; if a frame corresponded with the most similar frame in the in-vehicle camera video stream, we judged it to be correct, while if there were other frames that were more similar, we judged it as false. Fig. 8 shows examples of in-vehicle camera images synchronized with the aligned range data.

TABLE IV
SUCCESS RATES OF ALIGNMENT BY DTW IN DIRECTION OF TRAVEL

Route	Success rate [%]	Number of samples
route A (left-hand lane) y	85.3	300
route A (right-hand lane) y	95.0	300
route B (left-hand lane) y	95.3	300
route B (right-hand lane) y	95.3	300
average y	92.7	

V. DISCUSSION

A. Construction of Range Data Map

To evaluate the accuracy of the construction of a Range Data Map, we examined the range data alignment performance of DTW. The success rate was 85.4% on average. The evaluation was performed in the same manner as the evaluation of vehicle localization in Section IV-C.

We discuss the effectiveness of averaging GPS coordinates for the improvement of position information of a Range Data Map. For this, we investigated the trend of positioning errors with the increase in number of runs. The location obtained by the RTK-GPS synchronized with the navigation GPS is defined as the ground truth at the location. First, Fig. 9 shows positioning errors of navigation GPS coordinates taken along the right-hand lane of route A and their average. It shows that the average of GPS coordinates became more accurate than the original GPS coordinates. Next, Fig. 10 shows the positioning error of the averaged GPS coordinates according to the number of runs. We can see that the positioning error decreased with the increase in number of runs. Thus, we confirmed that the more runs we have, the more accurately the Range Data Map could be constructed. Thus, using many GPS coordinated range data sequences improves the accuracy of constructing of a Range Data Map.

(a) Nov. 4, 2005 (b) Nov. 7, 2005 (c) Nov. 8, 2005

Fig. 8. Examples of in-vehicle camera images synchronized with aligned range data measured on different days. The date is indicated under each image. In this case, we aligned (a) with the other three. The alignments succeeded in (c). They failed in (b), because of a vehicle in front waiting for a traffic signal to change.

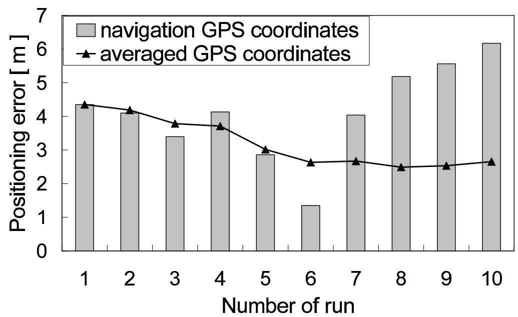


Fig. 9. Positioning error of averaged GPS coordinates by number of runs and of navigation GPS coordinates for each run.

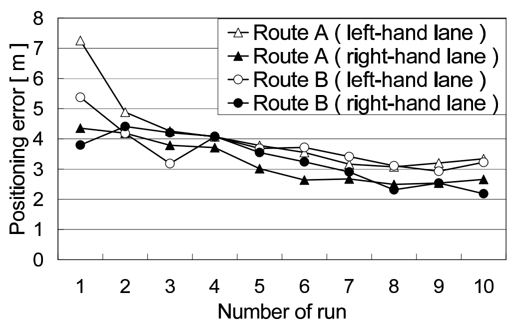


Fig. 10. Relation between number of runs and positioning error of averaged navigation GPS coordinates.

As shown in Fig. 8, false range data alignment by DTW often occured during waiting time for a traffic light. The reason for this seems to be that information important to align them was lost because another vehicle was too close in front. To solve this problem, we need to eliminate noise or interpolate the lost information, which is left for future works.

B. Vehicle localization

Suppose that position information of a Range Data Map is correct and the vehicle localization succeeds. In the case that vehicle speed is less than 40 km/h ($\simeq 11.1$ m/s) and the scanner rate is 20 scan/s, the distance between two consecutive frames is less than 0.56 m in the direction of travel. This means that the proposed method is able to provide a vehicle location to an accuracy of less than 0.56 m in the direction of travel at 92.7%.

As for traveling lane classification, we consider that accuracy can be improved by considering the cost of lane shifting. Thereby, we should be able to eliminate impossible situations in actual driving.

As was discussed in Section V-A, there are some situations for which we cannot obtain important information necessary to align range data with a Range Data Map as shown in Fig. 8. We will consider solutions for such cases in future works.

VI. Conclusion

This paper has proposed a method of accurate vehicle localization by using a Range Data Map. A Range Data Map consists of an absolute position on a road map and the range data at the position, which is constructed from many range data sequences for each lane by using DTW. To locate a vehicle position, the proposed method aligns range data sequences taken from a running vehicle with each range data sequence of multiple traffic lanes extracted from a Range Data Map.

In order to demonstrate the effectiveness, we conducted experiments using actual data. In experiments using 40 data sequences collected by a vehicle running along the same route with multiple traffic lanes, we constructed a Range Data Map (alignment performance by DTW, 85.4%). The results using the Range Data Map are summarized as follows:

- Performance of vehicle localization
  - Accuracy of traveling lane classification, 89.3%
  - Alignment accuracy in the direction of travel, 92.7% (Probability of vehicle localization in an accuracy of less than 0.56 m.).

We conclude that the experimental results demonstrated the effectiveness of our method for vehicle localization and traveling lane classification.

In the future, we will consider methods for eliminating noise such as that from preceding vehicles and for interpolating range data where data is missing because of noise. In addition, we will apply a larger amount of data taken in various situations.

VII. Acknowledgments

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