Performance of Novel Target Detection in Radar Network Systems with a 3D Vehicle Model

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***Abstract*—We focus on forward-looking systems with automotive radar network systems. By using multiple radars, the radar network systems will achieve reliable detection and wide observation area. The forward-looking systems by cameras are famous, but not all-around system. In order to realize more reliable safety, the cameras had better be used with other sensing devices such as the radar network. In the radar network, processing of the data derived from the multiple receivers is important because the processing decides the detection performance. In this paper, we will introduce our data processing and detection algorithm. Finally, the performance will be evaluated via a 3D target model. From results of computer simulations, we can confirm that our proposal can achieve stable detection even if the target positions differ.**

Keywords-Radar Network; forward-looking radar; multiple radars; Wide detection

I. INTRODUCTION

By applying intelligent devices, more safety and comfortable driving is desired. Intelligent Transportation Systems (ITS) is considered to solve some transportation problems such as an accident, a traffic jam and an environmental pollution. The forward-looking alert or braking system is one of the elemental technologies for the realization of ITS world as described by Rasshofer and Gresser [1]. For the forward-looking, various devices are now researched and some systems are realized. Examples are shown in the researches by Meinecke et al. [2] and Sakamoto [3]. Especially, image processing technologies with cameras are famous. Sensing by the image processing can detect targets in wide area. Such system can alert sudden pedestrians from blind spots. In such case, the wide detection for wide are is needed.

However, the image processing has fatal weaknesses. The poplar cameras cannot achieve the adequate performance under optical disturbances, such as bad weather. In order to realize more reliable safety, the cameras had better be used with other sensing devices. In this paper, we focus on radar sensors as other devices.

For achievement of wide and reliable detection, we focus on radar network systems which have multiple receivers. Fig. 1 shows the example structure of the radar network. By using multiple distributed radars, wide observation area and detection will be realized. So, these systems have been researched as the forward-looking systems in automotive usages. The similar structures of the radar network are also researched by Klotz et al. [4] and Folster et al. [5].

In the radar network systems, it is important to process the data derived the from multiple receivers because the process decides the detection performance. In the articles [6] [7], we have proposed some algorithm for position estimation in the forward-looking radar network systems for automotive. In order to estimate target positions precisely, our methods regard the distances to the targets as stochastic variables. Then, the target positions are derived from the calculated probability, which means “target existence”.

As our past works, we have discussed our novel estimation algorithm, Existence Probability Estimation Method (EPEM) and Existence Probability Estimation Method using Reflected Signals (EPEMR) in our articles [6] [7]. However, the evaluation is simple simulator as the target is single point. In this paper, we will evaluate the detection performance by 3D target models.

This paper is organized as follows. In Section II, we introduce the position estimation algorithm briefly. In Section III, we present the simulation settings for the evaluation. Especially, the simulation tools, data processing, simulated cases and results are described. Finally, Section IV summarizes

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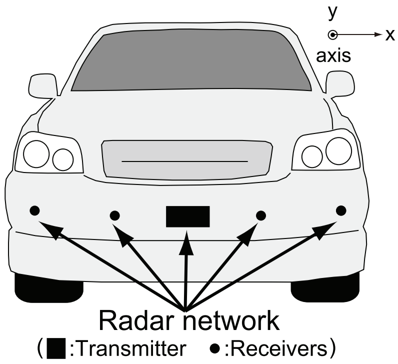

Figure 1. Example of radar network structure

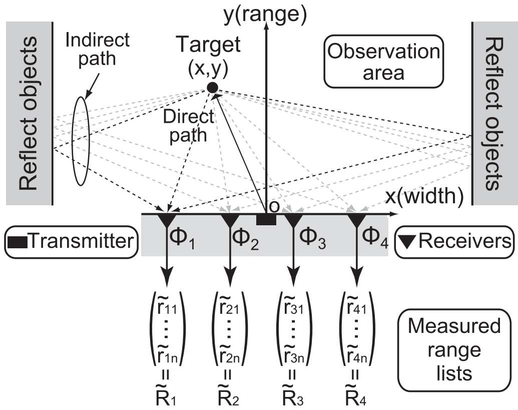

Figure 2. System model of radars and target

the paper.

II. Position estimate algorithm

A. System model

In this section, we will present our system model. The radar network is constructed with a transmitter and multiple receivers (Fig. 2). We assume four receivers. The transmitter is set up at a origin of x-axis. The four receivers are set up in equal interval. The center of the receivers is also the origin of x-axis (see Fig. 2). x-position of the receivers are $\phi_1, \phi_2, \phi_3, \phi_4$ [m] respectively. The position of a target is (x, y). The kth receiver outputs measured ranges. We obtain measured range lists $\tilde{R}_k = \{\tilde{r}_{k1}, \tilde{r}_{k2}, ..., \tilde{r}_{kN_k}\}$ from the kth receiver. The variable N_k refers to the number of measured ranges in the measured range list of the kth receiver's. The variable $\tilde{r}_{kn}$ refers to the distance of wave propagation, that is, the sum of the distances from the transmitter to the nth reflection point and from the reflection point to the kth receiver. The N_k reflection points include, of course the target and other objects such as walls.

The measured range $\tilde{r}_{kn}$ has the measurement error. The error is modeled as follows.

$$\tilde{r}_{kn} = r_{kn} + \epsilon_k \tag{1}$$

The variable r_{kn} means the real distance between the nth reflection points, the transmitter and the kth receiver. The variable ϵ_k means the measurement error which is modeled as a random variable with variance σ^2. Also, the notation "˜" means measured values. The position of the target has to be estimated by the above measured range lists $\tilde{R}_k$ of all receivers.

B. EPEM

EPEM is used as the position estimation method. Our final estimation method EPEMR is based on EPEM. In this section, we will introduce EPEM briefly. The detailed algorithm of EPEM is introduced in our past article [6].

EPEM estimates the target position by calculating the existence probability of the targets, which is explained in this section. In this method, the measured ranges, that is $\tilde{r}_{kn}$, is regard as the random variables.

In order to estimate the target position, EPEM calculates the following conditional probability.

$$P(\hat{x}, \hat{y} \mid \tilde{R}_1, \tilde{R}_2, \tilde{R}_3, \tilde{R}_4). \tag{2}$$

The above probability means that the target exists on the coordinate (x, y) when the measured range lists $\tilde{R}_1, \tilde{R}_2, \tilde{R}_3, \tilde{R}_4$ are obtained. The notation "ˆ" means estimated values.

By using Bayes'theorem and assumptions, (2) can be transformed. The following equation has the same distribution shape of (2).

$$\prod_{k=1}^{4} \sum_{n=1}^{N_k} P(\tilde{r}_{kn} \mid \hat{x}, \hat{y}) \tag{3}$$

$$= \prod_{k=1}^{4} \sum_{n=1}^{N_k} P(\tilde{r}_{kn} \mid \hat{r}_k) \tag{4}$$

where is $\hat{r}_k = \sqrt{(\hat{x} - \phi_k)^2 + \hat{y}^2} + \sqrt{\hat{x} + \hat{y}}$. The probability $P(\tilde{r}_{kn} \mid \hat{r}_k)$ means the probability of getting the measured range $\tilde{r}_{kn}$ when the target exists in the range $\hat{r}_k$. This means the measurement characteristic which each radar has. The measurement characteristic means the error ϵ_k in (1).

From the measured range lists and (4), we can calculate the distribution of the probability which means the target exists on the coordinate (x, y). The distribution of (4) is called as "existence probability distribution". The high probability in the above distribution indicates the target position. An example of the existence probability distribution is shown in Fig. 3.

C. EPEMR

EPEM does not have enough accuracy. EPEM tends to generate large error in the same direction to the receiver layout. In order to improve estimation accuracy, we also construct novel estimation algorithm "EPEMR". EPEMR uses not only direct path from the target but also indirect path which is reflected other objects (see Fig. 2). By using indirect paths, EPEMR can observe the target as the target is surrounded by both the real and virtual receivers. EPEMR

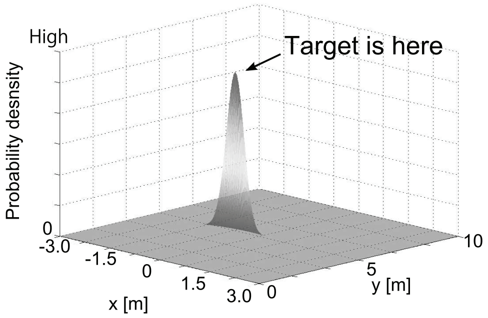

Figure 3. Example of existence probability distribution

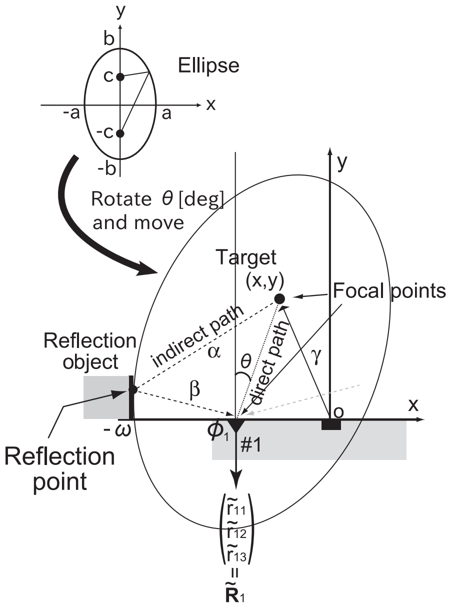

Figure 4. Ellipse image (focuses, target, receiver)

is expanded from the above mentioned EPEM. From now, we will introduce EPEMR briefly. The detailed procedure is introduced in our past work [7].

We estimate according to the following procedure.

Step(a) Estimating the position of the target by EPEM

EPEMR is based on EPEM. First, we estimate the positions of the target by using EPEM as described in Sec. II-B. EPEM can estimate the rough positions under multipath environment.

Step(b) Estimating the reflected points

Next, we estimate reflecting points on other objects except the target. In order to estimate reflecting points, we focus on the properties of a ellipse.

The distance of direct path is presented as the distance from the target to each receiver (Fig.4). The indirect path means the path which is reached by reflecting at a kind of objects, such as walls. We can derive the distance (length) of the direct path from the estimated position of the target at Step(a). By comparing the distance value of the direct path, we eliminate the close value in the measured range lists. After eliminating, only the measured distances of indirect path remain in the lists.

By using the derived distances of the indirect paths, we construct a virtual ellipse. From now, we prepare the ellipse which is illustrated in Fig. 4. The ellipse, which we will prepare, has two focuses at the positions of both the target and each receiver.

Generally, an elliptical equation is expressed as follows.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (a < b) \tag{5}$$

The sum of the distance from a arbitrary point to 2 focus points, that is $\alpha+\beta$ in Fig. 4, is constant. This distance is equal to the measured value $\tilde{r}_{kn}$ of the indirect path. As mentioned before, the distance of the indirect path can be gotten from the measured range lists after removing the direct distance. Then, the relation among the ellipse parameters and the distance $\tilde{r}_{kn}$ is:

$$2b = \tilde{r}_{kn} \tag{6}$$

$$a^2 = b^2 - c^2 \tag{7}$$

where the parameters a, b are coordinates of the intercept of long/short axis on the ellipse. The focal distance of the ellipse is denoted as c. These parameters are also illustrated in Fig. 4.

To fit the ellipse in the geometric relation between the receiver and the target, we rotate and move the above ellipse. The rotation angle θ and the amount of the movement are decided as the two focal points of the ellipse are placed at the receiver and the estimated target respectively. The detailed procedure is explained in our past work [7].

The wall's positions are known. Then, by using both the derived ellipse equation and the wall's position, we can compute the candidate positions of the reflections on the wall.

Step(c) Set up virtual receivers

We set the virtual receivers at the reflection points. We also calculate the distance α, β from the reflection points. Then, we prepare new measured range lists R'_k. These new lists means the range lists of the virtual receivers. The distance in the lists R'_k is α. We have prepared the virtual receivers which has own virtual measured range list. We estimate the target position by EPEM with the all measured range list, that is both the virtual receivers and the real receivers again.

III. Estimation performance by simulations with 3D vehicle model

A. 3D vehicle model

We introduce the characteristic of our estimation algorithm by computation simulations. In our past works, we

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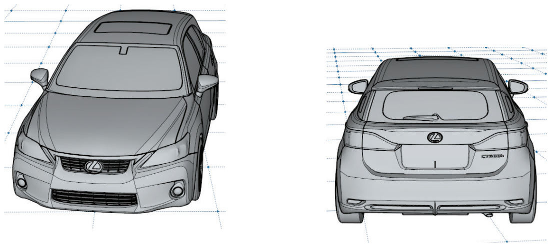


(a) Front view (b) Rear view

Figure 5. Target model

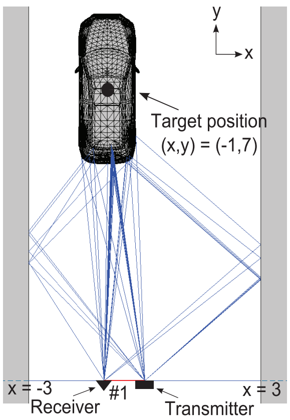


Figure 6. Example of the propagation path

considered and evaluated the position estimation algorithm using the target which is modeled as a single point. The single point model is important to evaluate a performance, in term of comparing the estimated position to the true one. However, it is also important to evaluate the estimation performance of using the 3D modeled object. So, we consider a 3D simulation model and re-construct data processing. From the new evaluations, we can grasp the performance in case of the surface which the real target has, not a single point.

We prepare the realistic 3D vehicle model as the target. We download the 3D vehicle model via Trimble 3D gallery (Fig. 5). In Trimble 3D gallery, we can download modeled files which can be imported to our simulation software, the file type is .skp. Size of the vehicle model is 3.6 meters long, 1.4 meters wide and 1.2 meters height. For calculating the measured ranges, we use software "Raplab" which is an analysis tool of radio propagation by 3D ray tracing. This tool can simulate the propagation path like Fig. 6. In Fig. 6, the receiver is denoted as a triangle mark and the transmitter as a rectangular mark. We set the target position (x, y) as the center of the vehicle like Fig. 6. By using this 3D model, the measured ranges at each receiver become more reality than before.

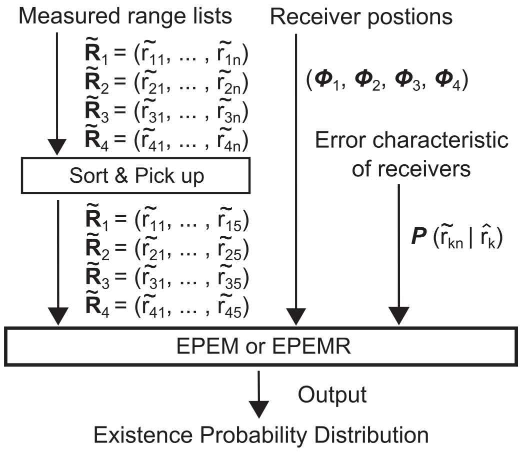


Figure 7. Data flow

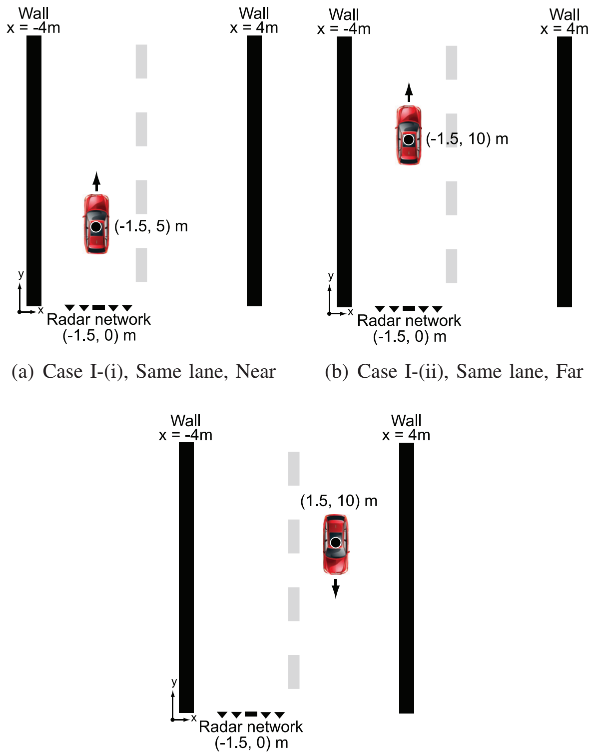
B. Data processing

Fig. 7 shows data flow. In our algorithm, we use the propagation distance calculated by the above-mentioned tool as the true value of the measured range. The measured range lists of each receiver have many measured ranges because there are about 100 propagation paths. Some of them are unnecessary information such as multipath. Moreover, some of the reflection points of these paths are not on the same plane which expends at the same ground level to the radar network. In the position estimation, we should get the direct path which propagates via the way of the transmitter - the target - the each receiver. That is the shortest path. For applying to EPEM, we sort the measured ranges of the lists $\tilde{R}_k$ in ascending order, and pick up s ranges from the smallest. The variable s means the number of the selected ranges. In this paper, we set the variable $s = 5$, this is not optimal but experimental. The parameter s affects the calculation time and the detection performance. The shorter time is desired. Moreover, in case of selecting larger s, we sense unnecessary part of the body such as the side of the target. This results in confusing detection. The most important part is the nearest part of the target. So, we pick up the shorter $s = 5$ ranges. Although the situation of multiple targets is not scope of this paper, the parameter s may be set larger value if there are multiple targets which we want to detect.

We derive the existence probability distribution of the target by EPEM with the measured range lists, the receiver position and the error characteristic of each of receivers. Finally, we get the result of the position estimation by choosing the high probability in the existence probability distribution.

C. Simulated cases and results

We simulate the following cases. In these cases, there is one target of the vehicle. We note that the coordinate (x, y) of the target position is denoted as the center of the vehicle; see Fig. 6. The important detected part is the rear of the



(a) Case I-(i), Same lane, Near

(b) Case I-(ii), Same lane, Far

(c) Case II, Opposite lane, Far

Figure 8. Simulated Cases (Target Layout)

vehicle. In the simulation, we assume two cases in different layout of the vehicle; see Fig. 8.

1) Case I: the target is arranged at the same lane in the front of own car.
   (i) Set on the target at near area $(x, y) = (-1.5, 5)m$.
   (ii) Set on the target at far area $(x, y) = (-1.5, 10)m$.
2) Case II: the target is arranged at opposite lane and far area $(x, y) = (1.5, 10)m$.

For comparison, we also simulate the conventional EPEM algorithm.

In 3D ray tracing, we set the maximum times of reflection and diffraction as 1, respectively. Simulation parameters are summarized in Table I. The measured ranges are modeled as (1). The distribution of the error ϵ_k in (1) is assumed as Gaussian distribution with standard deviation σ. The standard deviation is decided by the error range of the measured range at each receiver. The error range of the direct path is set as 0.3m. The amount 4σ means including more than 90 % in Gaussian distribution. So, we set $4\sigma = 0.3$ [m].

As a result, we summarize the existence probability distribution in Figs. 9, 10, and 11. The presented figures indicate the existence probability at $x - y$ plane. Each figure has the color bar which distributes from red color to white color.

TABLE I
SIMULATION PARAMETERS

Number of radars: k	4
Position of receivers: ϕ_k	-2.4,-1.8,-1.2,-0.6 [m]
x-coordinate of wall: ω	-4,4 [m]
Distribution of error ϵ_k [m]:	Gaussian
Measurement error of the radar [m]	0.3 ($4\sigma = 0.3$)
Resolution of x-y plane	$x = 0.05$, $y = 0.05$ [m]
Height of receivers and transmitter	0.3 [m]

The red color means high probability. So, the place of the red color has possibility of the target existence. Figures 9 and 10 show the results of Case I-(i) and -(ii), respectively. Figure 11 shows the results of Case II. We note that the coordinate of the each target is the center of the car. So, the detected areas of Figs. 9, 10 and 11 are the nearest part of the car, that is outside of the body. From Figs. 9, 10 and 11, it results that the proposed EPEMR can reduce the error compared to EPEM. Especially, in EPEM, the farther the distance between the target and the radar is, the larger the error in the x-direction is. This is the typical problem of multiple sensing system such as radar network. The multiple sensing from the same side generates large error in the same direction of the sensor arrangement. For example, from Figs. 10 and 11, the high probability in EPEM can be found along about 2.31m in x-direction. It results that the target exists over the width of the car. On the other hand, EPEMR can suppress the error and the detected area becomes within the car width. This improvement can be confirmed in all cases.

IV. CONCLUSION

In the realization of ITS world, we research the forward-looking radar network. Especially, we focused on the combination between the imaging detection and the radar network detection. In order to be more accurate radar sensing, we regarded the measured ranges to targets as the random variables. We have proposed and evaluated some position estimation algorithms. In this paper, we introduced our proposals EPEMR, the data processing and the estimation performance with new 3D target model. EPEMR estimates the reflection points on the surrounding structures with the results by the imaging devices. EPEMR sets the virtual receivers on the estimated reflection points. By adding the virtual receivers, the target can be observed from various directions. From the computer simulations with 3D target model, we confirmed that the EPEMR can reduce the positioning error. We also confirmed the advantage and robustness of the proposal by different situations.

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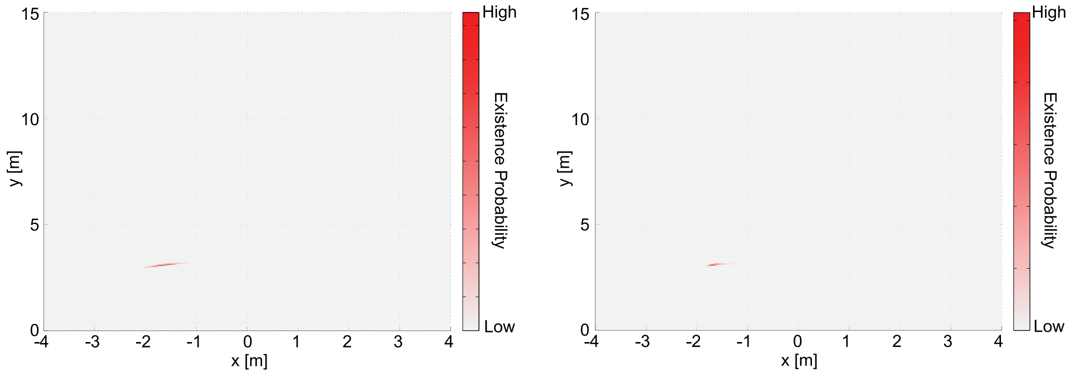
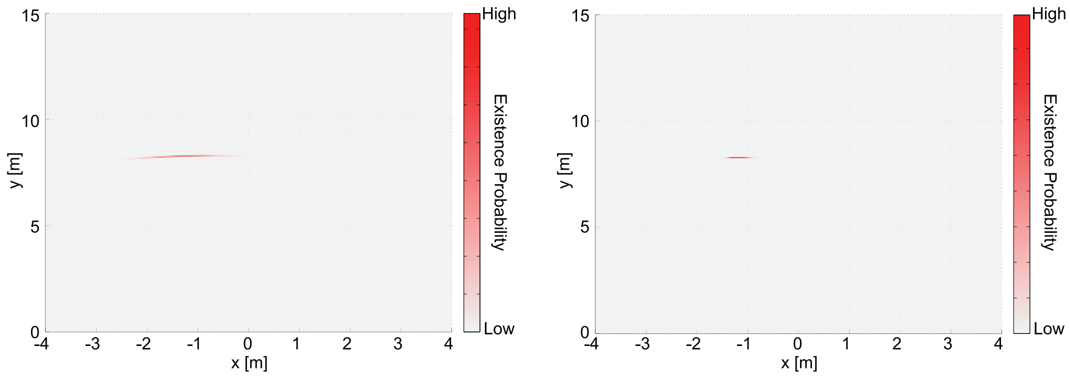


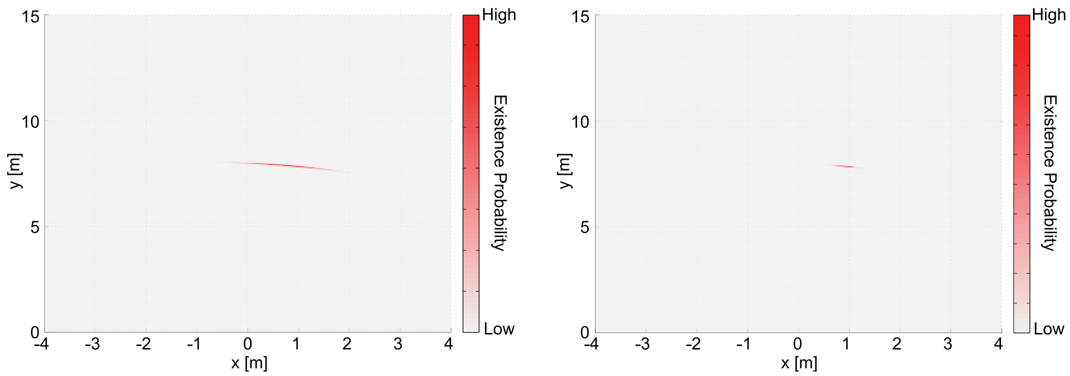
(a) EPEM (b) EPEMR

Figure 9. Target existence probability(Case I-(i), 5m, EPEM vs EPEMR)



(a) EPEM (b) EPEMR

Figure 10. Target existence probability(Case I-(ii), 10m, EPEM vs EPEMR)



(a) EPEM (b) EPEMR

Figure 11. Target existence probability(Case II, Oncoming, 10m, EPEM vs EPEMR)

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