1Pa2-2

Separation method for multipath response in time-of-flight measurement using Doppler effect

Atsushi Tsuchiya[1‡], Naoto Wakatsuki[2], Tadashi Ebihara[2], Keiichi Zempo[2]
and Koichi Mizutani[2] ([1]Univ. Tsukuba; [2]Univ. Tsukuba)

1. Introduction

Recently, robot navigation technology has been introduced to automate construction sites and factories. Beacons and vehicle-mounted sensors are elemental technologies for building automated systems[1)]. Vehicle-mounted sensors are essential for measuring the relative position of the vehicle to surrounding structures. Light detection and ranging (LiDAR) and ultrasonic sensors are typical vehicle-mounted sensors[2)]. However, LiDAR cannot detect transparent objects. In addition, false detections occur with light scattering objects such as dust and fog. Ultrasonic sensors can measure accurately even against the glass. However, placing multiple sensors on a circumference is necessary to measure the omnidirectional distance using an ultrasonic sensor.

Therefore, we proposed an all-around ranging method using a single audible source. We proposed a self-position estimation method focusing on the fact that the position can be estimated from impulse response of the room[3)]. However, this method has the problem of reduced detection sensitivity in a multipath environment. This problem is caused by the interference of reflected waves from different paths. We propose a method to separate and detect reflected waves from different directions, focusing on the fact that the Doppler effect occurs differently for each arrival direction of the reflected waves.

2. Proposed methods

Fig. 1 shows the flow of time-of-flights (ToFs) detection. The transmitted signal is a phase-modulated signal by M-sequence. The sequence length of the M-sequence signal is L, the chip rate is R_c, and the sampling rate is f_s. The PC continuously plays this signal. The transmitted signal of length $L \cdot M \cdot (f_\mathrm{s}/R_\mathrm{c})$ is denoted by $s(k)$, and the received signal is denoted by $r(k)$. M is the number of blocks when the sequence length of the M-sequence is one block. $r(k)$ is the signal of interference of reflected waves from all directions. When the robot is moving, different Doppler effects occur for each arrival direction of the reflected wave. Therefore, canceling the Doppler effect in a particular arrival direction can only emphasize the reflected wave in that direction. In practice, this is achieved by computing the cyclic cross-correlation of $r(k)$ resampled by a factor of $1/p_n$ and the transmitted signal $s(k)$, where p_n is $(v_\mathrm{a} - v\cos\theta_n)/(v_\mathrm{a} + v\cos\theta_n)$, v is the robot's moving velocity, v_a is speed of sound wave and θ_n is the arrival direction of the reflected wave. Resampling is calculated by up-sampling, anti-aliasing filter, and down-sampling in that order. The signal computed by the circular cross-correlation is the impulse response corresponding to the respective Doppler frequency. The background difference of their impulse responses $h^n_\mathrm{diff}(k)$ is calculated to remove the direct wave component. The envelope of $h^n_\mathrm{diff}(k)$ is $|h^n_\mathrm{diff}(k)|$. Cell averaging constant false alert rate (CA-CFAR) determines the threshold used for peak detection. When the moving average of $\pm\lambda_\mathrm{ave}$ samples excluding guard cells is $\langle|h^n_\mathrm{diff}(k)|\rangle_{\lambda_\mathrm{ave}}$, $C_\mathrm{th} \cdot \langle|h^n_\mathrm{diff}(k)|\rangle_{\lambda_\mathrm{ave}}$ is used as the threshold value. C_th is a constant threshold parameter. The peak detector detects a value higher than the threshold set by CA-CFAR, and its arrival time is τ_n. Finally, multiple ToFs detected by each detector are merged.

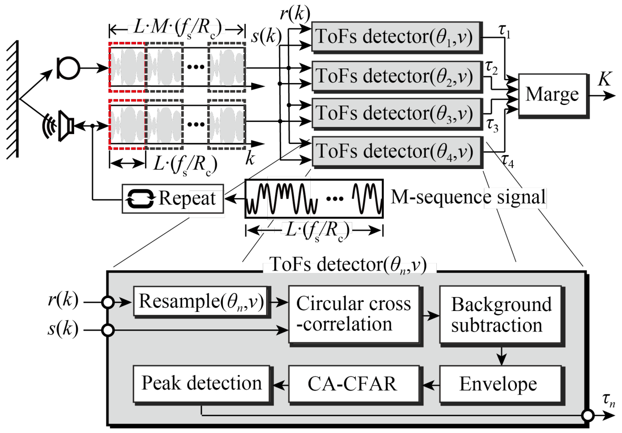

Fig. 1 Schematic diagram of ToF detection.

3. Experiment setup

Fig. 2 shows the experimental environment. The experiment was conducted in an anechoic chamber. The wall material is a plastic plate with a height of 0.9 m. A unit with a microphone (WM-61A; Panasonic) installed on top of a loudspeaker (PT20K; FOSTEX) was moved by a stage (RSB2; MISUMI). The distance moved was 1 m, and the average speed of movement was 0.93 m/s. The

---

e-mail:wakatuki@iit.tsukuba.ac.jp

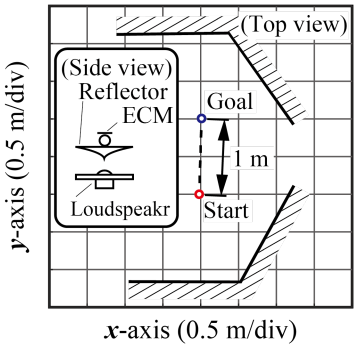

Fig. 2 Experimental environment. The experiment was conducted in an anechoic chamber.

carrier frequency of the M-sequence signal is 10 kHz, the sequence length is 1023, and the chip rate is 10 kcps. θ_n is $(n-1)(\pi/3)$, $n \in \{1,2,3,4\}$. The sampling frequency is 40 kHz, λ_{ave} is 75, and the number of guard cells is 15. The number of false positives N_{FP}, the number of false negatives N_{FN}, and the number of true positives N_{TP} were calculated by

$$a_j = \begin{cases} 1, & \min\limits_i |\kappa_i - \hat{\kappa}_j| > T_{\mathrm{a}} \\ 0, & otherwise \end{cases}, \tag{1}$$

$$b_i = \begin{cases} 1, & \min\limits_j |\hat{\kappa}_j - \kappa_i| > T_{\mathrm{a}} \\ 0, & otherwise \end{cases}, \tag{2}$$

$$N_{\mathrm{FP}} = \sum_j^{|K|} a_j, N_{\mathrm{FN}} = \sum_i^{|\widehat{K}|} b_i, N_{\mathrm{TP}} = |K| - N_{\mathrm{FP}}, \tag{3}$$

where K is the set of measured ToFs, $\widehat{K}$ is the set of true ToFs, κ is an element of K, $\hat{\kappa}$ is an element of $\widehat{K}$, and T_{a} is the error margin.

4. Results and discussion

Fig. 3 shows the results of the measured ToF. The horizontal axis is the ToF value, and the vertical axis is the movement time of the robot stage. **Fig. 3** (a) shows the measurement results of the conventional method without the Doppler effect, and **Fig. 3** (b) shows the measurement results of the proposed method with the Doppler effect. We set the threshold so that precision is close between the conventional and proposed methods. Conventional methods are not sufficiently sensitive to correct data. In particular, the detection sensitivity is low for the front and back walls relative to the direction of motion. The proposed method succeeds in detecting more ToFs than the conventional method. **Fig. 4** shows the sensitivity and precision when the threshold parameter C_{th} is varied. **Fig. 4** (a) shows the results of the conventional method, and **Fig. 4** (b) shows the results of the proposed method. The proposed method achieves higher sensitivity with comparable precision compared to the conventional method. The sensitivity of the proposed method was increased by increasing the number of blocks of M-sequence signals. This effect is due to the increased signal length and frequency resolution resulting from the increased number of blocks.

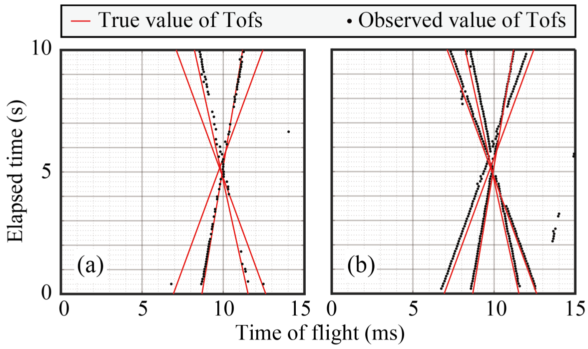

Fig. 3 Results of the measured ToF. (a) Conventional method (M=2) and (b) Proposed method (M=6).

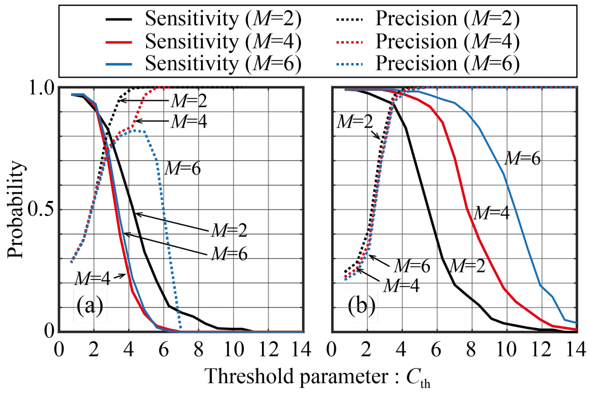

Fig. 4 Sensitivity and precision of ToFs (T_{a} = 1 ms). (a) Conventional method and (b) Proposed method.

5. Conclusion

We proposed a method to separate and detect reflected waves from different directions in a multipath environment. The implementation is based on the fact that the movement of the sound source produces a Doppler effect corresponding to the arrival direction. As a result, high detection sensitivity was achieved with a low false positive rate compared to the conventional method.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 22J20610.

References

1. H. Iwaya, K. Mizutani, N. Wakatsuki, T. Ebihara: Jpn. J. Appl. Phys. **57** (2018) 07LC03.
2. Y. Asakura, K. Okubo, N. Tagawa: Jpn. J. Appl. Phys. **56** (2017) 07JC14.
3. A. Tsuchiya, N. Wakatsuki, T. Ebihara, K. Zempo and K. Mizutani: Jpn. J. Appl. Phys. **61** (2022) SG1037.