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Indoor Self-Localization of Moving Vehicle Using Acoustic Multipath Arrival Time
音響マルチパス到来時間計測を使用した移動体の屋内自己位置推定

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1. Introduction

Vehicle navigation technology has widely been used in the automation of construction sites and factories. In such technology, the use of markers, beacons, vehicle-mounted sensors, and a combination of thereof have been utilized[1-5]. The method using sensors mounted on the vehicle measures the position of the object to perform self-location, and light detection and ranging (LiDAR) and ultrasonic sensors are typically used. However, LiDAR is not able to detect a transparent object. In addition, it is not robust against optical scatterers such as dust and fog. The method using ultrasonic sensors can detect the transparent object and is not much affected by optical scatterers. However, ultrasound is not suitable for large-space applications due to its high attenuation in the air[3]. In addition, multiple transmitters and receivers are required to be placed on the vehicle to acquire the distance in all directions. Therefore, a method to obtain omnidirectional distance using only a loudspeaker and a microphone was proposed[5]. This sensor emits the sound in all directions and measures the time-of-flight (ToF) of the reflected waves from around. However, since the arrival direction of the reflected wave is unknown, the location of the reflection point cannot be determined.

In this study, we propose a self-localization method using a single acoustic ranging sensor, and show that the self-localization was successfully achieved in an indoor environment. Since the actual acoustic environment is a complex multipath environment, it is challenging to measure the position of the wall and estimate the self-location. Many studies about the acoustic self-localization method focus on the first reflection peak. However, there exist multiple reflections in case of actual. We show that the accuracy of the self-localization method can be improved by including a three-dimensional reflection path.

2. Principle of self-localization method

The proposed method uses the ToF of the reflected wave obtained from the acoustic ranging sensor and the velocity command input to the vehicle to estimate self-location. The self-location is performed by computing the processes (i) to (iv) in **Fig. 1**. Process (i) uses the kinematic model of the vehicle to predict the location after one step $\boldsymbol{\alpha}_{i|i-1} = [x_{i|i-1} \quad y_{i|i-1} \quad \phi_{i|i-1}]^T$. The vehicle has two drive wheels and operates them by commanding a straight-line velocity v and a turning angular velocity $\dot{\phi}$. The kinematic model of the vehicle is

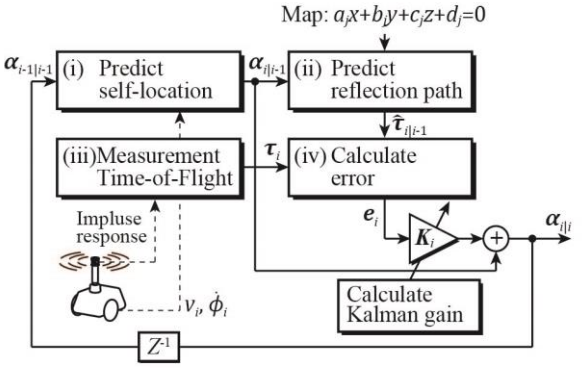

Fig. 1 Self-localization process.

$$\begin{bmatrix} x_{i|i-1} \\ y_{i|i-1} \\ \phi_{i|i-1} \end{bmatrix} = \begin{bmatrix} x_{i-1} + v_i \Delta t \cos \phi_{i-1} \\ y_{i-1} + v_i \Delta t \sin \phi_{i-1} \\ \phi_{i-1} + \Delta \dot{t} \dot{\phi}_{\iota} \end{bmatrix}, \qquad (1)$$

where x_i and y_i are the vehicle's location in the two-dimensional plane and ϕ is the horizontal angle of the vehicle. Process (ii) predicts the ToF of the reflected wave after one step. The equation of plane $a_j x_i + b_j y_i + c_j z_i + d_j = 0$ is given in advance as the map information. The location of the mirror image of the source $\boldsymbol{P}_i = [x_i \; y_i \; z_i \; 1]^T$ due to the effect of the wall $\#j$ is

$$\overline{\boldsymbol{P}}_i^{(j)} = \boldsymbol{R}_j \boldsymbol{P}_i, \qquad (2)$$

where $\boldsymbol{R}_j$ is a linear transformation that computes the points symmetric to the plane. Since the length of the reflection path equals to the distance between the source $\boldsymbol{P}_i$ and the mirror image source $\overline{\boldsymbol{P}}_i^{(j)}$, the ToF of the reflected wave is

$$\hat{\tau}_i^{(m)} = \begin{cases} \left|\left(\boldsymbol{I} - \boldsymbol{R}_{j_1}\right)\boldsymbol{P}_i\right| / c_{\mathrm{a}} & (j_1 = j_2) \\ \left|\left(\boldsymbol{I} - \boldsymbol{R}_{j_2}\boldsymbol{R}_{j_1}\right)\boldsymbol{P}_i\right| / c_{\mathrm{a}} & (j_1 \neq j_2) \end{cases}, \qquad (3)$$

$$j_2 = m \bmod M, j_1 = (m - j_2)/M + 1,$$

where $\boldsymbol{I}$ is the unit matrix, c_{a} is the speed of sound,

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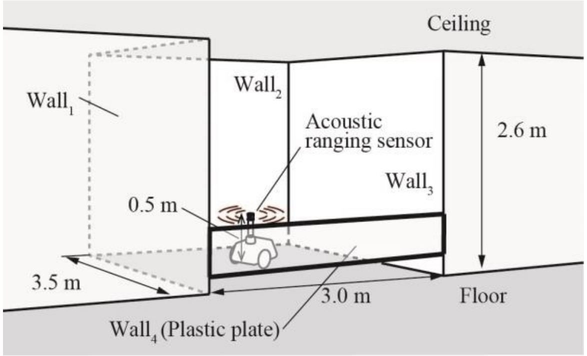

Fig. 2 Experimental environment.

M is the number of walls and m is an integer of $1 \leq m \leq M^2$. $\hat{\boldsymbol{\tau}}_{i|i-1}$ is the predicted ToF to be observed at location $\boldsymbol{\alpha}_{i|i-1}$. Process (iii) measures the actual ToF of the reflected wave $\boldsymbol{\tau}_i$ using an acoustic ranging sensor. The acoustic ranging sensor measures the impulse response of the channel using the M-sequence signal and measures the ToF of the reflected wave by detecting the peak from the impulse response waveform. Process (iv) calculates the error between the predicted and measured ToFs using

$$q_i^{(n)} = \underset{m\in\{1,2,\cdots,M^2\}}{\mathrm{argmin}} \left\{\tau_i^{(n)} - \hat{\tau}_{i|i-1}^{(m)}\right\}^2, \quad (4)$$

$$e_i^{(n)} = \tau_i^{(n)} - \hat{\tau}_{i|i-1}^{\left(q_i^{(n)}\right)}. \quad (5)$$

Estimation of the self-location is done by

$$\boldsymbol{\alpha}_{i|i} = \boldsymbol{\alpha}_{i|i-1} + \boldsymbol{K}_i \boldsymbol{e}_i, \quad (6)$$

where $\boldsymbol{K}_i$ is the Kalman gain. The Kalman gain is based on the extended Kalman filter algorithm to determine the optimal gain.

3. Experiment setup

We implemented the proposed method on a mobile robot and verified the accuracy of self-localization in an experiment. **Fig. 2** shows the experimental environment. The acoustic ranging sensor is located on the top of the vehicle (iRobot Create; iRobot). The acoustic ranging sensor consists of a loudspeaker (LSPX-S2; SONY) and a microphone (WM-61A; Panasonic). The A-D/D-A converter (NI-6212; National Instruments) performs analog conversion of the transmitted signal generated by the PC and digital conversion of the signal received by the microphone. A motion capture system (OptiTrack Prime13x; OptiTrack) consisting of two infrared cameras acquires the vehicle's reference location. Three models were used to estimate the self-location (a) a model of reflection by a single wall, (b) a model of reflection by a single wall and two walls in a two-dimensional plane (the ceiling and floor were not added to the model), and (c) a model of a three-dimensional reflection.

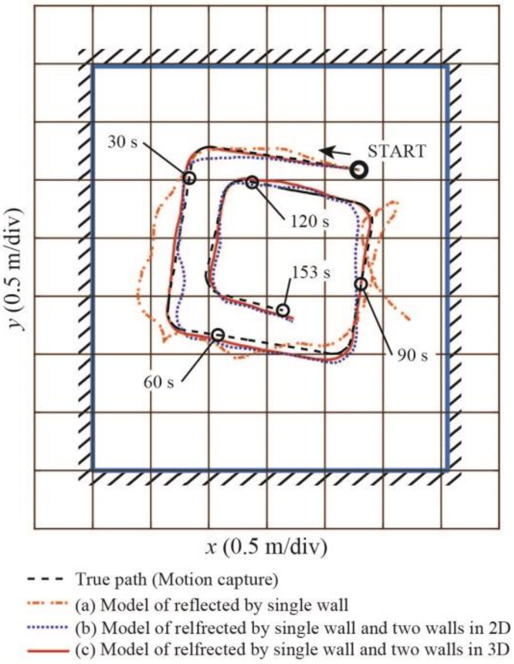

Fig. 3 Estimation result of the trajectory of the vehicle.

4. Result and Discussion

Figure 3 shows the result of the self-localization. First, the estimation results using (a) deviated significantly from the true value, and the path changed in the middle of the estimation in a direction different from the true value. The estimation results using (b) and (c) are close to the true value, and (c) is the best, with an average estimation error of 0.085 m. This means that the use of multiple reflection paths in the model improves the accuracy, and it was found that the reflection paths through the two walls and those occurring at the ceiling and floor could not be ignored.

5. Conclusion

The objective of this study is to estimate the self-location of a vehicle using a single acoustic ranging sensor in a multipath environment. The experiment result shows that the accuracy of the localization can be improved by taking multiple reflections in the model.

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