Lane recognition for moving vehicles using multiple on-car RFID receiver antennas - Algorithm and its experimental results

Hiroaki Togashi, Cristian Borcea, and Shigeki Yamada

Abstract— **Accurate lane recognition for moving vehicles is important for lane keeping and lane changing assistance systems. Additionally, this information could be leveraged by Intelligent Transportation Systems to suggest lane changes for improved traffic load balancing across lanes. This paper presents a position estimation algorithm for moving vehicles based on RFID (Radio Frequency Identification) active sensors placed on roadsides and lane boundaries, and multiple on-car RFID receiver antennas. To improve localization accuracy, the algorithm proposes two novel ideas: (1) compute pair-wise position estimates using the RSSI (Received Signal Strength Indication) of all pairs of signals received from RFIDs, and (2) compute the final position as a weighted average of these pair-wise estimates using a dynamic weighting function that assigns higher weights to positions estimated based on closer RFIDs.**

The results from our field experiments indicate that the proposed method achieves 0.7-meter localization accuracy when RFIDs are placed at 0.5-meter intervals and a vehicle has 8 antennas. This accuracy allows a moving vehicle to recognize which lane it is in. The localization accuracy of the proposed method was found to be mostly stable for any type of road shape and any number of lanes. A further 14% accuracy improvement is achieved when RFIDs are placed at 0.25-meter intervals and the RFIDs located farther than 30-meter are excluded from computation.

I. Introduction

WHILE investigating a vehicular information providing system based on roadside RFIDs, we found out that accurate lane recognition is important for many applications. For example, it can provide automatic support for lane keeping or assist the drivers with lane changing. This information can also be leveraged to suggest lane changes when traffic is stuck on certain lanes ahead. A 1.5-meter localization accuracy is required in order to recognize the lane where a vehicle is in. However, the accuracy of GPS (Global Positioning System) [1], which is widely used for localization, is approximately several meters for consumer devices. While an accuracy of about 1m is achieved in military use, such devices are not available for civilians. Additionally, GPS does not work in certain areas (e.g., tunnels) or work poorly in others (e.g., nearby high-rise buildings). Other highly accurate methods (e.g., ultrasonic-based systems [2]) require expensive dedicated equipment for localization. On the other hand, RFID-based platforms can be cost-effective when using them for both position estimation of moving vehicles and information providing.

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This paper presents a position estimation algorithm for moving vehicles based on active RFIDs placed on roadsides and lane boundaries, and multiple on-car RFID receiver antennas. To improve localization accuracy, the algorithm proposes two novel ideas:

(1) It computes pair-wise estimated positions based on the RSSI of all pairs of signals received from RFIDs. This large number of pair-wise positions leads to improved accuracy when they are merged to compute the final antenna position.

(2) During the merge, the algorithm uses a dynamic weighting function to assign higher weights to estimates computed based on signals received from closer RFIDs. The merge also uses an iterative process to refine the final position until the difference between two consecutively computed values falls below a certain threshold. In the end, the algorithm uses the final antenna positions to compute the accurate center of the car.

The rest of the paper is organized as follows. Sec. 2 briefly describes the related work. Sec. 3 explains the proposed algorithm, and its evaluation results are shown in Sec. 4. Considerations toward achieving a higher level of accuracy are presented in Sec. 5. Sec. 6 discusses issues related to the practical use of our research, and Sec. 7 concludes the paper.

II. Related work

A. *Lane Recognition*

Most existing lane recognition methods aim at being used in lane-keeping or lane-changing assistance systems. Several methods recognize which lane the vehicle is in using image recognition [3][4][5][6]. However, these systems suffer in the presence of poor visibility; they cannot work if the lane boundaries cannot be recognized.

In order to solve this problem, several alternatives have been proposed. For example, laser-scanned data [7] can be used for position estimation and lane recognition. Another example employs magnetic lane markers [8] to prevent vehicles from straying off the road. However, these technologies are difficult to be applied to information providing systems because the localization and information providing require separate equipment and systems. Our method uses a low-cost RFID-based platform to enable both localization and information provisioning.

B. RFID

RFID [9] uses radio waves to transmit the ID of RFID tags and potentially several data items stored in the tags. RFIDs are categorized as follows. Passive RFIDs do not have batteries and transmit signals by the power of the radio waves sent by the RFID reader; only one passive RFID can be read by one reader at a time. Semi-passive RFIDs have batteries, but transmit signals only in response to requests from RFID readers; when there are many readers, significant radio wave interference may be caused. Active RFIDs also have batteries, but transmit signals when they desire (i.e., do not need to wait for a reader's request); in this way, radio wave interference may be reduced by programming them to transmit at different times.

Due to high vehicular speeds and low transmission range, our system should be able to read multiple RFIDs at the same time; thus, passive RFIDs are not feasible. Similarly, semi-passive RFIDs cannot be used because they would lead to significant interference, especially due to the multiple on-car receiver antennas. Therefore, the proposed method uses active-type RFIDs.

C. Position estimation methods utilizing RFID schemes

There are several research projects on using RFIDs to estimate the position of objects. Most of them refer to the previously measured RSSI [10][11] or assume that the RFIDs are placed at known positions [10][11][12] because they use fixed receivers to estimate the positions of mobile RFIDs. These methods cannot be used for our purpose because a dense placement of RFID receivers on the roads to accurately localize RFIDs in the cars is too expensive. It is also impractical to prepare RSSI data for a road environment because the RSSI varies function of the current vehicles (and their positions) on the road. Similar to [10][11], our method uses multiple on-car antennas to improve localization accuracy. From the viewpoint of weighting technique, these projects use the k-neighbor [10][11] or least-square techniques [12]. Our method uses a technique which has a similar effect to k-neighbor, with the difference that k is not fixed; thus, the proposed method is able to gradually exclude the RFIDs located far from the vehicle from the final computation.

More similar to our solution, several methods work without fixed receivers and previously measured RSSI. Lim et al. [13] use passive RFIDs and an on-object antenna to estimate the position of the object; the estimation is done by taking the average of the maximal and minimal positions of the RFIDs whose signals are received. This method achieves a 0.02-meter localization accuracy when the RFIDs were placed at 0.1-meter intervals on a quadrangle grid. Moeeni [14] also uses passive RFIDs and estimates the position of the receiver antenna by taking the average of the positions of the RFIDs whose signals are received; this method achieves a 0.2-meter localization accuracy when the RFIDs were placed at 0.3-meter and 0.6-meter intervals on a quadrangle grid. However, these methods do not take displacements of objects into consideration (like our method) because their target object moves much slower than vehicles (i.e., their target object moves at a few meters per second while vehicles may move faster than 10-meter per second). Also, these methods do not take into consideration the conditions for estimating the positions of moving vehicles presented in Sec.3, while our method does (i.e., RFIDs cannot be easily placed in a quadrangle grid on the roads). In addition, our method includes several new ideas in the algorithm, such as the use of pair-wise positions and dynamic weighting, to estimate more accurately the positions of on-car antennas.

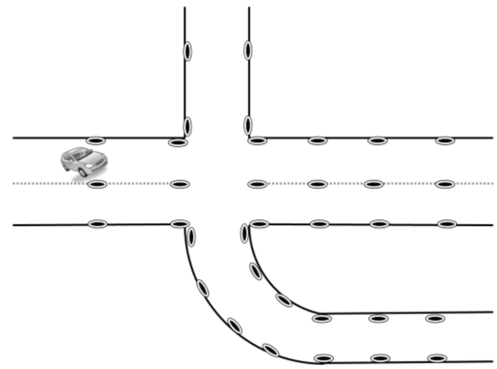

Fig. 1. Placement of RFIDs on the roadsides and lane boundaries

D. Observation of vehicular displacements

The accuracy of position estimation is improved with the use of vehicular displacements. For example, the method presented in [15] uses mainly laser radar to observe the vehicular displacements, while the method discussed in [16] uses a gyro sensor to observe the vehicular displacements. Our method also uses the gyro/acceleration sensor to observe the vehicular displacements from the acceleration and angular velocity, thus improving the positioning accuracy

III. PROPOSED METHOD

A. Conditions for estimating position of moving vehicles

The proposed localization system and algorithm must satisfy the following three conditions when estimating the position of moving vehicles:

1) They should be able to deal with high speeds, specific to vehicles which are the targets whose positions must be estimated. This condition is met by our use of active RFIDs and multiple on-car antennas.

2) The RFIDs can be installed in a limited number of places on the roads. For instance, they cannot always be placed in quadrangle grid. Our system places them on roadsides and lane boundaries. Additionally, to achieve the desired accuracy level, we propose improvements in the algorithm for estimating the vehicular positions.

3) Due to the road gradients, the algorithm must work in 3D. For instance, existing 2-D methods may not be able to achieve a high degree of accuracy [21]. The proposed method satisfies this condition by considering height in addition to latitude and longitude.

B. Outline of proposed method

The active RFIDs are placed not only on the roadsides, but also on the lane boundaries at certain distance intervals as shown in Fig. 1. The vehicles are equipped with multiple

TABLE I
PSEUDO-CODE OF PROPOSED METHOD

```
1:  obtain positions for RFIDs whose signals are received by looking
    up their IDs in the local database
2:  estimate vehicular displacements using gyro/acceleration sensor
    data
3:  adjust RFID positions as function of the vehicle displacement
4:  for (r=0; r < no. of on-car receiver antennas; i++){
5:     for (k=0; k < no. of pair-wise combinations of received
          signals; k++){
6:        {distance-a, distance-b}[k] = estimated distances from
          RFIDs to antenna[r] computed using RSSIs
7:        compute pair-wise position estimation of antenna[r]
          based on {distance-a, distance-b}[k]
8:     }
9:     m = 0 //value of exponent for dynamic weighting
10:    while (position of antenna[r] not converged){
11:       for (k=0; k < no. of pair-wise position estimations; k++)
12:          weight[k] = (distance-a[k] × distance-b[k])^-m
13:       compute position of antenna[r] using the pair-wise
          positions and the weights
14:       m=m+1
15:    }
16: }
17: estimate vehicular position based on all antenna positions
18: compute final position by adjusting for the vehicle displacement
    since the last position estimation
19: return final position
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on-car antennas (i.e., one RFID receiver with multiple antennas), aiming to achieve higher degree of accuracy for the position estimation. Informally, the proposed algorithm computes the position of each antenna based on the RSSI of the received RFID signals and the known positions of each RFID. Then, the vehicular position is estimated from the positional relationship of these antennas. This position estimation is periodically done at a certain estimation interval time.

In estimating vehicular positions, the position information of where the RFIDs are placed is stored in an on-car database, and this information is retrieved by looking up the IDs whose signals are received by the on-car antennas. We measure the RSSI between the RFIDs and on-car antennas to estimate the distances between the antennas and the RFIDs. The distance (d) is obtained as shown in (1) by transforming the formula for free space loss [17]. In (1), r(d) is the observed RSSI, and r(1) is the pre-measured RSSI when the distance is 1-meter.

$$d = 10\wedge\left(\frac{r(1) - r(d)}{20}\right) \qquad (1)$$

Our method uses vehicular displacement to adjust the RFID positions as function of how much the car has moved since the time the RSSI measurements had been performed. Similarly, the vehicular displacement from the time of the last position estimation until the time of the current position estimation is used to compute the final position. The displacements are estimated from the integration of the acceleration data obtained from the gyro/acceleration sensors. These data are transformed from the coordinates used in the sensors to the coordinates used in the position estimation using the gyro sensor data and direction of gravity.

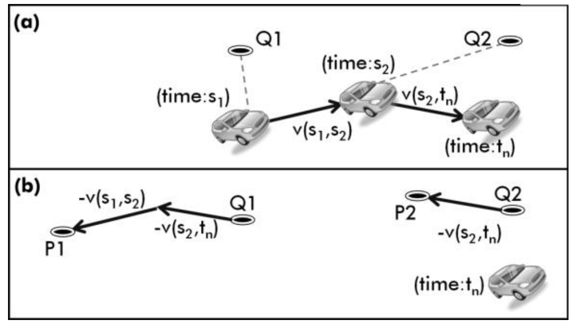

Fig. 2. Adjusted RFID positions using vehicular displacement
(a): the vehicle receives signals from two RFIDs, located at Q_1 and Q_2, at times s_1 and s_2
(b): the RFIDs are moved to virtual positions P_1 and P_2, corresponding to time t_n

In the following, all the positions used in the estimations are represented according to the format {latitude, longitude, and height}. The original point of the vectors, O, is used in the figures and formulas.

C. Algorithm of the proposed method

Tab. I lists the pseudo-code of the proposed method, and a summary of each step is given below. The algorithm first adjusts the position of the RFIDs as function of the vehicular displacement (lines 1-3). The locations where the vehicle receives signals from RFIDs differ from the location where the position estimation takes place, as shown in Fig. 2(a), because the vehicle is moving and each RFID transmits its signal independently. Fig. 2(b) shows how the positions of the RFIDs are adjusted for time t_n when the computation takes place. Specifically, the position of the vehicle is fixed to the location at the current time, and the positions of RFIDs are virtually moved from Q_h (actual position of the h-th RFID) to P_h (virtually moved position) by using vehicular displacements $\overrightarrow{v(s_h,t_n)}$ as shown in (2) below.

$$\overrightarrow{OP_h} = \overrightarrow{OQ_h} - \overrightarrow{v(s_h, t_n)} \qquad (2)$$

Here, s_h is the time when a signal from an RFID placed on Q_h was received by the on-car antenna. The following calculations use the virtual positions P_h.

The algorithm continues by estimating the position of each on-car antenna using the signal received from roadside RFIDs (lines 4-8). The algorithm first computes the pair-wise positions based on the signals received from each pair of RFIDs. These pair-wise positions improve the localization accuracy because they use the measured RSSI. Figure 3 shows this process. The radiuses of the two circles represent

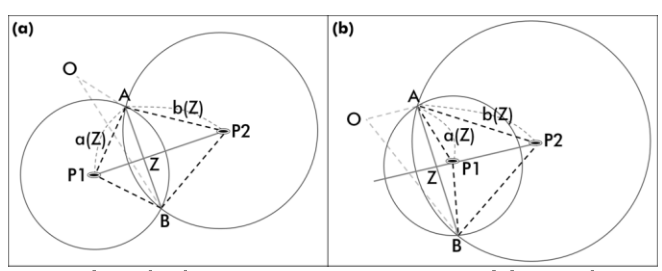

Fig. 3. Relationship between pair-wise positions, Z, and distances between RFIDs and receivers, a(Z) and b(Z)
(a): Z is internal to P_1P_2, the segment connecting the two RFIDs
(b): Z is external to this segment.

the distances between the RFIDs and on-car antenna. The estimated position will be at the intersection between the line connecting the two RFIDs (segment P_1P_2) and the line connecting the two intersection points of the circles (segment AB). The position is computed as shown in (3).

$$\overrightarrow{OZ} = \begin{cases} \dfrac{\left|\overrightarrow{P_2Z}\cdot\overrightarrow{OP_1}\right| + \left|\overrightarrow{P_1Z}\right|\cdot\overrightarrow{OP_2}}{\left|\overrightarrow{P_1P_2}\right|} & if\ (\cos\angle AP_1P_2 \geq 0) \wedge (\cos\angle AP_2P_1 \geq 0) \\ \dfrac{\left|\overrightarrow{P_2Z}\cdot\overrightarrow{OP_1}\right| - \left|\overrightarrow{P_1Z}\right|\cdot\overrightarrow{OP_2}}{\left|\overrightarrow{P_1P_2}\right|} & otherwise \end{cases} \quad (3)$$

Then, the algorithm uses these pair-wise positions and a dynamic weighting function to compute the final position of each on-car antenna (lines 9-16). The estimated pair-wise positions are merged to determine the final antenna positions (X'). During the merge, the dynamic weighting function assigns higher weights to pair-wise positions that are closer to RFIDs (e.g., a(Z) and b(Z) in Fig. 3 are shorter) because they are expected to be more accurate. The algorithm refines the final position estimation in an iterative function (i.e., increments the value of the negative exponent, m, in the weight formula) until the difference between the estimations computed in two iterations is under a certain threshold. This is computed as shown in (4). In (4), |Z| is total number of pair-wise positions.

$$\overrightarrow{OX'(m)} = \frac{\sum_{i=1}^{|Z|}\left\{\left(a(Z_i)\cdot b(Z_i)\right)^{(-m)}\cdot\overrightarrow{OZ_i}\right\}}{\sum_{i=1}^{|Z|}\left(a(Z_i)\cdot b(Z_i)\right)^{(-m)}} = \sum_{i=1}^{|Z|}\left\{w(Z_i)\cdot\overrightarrow{OZ_i}\right\} \quad (4)$$

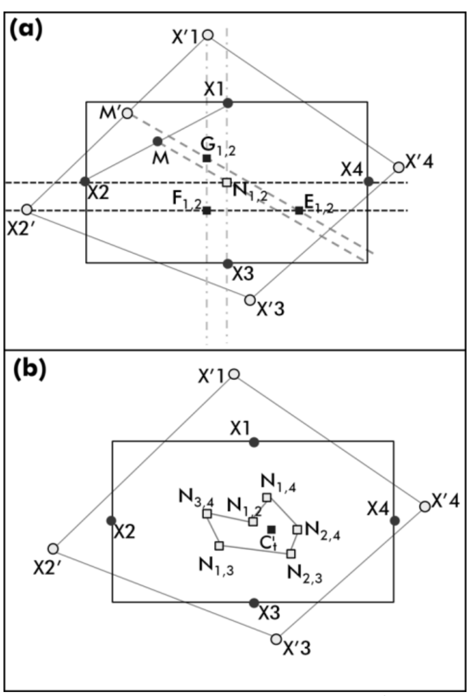

Fig. 4. Estimating vehicular position using positions of on-car antennas
(a) Candidate positions, Ni,j, are computed for each pair of antennas
(b) Final position, C'_{t_n}, is determined by averaging the candidate positions

The vehicular position (i.e., the center of the vehicle) is determined from the estimated positions of each on-car antenna (line 17); the positional relationship of antennas is known and used in the computation. First, candidate positions, $N_{i,j}$, are calculated for each pair of antennas, as the center of three intersections (e.g., $E_{1,2}$,$F_{1,2}$,$G_{1,2}$ in Fig. 4(a)). In Fig. 4(a), X_i is the actual position of an on-car antenna, and X'_i is its estimated position. Then, the final estimated position (C'_{t_n}) is obtained by averaging these candidate positions as shown in Fig. 4(b) and (5). In (5), |X'| is the total number of on-car antennas. This shows that an increase in the number of antennas may improve the localization accuracy.

$$\overrightarrow{OC'_t} = \sum_{i=1}^{|X'|}\sum_{j=i+1}^{|X'|}\frac{\overrightarrow{ON_{i,j}}}{0.5|X'|(|X'|-1)} \quad (5)$$

Before the final result is returned, C'_{t_n} is corrected by using $C''_{t_{n-1}}$, the final position at time t_{n-1}, and $\overrightarrow{v(t_{n-1},t_n)}$, the vehicular displacements from t_{n-1} to t_n (line 18). C''_{t_n} (final position at time t_n) is obtained using (6) and (7). In (7), C''_{t_n} is estimated by taking the average of the estimated position (C'_{t_n}), and vehicular displacement ($\overrightarrow{v(t_{n-1},t_n)}$), aiming to improve localization accuracy by combining localization based on RSSI and dead reckoning navigation using gyro/ acceleration sensors.

$$\overrightarrow{OC''_{t_0}} = \overrightarrow{OC'_{t_0}} \quad \left(\because \overrightarrow{v(t_0,t_0)} = (0,0,0)\right) \quad (6)$$

$$\overrightarrow{OC''_{t_n}} = \frac{\overrightarrow{OC'_{t_n}} + \left(\overrightarrow{OC''_{t_{n-1}}} + \overrightarrow{v(t_{n-1},t_n)}\right)}{2} \quad (7)$$

IV. Results of Field Experiment

A. Evaluation methods

A field experiment was conducted at the Hayama campus of our university, and the specifications for the experimental driving courses are listed in Tab. II. A list of the equipment is presented in Tab. III, and the parameters used in the evaluations are listed in Tab. IV.

The actual vehicle position (C_{t_n}) used for the evaluations was observed by using web cameras and on-road gaging tapes. The localization error is the difference between the actual position (C_{t_n}) and the estimated final position (C''_{t_n}). We calculate the average localization error excluding the

TABLE II
Specification of driving courses

	Main street	Backstreet
Road shape	Curves	Straight/corner
Road width	5m	3.5m
Vehicle speed (max.)	35km/h	30km/h
Course length[a]	45-60m	40-60m

a this length changes according to placement interval of RFIDs

TABLE III
List of equipment

RFID tags/ receivers	NIRE-Type2 (NTT-AT) (Active-type RFID)
Gyro/acceleration sensor	e-nuvo IMU-Z Lite (ZMP)

TABLE IV
LIST OF PARAMETERS

Course	Main street, backstreet
Placement intervals of RFIDs (RFIDs are placed on both road boundaries)	0.25, 0.5, 1, 2, 5, 10, 20 (meter)
Estimation interval	1 Sec.
No. of on-car antennas	4[a],8[b]
Measurement interval of Gyro/acceleration sensor	1/30 Sec. (Fixed[c])
Transmission interval of RFIDs	3 Sec. (Fixed[c])
Communication distance of RFIDs	40 meter (Fixed[c])
Frequency used in RFIDs	312MHz (Fixed[c])
Size of vehicle	Width: 1.5 meter Length: 3.5 meter

a antennas are placed at each corner of vehicle

b antennas are placed at each corner of vehicle and center of each length of vehicle

c Fixed by manufacturer

first and last values, as shown in Fig. 5, because these values are obtained under conditions where the vehicle has not entirely reached the region where the RFIDs are placed and these conditions result in large localization errors.

B. Evaluation

Fig. 5 shows the time-line data of the localization error when the number of on-car antennas is 4. The plots obtained at the same placement intervals are combined on the same graph, and each series of plots represents the results obtained from two courses ("main street" and "backstreet"). We found that the characteristics of localization error are mostly similar for both road shapes and all the placement intervals. Some points show apparently larger localization error than the neighbor data because the number of received RFID signals is lower than the number for the other points.

In the case where the placement interval is 10-meter, the number of successful position estimations is too small to obtain an averaged localization error, and in the case where the placement interval is 20-meter, the proposed method could not estimate the position under the conditions given in Tab. IV.

Fig. 6 shows the relationship between the placement intervals of the RFIDs and the localization accuracy when the number of on-car antennas is 8. On average, a 1.5-meter localization error is achieved when the RFIDs are placed on each side of the road at less than 2-meters intervals; a 0.7-meter accuracy was achieved when the RFIDs were placed at 0.5-meter intervals. Therefore, we conclude that the proposed method improves localization accuracy by 30%-70%, compared to the existing methods [13][14].

We also believe that this localization accuracy is independent of the number of lanes because the RFIDs are placed not only on the roadsides, but also on the lane boundaries. The effect of the RFIDs placed on other lane boundaries than the lane the vehicle is in is reduced significantly by our dynamic weighting function which removes farther away RFIDs from the final computation (as shown in (4)). Consequently, the proposed method can achieve a similar accuracy with the one observed in the experiments no matter how many lanes are taken into consideration.

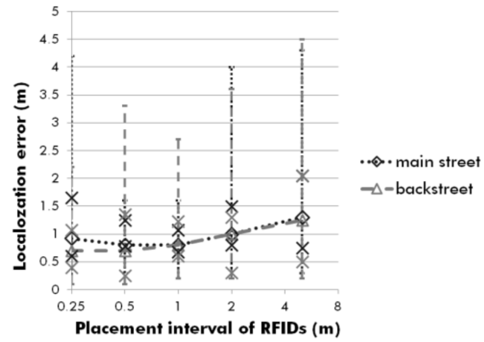

Fig. 6. Relationship between placement interval and localization error (the number of on-car antennas = 8, × indicates quartile)

V. FURTHER IMPROVEMENTS FOR BETTER ACCURACY

The proposed method has achieved accuracy better than 1.5-meter, and this accuracy allows a moving vehicle to recognize which lane it is in. However, an RFID-based platform aims at supporting many types of systems and applications, and it should be applicable, for example, to lane keeping assistance systems. This type of systems may require higher accuracy. This section considers additional improvements toward higher accuracy. There are three main approaches to achieve this goal:

1) Increase the number of on-car/on-road RFIDs antennas/sensors.
2) Improve the accuracy of estimating the distance based on RSSI.
3) Improve the position estimation algorithm.

This section considers only 1) and 2) because 3) was already considered in the proposed method.

A. Increasing the number of RFID sensors/antennas

Fig. 7 illustrates the relationship between the localization

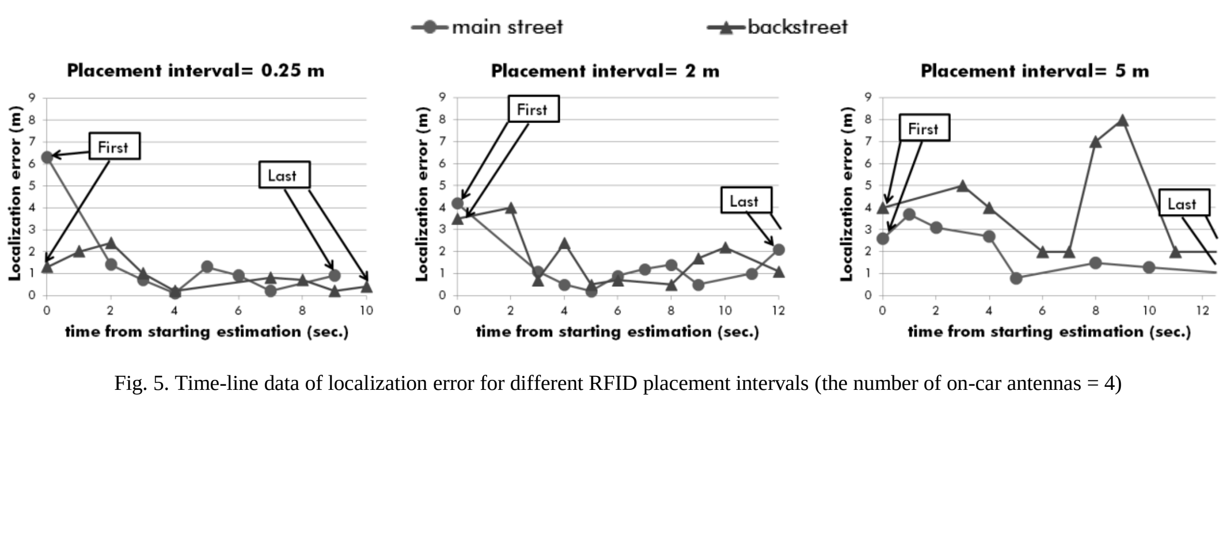

Fig. 5. Time-line data of localization error for different RFID placement intervals (the number of on-car antennas = 4)

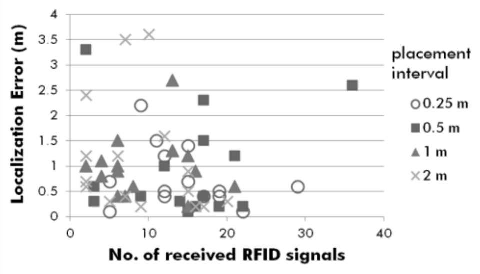

Fig. 7. Relationship between localization error and number of received RFID signals (the number of on-car antennas = 8, course is backstreet)

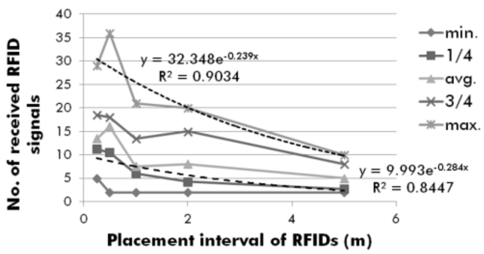

Fig. 8. Relationship between placement interval and the number of received RFID signals (the number of on-car antennas = 8, course is backstreet)

error and the number of received RFID signals. This plot shows that the localization accuracy can generally be improved by a larger number of received RFID signals; when the number of received RFID signals is larger than 20, the localization error decreases to less than 1m. However, the number of received RFID signals does not indefinitely increase according to Fig. 8. By considering the exponential regression between the number of received RFID signals and the RFID placement interval, the maximum number of received signals remains around 33, while the quartile remains at around 10.

Fig. 9 shows the relationship between the number of on-car antennas and localization accuracy. An increase in the number of on-car antennas improves the localization accuracy: the average of localization accuracy was improved by 30% when the number of antennas changed from 4 to 8. This plot also suggests that 15 on-car antennas may achieve a 0.1-meter accuracy if the RFIDs are placed at 0.25-meter intervals and the localization error linearly decreases according to the number of on-car antennas.

B. *Relationship between RSSI and estimated distance*

The relationship between the RSSI and the estimated distance obtained from (1) is shown in Tab. V. This table

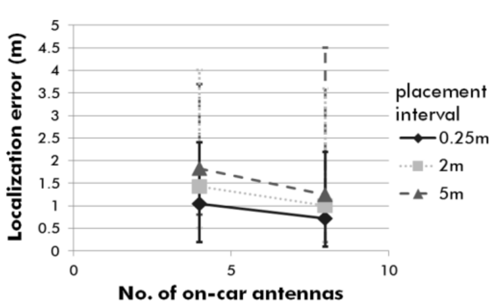

Fig. 9. Relationship between localization error and number of on-car antennas (course is backstreet)

TABLE V
RELATIONSHIP BETWEEN RSSI AND ESTIMATED DISTANCE

±0 dB		+1-dB change	
RSSI (dB)	***Distance (m)***	***RSSI (dB)***	***Distance (m)***
-110	100	-109	89.1
-100	31.6	-99	28.2
-90	10	-89	8.91
-80	3.16	-79	2.82
-70	1.0	-69	0.89

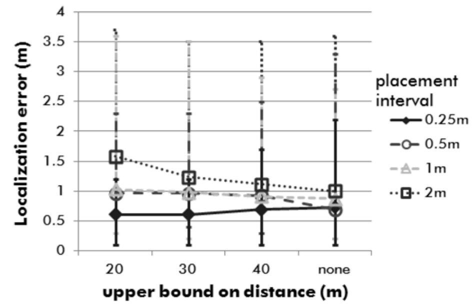

Fig. 10. Relationship between localization accuracy and boundary condition on distance computed based on RSSI (the number of on-car antennas = 8, course is backstreet)

shows that a 1-dB change in the RSSI has a larger effect on the absolute value of the estimated distance when the distance between an RFID and an on-car antenna is longer. We believe that the localization accuracy may be improved by setting a boundary condition on the estimated distance between the RFIDs and on-car antennas, and excluding the data received from RFIDs whose distance is larger than this boundary.

The relationship between this boundary condition and the localization accuracy is shown in Fig. 10. When the placement interval is short, this boundary condition can improve the localization accuracy, especially for the maximum value of the localization error. In the case where the placement interval is 0.25-meter and the boundary is 30-meter, the average of localization error is 0.6-meter, which is about 8.5% improvement compared to the non-boundary case.

Improving the function that models the relationship between the RSSI and the distance between the RFIDs and the on-car antennas may represent another way to achieve even better accuracy. Similarly, error compensation in the distance estimation computation may help as well.

VI. COST CONSIDERATIONS FOR PRACTICAL USE

First, we estimate the cost when the proposed method is installed on a road whose length is 1-killometer and has 4-lanes. Suppose that the placement interval of the RFIDs is 1m; then, the installation cost of RFIDs would be about 150-thousand dollars because an active RFID currently costs about 20-30 dollars. Since it costs about 11-million dollars to construct a 1-killometer road with 4-lanes [18], excluding the cost of the land, this installation cost is about 1% of the cost for road construction.

We also estimate that the price of an on-car receiver with 8-antennas could drop about 100-dollars because Wi-Fi routers with multiple antennas cost less than 100-dollars and RFID receivers require primitive functions compared to Wi-

Fi router functions. Therefore, we conclude that the installation cost of the proposed method is feasible in practice.

From the viewpoint of the maintenance of the system, we need to consider several issues. Here, we assume that 1) RFIDs were installed at random days, 2) battery life of RFIDs is one year, 3) Batteries of RFIDs are of single use (non-rechargeable) type and cost less than 1-dollar, and 4) lifetime of RFIDs is 5-years. Then, about 14 batteries should be changed daily, and about 3-RFIDs should be replaced daily. Consequently, it costs about 36.5-thousand dollars to maintain this platform for 1-killometer every year. This maintenance cost is less than 2% of the road maintenance cost (about 2 million dollars to repave 1-killometer road with 4-lanes[19]). Furthermore, if we add this cost with the installation cost, the result is less than 2% of the total cost for road construction and maintenance. Finally, energy harvesting techniques could be used to re-charge the batteries in the future to simplify the maintenance process [20].

VII. Conclusion

We proposed a new position estimation method for moving vehicles based on RFIDs placed on the roadsides and lane boundaries and multiple on-car RFID antennas. The results obtained from a field experiment indicate that the proposed method achieved very good accuracy, 0.7-meter error when the RFIDs were placed at 0.5-meter intervals and the vehicle was equipped with 8-antennas. This accuracy allows a moving vehicle to recognize which lane it is in. It was also revealed that the localization accuracy is mostly stable for any kind of road shape.

The paper also considered several improvements toward achieving a higher level of accuracy. A 14% accuracy improvement is achieved when RFIDs were placed at 0.25-meter intervals and the RFIDs located farther than 30-meter were excluded from computation. In order to achieve even higher accuracy levels, the relation between the RSSI of the RFID signals and the estimated distances was found to be essential.

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