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Distance and Velocity Measurement of Moving Objects Using Digital Acoustic Communication and Basis Expansion Model

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1. Introduction

Indoor positioning data is important data for labelling big data and is expected to be used in various fields such as IoT, 5G and disaster prevention. Therefore, there are growing expectations for positioning in dynamic environments using acoustic communications, which can utilize existing indoor broadcasting equipment and smartphones as terminals. In a previous study, the distance to the moving object was successfully estimated by spectral pattern analysis using periodic M-sequence signals[1)]. However, in a dynamic multipath environment, where signals are received at various relative speeds, it would be desirable if time-of-flights (ToFs) could be measured simultaneously at multiple Doppler shifts. We proposed signal modulation and demodulation techniques that can estimate the ToFs at multiple Doppler shifts by using the basis expansion model (BEM). The proposed method can be utilized for acoustic positioning in multipath environments, such as indoors. This paper confirms that the proposed method can estimate the velocity of the receiver (Rx) and the distance between the transmitter (Tx) and the Rx in a dynamic multipath environments with multiple Doppler shifts corresponding to reflections from a wall.

2. Measurement principle of distance and velocity

We would like to show the measurement principle of mobile distance measurement using digital acoustic communication[2)]. We also show the velocity measurement technique, which is newly introduced here. **Figure 1** shows a block diagram of the proposed method in the Tx and Rx. The transmitter modulates M-sequence signal $\boldsymbol{p}$ and obtains $\boldsymbol{x}$, which maps $\boldsymbol{p}$ in the time-frequency domain.

The signal $\boldsymbol{x}$ transmitted from the Tx reaches the Rx under the influence of Doppler and multiple reflections. The received and down-converted signal $\boldsymbol{y}$ can be modeled using BEM as[3)],

$$\boldsymbol{y} = \boldsymbol{x}\sum_{q=-Q}^{Q} \boldsymbol{H}_q \boldsymbol{\Lambda}_q \, , \qquad (1)$$

where $\boldsymbol{H}_q$, $\boldsymbol{\Lambda}_q$ and q represent delay and Doppler shifts, the size of the Doppler shift discretized by the frequency resolution, respectively. The Rx solves Eq. (1) to obtain the impulse response $h_{l,q}$ for each Doppler shift q [**Fig. 2(a)**]. 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 rotation amount of the peak, $\arg(h_{l',q'})$, as,

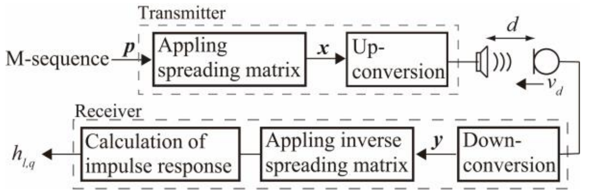

Fig. 1 Block diagram of transmitter and receiver.

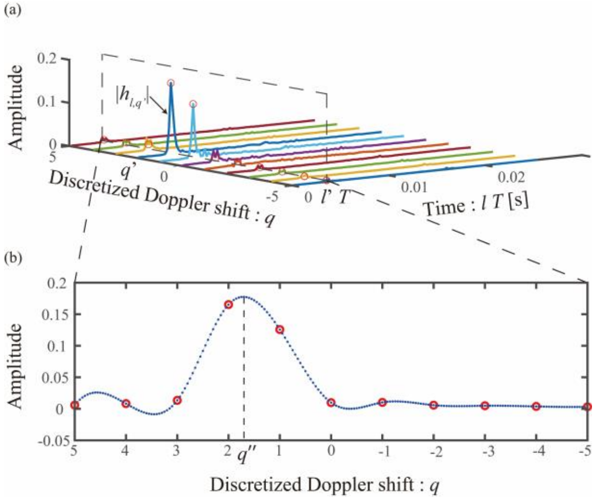

Fig. 2 (a) Example of $h_{l,q}$ obtained and (b) frequency domain of $h_{l',q}$.

$$d = cT\left\{l' + \frac{\arg\left(h_{l',q'}\right)}{\theta_{q'}}\right\}, \qquad (2)$$

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

Figure 2(b) shows the impulse response $h_{l,q}$ in the frequency domain at the peak corresponding to the direct wave. By interpolating the spectrum, which is shown as red circles in the figure, we obtain the peak q'' on the frequency domain and estimate the maximum Doppler shift f_{d} of the direct wave as

$$f_{\mathrm{d}} = \frac{q''}{MNT}, \qquad (3)$$

where M and N are the length of the M-sequence

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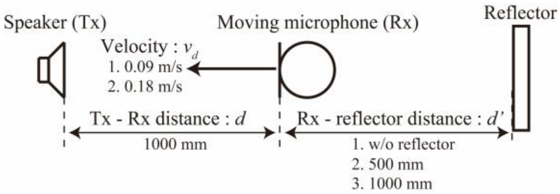


Fig. 3 Experimental environment (top-view).

signal and the repeat number of M-sequence signals, respectively. The Rx velocity v_d can be calculated using the obtained maximum Doppler shift f_d as

$$v_\mathrm{d} = \frac{f_\mathrm{d}}{f_\mathrm{c}} c, \qquad (4)$$

where f_c is the carrier frequency.

3. Experiment

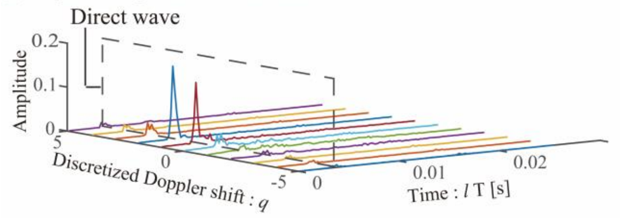
In the experiments, the performance of the proposed method was evaluated in a multipath environment with multiple Doppler shifts corresponding to reflections from walls. The experiment was conducted in an anechoic chamber as shown in **Fig. 3**, where the Tx consists of a PC and software (MATLAB, MathWorks), a digital-to-analog converter (USB-6212, National Instruments), a signal amplifier (AP15d, Foster), and a speaker (P650K, Foster). The Rx consists of the same software as the PC, a digital-to-analog converter (USB-6212, National Instruments), a signal amplifier (MP13, Rolls), and a microphone (PC60, SONY). 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 the Tx at a constant speed of 0.09 and 0.18 (m/s). Communications were triggered when the distance between the Tx and Rx d was 1000 mm, and measurements were performed in three conditions: with a reflector [the distance between the Rx and reflector d' were 500 and 1000 (mm)], and without reflector. 10 measurements were repeated for each condition.

Figure 4 shows an example of the impulse response with and without a reflector. The proposed method simultaneously separates the direct and reflected waves by processing the received signal in the time-frequency domain calculating the impulse response for multiple Doppler shifts, as shown in the figure. **Tables 2** and **3** summarize the average absolute error of the Rx velocity and Tx-Rx distance at each speed. As shown in the tables, the proposed method was able to estimate the Tx-Rx distance with a mean absolute error of approximately 40 and 30 (mm), when the Rx velocity is 0.09 and 0.18 (m/s). The Rx velocity could also be estimated with an error of about 0.02 m/s for each condition. These results show that the Tx-Rx distance and the Rx velocity can be measured stably even in multipath environments with multiple Doppler shifts.

Table 1 Parameters used in experiments.

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

(a) Impulse response without reflector



(b) Impulse response with reflector (Rx-reflector distance : 500mm)

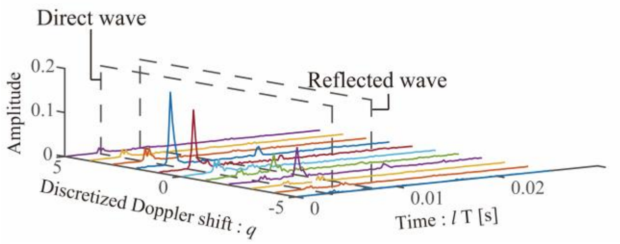


Fig. 4 Comparison of impulse response (a) without and (b) with a reflector.

Table 2 Average absolute error of Rx velocity and Tx-Rx distance when Rx velocity is 0.09 m/s.

Experimental conditions		Average error of velocity (mm/s)	Average error of distance (mm/s)
w/o reflector		23.9	38.2
w/ reflector	d'=500	23.6	38.2
	d'=1000	23.3	42.4

Table 3 Average absolute error of Rx velocity and Tx-Rx distance when Rx velocity is 0.18 m/s.

Experimental conditions		Average error of velocity (mm/s)	Average error of distance (mm/s)
w/o reflector		16.8	25.1
w/ reflector	d'=500	16.2	30.3
	d'=1000	18.1	29.0

4. Conclusions

In this paper, a method for estimating the Tx-Rx distance and Rx velocity using impulse responses modeled by BEM in dynamic environment is proposed, and its performance verified in experiments. The results showed that the proposed method can estimate distance and velocity regardless of the presence of reflectors by processing the received signal in the time-frequency domain.

References

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