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Position estimation method using recursive MAP estimation for ultrasonic sensor arrays

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SUMMARY We are working on the measurement of obstacle positions by an ultrasonic sensor array. This paper proposes a recursive position estimation method using signals from eight ultrasonic sensors forming a linear array. First, we estimate the distance to the obstacle from the time difference between the eight received signals. Then, assuming that the ranging error follows a Gaussian distribution and that each of the eight ranging values is independent, we can get the existence probability of the obstacle's position by a pair of two obtained distances. Finally, we estimate the position of the obstacle by multiplying 28 (${}_8C_2$) existence probabilities obtained. The conventional method estimates the position of an obstacle by the above procedure. However, the estimation accuracy in the angular direction was poor, resulting in the spread of the existence probability in the horizontal direction. In the proposed recursive position estimation, we obtain the existence probability of an obstacle by the procedure shown above, and then use it as the prior probability of the obstacle's estimated position. Furthermore, we recursively perform the same process to obtain the existence probability of the obstacle. In this way, we improve the accuracy of the estimation of the position of the obstacle by the existence probability. We present the experiment results to show the effectiveness of the proposed method.

key words: *position estimation, ultrasonic sensor, recursive, MAP estimation*

1. Introduction

Ultrasonic sensors are widely used for vehicles such as parking assistance and industrial applications such as robotics because of their simple structure, low cost, and excellent environmental resistance [1], [2]. We can extend the detection range and estimate the positions of obstacles using an array of ultrasonic sensors [3]–[6]. It is expected to be used in low-speed autonomous vehicles. However, the precision of the estimation of the position of the obstacle, especially in the angular direction, is poor, resulting in a wide distribution of the probability of the existence of the obstacle [3]–[6].

This paper proposes a recursive maximum a posteriori probability (MAP) estimation method to improve the accuracy of angular estimation and suppress the spread of the existence probability. Several works, for example [7] and [8], adopt Maximum Likelihood (ML) to estimate obstacle position using ultrasonic signals, but few adopt MAP estimation methods. In particular, to the best of our knowledge, the recursive MAP estimation proposed in this study has not been studied. One reason MAP estimation is not used is that MAP estimation requires a prior probability, but obtaining it is difficult. When estimating the position of an obstacle, a prior distribution of the obstacle's position is not available; therefore, it is common to treat it as a uniform distribution. In other words, the problem is solved using ML estimation instead of MAP estimation. On the other hand, other than ultrasonic fields, recursive MAP methods have been considered. Fu et al. use recursive MAP estimation to solve the problem of estimating the frequency and carrier phase of a single sinusoid observed in additive white Gaussian noise[9]. In addition, Krishnamurthy et al. use recursive MAP estimation for state estimation of the bilinear system[10].

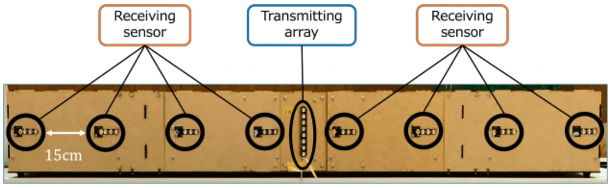

Fig. 1 Experimental equipment with transmitting array and receiving array

This paper is organized as follows. Section **1** describes an overview of obstacle detection with ultrasonic sensors. Section **2** describes the system model and the proposed method. In Section **3**, we evaluate the effectiveness of the proposed method using experimental data. Finally, in Section **4**, we summarize this article.

2. System model

The assumed environment for this study is low-speed automatic driving, and we assume a situation in which obstacles are detected when the vehicle is traveling at 20 km/h. For simplicity, we consider a stationary obstacle.

2.1 Experimental equipment

The equipment is shown in Fig. 1. There is the transmitting array in the center of the experimental equipment. The receiving array consists of eight ultrasonic sensors and is installed horizontally on the ground. The transmission array consists of eight ultrasonic transmitters that are mounted

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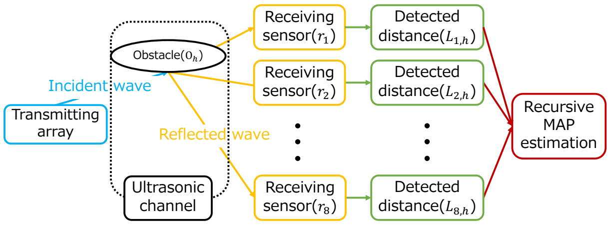

Fig. 2 System model of proposed method

vertically to the ground, facilitating the enhancement of ultrasonic waves. The frequency of the wave is 44.5 kHz. The reception sensor interval is 15 cm.

2.2 System model

Fig. 2 shows the system model. Ultrasonic waves transmitted from the transmitting array are reflected by obstacles and each receiving sensor receives the reflected wave. Finally, recursive MAP estimation with eight detected distances is performed using eight detected distances. We denote the ith receiving sensor as r_i and the hth obstacle as o_h. We assume there are h_o obstacles in the detection area.

2.3 Detected distance

We find the detected distance $L_{i,h}$. The detected distance $L_{i,h}$ is obtained by getting the time $t = t_{i,h}$ at which r_i receive waves. Let $t = 0$ be the transmission time. We define $t_{i,h}$ as the time when the threshold is exceeded. In this paper, $threshold = 35$ is used as shown in Fig. 3. $L_{i,h}$ can be obtained by the product of $t_{i,h}$ and the speed of sound V.

$$L_{i,h} = V * t_{i,h} \tag{1}$$

2.4 Recursive MAP Estimation

Let the coordinates of the transmitting array be the origin, the coordinates of r_i be $(x_{r_i}, 0)$ and the coordinates of o_h be (x_{t_h}, y_{t_h}). We define the distance from the transmitting array to o_h as l_h. It can be expressed as in Eq. (2).

$$l_h = \sqrt{x_{T_h}^2 + y_{T_h}^2} \tag{2}$$

We define the distance from o_h to r_i as $l_{i,h}$. It can be expressed as in Eq. (3).

$$l_{i,h} = \sqrt{(x_{T_h} - x_{r_i})^2 + y_{T_h}^2} \tag{3}$$

The detected distance $L_{i,h}$ can be expressed as the sum of l_h and $l_{i,h}$.

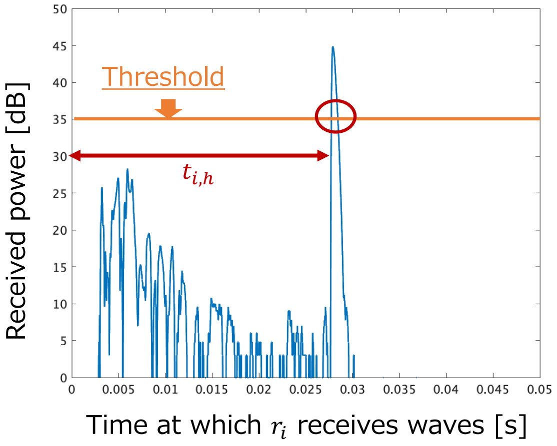

Fig. 3 Example of propagation time acquisition Using threshold from Received power-Time waveform in ultrasonic sensor. The detected distance $L_{i,h}$ is obtained by getting the time $t = t_{i,h}$ at which r_i receive waves. $t_{i,h}$ is the time when the threshold is exceeded.

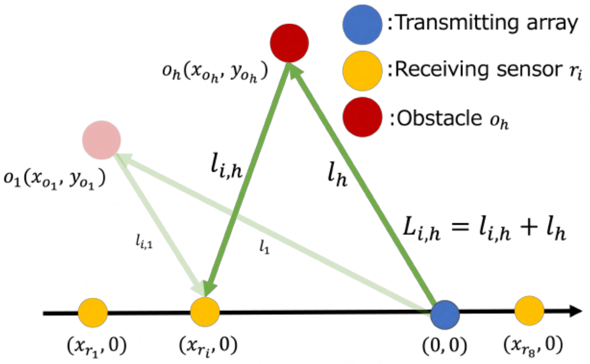

Fig. 4 Coordinates of receiving sensors, transmitter array and the obstacle. Let the coordinates of the transmitting array be the origin, the coordinates of r_i be $(x_{r_i}, 0)$ and the coordinates of o_h be (x_{t_h}, y_{t_h}).

$$L_{i,h} = \sqrt{x_{T_h}^2 + y_{T_h}^2} + \sqrt{(x_{T_h} - x_{r_i})^2 + y_{T_h}^2} + \varepsilon \tag{4}$$

ε indicates error and we assume the error characteristic of r_i is Gaussian $N(0, \sigma^2)$. Suppose that r_1 to r_8 obtain $L_{1,h}$,$L_{2,h}$,...,$L_{8,h}$ for o_h, respectively. In the $n(n \in \mathbb{N})$th estimate, we define the posterior probability of existence $P(\hat{x}, \hat{y} | L_{1,h}, L_{2,h}, \ldots, L_{8,h})$ as $P_n(\hat{x}, \hat{y})$. Using the Bayesian theorem, P_n can be expressed as in Eq. (5).

$$\begin{aligned} P_n(\hat{x}, \hat{y}) &= P(\hat{x}, \hat{y} | L_{1,h}, L_{2,h}, \ldots, L_{8,h}) \\ &= \frac{P(L_{1,h}, L_{2,h}, \ldots, L_{8,h} | \hat{x}, \hat{y})}{P(L_{1,h}, L_{2,h}, \ldots, L_{8,h})} \cdot P(\hat{x}, \hat{y}) \end{aligned} \tag{5}$$

where $P(L_1, L_2, \ldots, L_8)$ is irrelevant to the estimate position, so we assume that $P(L_1, L_2, \ldots, L_8) = 1$. $P(\hat{x}, \hat{y})$ is the probability that there is an obstacle at $(\hat{x}, \hat{y})$. Assume that each receiving sensor is making independent measurements, Eq. (5) can be transformed as in Eq. (6).

$$\begin{aligned} P_n(\hat{x},\hat{y}) &= P(L_{1,h}, L_{2,h}, ..., L_{8,h}|\hat{x},\hat{y}) \cdot P(\hat{x},\hat{y}) \\ &= \prod_{i=1}^{8}(P_i(L_{i,h}|\hat{x},\hat{y})) \cdot P(\hat{x},\hat{y}) \end{aligned} \tag{6}$$

where $P_i(L_{i,h}|\hat{x},\hat{y})$ denotes the error characteristic by r_i in the measurement of propagation distance. Therefore, we obtain P_n by getting the error characteristics of the receiving sensor. In this study, the error characteristic of r_i is assumed to be Gaussian distribution $\mathrm{N}(0,\sigma^2)$, so $(L_{i,h}|\hat{x},\hat{y})$ can be expressed by the following probability density function.

$$P_i(L_{i,h}|\hat{x},\hat{y}) = \sum_{h=1}^{h_o} \exp\{-\frac{(F_i(\hat{x},\hat{y}) - L_{i,h})^2}{2\sigma^2}\} \tag{7}$$

Therefore, the probability distribution of existence $P_n(\hat{x},\hat{y})$ can be expressed as in Eq. (8).

$$P_n(\hat{x},\hat{y}) = \prod_{i=1}^{8}\left[\sum_{h=1}^{h_o} \exp\{-\frac{(F_i(\hat{x},\hat{y}) - L_{i,h})^2}{2\sigma^2}\}\right] \cdot P(\hat{x},\hat{y}) \tag{8}$$

In the previous study, we have not known $P(\hat{x},\hat{y})$ and assumed that it is uniform distribution, i.e. $P(\hat{x},\hat{y}) = 1$. In proposed method, we define that $P(\hat{x},\hat{y}) = P_{n-1}(\hat{x},\hat{y})$ when we estimate for the nth time, but $P(\hat{x},\hat{y}) = 1$ for first time.

$$P_n(\hat{x},\hat{y}) = \begin{cases} \prod_{i=1}^{8} P_{i,n}(\hat{x},\hat{y})(L_{i,h}|\hat{x},\hat{y}) & (n = 1) \\ \prod_{i=1}^{8} P_{i,n}(\hat{x},\hat{y})(L_{i,h}|\hat{x},\hat{y}) \cdot P_{n-1}(\hat{x},\hat{y}) & (n > 1) \end{cases} \tag{9}$$

3. Evaluation of the proposed method

In this chapter, we present the evaluation results of the proposed method. The proposed method is evaluated with the results of numerical calculations with the experimental data on June 4, 2022. We considered the case of a single obstacle, thus $h_o = 1$. Fig. 5 shows experimental scene. The experimental specifications are summarized in Table1. The experimental equipment was set at the origin and the obstacles were placed at Fig. 6. We used an aluminum plate (L: 137cm × W: 46cm) as an obstacle.

Figs. 7, 8 and 9 show the position estimation result. The x-axis indicates the horizontal direction, the y-axis the vertical direction, the z-axis the normalized existence probability and a cross mark indicates the coordinates of the center of the obstacle. Fig. 7 is the result of a conventional method. Figs. 8 and 9 are the results of a proposed method. Fig. 8 is the result when the the probability of existence, or a prior probability is $P(\hat{x},\hat{y}) = P_1(\hat{x},\hat{y})$, that is, the case shown in Fig. 7. Fig. 9 is the result $P(\hat{x},\hat{y}) = P_2(\hat{x},\hat{y})$ (Fig. 8).

Fig. 5 Experimental scene

We also evaluate the size of the area where it may be present. The area defines as the sum of areas with a normalized existence probability greater than 0.2. The smaller the area, the more accurately the obstacle position is estimated. The results in Fig. 7, Fig. 8 and Fig. 9 are 3.4m^2, 1.35m^2 and 0.3m^2, respectively. The results show that as the number of estimations increases, the proposed method has a smaller area. Therefore, we were able to prove that the position of the obstacle can be estimated more accurately using a proposed method.

Table 1 Experimental specifications

Experimental date	2022/06/04
Atmospheric temperature	28 ℃
Wind speed	0 - 1.6 m/sec
Height of experimental equipment	80 cm
Transmitting frequency	44.5 kHz
obstacle	Aluminum plate(width: 46 cm)
obstacle position	(-1.29 m, 4.83 m)

4. Conclusion

In this study, we propose a recursive MAP estimation method to improve the accuracy of obstacle location estimation. In the proposed method, we perform the MAP estimate using the result of the $n-1$th estimation as a prior probability for the nth estimate. Experimental results show that the proposed method can improve the estimation accuracy in the angular direction and suppress the horizontal spread of the existence probability distribution compared to the conventional method. The proprietary area of the existence probability distribution is also reduced.

Future studies include estimating the position of multiple obstacles. In principle, we believe that this method can be extended.

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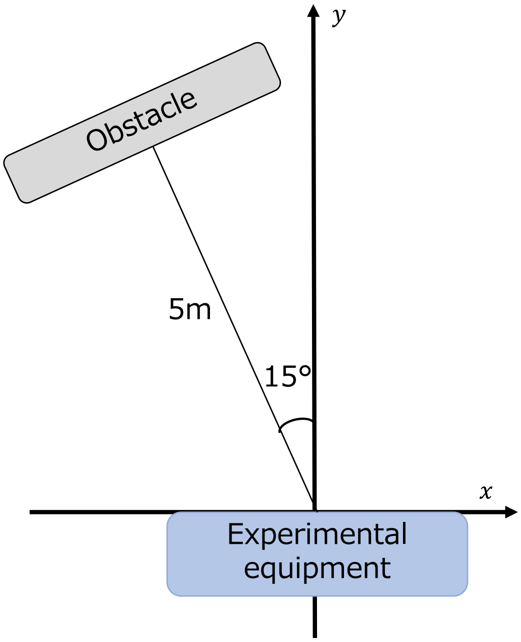

Fig. 6 Obstacle installation conditions. The obstacle is placed at a distance of 5m and at an angle of 15°.

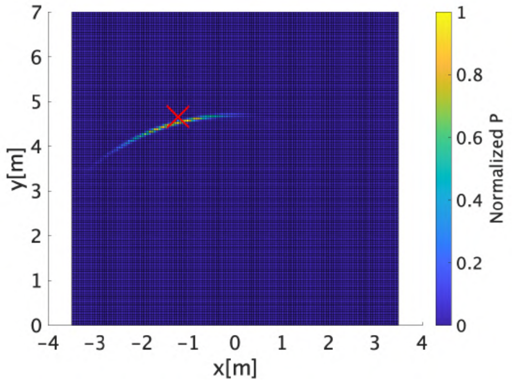

Fig. 7 Position estimation result of a conventional method: P_1. We use the obtained probability as a prior probability for a conventional method.

valuable input.

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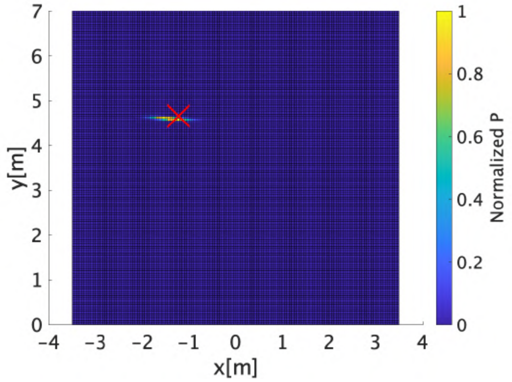

Fig. 8 Position estimation result of our proposed method: P_2. We use the obtained probability as a prior probability for our proposed method.

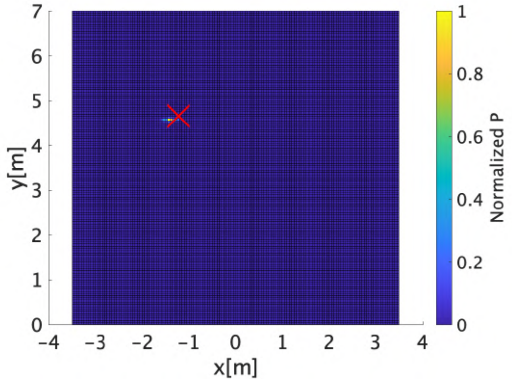

Fig. 9 Position estimation result of our proposed method: P_3. We use the obtained probability as a prior probability for our proposed method.

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