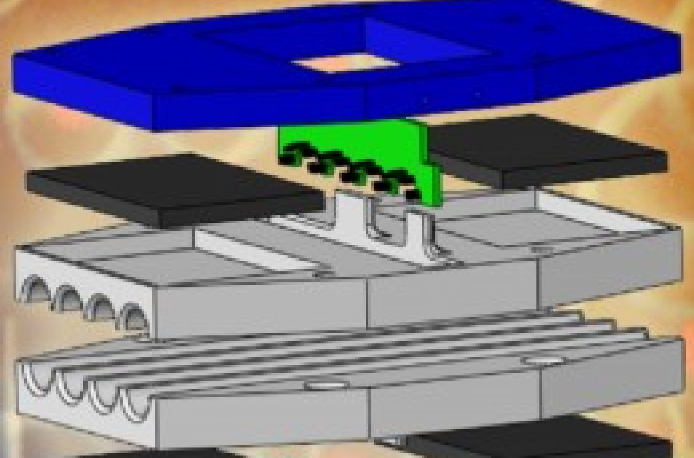
ISSN 1726-5749

SENSORS & TRANSDUCERS

12/10
vol. 9
Special



Modern Sensing Technologies III

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 9, Special Issue, December 2010

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

Sensors & Transducers Journal

Contents

Volume 9
Special Issue
December 2010

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol. 9, Special Issue, December 2010, pp. 56-70

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Extended Phase Accordance Method: A Real-time and Accurate Technique for Estimating Position and Velocity of Moving Objects Using Ultrasonic Communication

[1]Tomohiko SATO, [1]Shigeki NAKAMURA, [1]Masanori SUGIMOTO and [2]Hiromichi HASHIZUME

[1]Graduate School of Engineering, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan
Tel.: 81-3-5841-6394
[2]Information Systems Architecture Science Research Division, National Institute of Informatics,
2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430 Japan
E-mail: {tomo,shigeki,sugi}@itl.t.u-tokyo.ac.jp, has@nii.ac.jp

Received: 27 September 2010 /Accepted: 30 November 2010 /Published: 30 December 2010

Abstract: The Phase Accordance Method, as previously proposed by the authors, shows a high level of accuracy in localizing static objects. However, its performance degrades when localizing moving objects because of the Doppler effect. In this paper, we propose an extension of the Phase Accordance Method, called the Extended Phase Accordance Method, to cancel the errors in localizing moving objects. Moreover, with this method we can obtain the velocities of objects, along with their positions, by using a combined ultrasound waveform of two different frequency carriers of a known power ratio. The fine point of the proposed method is that it uses virtually the same algorithm as the original position-only method but it can estimate positions and velocities simultaneously and hence achieve real-time tracking of moving objects. Through computer simulations and real-world experiments, we have proved that the proposed method has the same level of accuracy as the Phase Accordance Method. In real-world experiments, the Extended Phase Accordance Method achieved less than 1 mm standard deviation in the 1.0–1.8 m distance measurement of a moving object whose velocity ranged from –1.5 m/s to 1.5 m/s. *Copyright © 2010 IFSA.*

Keywords: Localization, Tracking, Velocity estimation, Doppler effect.

---

1. Introduction

Position data play an essential part in location-aware computing, which provides location-related services to individual users. The Global Positioning System (GPS) is widely used in outdoor environments to obtain location information; however, the GPS is not usually available for indoor situations. Therefore, many studies have been conducted for developing indoor localization systems [1] based on ultrasound, radio frequency (RF), optical sensing, and related techniques. Above all, ultrasonic-based systems have been studied actively because they can be implemented easily and at low cost.

Localization systems include two types of devices: beacons and a target. To locate the target in a three-dimensional space, multiple beacons are required (e.g. GPS uses three or four satellites as beacons). Therefore, the performance of localization systems is evaluated by positioning accuracy, the number of required beacons, localizable area, and ease and cost of deployment.

As well as the positioning ability in static situations, the accuracy of moving targets is also considered an important performance metric of localization systems. In some applications, we need to track objects that have complex movements such as sudden starts, stops, and turns. Such requirements are found in precise indoor navigation, robot tracking, motion captures [2], etc. For such applications, velocity data of moving objects are useful if we can measure velocity and the position data simultaneously to correct and interpolate the trajectory.

In our past papers, we proposed an indoor localization system and its application using the Phase Accordance Method [3, 4]. The method uses an ultrasonic signal of two component carrier frequencies. The two carriers have the same phase value only once in the waveform. The timing of the phase accordance can be computed precisely; hence, that point can be used as a reference for the time-of-arrival (TOA)-based localization procedures. The method has shown extremely high performance in localizing a static object. To measure the distance between a transmitter and a receiver placed 3 m apart, we obtained the value with a standard deviation of 0.2 mm. Using two receiver sensors at 80 mm distance, we obtained the orientation of the same transmitter with a standard deviation of 0.5 degrees. However, when we tracked a moving transmitter we observed that the performance was degraded because of the Doppler effect. Thus, in our previous paper [5], we proposed a new method called the Extended Phase Accordance Method to compensate for the Doppler effect and to accurately and rapidly localize a moving transmitter.

The proposed method uses the same waveform as the Phase Accordance Method, and it extracts the velocity from the power ratio of the two component carrier waves to identify accurately their Doppler shift frequencies. The fine point of the method is that it is capable of correcting the distance measurement error of a moving object while simultaneously obtaining the velocity data. Moreover, the algorithms to obtain the distance and the velocity share the same core algorithm as the Phase Accordance Method, and the velocity measurement can be carried out without a substantial increase in computation time. Through evaluations of the proposed method, we confirmed that the method showed the same level of performance for estimating positions of moving objects as the Phase Accordance Method for static objects.

In addition to the proposed algorithm and the experimental results described in the previous paper [5], the present paper reports in detail the additional experimental results of computer simulations and in real-world environments. The results show that the proposed method is effective in dynamic tracking situations. This paper also details the mathematical explanations of the Phase Accordance Method and the proposed method.

The paper is organized as follows. Section 2 shows the related work, and then the next two sections describe the Phase Accordance Method and the Extended Phase Accordance Method. Experiments for evaluating the performance of the Extended Phase Accordance Method in computer simulations and in real-world experiments are intensively discussed in Sections 5 and 6. Finally, our conclusions and plans for future work in this research area are given.

2. Related Work

Active Bat [6] uses an ultrasonic transmitter as a target, called the Bat, and beacon receivers are installed in the environments. This system uses the TOA technique, and conducts target localization with a median error of 6 cm. The Cricket location system [7] has been augmented with the extended Kalman Filter, and it has been used as a position tracking system [8] in an experiment using a model train moving at 1.43 m/s. The experiment used six beacons, and showed that the median error was 4 cm. The Cricket Compass [9] is an extended version of the Cricket. This system measures the orientation of the target to identify its position by using the angle-of-arrival (AOA) technique. The localization error of the system was reported to be around 5 cm.

Hazas et al. [10] developed a localization system using modulated ultrasonic signals with Gold Codes. Because of the wide-band frequency of the transmitted signal, which achieves high resolution in the time domain, its distance measurement became accurate, and the localization error was reported to be 2.5 cm.

McCarthy et al. [11] proposed an algorithm to calibrate the beacons automatically. With this method, the beacons could be placed at any position. The position measurement had a standard deviation of 1.1 cm. They also proposed a localization system that uses the Doppler effect within observed periods of ultrasonic packet sequences to measure the displacements between the beacons and the target [12, 13]. Tracking experiments using eight beacons were conducted, and the 50 % CEP (circular error probability) was reported to be around 25 cm.

Kuang et al. [14] proposed a robot tracking system that combined time-of-flight (TOF)-based distance measurement with Doppler effect estimation. When the robot moved, the duration of an ultrasonic pulse varied along with the velocity of the robot because of the Doppler effect, indicating displacements in distance. A distance of 211 mm was measured to an accuracy of ± 0.06 mm in 3-sigma error. A frequency measurement method using the Doppler effect of ultrasound to track high-speed robot motion was also proposed [15]. To reduce the computation cost for processing the 40 kHz transmitted ultrasound signal, the signal was down-converted to 1 kHz. By using a short-time Fourier Transform and an adaptive filter constructed with a wavelet packet filter bank, this system measured a frequency shift of around 80 Hz in mean squared error.

Imou et al. [16] developed a frequency estimation method to detect the speed of a slow moving vehicle. The measurement system was based on ultrasound echoes. The transmitted signal of 200 kHz was reflected off the ground, and the received signal with the Doppler shift was up-converted to 1 MHz and mixed with a reference frequency of 950 kHz. The beat frequency of 50 kHz varied with the Doppler effect and was used to estimate the velocity of a vehicle. This technique was effective at measuring a slow moving object and could detect speeds as low as 10 mm/s. The percentage error of velocity estimation at 0.7 m/s, 1.0 m/s, and 1.5 m/s was reported to be less than 1.63 %.

Maróti et al. [17] proposed a localization technique using radio interferometry. This system used the relative phase offset of beat signals received at two nodes to estimate the relative distances between four nodes involving the receiver nodes. RF signals whose frequencies are between 400 and 460 MHz were used so that their resulting beat signals had frequencies between 100 and 800 Hz. The two-dimensional localization experiments using 16 nodes were conducted in outdoor situations, on a flat grassy area

(18 m × 18 m), without obstacles, and the average accuracy was reported to be 3 cm. This system was extended as a radio interferometric tracking system by Kusý et al. [18]. When the localized nodes moved, the changes in the frequency and wavelength of the beat signal were observed at receiver nodes. The two-dimensional tracking experiments were carried out with two target nodes and five observing nodes. The average absolute error of 100 velocity measurements at each node was 0.18 m/s, and the 95th-percentile calculation was 0.45 m/s.

The remarkable difference between these existing systems and the proposed method is that our method can accurately locate a transmitter in a three-dimensional space by using only one compact receiver unit [20], because of the accurate measurement of the distance between the transmitter and the receiver sensor. Moreover, our method can accurately and rapidly estimate the Doppler effect of ultrasound signals. The technical details are explained in the following sections.

3. Phase Accordance Method

3.1. Algorithm

The Phase Accordance Method can estimate the arrival time of the ultrasonic burst signal very accurately. The burst signal, called a synchronized pattern (we call it a sync pattern), is a beat signal composed of two ultrasonic sine waves whose frequencies are different from each other, as shown in Fig. 1. In the sync pattern, the phases of two ultrasonic carrier waves accord at only one time point, called an epoch. The epoch is used as a reference point to determine the propagation time of the sync pattern. The detection of the epoch by the Phase Accordance Method is described below.

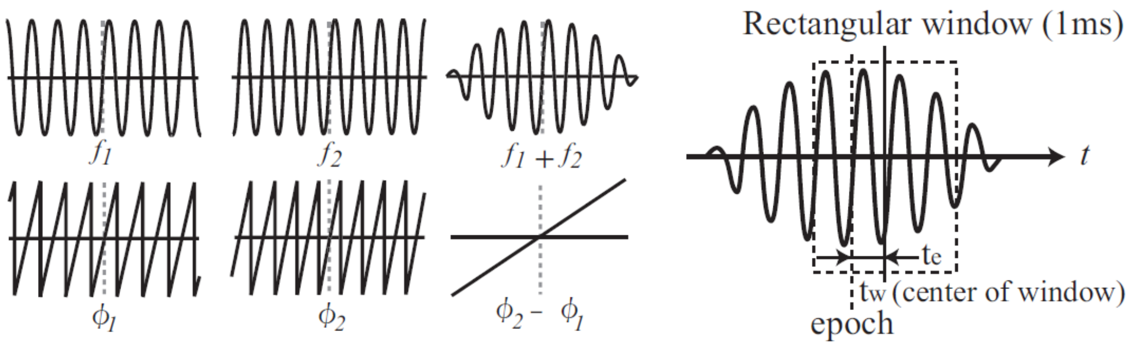


Fig. 1. Sync pattern and epoch.

Mathematically the sync pattern is expressed as:

$$s(t) = a_1 \sin(\omega_1 t + \phi_1) + a_2 \sin(\omega_2 t + \phi_2) = a_1 \sin(2\pi f_1 t + \phi_1) + a_2 \sin(2\pi f_2 t + \phi_2)\,, \tag{1}$$

where a_1, a_2 are amplitudes, and f_1, f_2 are frequencies of two carrier waves. The phases, ϕ_1 and ϕ_2, are identified by conducting quadrature detection and are calculated through the inner products of a sync pattern and complex exponential functions of the corresponding frequencies as shown in equation (2). Let us define the inner product of a sync pattern $s(t)$ and $e^{j\Omega t}$ as:

$$\left\langle s(t), e^{j\Omega t} \right\rangle \equiv \frac{1}{T} \int_{-T/2}^{T/2} s(t)\ e^{-j\Omega t} dt \ = I_\Omega + jQ_\Omega\,. \tag{2}$$

In this equation, time T is the integration interval of a rectangular window and the frequency Ω is called a reference frequency. When the reference frequency is ω_1, we get the equations below by inner product:

$$I_{\omega_1} = \frac{1}{2}\left(\operatorname{sinc}\omega_1 T + 1\right)\cdot a_1 \sin\phi_1 + \frac{1}{2}\left\{\operatorname{sinc}(\omega_1+\omega_2)\frac{T}{2} + \operatorname{sinc}(\omega_1-\omega_2)\frac{T}{2}\right\}\cdot a_2 \sin\phi_2 , \tag{3}$$

$$Q_{\omega_1} = \frac{1}{2}\left(\operatorname{sinc}\omega_1 T - 1\right)\cdot a_1 \cos\phi_1 + \frac{1}{2}\left\{\operatorname{sinc}(\omega_1+\omega_2)\frac{T}{2} - \operatorname{sinc}(\omega_1-\omega_2)\frac{T}{2}\right\}\cdot a_2 \cos\phi_2 . \tag{4}$$

$a_1 \sin\phi_1$, $a_1 \cos\phi_1$, $a_2 \sin\phi_2$, and $a_2 \cos\phi_2$ are unknowns in the equations above, and $I_{\omega_2} + jQ_{\omega_2}$, calculated with reference frequency ω_2, are used to solve for these unknowns. Therefore, the amplitudes, a_1 and a_2, and phases, ϕ_1 and ϕ_2, of a sync pattern are obtained by solving a set of equations. The epoch is identified, and the time delay, t_e, is calculated by using equation (5). Then, the total time-of-flight, t_{TOF}, of a sync pattern estimated with t_w, the center of window, is obtained by equation (6).

$$t_e = -\frac{\phi_1 - \phi_2}{\omega_1 - \omega_2} , \tag{5}$$

$$t_{TOF} = t_w + t_e . \tag{6}$$

In our current implementation, we use a sync pattern consisting of carrier waves whose frequencies are 39.75 and 40.25 kHz and that last 2 ms each. By processing the T = 1 ms waveform from the received sync pattern, the Phase Accordance Method can conduct 3 m distance measurements with 0.18 mm standard deviations [4]. This is almost 1 % of the standard deviation of the previously reported systems using the TOA technique.

3.2. Localization Using Phase Accordance Method

The AOA technique usually tries to identify a phase difference of a transmitted signal received by different sensors; then, it calculates the difference of their propagation path length, which is used for orientation estimation, as shown in Fig. 2. This is because the propagation path difference can be correctly identified through the phase difference, rather than TOF-based distance measurements. One serious obstacle to using the AOA technique based on the phase difference is the 2π-phase ambiguity problem. To avoid this, the Cricket Compass system employed five microphones to resolve the ambiguity. Because of the accurate distance estimation of the Phase Accordance Method, it can implement both the TOA and AOA techniques simultaneously. This is the remarkable difference from existing localization systems and it allows us to design a very compact receiver unit [3, 19, 20].

Fig. 2 demonstrates how to measure the distance and angle between a transmitter and a receiver unit. The distances, $d1$ and $d2$, between two ultrasonic sensors on the single receiver unit and an ultrasonic transmitter are calculated accurately enough to estimate the angle. Then, the angle of arrival, θ, which is estimated by the difference between $d1$ and $d2$, is calculated as:

$$\theta = \sin^{-1} \frac{d_2 - d_1}{L}, \tag{7}$$

where the baseline, L, is the distance between the two ultrasonic sensors on the receiver. Since the Phase Accordance Method can conduct accurate distance measurements, the baseline, L, can be set small (in our current implementation, L = 76.2 mm) while retaining an accurate estimation of the angle of arrival.

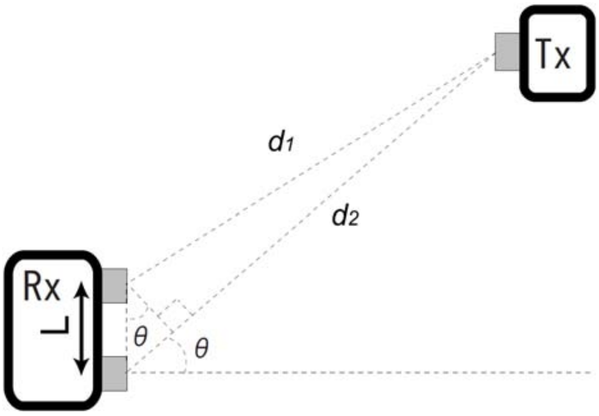


Fig. 2. Distance and orientation measurement using the Phase Accordance Method.

3.2. Issues in Localizing a Moving Object

In the Phase Accordance Method, received frequencies are assumed to be fixed to ω_1 and ω_2, as a transmitter and a receiver are placed statically. However, in positioning moving objects, received frequencies of a sync pattern vary to unknown frequencies $\omega_1^{'}$ and $\omega_2^{'}$, owing to the Doppler effect. Therefore, phases ϕ_1 and ϕ_2 are detected incorrectly, and equation (5) gives a false t_e. The error in distance measurements becomes several centimeters, which does not provide an advantage over conventional methods.

If we can identify the received frequencies $\omega_1^{'}$ and $\omega_2^{'}$, the correct phases, ϕ_1 and ϕ_2, can be obtained by calculating equation (5). Given are c, the velocity of sound (at room temperature, about 340 m/s in air), and v, the velocity of a moving transmitter that transmits a signal of frequency f. Then, the frequency at the static receiver is observed as:

$$f^{'} = \frac{c}{c - v} f\ . \tag{8}$$

Fig. 3 shows the frequency spectra of a Doppler-shifted sync pattern. Such a frequency shift can be estimated by the peak spectrum calculated by using an FFT (Fast Fourier Transform). In this case, frequency spectra from 0 to ± 1/2 × (sampling frequency) are calculated, which requires significant computation. Because the magnitude of the velocity to be estimated in this study is at most a human's walking speed (about 1.5–2.0 m/s), which is much smaller than the velocity of sound, the maximum frequency shift is approximately ± 240 Hz. Therefore, to detect the Doppler effect, a small part of the frequency domain that includes the maximum frequency shift should be investigated. However, to identify precisely the Doppler shift, the frequency interval for calculating the spectra must be sufficiently small, around 1 Hz, which still demands significant computation. If we can reduce this computational cost, we can increase the update rate of velocity estimation.

Therefore, we propose a new velocity estimation method that extends the Phase Accordance Method and reduces the computation cost compared with FFT-based estimation methods.

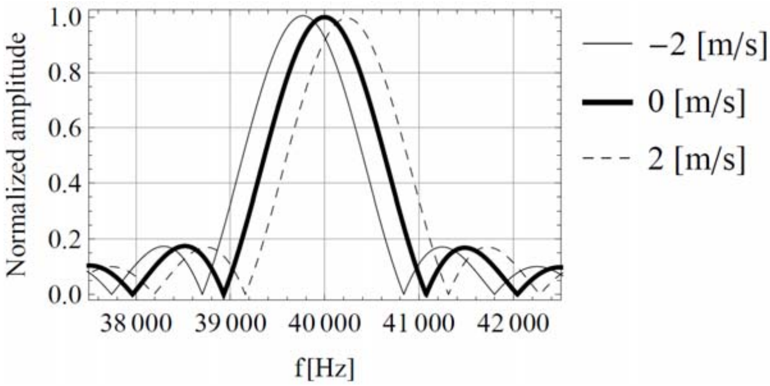


Fig. 3. Frequency spectra of Doppler shifted sync pattern.

4. Velocity Estimation and the Extended Phase Accordance Method

4.1. The Velocity Estimation Algorithm

When an object is moving, the frequencies of two carrier waves in a sync pattern become unknown because of the Doppler effect. A received sync pattern with the Doppler-shift is described as:

$$s_{\omega_1',\omega_2'}(t) = a_1 \sin(\omega_1' t + \phi_1) + a_2 \sin(\omega_2' t + \phi_2)\,. \tag{9}$$

Let us define a reference frequency as $\Omega_A = 2\pi \times 39.75$ kHz. If we calculate the inner product as shown in equation (3), the real part, I_A, and the imaginary part, Q_A, of the calculated complex number are represented as follows.

$$\begin{aligned} I_A &= \frac{1}{2}\left\{\mathrm{sinc}(\omega_1' + \Omega_A)\frac{T}{2} + \mathrm{sinc}(\omega_1' - \Omega_A)\frac{T}{2}\right\}\cdot a_1 \sin\phi_1 \\ &+ \frac{1}{2}\left\{\mathrm{sinc}(\omega_2' + \Omega_A)\frac{T}{2} + \mathrm{sinc}(\omega_2' - \Omega_A)\frac{T}{2}\right\}\cdot a_2 \sin\phi_2\,, \\ &\equiv r_A(\omega_1')\, a_1 \sin\phi_1 + r_A(\omega_2')\, a_2 \sin\phi_2 \end{aligned} \tag{10}$$

$$\begin{aligned} Q_A &= \frac{1}{2}\left\{\mathrm{sinc}(\omega_1' + \Omega_A)\frac{T}{2} - \mathrm{sinc}(\omega_1' - \Omega_A)\frac{T}{2}\right\}\cdot a_1 \cos\phi_1 \\ &+ \frac{1}{2}\left\{\mathrm{sinc}(\omega_2' + \Omega_A)\frac{T}{2} - \mathrm{sinc}(\omega_2' - \Omega_A)\frac{T}{2}\right\}\cdot a_2 \cos\phi_2\,. \\ &\equiv i_A(\omega_1')\, a_1 \cos\phi_1 + i_A(\omega_2')\, a_2 \cos\phi_2 \end{aligned} \tag{11}$$

As mentioned in Section 3.1, $a_1 \sin\phi_1$, $a_1 \cos\phi_1$, $a_2 \sin\phi_2$, and $a_2 \cos\phi_2$ included in I_A and Q_A are not related to the reference frequency Ω_A. If we use a different reference frequency Ω_B, we can calculate

I_B and Q_B that also include $a_1 \sin\phi_1$, $a_1 \cos\phi_1$, $a_2 \sin\phi_2$, and $a_2 \cos\phi_2$. Therefore, we can derive the following two complex amplitudes.

$$a_1 e^{j\phi_1} = \left\{ \frac{i_B(\omega_2^{'})Q_A - i_A(\omega_2^{'})Q_B}{i_A(\omega_1^{'})i_B(\omega_2^{'}) - i_A(\omega_2^{'})i_B(\omega_1^{'})} \right\} + j\left\{ \frac{r_B(\omega_2^{'})I_A - r_A(\omega_2^{'})I_B}{r_A(\omega_1^{'})r_B(\omega_2^{'}) - r_A(\omega_2^{'})r_B(\omega_1^{'})} \right\}, \tag{12}$$

$$a_2 e^{j\phi_2} = \left\{ \frac{-i_B(\omega_1^{'})Q_A + i_A(\omega_1^{'})Q_B}{i_A(\omega_1^{'})i_B(\omega_2^{'}) - i_A(\omega_2^{'})i_B(\omega_1^{'})} \right\} + j\left\{ \frac{-r_B(\omega_1^{'})I_A + r_A(\omega_1^{'})I_B}{r_A(\omega_1^{'})r_B(\omega_2^{'}) - r_A(\omega_2^{'})r_B(\omega_1^{'})} \right\}. \tag{13}$$

By using equation (8), the unknown received frequencies, $\omega_1^{'}$ and $\omega_2^{'}$, can be converted into velocity, v, so that equations (12) and (13) can be rewritten as functions of v. The received signal powers, a_1^2 and a_2^2, are easily derived as equations (14) and (15) by using equations (12) and (13). In the equations below, some functions are redefined, such as $r_A(\omega_1^{'}) \rightarrow r_{A_1}(v)$ and $r_A(\omega_2^{'}) \rightarrow r_{A_2}(v)$.

$$a_1^2 = \left\{ \frac{i_{B_2}(v)Q_A - i_{A_2}(v)Q_B}{i_{A_1}(v)i_{B_2}(v) - i_{A_2}(v)i_{B_1}(v)} \right\}^2 + \left\{ \frac{r_{B_2}(v)I_A - r_{A_2}(v)I_B}{r_{A_1}(v)r_{B_2}(v) - r_{A_2}(v)r_{B_1}(v)} \right\}^2 \equiv a_1(v)^2, \tag{14}$$

$$a_2^2 = \left\{ \frac{-i_{B_1}(v)Q_A + i_{A_1}(v)Q_B}{i_{A_1}(v)i_{B_2}(v) - i_{A_2}(v)i_{B_1}(v)} \right\}^2 + \left\{ \frac{-r_{B_1}(v)I_A + r_{A_1}(v)I_B}{r_{A_1}(v)r_{B_2}(v) - r_{A_2}(v)r_{B_1}(v)} \right\}^2 \equiv a_2(v)^2. \tag{15}$$

The left sides of the above equations are real received signal powers. They are constant values and do not change, although their frequencies are Doppler shifted. The right sides are the signal powers estimated as functions of the velocity of a moving object. By using equations (14) and (15) and assuming that the signal powers are equal, that is, $a_1^2 = a_1^2$ as shown in equation (16), we can estimate the velocity of a moving transmitter as v_T.

$$a_1^2(v) = a_2^2(v)\,|_{v=v_T}\,. \tag{16}$$

In real environments, frequency responses of individual ultrasonic sensors are not always the same, and equation (16) does not hold. However, by calculating the signal power ratio between a_1^2 and a_2^2 beforehand, we can correctly calculate the velocity, v_T. In this study, we discuss the case in which ultrasonic sensors have linear frequency responses to logarithmic amplitudes. When the velocity, v, is small compared with the sound velocity, the difference between the Doppler-shifted frequencies, $\omega_1^{'}$ and $\omega_2^{'}$, can be regarded as constant. Therefore, we can assume that the ratio between a_1 and a_2 is always constant, and we have confirmed that this assumption holds through experiments. Thus, we are able to calibrate signal power in a moving state by using the ratio in the static state ($\eta \equiv a_{1_0} / a_{2_0}$). The velocity of a moving transmitter, v_T, is found through the equation below, which is rewritten from equation (16).

$$a_1^2(v) = \eta^2 a_2^2(v)\,|_{v=v_T}\,. \tag{17}$$

This equation cannot be solved analytically, and so we use Newton's Method. Fig. 4 shows that the signal power functions, $a_1(v)^2$ and $\eta^2 a_2(v)^2$, intersect at $v = v_T$. When ultrasonic sensors have nonlinear frequency responses, the velocity estimation will be conducted by using a filter so that frequency responses of individual signals are compensated and equation (17) holds.

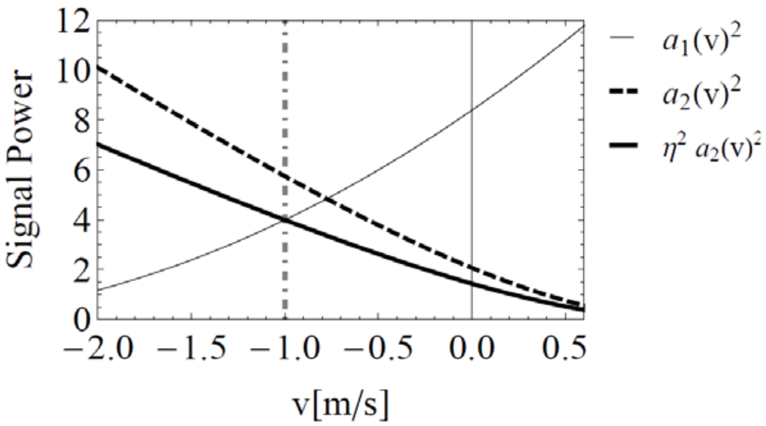


Fig. 4. Received signal power functions which estimate $v_T = -1$ m/s.

4.2. The Extended Phase Accordance Method

When the velocity, v_T, is correctly determined, it becomes possible to find ϕ_1 and ϕ_2 by using equations (12) and (13). Because we can also identify the Doppler-shifted angular velocities, $\omega_1^{'}$ and $\omega_2^{'}$, we can correctly estimate the arrival time, t_e, through equation (5).

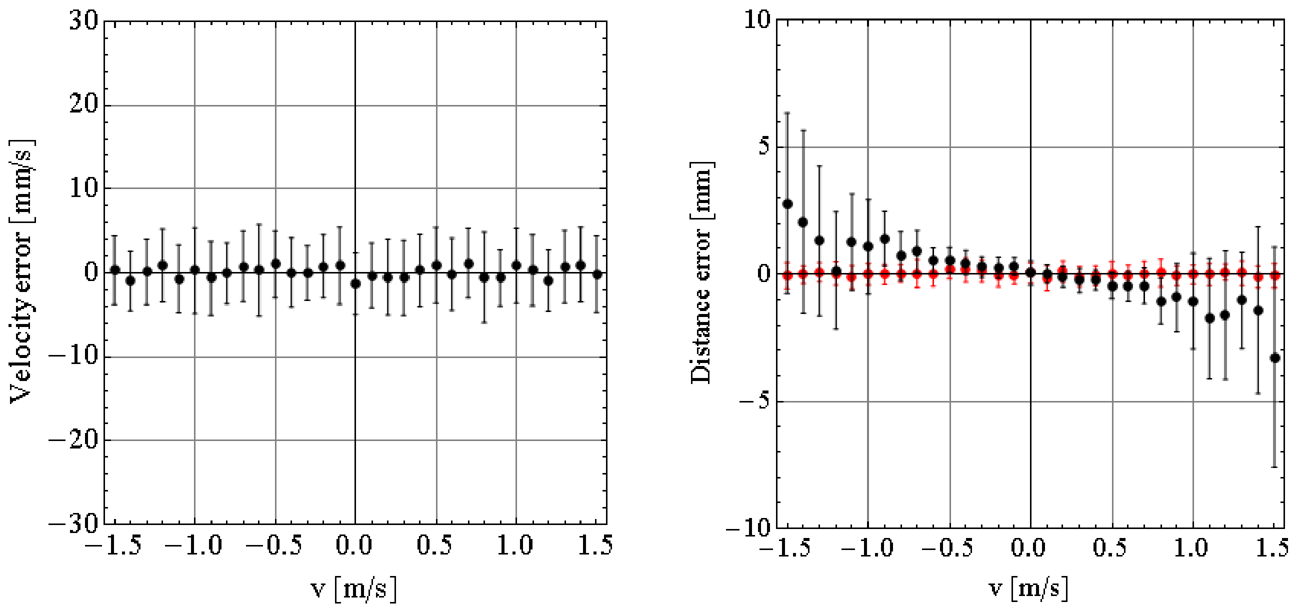
Although the calculation process in the proposed method becomes slightly complicated, in principle, it uses the same core algorithm as the Phase Accordance Method for conducting the quadrature detection represented in equation (2). Thus, the proposed method is an extended version of the Phase Accordance Method, and it can correctly identify not only positions but also velocities of moving objects.

5. Computer Simulations

To validate the performance of the Extended Phase Accordance Method, we carried out velocity and distance estimation experiments via computer simulations. We substituted $v =$ 0 to ± 1.5 m/s at intervals of 0.1 m/s into equation (8) and generated the Doppler effect artificially. Gaussian noise was added to a sync pattern so that the signal-to-noise ratio (SNR) became 40 dB when the distance was 1.0 m. It was assumed in the simulations that the amplitudes of the two different frequency waves were the same ($a_1(v_T) = a_2(v_T)$) and that they varied in inverse proportion to the square of the distance. For example, when the propagation distance of a sync pattern was 1.8 m, the SNR was assumed to be around 30 dB.

The simulations were carried out 30 times at each velocity. Errors of estimated velocities and distances were obtained as differences between the estimated and true values. Fig. 5(a) shows the errors of estimated velocities as dots and the standard deviations as the error bars (±σ). The errors and standard deviations of estimated distance are plotted in Fig. 5(b) in the same way.

Fig. 5(a) proves that the proposed method could estimate the velocity at several mm/s accuracy. Since the standard deviations and errors are so small, the proposed method enables accurate estimation of the velocity in noisy environments. From Fig. 5(b), as the velocity increased, the errors in distance estimations became large when the Doppler effect was not compensated. The standard deviations at each velocity also deteriorated because of differences between real and reference frequencies. By contrast, with the Doppler-effect compensation, the distance errors and standard deviations became very small and almost constant with velocity changes. The simulations prove that the Extended Phase Accordance Method could also estimate the distance accurately in dynamic tracking situations.



(a) Velocity error and standard deviation.

(b) Distance error and standard deviation (Black: without the Doppler-effect compensation, Red: with the Doppler-effect compensation).

Fig. 5. Experimental results of velocity and distance estimation.

6. Experiments

6.1. Experimental System

The experimental setup is shown in Fig. 6.

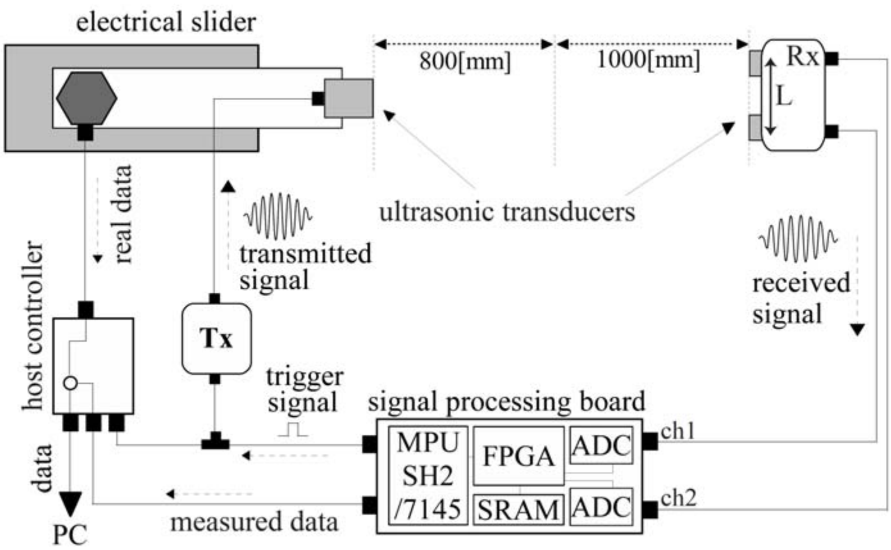


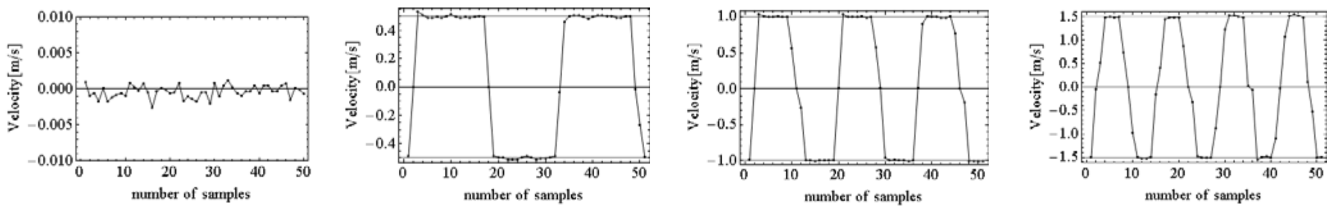
Fig. 6. Experimental setup.

To generate the Doppler effect, we put a transmitter (Nippon Ceramic Corporation) on an electrical slider (SPVL8M150UA, Oriental Motor Corporation). Two ultrasonic receiver sensors (Knowles Acoustics Corporation), placed at an interval of L = 76.2 mm, receive a sync pattern signal from the moving transmitter. The signal processing board includes AD converters, SRAM, an FPGA, and an MPU (SH2/7145, 48 MHz, Renesas Technology Corporation). The real data, such as the true distance obtained by the electrical slider system and the measured data, are gathered to the host controller. The entire system is synchronized by an RF trigger signal.

The electrical slider mounts a transmitter transducer, is placed in front of the receiver, and it moves a transducer between 1000 and 1800 mm. The velocity of the slider is set between $v = 0$ and ± 1.5 m/s, at intervals of 0.1 m/s. The velocity of a moving transmitter is positive when it comes close to the receiver. Otherwise, the velocity is negative.

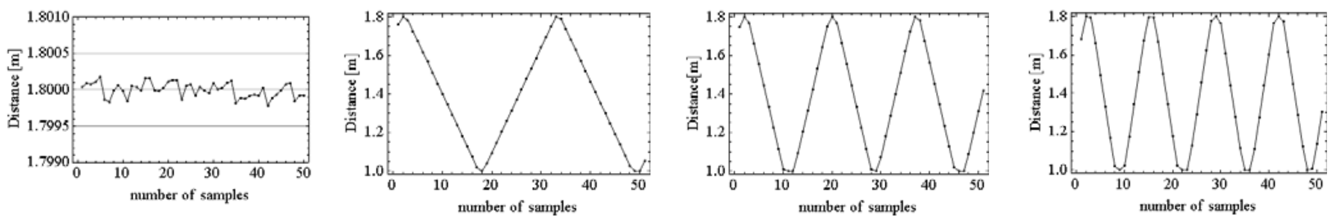
6.2. Velocity and Distance Estimations

The velocity and distance are estimated individually through each channel (each of two ultrasonic sensors) on an ultrasonic receiver. Because the results are almost the same, we show the observed velocities and distances through channel 1 (ch1) in Figs. 7 and 8. These figures indicate that the Extended Phase Accordance Method is also valid in real environments.



(a) $v = 0$ m/s (b) $v = \pm 0.5$ m/s (c) $v = \pm 1.0$ m/s (d) $v = \pm 1.5$ m/s

Fig. 7. Experimental results of velocity estimation in the real world (ch1).



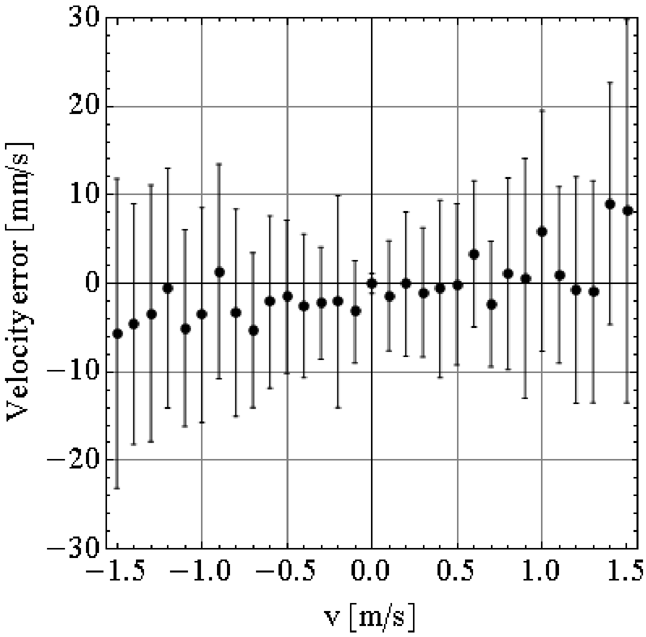
(a) $v = 0$ m/s (b) $v = \pm 0.5$ m/s (c) $v = \pm 1.0$ m/s (d) $v = \pm 1.5$ m/s

Fig. 8. Experimental results of distance estimation in the real world (ch1).

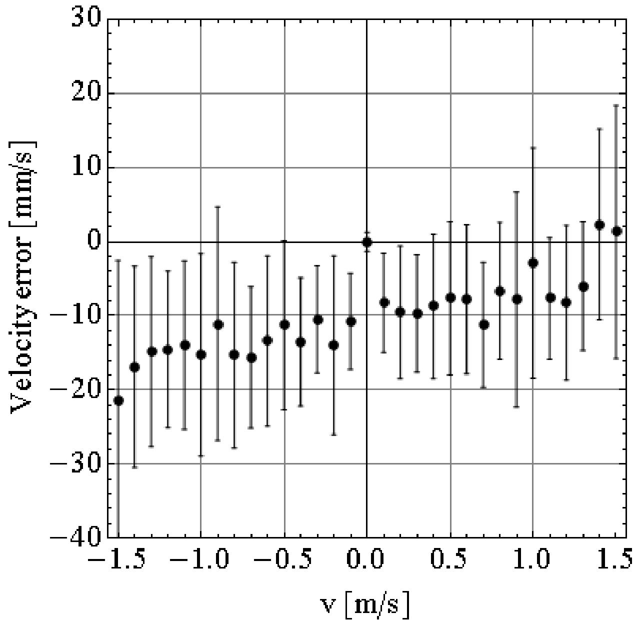
The simultaneous measurements of the velocity and the distance were conducted 50 times at each channel and each velocity to evaluate the standard deviations and errors. First, we present the experimental results of velocity estimations in Fig. 9.

From the velocity errors in channel 2 (ch2) shown in Fig. 9 (b), there are offsets between the errors at 0 m/s and the other velocities, whereas ch1 does not show such differences. This is because the calibration value and the ratio of each signal power at 0 m/s of ch2 were not set as precisely as those of the other channel. However, since the average of offsets was around –10 mm/s, which is almost

0.7 – 10 % of real velocities, these offsets can be regarded as sufficiently small. The results obtained through the experiments also indicate that observed velocities have a bias attendant on the variation of velocities, which is different from the results from computer simulations, as shown in Fig. 5. It is assumed that these systematic errors are caused by transient responses of ultrasonic sensors. We are now inspecting this behavior by examining the transient response model of a sync pattern.



(a) ch1



(b) ch2

Fig. 9. Errors and standard deviations of velocity estimations in the real-world experiments.

Both Figs. 9 (a) and 9 (b) demonstrate that the standard deviation is very small at 0 m/s but not so small at the other velocities. From an algorithmic point of view, there is no reason for the Extended Phase Accordance Method to show a difference between static and moving settings. Therefore, the cause of this performance deterioration while moving is not the Extended Phase Accordance Method itself but rather external factors. We suspect that the vibration of the electrical slider in motion caused the deterioration in standard deviations.

As shown in Fig. 10, when the Doppler effect was not compensated for by using the Phase Accordance Method, the estimation errors and standard deviations became larger as the velocity of the transmitter increased. On the other hand, the errors and standard deviations decreased when the Doppler effect was compensated for by using the Extended Phase Accordance Method. However, the errors still became larger as the velocity increased. Our previous study [21] proved that this was caused by frequency responses of phases of individual ultrasonic sensors. Because the errors are reproducible and can be regarded as systematic errors, they can be eliminated through a correction curve estimated by using the least-square method. Fig. 11 shows the resulting distance errors and standard deviations. After this elimination, we finally obtained 0.78 mm (ch1) and 0.94 mm (ch2) standard deviations by averaging standard deviations at each velocity ($v =$ 0 to $\pm$ 1.5 m/s), which is almost the same accuracy level as the Phase Accordance Method in static settings. The experiments also prove that the reduction in the update rate between the Phase Accordance Method and the Extended Phase Accordance Method is less than 0.9 %, which means that there is almost no difference between the two methods. Therefore, although the small performance degradation is confirmed, the performance of the Extended Phase Accordance Method is still similar to the Phase Accordance Method.

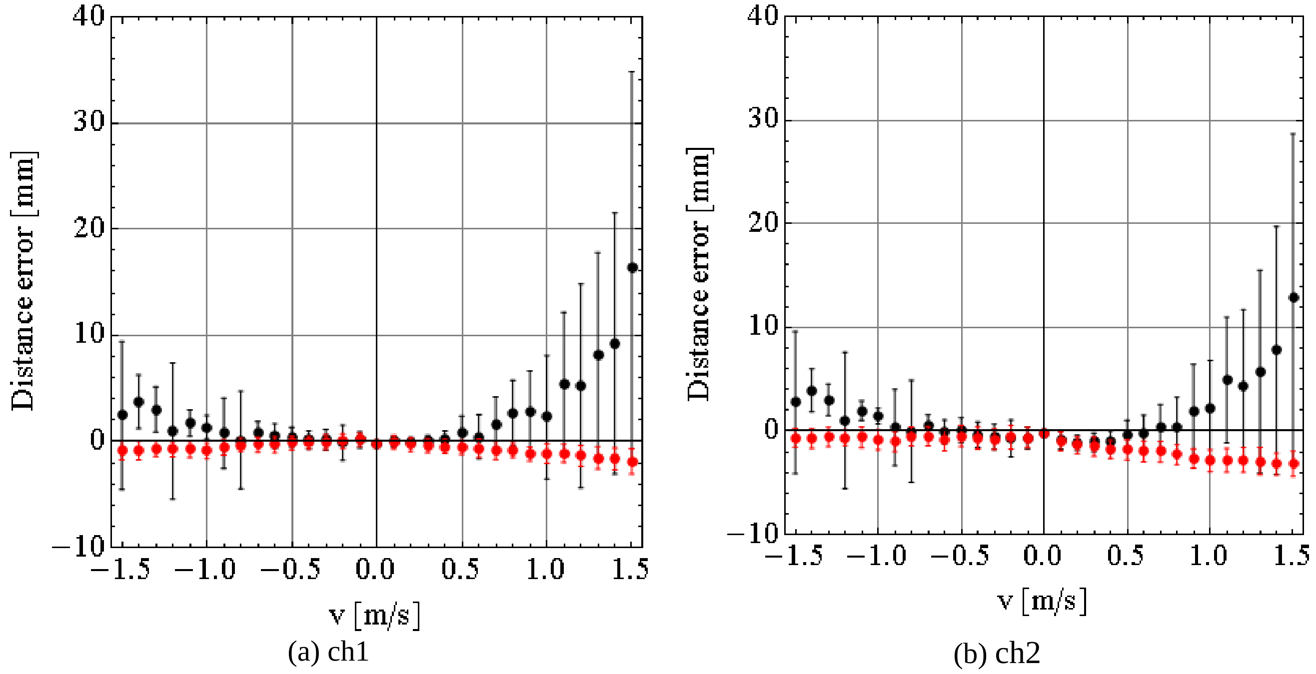


Fig. 10. Errors and standard deviations of distance estimations in the real-world experiments. (Black: without the Doppler-effect compensation, Red: with the Doppler-effect compensation).

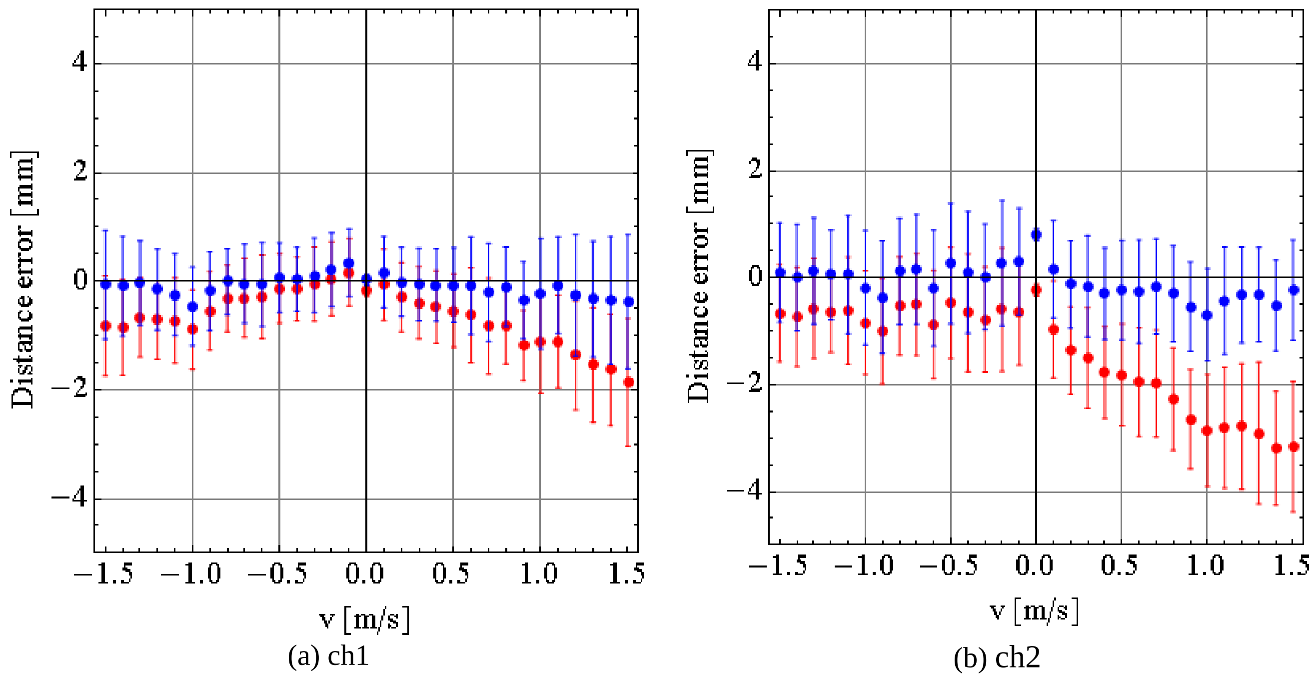


Fig. 11. Errors and standard deviations of distance estimations in the real-world experiments. (Red: without the phase-response compensation, Blue: with the phase-response compensation).

7. Conclusion and Future Work

In this paper, we proposed a velocity estimation method for localizing moving objects with high accuracy by extending the Phase Accordance Method. The key feature of the proposed method is the use of the signal power ratio between two different frequency waves that compose a sync pattern.

The performance of the Extended Phase Accordance Method was validated through experiments in computer simulations and real-world environments. Because the Extended Phase Accordance Method uses the same core algorithm as the Phase Accordance Method, the difference in computation cost between the two methods is small, although the Extended Phase Accordance Method can estimate not only positions but also velocities. Through the real-world experiments using a moving transmitter, the standard deviation of the distance estimations was verified to be less than 1 mm.

Several issues remain to be addressed. The current experimental system can measure one- or two-dimensional velocities and positions of moving objects. Therefore, improving the current system so that it can measure three-dimensional velocities and positions is one of our important areas of future work. Preliminary results of three-dimensional velocity and position measurements will be presented in our next paper [22]. We are also interested in developing useful applications that use this proposed method, such as low-cost but high-performance robot navigation systems or motion capture systems.

References

[1]. J. Hightower, G. Borriello, Location Systems for Ubiquitous Computing, *Computer*, Vol. 34, No. 8, 2001, pp. 57–66.

[2]. D. Vlasic, R. Adelsberger, G. Vannucci, J. Barnwell, M. Gross, W. Matusik, J. Popovic, Practical motion capture in everyday surroundings, *ACM Transactions on Graphics*, Vol. 26, No. 3, Article 35, 2007.

[3]. H. Hashizume, A. Kaneko, Y. Sugano, K. Yatani and M. Sugimoto, Fast and Accurate Positioning Technique Using Ultrasonic the Phase Accordance Method, in *Proceedings of IEEE TENCON'05*, Melbourne, Australia, 2005, pp. 826–831.

[4]. H. Hashizume, A. Kaneko, and M. Sugimoto, Phase accordance method - an accurate ultrasonic positioning method and its characteristics, *IEICE Transactions*, Vol. J91-A, No. 4, 2008, pp. 435–447.

[5]. T. Sato, S. Nakamura, M. Sugimoto, H. Hashizume, A Realtime and Accurate Technique for Estimating Position and Velocity of Moving Node using Ultrasonic Communication, in *Proceedings of the 4th International Conference on Sensing Technology (ICST 2010)*, Lecce, Italy, June 2010, pp. 428-433.

[6]. A. Ward, A. Jones, A. Hopper. A new location technique for the active office, *IEEE Personal Communications*, 4, 5, 1997, pp. 42–47.

[7]. N. B. Priyantha, A. K. L. Miu, H. Balakrishnan, The cricket location-support system, in *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking (MobiCom 2000)*, Boston, 2000, pp. 32–43.

[8]. A. Smith, H. Balakrishnan, M. Goraczko, N. Priyantha, Tracking moving devices with the cricket location system, in *Proceedings of the 2nd International Conference on Mobile Systems, Applications, and Services (MobiSys 2004)*, Boston, 2004, pp. 190–202.

[9]. N. B. Priyantha, A. K. L. Miu, H. Balakrishnan, S. Teller, The cricket compass for context-aware mobile applications, in *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking(MobiCom 2001)*, Rome, 2001, pp. 1–14.

[10]. M. Hazas, A. Hopper, Broadband ultrasonic location systems for improved indoor positioning, *IEEE Transactions on Mobile Computing*, 5, 5, 2006, pp. 536–547.

[11]. M. McCarthy, P. Duff, H. Muller, C. Randell, Accessible ultrasonic positioning. *IEEE Pervasive Computing*, 5, 4, 2006, pp. 86–93.

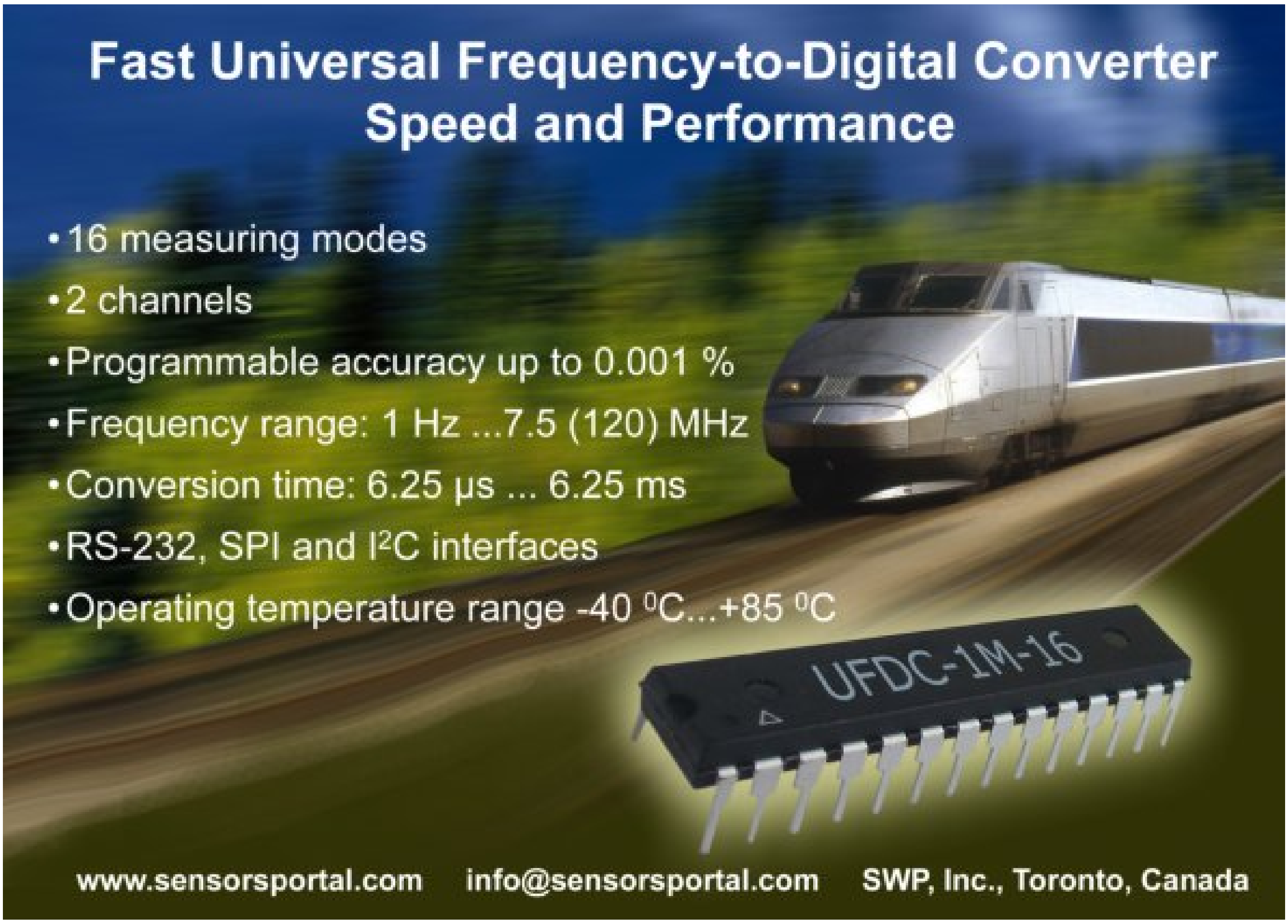
[12]. M. McCarthy, H. Muller, A. Calway, R. E. Wilson, Position and velocity recovery from independent ultrasonic beacons, in *Proceedings of European Signal Processing Conference (EUSIPCO 2006)*, Florence, Italy, Sept. 2006.

[13]. M. McCarthy, H. Muller, Positioning with Independent Ultrasonic Beacons, CSTR-05-005, *Department of Computer Science, University of Bristol*, 2005.

[14]. W. T. Kuang and A. S. Morris， Combined time-of-flight and Doppler ultrasonic tracking system for better performance in robot tracking, in *Proceedings of IEE Science, Measurement and Technology*, Vol. 147, No. 5, Sept. 2000, pp. 213-218.

[15]. W. T. Kuang and A. S. Morris, Using Short-Time Fourier Transform and Wavelet Packet Filter Banks for Improved Frequency Measurement in a Doppler Robot Tracking System, *IEEE Transactions on Instrumentation and Measurement*, Vol. 51, No. 3, June 2002, pp. 440-444.

[16].K. Imou, M. Ishida, T. Okamoto, Y. Kaizu, A. Sawamura and N. Sumida, Ultrasonic Doppler Sensor for Measuring Vehicle Speed in Forward and Reverse Motions Including Low Speed Motions, *CIGR Journal of Scientific Research and Development*, Vol. III, 2001, pp. 1–14.
[17].M. Maróti, B. Kusý, G. Balogh, P. Völgyesi, A. Nádas, K. Molnár, S. Dóra, A. Lédeczi., Radio interferometric geolocation. in *Proc. of ACM 3rd Conference on Embedded Networked Sensor Systems (SenSys2005)*, Nov. 2005, pp. 1-12.
[18].B. Kusý, J. Sallai, G. Balogh, A. Ledeczi, V. Protopopescu, J. Tolliver, F. DeNap, M. Parang, Radio Interferometric Tracking of Mobile Wireless Nodes, in *Proc. of ACM 5th Conference on Mobile Systems, Applications, and Services (Mobisys 2007)*, June. 2007, pp. 139-151.
[19].T. Ito, T. Sato, K. Tulathimutte, M. Sugimoto, H. Hashizume, A Scalable Ultrasonic- Based Localization System Using the Phase Accordance Method, *Recent Advances in Sensing Technology, Lecture Notes in Electrical Engineering*, Vol. 49, Springer, 2009, pp. 35–54.
[20].M. Sugimoto, K. Tulathimutte, T. Ito, T. Sato, H. Hashizume, An Ultrasonic 3D Positioning System using a Single Compact Receiver Unit, in *Proceedings of 4th International Symposium on Location and Context Awareness*, Tokyo, Japan, May 2009, pp. 240-253.
[21].T. Sato, M. Sugimoto, H. Hashizume, An Extension Method of the Phase Accordance Method for Accurate Ultrasonic Localization of Moving Node, *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, Vol. J92-A, No. 12, 2009, pp. 953–963.
[22].S. Nakamura, T. Sato, M. Sugimoto, H, Hashizume, An Accurate Technique for Simultaneous Measurement of 3D Position and Velocity of a Moving Object Using a Single Ultrasonic Receiver Unit, in *Proceedings of 2010 International Conference on Indoor Positioning and Indoor Navigation*, ETH Zurich, Switzerland, Sept. 2010 (to appear).



The Second International Conference on Sensor Device Technologies and Applications

SENSORDEVICES 2011

August 21-27, 2011 - French Riviera, France

www.sensorsportal.com

Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

Tracks:
- Sensor devices
- Photonics
- Infrared
- Ultrasonic and Piezosensors
- Sensor device technologies
- Sensors signal conditioning and interfacing circuits
- Medical devices and sensors applications
- Sensors domain-oriented devices, technologies, and applications
- Sensor-based localization and tracking technologies

http://www.iaria.org/conferences2011/SENSORDEVICES11.html

The Fifth International Conference on Sensor Technologies and Applications

SENSORCOMM 2011

August 21-27, 2011 - French Riviera, France

www.sensorsportal.com

Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

Tracks:
- APASN: Architectures, protocols and algorithms of sensor networks
- MECSN: Energy, management and control of sensor networks
- RASQOFT: Resource allocation, services, QoS and fault tolerance in sensor networks
- PESMOSN: Performance, simulation and modelling of sensor networks
- SEMOSN: Security and monitoring of sensor networks
- SECSED: Sensor circuits and sensor devices
- RIWISN: Radio issues in wireless sensor networks
- SAPSN: Software, applications and programming of sensor networks
- DAIPSN: Data allocation and information in sensor networks
- DISN: Deployments and implementations of sensor networks
- UNWAT: Under water sensors and systems
- ENOPT: Energy optimization in wireless sensor networks

http://www.iaria.org/conferences2011/SENSORCOMM11.html

The Fourth International Conference on Advances in Circuits, Electronics and Micro-electronics

CENICS 2011

August 21-27, 2011 - French Riviera, France

www.sensorsportal.com

Important deadlines:

Submission deadline	March 23, 2011
Notification	April 30, 2011
Registration	May 15, 2011
Camera ready	May 22, 2011

Tracks:
- Semiconductors and applications
- Design, models and languages
- Signal processing circuits
- Arithmetic computational circuits
- Microelectronics
- Electronics technologies
- Special circuits
- Consumer electronics
- Application-oriented electronics

http://www.iaria.org/conferences2011/CENICS11.html

Sensors & Transducers Journal

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2009.pdf