ICIC Express Letters
Part B: Applications
Volume **9**, Number **9**, September **2018**

ICIC International ©2018 ISSN 2185-2766
pp. 899–906

IMPLEMENTATION OF A ONE-CHANNEL ACOUSTIC DISTANCE MEASUREMENT METHOD USING THE CROSS-SPECTRUM OF ACTUAL AND PSEUDO OBSERVATIONS

Changryung Song, Toshihiro Shinohara, Tetsuji Uebo and Noboru Nakasako

Faculty of Biology-Oriented Science and Technology
Kindai University
930, Nishi-Mitani, Kinokawa City, Wakayama 649-6493, Japan
{ 1633730014e; sinohara; uebo; nakasako }@waka.kindai.ac.jp

Received February 2018; accepted May 2018

Abstract. *The distance to a target is fundamental information required in many engineering applications. We have previously proposed two acoustic distance measurement (ADM) methods, one based on the phase interference between transmitted and reflected waves and the other using a cross-spectral technique. However, the former method is affected by the components of the measurement system. Furthermore, although the latter method mitigates the influence of the measurement system by applying the cross-spectral method to the recordings obtained by two-channel microphones, this method is sensitive to ambient noise. Therefore, we have also proposed a third ADM method applying the cross-spectral technique to different signals. This method estimates the distance to a target using the cross-spectrum of the actual observation and a pseudo-observation, which is the convolution of a pre-estimated impulse response and the dry source signal. Using the pseudo-observation as an input signal in the cross-spectral method makes this method robust against ambient noise. This paper presents a fundamental study on the proposed ADM method using the cross-spectrum of the actual and pseudo observations. In this study, this method was implemented in a prototype system using a microcontroller. The validity of the method was confirmed by applying it in an actual sound field, and the robustness of the prototype system in which the ADM method was implemented against noise was demonstrated.*

Keywords: Acoustic distance measurement, Prototype system, Microcontroller, Cross-spectral method, Impulse response

1. **Introduction.** The aging population of Japan poses a number of social problems for the country. According to a publication by the Cabinet Office, Government of Japan [1], as of 2016, elderly people (aged 65 and over) comprised 27.4% of the entire population of Japan. This publication also reported that the ratio of elderly people to people of working age (i.e., between 15 and 64 years of age) is projected to be 1:1.3 by 2065 [1]. This estimation suggests that the younger generation will likely need to help a considerable number of elderly people in the future, which is a difficult task for a society to put into practice. To mitigate this problem, nursing robots designed to assist the elderly have recently gained attention and been demanded increasingly.

One fundamental requirement for a nursing robot, as well as devices used in many other engineering applications, is the ability to determine the distance to a target. Currently, robots typically employ triangulation using optical distance sensors [2] or stereo cameras [3] to estimate this distance. However, it is difficult to apply these methods to targets with specular or nonreflective surfaces or to environment with fog or smoke. Furthermore, although microwaves and millimeter waves are also widely used in distance estimation

DOI: 10.24507/icicelb.09.09.899

techniques, the use of such signals is regulated by the Radio Law. In addition to radio signals, acoustic signals, which are propagate even in fog or smoke and are unregulated by the Radio Law, are also widely used for distance estimation.

The acoustic distance measurement (ADM) method generally measures the time of flight (TOF), which is the delay between the transmitted and reflected signals of a wave pulse [4, 5]. However, this method cannot be used to estimate the distance to a target when the transmitted wave interferes with its reflected wave [6]. This means that this method cannot be used to estimate the distance to a close-range target.

A distance measurement method using standing waves to estimate the distance to close-range targets from the phase interference between the transmitted and reflected waves has been proposed in the field of microwave radar [7, 8, 9]. We have applied this method to ADM and have proposed an ADM method based on the phase interference between the transmitted and reflected waves [10, 11, 12]. In this method, the power spectrum of the observed signal accompanied by the phase interference is a periodic function whose period is inversely proportional to the distance from the microphone to the target. Therefore, the distance is estimated as the position of the peak of the range spectrum, which is the absolute value of the Fourier transform of the power spectrum. However, the power spectrum is generally affected by the components of the measurement system, the frequency characteristic of the microphone, the loudspeaker, and such other elements, which influences the distance estimation and produces a spurious peak near 0 m.

Thus, an ADM method based on the phase interference using a cross-spectral method has been proposed [13, 14]. This method uses the cross-spectrum of adjacent two-channel (2ch) microphones as input and output signals. Because the influence of the measurement system on the signals recorded using adjacent 2ch microphones can be regarded as approximately equivalent, the influence can be removed using the cross-spectrum of the two signals. However, to remove the influence of measurement system, this method requires the use of 2ch microphones, which are easily influenced by ambient noise. To overcome this problem, we have proposed an ADM method based on phase interference using the cross-spectrum of the actual observation and the pseudo-observation [15]. In this method, the pseudo-observation is the convolution of a pre-estimated impulse response without a target and the dry source signal. Because the pre-estimated pseudo-observation is used as an input signal in obtaining the cross-spectrum, this method uses a one-channel (1ch) microphone and is thus little influenced by the ambient noise.

In this study, toward the realization of effective nursing robots, robots for engineering applications, and vehicles with accurate distance sensing systems, the previously developed 1ch ADM method using the cross-spectrum of the actual and pseudo observations [15] was implemented in a prototype system. The effectiveness of the prototype system was confirmed through a distance estimation experiment in an actual sound field, and the robustness of the proposed method in a noisy environment was demonstrated.

2. **Principles of the ADM Method Using the Cross-Spectrum of the Actual and Pseudo Observations.** This section provides the previously developed 1ch ADM method using the cross-spectrum of the actual and pseudo observations [15]. As shown in Figure 1, the coordinate system is defined such that the loudspeaker, microphone, and target all lie on the x-axis. The transmitted wave $v_{\mathrm{T}}(t, x_s)$ is then represented as

$$v_{\mathrm{T}}(t, x_s) = \int_{f_1}^{f_N} A(f) e^{j\left(2\pi f t - \frac{2\pi f}{c} x_s + \theta(f)\right)} \mathrm{d}f, \tag{1}$$

where t [s] is time; x_s [m] is the position of the microphone; f [Hz] is the frequency; f_1 [Hz] and f_N [Hz] are the minimum and maximum frequencies in the spectrum, respectively; c [m/s] is the sound velocity; $A(f)$ is the amplitude of the transmitted wave; and $\theta(f)$ [rad]

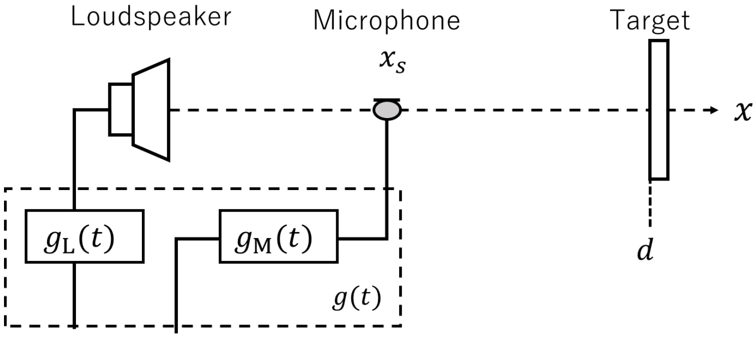


Figure 1. Measurement environment

is the initial phase. Furthermore, the wave $v_{\mathrm{R}}(t, x_s)$ reflected from the target is then represented as

$$v_{\mathrm{R}}(t, x_s) = \int_{f_1}^{f_N} A(f)\gamma e^{j\phi} e^{j\left(2\pi f t - \frac{2\pi f}{c}(2d - x_s) + \theta(f)\right)} \mathrm{d}f, \tag{2}$$

where $\gamma e^{j\phi}$ is the reflection coefficient and d [m] is the position of the target.

In an actual sound field, the influence of the components of the measurement system, including the microphone, the loudspeaker, and other such elements, must be considered; this is achieved by using a function called the impulse response $g(t)$. The actual observation is then represented by the convolution of the impulse response $g(t)$ and the composite wave $v_{\mathrm{C}}(t, x_s)$ $(= v_{\mathrm{T}}(t, x_s) + v_{\mathrm{R}}(t, x_s))$ as

$$v_{\mathrm{C_A}}(t, x_s) = g(t) * v_{\mathrm{C}}(t, x_s) + g_{\mathrm{M}}(t) * w(t), \tag{3}$$

where $g(t)$ is the impulse response including the impulse responses $g_{\mathrm{L}}(t)$ for the transmission system and $g_{\mathrm{M}}(t)$ for the sound receiving system, $w(t)$ is additive ambient noise, and $*$ is the convolution operator. Furthermore, the pseudo-observation is represented by the convolution of the pre-estimated impulse response without the target and the transmitted wave as

$$v_{\mathrm{C_P}}(t, x_s) = g(t) * v_{\mathrm{T}}(t, x_s). \tag{4}$$

The Fourier transform is then applied to Equations (3) and (4), respectively, as

$$V_{\mathrm{C_A}}(f, x_s) = A(f)G(f)V_{\mathrm{C}}(f, x_s) + G_{\mathrm{M}}(f)W(f), \tag{5}$$

$$V_{\mathrm{C_P}}(f, x_s) = A(f)G(f)V_{\mathrm{T}}(f, x_s). \tag{6}$$

Furthermore, the cross-spectral method is applied using Equations (6) and (5) as the input and output signals, respectively, as

$$C(f, x_s) = \frac{V_{\mathrm{C_P}}^*(f, x_s)V_{\mathrm{C_A}}(f, x_s)}{|V_{\mathrm{C_P}}(f, x_s)|^2} + \widehat{W}(f), \tag{7}$$

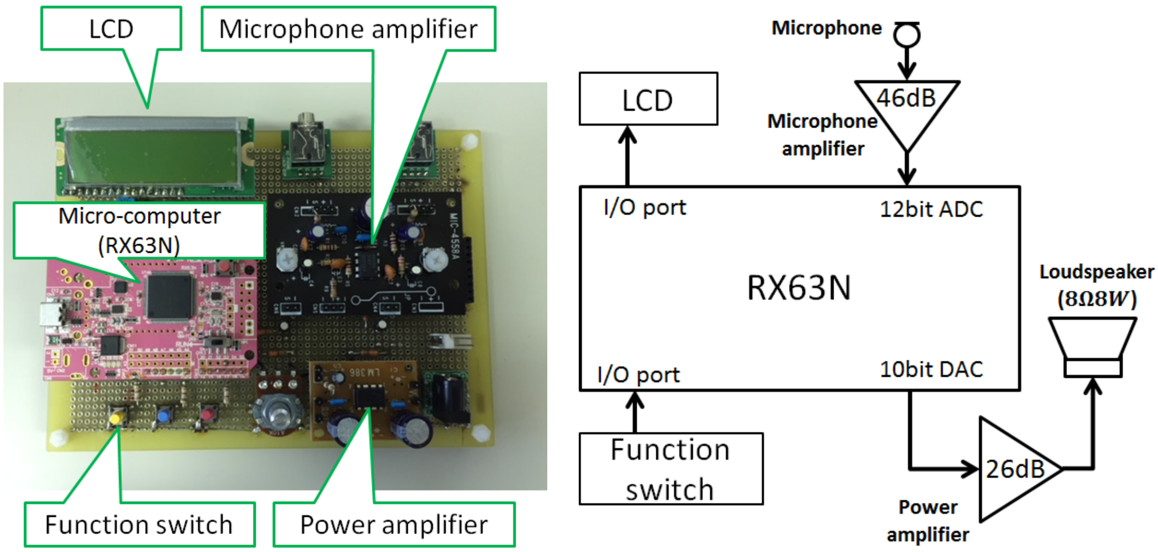
$$\widehat{W}(f) = \frac{A^*(f)G^*(f)G_{\mathrm{M}}(f)W(f)e^{-\left(\frac{2\pi f}{c}x_s\right)}}{|A(f)G(f)|^2}, \tag{8}$$

where * is the complex conjugate. With $\widehat{W}(f)$ considered negligible, when $\gamma \ll 1$, the power spectrum of $C(f, x_s)$, given by $p(f, x_s) = |C(f, x_s)|^2$, can be approximated as follows:

$$p(f, x_s) \approx 1 + 2\gamma \cos\left(\frac{4\pi f}{c}(d - x_s) - \phi\right). \tag{9}$$

The first term in Equation (9) is the direct current (DC) component, which corresponds to the transmitted signal. The second term, which corresponds to the phase interference, is a periodic function whose period is inversely proportional to the distance $d - x_s$ from the microphone to the target. Therefore, the distance can be estimated by applying a Fourier transform to the delta power spectrum $\Delta p(f, x_s)$ obtained by removing the DC component from Equation (9): $P(x) = \int_{f_1}^{f_N} \Delta p(f, x_s) e^{-j2\pi \frac{2x}{c} f} \mathrm{d}f$. $|P(x)|$ is referred to as the range spectrum, and the position of the maximum value of $|P(x)|$ is the estimated distance from the microphone to the target. Then, the minimum measurable distance is $d_{\min} = \frac{c}{2(f_N - f_1)}$.

3. **Prototype System Using a Microcontroller.** To realize the ADM method, a prototype system using a microcontroller was constructed. Figures 2(a) and 2(b) show the appearance and block diagram of the prototype system, respectively. The circuit board for the system contains a microcontroller, microphone amplifier, power amplifier, liquid crystal display (LCD), and function switch. The RX63N microcontroller (Renesas) is a 32-bit central processing unit (CPU) with floating point unit that operates at 96-MHz clock frequency.



(a) Appearance (b) Block diagram

FIGURE 2. Prototype of the proposed system

A time-stretched pulse (TSP) signal [16] pre-recorded to the microSD card was used to pre-estimate the impulse response without the target. The transmitted signal was generated using a 10-bit digital-to-analog (D/A) converter built into the RX63N microcontroller. The observed signals were imported back into the RX63N using a 12-bit analog-to-digital (A/D) converter. In all processing steps, the sampling frequency was 44.1 kHz.

4. **Evaluation of the Prototype System.** The effectiveness of the prototype system is confirmed through a distance estimation experiment in an actual sound field. Furthermore, by adding computer-generated noise to experimentally recorded observations, the robustness of the prototype system against noise is confirmed.

4.1. **Experimental methods.** To obtain the pseudo-observation, the impulse response without the target is estimated using a TSP signal. The pseudo-observation is calculated and recorded in the microcontroller. Thereafter, actual observations are obtained with a target present. The distance estimation is performed using the actual and pseudo-observations and is output on the LCD.

4.2. **Experimental conditions.** Tables 1 and 2 list the components of the experimental apparatus and describe the conditions of the experiment, respectively. Figure 3 shows the experimental setup. The experiment is performed in an isolated portion of a room (depth: 6.14 m, width: 7.43 m, height: 2.71 m). A band-limited impulse signal with a bandwidth of 5.5 kHz ($= f_W$) from 2.1 kHz ($= f_1$) to 7.6 kHz ($= f_N$) is used as the transmitted signal. For this bandwidth, the minimum measurable distance is $d_{\min} \approx 31.06 \times 10^{-3}$ m. The number of sampling points of the delta power spectrum is 256 and increased to 2048 by 0-padding. Then by applying fast Fourier transform (FFT), the range spectrum is derived at $d_{\min} \times \frac{256}{2048} \approx 3.9 \times 10^{-3}$ m intervals.

Table 1. Experimental apparatus

Target	Plywood square (H: 30 cm × W: 30 cm × D: 0.5 cm)
Micro-SD card	TRANSCEND JAPAN, TS8GUSDHC4
Microphone	AUDIO-TECHNICA, AT9904
Loudspeaker	8 Ω 8 W
Speaker drive amplitude	3 V (max)
Microphone amplifier gain	46 dB
Sampling frequency	44.1 kHz
Quantization	12 bit (A/D), 10 bit (D/A)

Table 2. Experimental conditions

Transmitted signal	Band-limited impulse
Data points (time domain)	2048
Room temperature	17°C
Sound speed	341.7 m/s
Sampling points of TSP	2^{15}
Tap number of impulse response	500
Distance from loudspeaker to microphone	0.5 m
Distance from microphone to target	1 m

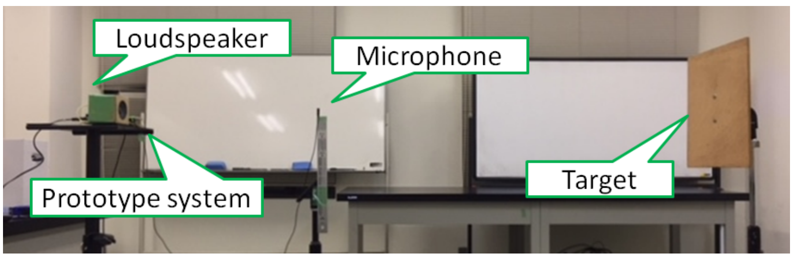
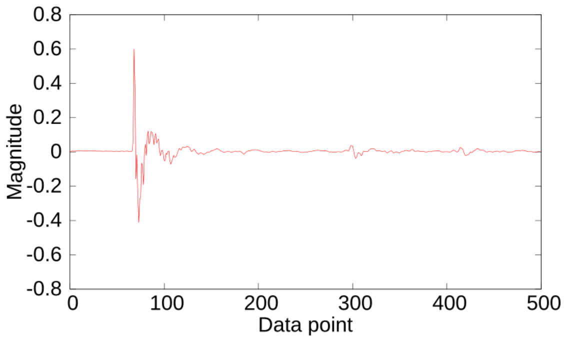
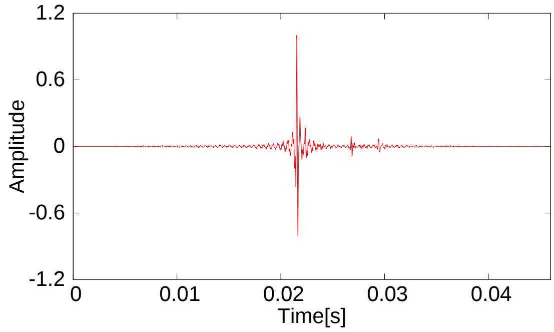


Figure 3. Experimental setup

4.3. **Experimental results.** Figures 4(a) and 4(b) show the pre-estimated impulse response and the pseudo-observation, respectively. Figures 5(a)-5(d) show the actual observation, the delta power spectrum, the range spectrum, and the estimated distance displayed on the LCD, respectively. As shown in Figure 5(b), the fundamental frequency component of the delta power spectrum has a period that is inversely proportional to the distance $d - x_s$ from the microphone to the target; this is clearly indicated by the large peak in the corresponding range spectrum (Figure 5(c)). The position of this peak is the estimated distance, and it is output on the LCD in the prototype system (Figure 5(d)).

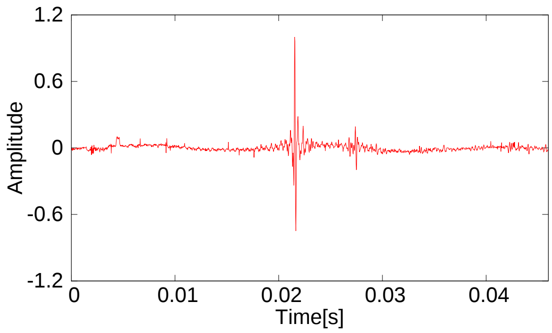


(a) Impulse response (without target)

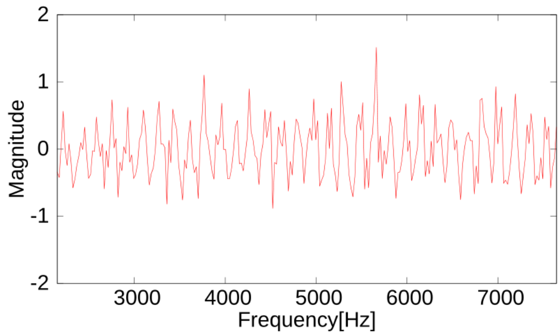


(b) Pseudo-observation

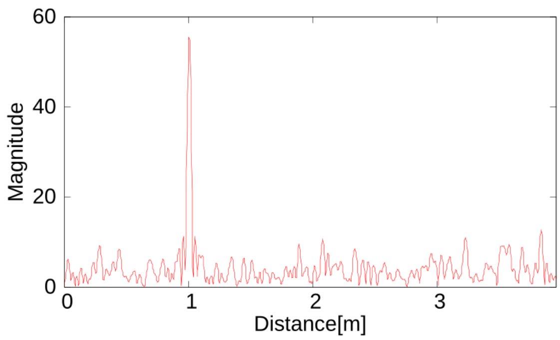
FIGURE 4. Pre-estimated signals



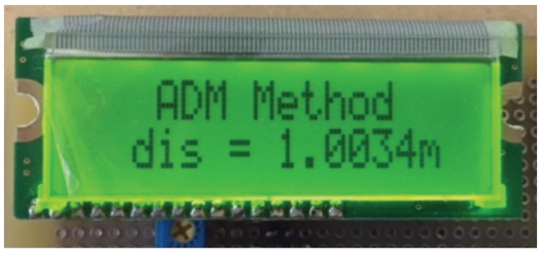
(a) Actual observation



(b) Delta power spectrum



(c) Range spectrum



(d) Estimated distance (output on LCD)

FIGURE 5. Distance estimation results

The estimated distance in this experiment was 1.0034 m, and the actual distance was 1 m. Thus, the experimental error of 3.4×10^{-3} m was less than the error tolerance (i.e., the stride of the distance domain) of 3.9×10^{-3} m.

4.4. **Noise robustness of the prototype system.** Figure 6 shows the error of the estimated distance with respect to the true distance for signal-to-noise ratios (SNRs) ranging from 10 to 0 dB. The error tolerance is indicated by a dashed line in this figure. The experimental error was smaller than the error tolerance for SNRs ranging from 10 to 4 dB. However, it exceeded the tolerance for SNRs from 3 to 0 dB.

5. **Conclusions.** In this study, the previously proposed 1ch acoustic distance measurement technique using the cross-spectrum of the actual and pseudo observations [15] was implemented in a prototype system using a microcontroller. In an experiment in an actual sound field, the distance from the microphone to the target was estimated as 1.0034 m

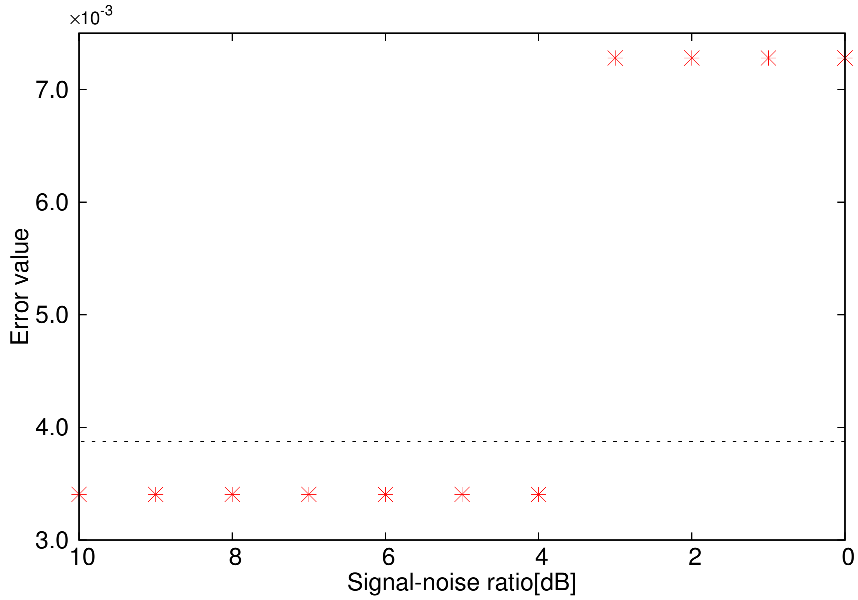


Figure 6. Experimental error with added noise for different SNRs

for an actual distance of 1 m; this is within the error tolerance of 3.9×10^{-3} m. Furthermore, the robustness of the prototype system in a noisy environment was confirmed by adding noise to the recorded signal with SNRs ranging from 10 to 0 dB. Under these conditions, the prototype system was able to estimate the distance within the error tolerance for SNRs ranging from 10 to 4 dB. These results suggest that the prototype system is sufficiently accurate and robust for practical use. However, although the prototype system is effective when the impulse response without a target can be pre-estimated, it is difficult to pre-estimate the impulse response in practical scenarios. Thus, alternatives to the pre-estimation method will need to be considered in future work.

Acknowledgment. This work was supported in part by a Grant-in-Aid for Scientific Research (No. 17K06473) and the MEXT-Supported Program for the Strategic Research Foundation at Private Universities, 2013-2017 (S1311045).

REFERENCES

[1] Cabinet Office, Goverment of Japan, *The Current State of Aging and Future*, http://www8.cao.go.jp /kourei/whitepaper/w-2017/html/zenbun/s1_1_1.html, 2018 (in Japanese).
[2] A. Shiratsuki, Optical workshop – Distance measurement using light, *Optics*, vol.36, no.9, pp.542-543, 2007 (in Japanese).
[3] Y. D. Salman, K. R. Ku-Mahamud and E. Kamioka, Distance measurement for self-driving cars using stereo camera, *Proc. of the 6th International Conference on Computing and Informatics*, Kuala Lumpur, Malayasia, pp.235-242, 2017.
[4] D. Marioli, C. Narduzzi, C. Offelli, D. Petri, E. Sardini and A. Taroni, Degital time of flight measurement for ultrasonic sensors, *IEEE Trans. Instrum. Means*, vol.41, no.1, pp.93-97, 1992.
[5] M. Okugumo, A. Kimura, M. Ohki and M. Ohkita, Development research on high performance ultra-sound sensor system, *IEEJ Trans. Electronics, Information and Systems*, vol.128, no.1, pp.55-61, 2008 (in Japanese).
[6] K. Itoh, *Story of Ultrasonic*, Nikkan Kogyo Shimbun Ltd., Tokyo, Japan, 1982 (in Japanese).
[7] T. Uebo, T. Kitagawa and T. Iritani, Short range radar utilizing standing wave of microwave or millimeter wave, *Proc. of IEEE Intelligent Vehicles Symposium*, pp.95-99, 2001.
[8] T. Uebo, Y. Okubo and T. Iritani, Standing wave radar capable of measuring distance down to zero meters, *IEICE Trans. Communications*, vol.E88-B, no.6, pp.2609-2615, 2005.
[9] T. Uebo, Measurement of distance down to zero meters by standing wave radar, *IEEJ Trans. Electronics, Information and Systems*, vol.125, no.11, pp.1646-1651, 2005 (in Japanese).

[10] N. Ohmata, N. Nakasako, T. Uebo and A. Mori, Distance measurement by audible sound (utilization of band-limited signal with random phase), *Proc. of the China-Japan Joint Conference of Acoustics 2007 (JCA2007)*, pp.1-6, 2007.

[11] N. Nakasako, T. Uebo, A. Mori and N. Ohmata, Fundamental consideration on distance estimation using acoustical standing wave, *IEICE Trans. Fundamentals of Electronics, Communications and Computer Sciences*, vol.E91-A, no.4, pp.1218-1221, 2008.

[12] T. Uebo, N. Nakasako, N. Ohmata and H. Itagaki, Distance estimation to multiple target using band-limited noise signal, *IEEJ Trans. Electronics, Information and Systems*, vol.128, no.7, pp.1117-1122, 2008 (in Japanese).

[13] M. Nakayama, N. Nakasako, T. Uebo and M. Fukushima, Acoustic distance measurement method based on phase interference using the cross-spectral method, *Acoustical Science and Technology*, vol.34, no.3, pp.197-205, 2013.

[14] M. Nakayama, K. Suzuki and N. Nakasako, Acoustic distance measurement based on phase interference using the cross-spectral method with adjacent microphones, *Proc. of IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp.423-427, 2013.

[15] S. Honda, N. Nakasako, T. Shinohara and N. Nakayama, Estimation of the distance to sound source based on phase interference using cross-spectrum between actual and pseudo observed waves of a single-channel microphone, *IEEJ Trans. Electronics Information and Systems*, vol.136, no.11, pp.1525-1531, 2016 (in Japanese).

[16] Y. Suzuki, F. Asano, H. Y. Kim and T. Sone, An optimum computer-generated pulse signal suitable for the measurement of very long impulse response, *The Journal of the Acoustical Society of America*, vol.97, pp.1119-1123, 1995.