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Ranging of Moving Object Using Digital Acoustic Communication and Basis Expansion model

ディジタル音響通信と Basis expansion model を用いた移動体の測距

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1. Introduction

In recent years, indoor location information has become important in various fields such as disaster prevention and marketing. Therefore, there are growing expectations for acoustic positioning technology that can utilize existing indoor broadcasting equipment and smartphones as transmitters and receivers. In the acoustic positioning in dynamic environment, the time-of-flight (ToF) of acoustic waves cannot be simply measured by calculating the cross-correlation function of between the transmitted and received signals due to the existence of the Doppler effect. In a previous study, the distance to the moving object was successfully estimated by pulse echo method using periodic M-sequence signals and spectrum-pattern analysis [1]. However, it is desirable if we can measure impulse responses at multiple Doppler shifts simultaneously.

In this paper, we propose a method for estimating the ToF and the distance between the transmitter (Tx) and the moving receiver (Rx) using M-sequence signals modulated by the Doppler effect by using the basis expansion model (BEM). The proposed method provides an impulse response for each Doppler shift, which can be utilized for acoustic positioning in multipath environment such as indoors.

2. Calculation of Impulse Response Using Basis Expansion Model

Figure 1 shows a block diagram of the proposed method in the Tx and Rx. The Tx calculates a transmission signal by modulating M-sequence and emits the signal to the channel. The Rx demodulates the received signal, obtains channel impulse responses at various Doppler shifts, and calculates Tx-Rx distance.

The Tx reads a M-sequence of length M, $\boldsymbol{p}$, and applies the transformation matrix $(\boldsymbol{F}_N \otimes \boldsymbol{I}_M)$ on $\boldsymbol{p}$ as

$$\boldsymbol{x} = (\boldsymbol{p}, \boldsymbol{0}_{1\times 2QM+L})(\boldsymbol{F}_N \otimes \boldsymbol{I}_M), \qquad (1)$$

where $\boldsymbol{0}_{R\times C}$, $\boldsymbol{F}_N$, $\boldsymbol{I}_M$ are all-zero matrix of size $R\times C$, inverse discrete Fourier transform matrix of size $N\times N$, and a unit matrix of size $M\times M$, respectively. Also, $\otimes$ represents the Kronecker product, Q is the maximum allowable Doppler shift, and $N = 1 + 2Q$. Then the Tx up-converts the frequency of $\boldsymbol{x}$ and emits the up-converted signal from the speaker.

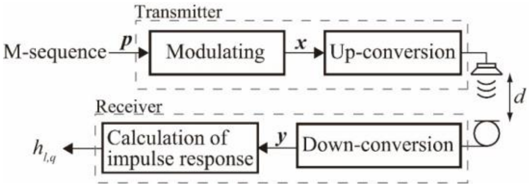

Fig. 1 Block diagram of transmitter and receiver.

In the channel, the signal is affected by both the delay and Doppler spreads. The received and down-converted signal $\boldsymbol{y}$ can be modeled using BEM as [2, 3],

$$\boldsymbol{y} = \boldsymbol{x} \sum_{q=-Q}^{Q} \boldsymbol{H}_q \boldsymbol{\Lambda}_q, \qquad (2)$$

where $\boldsymbol{H}_q$ and $\boldsymbol{\Lambda}_q$ represent delay and Doppler shifts, respectively, and

$$\boldsymbol{H}_q = \begin{pmatrix} h_{0,q} & h_{1,q} & \cdots & h_{L-1,q} \\ h_{L-1,q} & h_{0,q} & \cdots & h_{L-2,q} \\ \vdots & \vdots & \ddots & \vdots \\ h_{1,q} & \cdots & h_{L-1,q} & h_{0,q} \end{pmatrix}, \qquad (3)$$

$$\boldsymbol{\Lambda}_q = \mathrm{diag}\left(W_{MN}^{0}, W_{MN}^{1}, \ldots, W_{MN}^{(MN+L-1)q}\right). \qquad (4)$$

$h_{l,q}$ (l = 0, 1, …, M-1, q = -Q, -Q+1, …, Q) is the impulse response of the communication channel at the Doppler shift of q, and

$$W_{MN}^{k} = \exp\left[2\pi\sqrt{-1}k/(MN)\right]. \qquad (5)$$

The Rx applies the transformation matrix $(\boldsymbol{F}_N^{*} \otimes \boldsymbol{I}_M)$ on the received signal $\boldsymbol{y}$ as

$$\boldsymbol{y}(\boldsymbol{F}_N^{*} \otimes \boldsymbol{I}_M) = \boldsymbol{p}(\boldsymbol{C}_{-Q}, \boldsymbol{C}_{-Q+1}, \ldots, \boldsymbol{C}_Q), \qquad (6)$$

where $(\cdot)^{*}$ represents phase conjugate and $\boldsymbol{C}_q$ is a matrix representing the impulse response of the communication channel with the Doppler shift of q,

$$\boldsymbol{C}_q = \begin{pmatrix} h_{0,q} & W_{MN}^{q} h_{1,q} & \cdots & W_{MN}^{(M-1)q} h_{M-1,q} \\ h_{M-1,q} & W_{MN}^{q} h_{0,q} & \cdots & W_{MN}^{(M-1)q} h_{M-2,q} \\ \vdots & \vdots & \ddots & \vdots \\ h_{1,q} & W_{MN}^{q} h_{2,q} & \cdots & W_{MN}^{(M-1)q} h_{0,q} \end{pmatrix}. \qquad (7)$$

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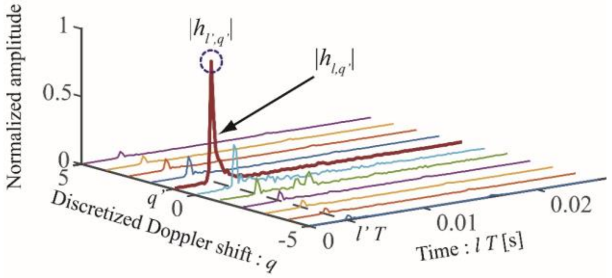

Fig. 3 Example of $h_{l,q}$ obtained in experiment.

The Rx obtains $\boldsymbol{C}_q$ by solving Eq. (6) since $\boldsymbol{p}$ is shared between the Tx and Rx prior to communication.

An example of the impulse response $h_{l,q}$ is shown in **Fig. 2**. As shown in the figure, the Rx can obtain the impulse response having a sharp peak even in dynamic condition (e.g., Rx is moving). The Rx detects the peak of the impulse response, $h_{l',q'}$ (l' and q' are position of the peak in the time- and frequency-domain, respectively), and calculates the Tx-Rx distance, d, by using l' and phase of the peak arg($h_{l',q'}$) as,

$$d = cT\left\{l' + \frac{\arg\left(h_{l',q'}\right)}{\theta_{q'}}\right\}, \tag{8}$$

where c and $\theta_{q'}$ are sound velocity and the maximum phase rotation during symbol interval T at Doppler shift of q', respectively.

3. Experiment

We evaluate the performance of the proposed method in experiment. The experimental environment is shown in **Fig. 3**. The experiment was performed in a sound-proof room. The Tx consisted of a PC with software (MATLAB, MathWorks), a digital-to-analog converter (USB-6212, National Instruments), a signal amplifier (AP15d, Foster), and a speaker (P650K, Foster). The Rx consisted of a PC with software (MATLAB, MathWorks), a digital-to-analog converter (USB-6212, National Instruments), a signal amplifier (MP13, Rolls), and a microphone (PC60, SONY). In experiment, the Tx calculates the transmission signal using parameters summarized in **Table 1** and emits the signal from the speaker. At the same time, the Rx moves toward to the Tx at a constant speed of 0, 0.09, 0.18, and 0.28 (m/s). Note that the communication starts when Tx-Rx distance was 900 mm. The experiment was repeated 20 times at each speed.

Figure 4 shows the experimental result. The horizontal axis and vertical axis represent velocity of the Rx and measurement error of Tx-Rx distance, respectively. As shown in the figure, the proposed method could estimate the distance with a mean error of 0.06, -0.02, 0.02 and 0.02 (m) at Rx velocity of 0, 0.09, 0.18, and 0.28 (m/s), respectively. Furthermore, the variance of each measurement was less than 4.2×10^{-4}. These results suggest that the proposed method can measure the Tx-Rx distance accurately even in dynamic environment.

Table. 1 Parameters used in experiments.

Parameters	Value
Massage length: M	127
Maximum delay spread: L	127
Maximum Doppler shift: Q	5
Bandwidth: $1/T$ (Hz)	5,000
Carrier frequency: f_c (Hz)	5,000
Sampling frequency: f_s (kHz)	50

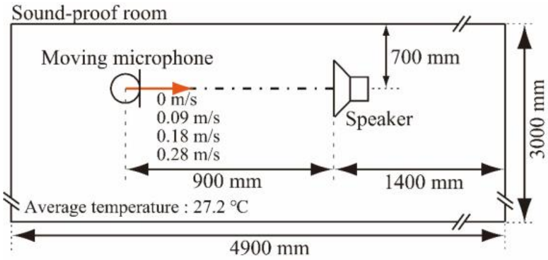

Fig. 2 Experimental environment (top-view).

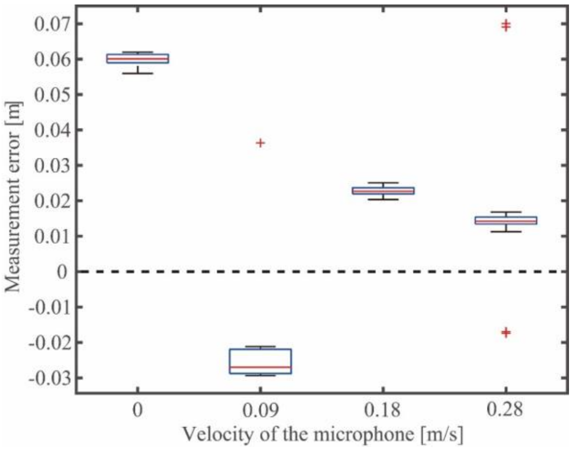

Fig. 4 Experimental result.

4. Conclusion

In this paper, we proposed a distance estimation between the Tx and the Rx using the impulse response modeled by BEM in dynamic environment. We found that proposed method can obtain impulse response having a sharp peak even in dynamic environment and the Tx-Rx distance can be measured accurately. Our next plan is to estimate the distance between the Tx and the Rx in dynamic environment with multiple different Doppler shifts.

References

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