Fast and Accurate Positioning Technique Using Ultrasonic Phase Accordance Method

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***Abstract*— An innovative measurement technique for use by positioning systems using ultrasonic signals was developed. The advantage of this technique is that it can accurately identify the relative distance and orientation between devices by using an one-time ultrasonic packet. It is therefore especially useful for ubiquitous computing applications where people with mobile devices continuously change their positions in indoor environments. The technique, which is named *phase accordance method*, uses two or more carriers in ultrasonic communication. A special ultrasonic burst signal, called *sync pattern* in the header part of the communication packet gives the base point of the time measurement. The whole time difference calculation is then carried out using this base point. An experiment based on the proposed method proved that the technique attains remarkable performance, namely, errors of less than ± 1 mm in three meter distance measurements and less than 0.5 degree errors in the zero, ten, twenty, and thirty degree measurements.**

***Index Terms*— Ultrasonic measurement, signal processing, positioning system, time of arrival, angle of arrival.**

I. Introduction

Estimating the position of people and mobile devices is a critical issue in the fields of ubiquitous computing [7], location-aware computing [5], and mixed reality [4]. In the open air, GPS signals can easily provide position information; however, inside buildings they can be blocked and become unusable. Consequently, the estimation of the position of multiple people's or devices' indoor is an active research issue.

Positioning systems for indoor use were based on, for example, infrared signals [10], weight-sensitive floors [1], radio-frequency (RF) signals [2], [6], and computer vision [3]. A major problem with these methods is accuracy, *i.e.*, estimation errors range from several centimeters to a dozen or so meters. Ultrasonic positioning systems provide more accurate in measurements than the above systems. Active Bat [11], using ultrasonic signals and radio waves, measures distances from multiple reference points (ultrasound receivers) and estimates the 3D position of an ultrasound transmitter.

The serious drawback, however, of ultrasonic systems is related to their installation. In Active Bat, for example, numerous receivers must be placed on the ceiling; thus, set up is expensive and involves laborious tasks. We believe that ubiquitous computing environments must be developed effortlessly and costlessly. In addition, they should be deployed in offices and homes as well as in laboratories. To reduce the number of ultrasound receivers, [8] proposed a positioning system based on iterative multilateration. However, reducing the quantity of positioned references considerably degraded the estimation accuracy of the system. A more precise estimation method for ultrasonic positioning is therefore required.

In response to this need, we have developed an innovative technique for measuring distances and orientations that improves the estimation performance of positioning systems. This technique named *phase accordance method* uses two or more carriers in ultrasonic communication. A special ultrasonic burst, a *sync pattern*, is placed in the header of a communication packet and gives the base point, which is called *epoch* for time measurement. This epoch is then used for a precise calculation of the propagation delay time. This technique is especially useful when there are few reference objects at known positions and multiple mobile devices (e.g., PDA) which mount both ultrasound transmitters and receivers. It can also be used to accurately determine relative positions of mobile devices without the need of reference objects.

The proposed technique has several advantages:

- The sync pattern not only gives a precise time mark for distance measurement, it also provides an exact phase and amplitude synchronization of carriers. Using a sync pattern enables arbitrary digital communication by phase-shift keying or multi-value QAM with ultrasound channels.
- When a transmitter sends out its estimated positional coordinate and a timestamp on the ultrasound channel, neighboring receivers that can detect the data packet can modify their estimated positions according to the distance measured with time of arrival method, provided that all nodes are time-synchronized using, *e.g.*, NTP (Network Time Protocol). In this manner the nodes in a system can maintain relative coordinates without having to set up special beacons in the room.

The proposed technique showed a remarkable accuracy in estimating the distance and orientation of nodes: less than ± 1mm in three-meter measurements, and less than 0.5 degrees in zero-, ten-, twenty-, and thirty-degree measurements. This means that the technique is more accurate than existing systems such as [9] and [11] that use ultrasounds for position estimation.

II. Location Measurement Using Ultrasound

A. Time of Arrival Method

The most popular technique used by of ultrasonic location systems is the time of arrival (TOA) method. When the transmitter (TX) node and receiver (RX) nodes are time synchronized, and if the RX knows when a TX node sends out an ultrasound packet, it can calculate the transmission delay of the packet. By dividing the delay value by the velocity of sound, the RX knows the distance between the TX and itself. The key issue with this algorithm is maintaining the time synchronization among the nodes and determining the exact arrival times of ultrasound packets.

The main cause of errors in measurements by a TOA location system is the estimation error of the arrival times of ultrasound packets. Ultrasonic transmitter and receiver devices resonate sharply to a specific frequency, *i.e.*, 40kHz, for the most popular devices. Wave packets communicated via those resonators get deformed from their original shape, which makes determining the TOA difficult at an RX. A 0.1 ms ambiguity in receiving time, for example, makes a 3 cm error in the distance measurement.

B. Angle of Arrival Method

Another technology for ultrasonic location measurement is the angle of arrival (AOA) method which became well known after it was used in *Cricket Compass*[9].

In those systems, RXs use two or more ultrasonic microphones in parallel to estimate the 2D or 3D positions of TXs using *triangulation.*

The signal reaches the two individual microphones at different moments. The time difference δt is calculated as

$$c\,\delta t = L \sin\theta \tag{1}$$

where c is the sound velocity and L is the distance between the two microphones, the *baseline* of the triangulation. And θ is the angle as shown in Fig. 3. (*N.B.* (1) is approximately correct when the distance to the nodes $R >> L$.) From (1) the angle θ is estimated as

$$\theta = \sin^{-1} c\,\delta t / L. \tag{2}$$

In the usual setting baseline L is relatively small compared to the speed of sound c, which renders the time difference δt a very small so the time difference is only observed from the phase difference between wave-packet carriers. For this reason almost all AOA systems sends a fairly long ultrasonic carrier wave to make phase detection and comparison easy.

Given phase difference $\delta\phi$ (2) can be rewritten as:

$$\theta = \sin^{-1} \frac{c\,\delta\phi}{2\pi f L} \tag{3}$$

where f is the carrier frequency.

However, the difficulty of solving (3) lies in the fact that the phase ϕ can only be retrieved from the sinusoidal function representing carrier which is a 2π-periodic function. If the observed phase difference is $\delta\phi$ the true value may be $\delta\phi, \pi - \delta\phi, 2\pi + \delta\phi$, etc. In most cases multiple candidates of $\delta\phi$ give different, reasonable solutions of (3) hence the choice of the correct solution is difficult. (If $L < c/2f = \lambda/2$ there is no such confusion, but for 40kHz ultrasound $\lambda/2$ is about 4mm which is too short for a triangulation.)

To cope with the 2π-phase ambiguity the Criket Compass system, for example, employs three microphones for a 2D measurement or five microphones for a 3D measurement in order to make simultaneous triangulations with the different baselines.

Another difficulty of the phase-oriented measurements of locations is the existence of a multipath. The objects around the ultrasonic wave channel reflect, or scatter the sound wave, and they spoil the phase accuracy.

III. Phase Accordance Method

A. Basic Idea

The authors propose a new method named *phase accordance method* for measuring ultrasonic distances. This method uses a burst of ultrasonic waves, as with burst-pulse systems. However, it does not use the envelope of the burst to determine the time-start information. Instead, the burst consists of two or more frequency sub-carriers $f_1, f_2, f_3, \ldots$, and the carriers' phases accord at a single time-marker *epoch*.

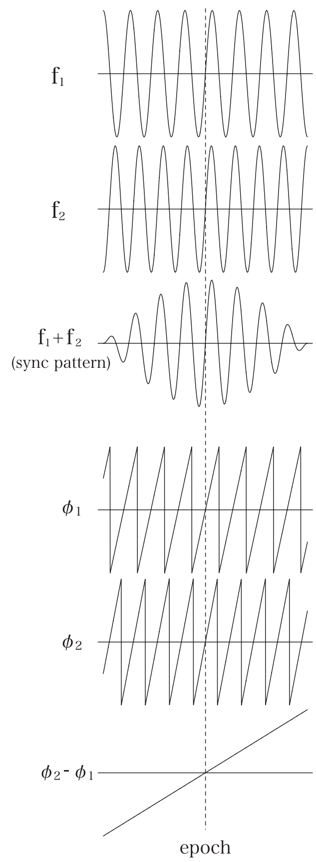

Fig. 1. Dual carrier wave

For simplicity's sake we explain this method with a dual carrier system $f_1 + f_2$, *e.g.*, $f_1 =$ 39.75kHz and $f_2 =$ 40.25kHz (Fig. 1). The superposition of the two frequency signals makes a beat, which shows a distinctive pattern on the envelope. We, however, do not pay attention to the shape; instead we look the phase difference of the component carriers. We call this beat pattern a *sync pattern*.

Mathematically the sync pattern is described as

$$\begin{aligned} & \sin 2\pi f_1 t + \sin 2\pi f_2 t \\ & \quad = \quad \sin\omega_1 t + \sin\omega_2 t. \end{aligned} \tag{4}$$

If the duration of a sync pattern length is equal to the inverse of frequency distance, *i.e.*, $1/(f_2 - f_1) = 1/500 =$ 2ms, the phase difference $\phi_2 - \phi_1$ sweeps from $-\pi$ to π, and the specific phase distance, *e.g.*, $\phi_2 - \phi_1 = 0$

occurs only once in the pattern. We use this matching point of the phases as the epoch.

The algorithm explained in the following section can determine the epoch very precisely, within a few microseconds, under experimental conditions. As a result, this technique provides distance measurements within an error range of a few millimeters. The time required for a measurement is the duration of a sync pattern, *i.e.*, 2ms. The analysis of the sync pattern also gives the base point and amplitude information which are useful for subsequent data communication using ultrasounds.

B. Phase Detection

When the sync pattern is received by the receiver, the component carriers f_1 and f_2 should be extracted, and the phase information of the carriers ϕ_1 and ϕ_2 should be precisely determined. To do this, we use the following mathematical process.

We define the inner product of two time domain functions $f(t)$ and $g(t)$ by

$$< f(t), g(t) >= \frac{1}{T}\int_{-T/2}^{T/2} f(t)\,\overline{g(t)}dt$$

where $\overline{g(t)}$ is the complex conjugate of $g(t)$.

The inner product of $\sin(\omega t+\phi)$ and the complex exponential function $e^{j\Omega t} = \cos\Omega t + j\sin\Omega t$ yields

$$\begin{aligned}
&< \sin(\omega t+\phi), e^{j\Omega t} >= \frac{1}{T}\int_{-T/2}^{T/2} \sin(\omega t+\phi)\,\overline{e^{j\Omega t}}dt \\
&= \frac{1}{2Tj}\int_{-T/2}^{T/2}(e^{j(\omega t+\phi)} - e^{-j(\omega t+\phi)})e^{-j\Omega t}dt \\
&= \frac{1}{2Tj}\int_{-T/2}^{T/2}(e^{j(\omega-\Omega)t+j\phi} - e^{-j(\omega+\Omega)t-j\phi})dt \\
&= \frac{1}{2Tj}\Big(e^{j\phi}\frac{e^{j(\omega-\Omega)T/2} - e^{-j(\omega-\Omega)T/2}}{j(\omega-\Omega)} \\
&\qquad -e^{-j\phi}\frac{e^{j(\omega+\Omega)T/2} - e^{-j(\omega+\Omega)T/2}}{j(\omega+\Omega)}\Big) \\
&= \frac{1}{2j}\Big(e^{j\phi}\frac{\sin(\omega-\Omega)T/2}{(\omega-\Omega)T/2} - e^{-j\phi}\frac{\sin(\omega+\Omega)T/2}{(\omega+\Omega)T/2}\Big) \\
&= \frac{1}{2j}\big(e^{j\phi}\,\mathrm{sinc}\,\frac{\omega-\Omega}{2}T - e^{-j\phi}\,\mathrm{sinc}\,\frac{\omega+\Omega}{2}T\big)
\end{aligned}$$

where $\mathrm{sinc}\,x = \sin x/x$ is the sampling function.

The receiver captures the sync pattern (4) from the transmitter and it can be written as $s(t) = a_1\sin(\omega_1 t+\phi_1) + a_2\sin(\omega_2 t+\phi_2)$, where ϕ_1 and ϕ_2 are the initial phase of the component carriers. We estimate them by calculating the inner products of the signals with standard signals $e^{j\omega_1 t}$ and $e^{j\omega_2 t}$.

From the above formula, the inner product of $s(t)$ with $e^{j\omega_1 t}$ is given as

$$\begin{aligned}
&< s(t), e^{j\omega_1 t} > \\
&= \frac{1}{2j}\big(a_1(e^{j\phi_1}\,\mathrm{sinc}\,\frac{\omega_1-\omega_1}{2}T - e^{-j\phi_1}\,\mathrm{sinc}\,\frac{\omega_1+\omega_1}{2}T) \\
&\quad +a_2(e^{j\phi_2}\,\mathrm{sinc}\,\frac{\omega_2-\omega_1}{2}T - e^{-j\phi_2}\,\mathrm{sinc}\,\frac{\omega_2+\omega_1}{2}T)\big)
\end{aligned}$$

observing the relations $\mathrm{sinc}(-x) = \mathrm{sinc}\,x$ and $\mathrm{sinc}\,0 = 1$

$$\begin{aligned}
&= \frac{1}{2j}\big(a_1(e^{j\phi_1} - e^{-j\phi_1}\,\mathrm{sinc}\,\omega_1 T) \\
&\quad +a_2(e^{j\phi_2}\,\mathrm{sinc}\,\frac{\omega_1-\omega_2}{2}T - e^{-j\phi_2}\,\mathrm{sinc}\,\frac{\omega_1+\omega_2}{2}T)\big) \quad (5)
\end{aligned}$$

Similarly the inner product of $s(t)$ and $e^{j\omega_2 t}$ is

$$\begin{aligned}
&< s(t), e^{j\omega_2 t} > \\
&= \frac{1}{2j}\big(a_1(e^{j\phi_1}\,\mathrm{sinc}\,\frac{\omega_1-\omega_2}{2}T - e^{-j\phi_1}\,\mathrm{sinc}\,\frac{\omega_1+\omega_2}{2}T) \\
&\quad +a_2(e^{j\phi_2} - e^{-j\phi_2}\,\mathrm{sinc}\,\omega_2 T)\big). \quad (6)
\end{aligned}$$

Equations (5) and (6) can be combined to a matrix equation where $a_1e^{j\phi_1}$ and $a_2e^{j\phi_2}$ are the unknowns.

$$\begin{aligned}
&\begin{pmatrix} 1 & \mathrm{sinc}\,\frac{\omega_1-\omega_2}{2}T \\ \mathrm{sinc}\,\frac{\omega_1-\omega_2}{2}T & 1 \end{pmatrix}\begin{pmatrix} a_1e^{j\phi_1} \\ a_2e^{j\phi_2}\end{pmatrix} \\
&-\begin{pmatrix} \mathrm{sinc}\,\omega_1 T & \mathrm{sinc}\,\frac{\omega_1+\omega_2}{2}T \\ \mathrm{sinc}\,\frac{\omega_1+\omega_2}{2}T & \mathrm{sinc}\,\omega_2 T \end{pmatrix}\begin{pmatrix} a_1e^{-j\phi_1} \\ a_2e^{-j\phi_2}\end{pmatrix} \\
&= 2j\begin{pmatrix} < s(t), e^{j\omega_2 t} > \\ < s(t), e^{j\omega_2 t} > \end{pmatrix}. \quad (7)
\end{aligned}$$

This equation can be strictly solved by examining the real part and the imaginary part individually.

When the integration interval T is chosen to make $\omega_1 T$, $\omega_2 T$ and $(\omega_1 \pm \omega_2)T/2$ as integer multiples of π, the terms with $\mathrm{sinc}\,\omega_1 T = \sin m\pi/m\pi$, *etc* will be equal to zero. The direct solutions can thus be derived from (7) as

$$\begin{aligned}
a_1e^{j\phi_1} &= 2j < s(t), e^{j\omega_1 t} > \\
a_2e^{j\phi_2} &= 2j < s(t), e^{j\omega_2 t} > .
\end{aligned}$$

The above expressions are also approximately true when T is large enough compared to the period of carrier frequencies.

In any case, phase and amplitude information of f_1 and f_2 components can be obtained from a sync pattern by the multiplication and the integration of the received signal with $\overline{e^{j\omega_1 t}}$ and $\overline{e^{j\omega_2 t}}$.

The multiplication of the received signal of carrier angular frequency ω with $\cos\omega t$ and $\sin\omega t$ is called *quadrature detection*, and is widely used for demodulation of phase modulated signals. The above equation shows that the same method can be applied to obtain precise phase information from multiple carrier signals. The integration interval T is called a *window*. Note that when the received signal $f(t)$ is converted to discrete-time series f_n, the inner product is approximately $< f(t), g(t) >\approx (1/N)\sum_{i=1}^{N} f_i\,\overline{g_i}$.

C. Finding Phase Accordance

With the above-mentioned algorithm, we can obtain carrier phases ϕ_1 and ϕ_2 at the center of the window, and set it as $t = 0$. As $\omega_1 < \omega_2$, ϕ_1 increases faster than ϕ_2. As time passes, ϕ_2 catches up with ϕ_1 and the two phases become identical again. This happens at

$$t = -\frac{\phi_1 - \phi_2}{\omega_1 - \omega_2} = -\frac{\phi_1 - \phi_2}{2\pi(f_1 - f_2)}.$$

This is the epoch retrieved from the received signal.

Fig. 2 shows the head part of an actual received signal. This is stored in the waveform memory after being digitized by an AD converter, so the decoding process is carried out with digital processing.

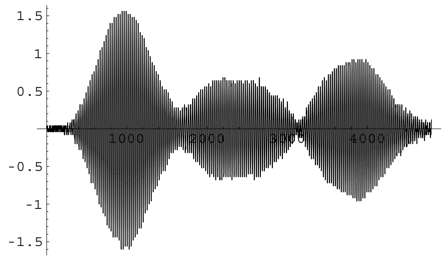

Fig. 2. Communication packet with leading sync pattern

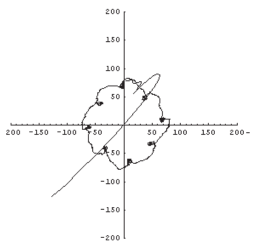

Fig. 3. An 8PSK diagram

D. Other Properties of Phase Accordance Method

The benefit of this technique is the short measurement time of an operation. It only requires a burst of two milliseconds. When the system is adopted in the full mobile environment in which only an intermittent communication is possible for a pair of nodes, a good consequence is expected.

Another benefit is that the sync pattern synchronizes the receiver's local oscillator to a certain transmitter's carrier phase. Using subsequent ultrasonic communication, we can communicate data by *phase shift keying* or *phase amplitude modulation*.

Fig. 3 shows the phase diagram when we processed the received 8-PSK ultrasonic signal. It shows that the eight phase positions can be clearly discriminated. This technology is therefore applicable for general digital communication using the modulated bit fields trailing the header sync pattern. We expect the maximum data rate of the ultrasonic transmission to be close to a telephone modem's, *e.g.*, a few to a few tens of kilobits per second. Transmission node ID, transmission timestamp, transmitter coordinate position and even network time can be sent with an ultrasonic channel. Ultrasonic-only positioning system (in which nodes do not use IR, wireless or other communication methods) is therefore theoretically possible.

Because this method is based on the mechanism of phase-tracking systems, we expect the measurement accuracy to be up to their level, *i.e.* a few millimeters. In addition, this system may be more tolerant to multipath errors, which were sometimes critical in phase-tracking systems.

The sync pattern is placed at the head of transmission packets so that it reaches the receiver first. The spatial length of a sync pattern is about 70 cm, so the multipath signals should arrive after the *real* sync pattern has been received and processed, provided that the reflection paths are longer than 70cm.

E. Integration of TOA and AOA methods

Following the principles of the phase accordance method both the TOA and AOA location systems can be constructed, and even more, they can be integrated in a single system.

Fig. 4 (a) shows the basic organization of a TOA system using phase accordance. Each node in the system is time-synchronized and exchanges timestamps and coordinates by using the digital communication capability of the system. The distance between a pair of nodes is determined when an RX node received a packet from a TX and compares the TX timestamp and the receiving time by using the epoch. (As demonstrated later the accuracy of a measurement is expected to be within a few millimeters.) Time synchronization is achieved, for example, via NTP (network time protocol) using the secondary wireless LAN channel, or even using the ultrasonic channel which is primarily devised for distance measurement, as it can communicate general data. The nodes in the system have to maintain their estimated positions as well as an estimated system time. This algorithm is already utilized in the GPS system.

Fig. 4 (b) shows the AOA measurement. When an RX node detects the direction to the TX node using AOA method, time synchronization between the nodes is not needed. In the conventional AOS systems the RX node receives carrier-wave from the TX node using least two microphones for a 2D positioning, or three or more for a 3D positioning and compares the phase between the received signals. The drawback of this method, however, is the difficulty of choosing single angle value form multiple candidates of the solution; we explained this effect as the 2π ambiguity in the previous section.

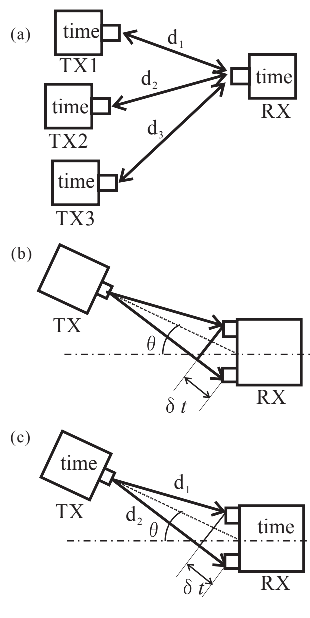

Fig. 4. Three different positioning methods. (a) TOA (b) AOA (c)Integration of TOA and AOA

Phase accordance method can also be applicable to AOA measurement. By receiving a sync pattern with two microphones, the time difference between the arrival times can be so precisely determined that the angle is calculated by solving equation (2) with time difference, rather than solving equation (3) with phase difference. Equation (2) gives a single, direct solution without the 2π-phase ambiguity problem which is hardly avoided when we use phase-oriented methods.

With phase accordance method TOA and AOA measurement can be integrated to a single system as schematically shown in Fig. 4 (c), since both the distance and the angle can be analized from time difference of epoch in the sync patterns. The nodes are time synchronized to the network time, and conduct the distance and the angle measurements at the same time. This means that the position determination (estimation of the coordinates) of a RX node is possible just by percepting a single packet from the TX node whose coordinates are known.

IV. Experimental System

To confirm the feasibility and expected properties of the phase accordance method, we have carried out the experiment described below.

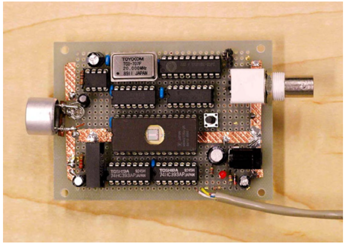

Fig. 5. An ultrasonic transmitter

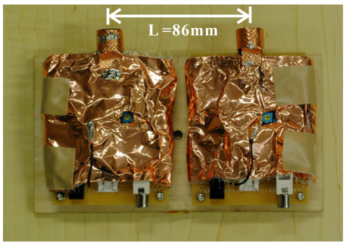

Fig. 6. An ultrasonic receiver

A. Transmitter and Receiver

Fig. 5 shows the transmitter. It has a waveform ROM which contains the transmission waveform, and a subsequent DA converter and an ultrasonic transducer which send out the sonic waveform. The dual carrier frequencies are 39.75kHz and 40.25kHz which compose a 2 ms burst of a sync pattern. It also has a connector that provides an electrical time pulse. To examine the transmission delay, a receiver compares the epoch time retrieved from the ultrasonic microphone with the electric time pulse. (N.B. It is just for the experiment purposes. In the case of a practical system we will make time synchronization among nodes using NTP or other methods.)

Fig. 6 shows the receiver. To conduct the AOA measurement of a planar angle, the receiver uses two microphones. They are placed at a distance L of 86 mm, which is the baseline for the triangulation. The receiver is very sensitive to environmental electric noise, so the entire setting is covered with copper foil as shielding.

The signal is converted to a digital form, and the detection process is implemented as software in the CPU. The AD converter operates at speed of 1Msps (sampling per second), and the resolution is 8bit linear with 256 levels.

B. Evaluations

We evaluated the developed method by placing the TX at six different positions, and conducted ten independent measurements at each position (Fig. 7). The physical distance between the TX and RX was kept to three meters.

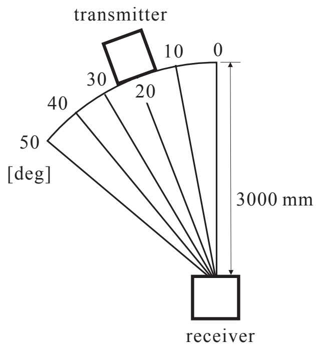

Fig. 7. Transmitter and receiver arrangement

Fig. 8 shows the results of the angle measurements. The retrieved angles of zero-, ten-, twenty- and thirty-degree positions. These results show that the phase accordance method improved measurement accurtcy compared with former methods in which the accuracy was usually a few centimeters or a few degrees. The retrieved angles, however, are showing errors at the angles of 40 degrees and beyond. We presume this error comes from the diffraction of the ultrasonic wave at the corner of the receiver transducer, and can be avoided by choosing a wider aperture device. The estimated angles still show a small distribution for these positions. This means the receiver still *sees* the ultrasonic source as a point in space even after the wave is deflected.

Fig. 9 shows the result of distance measurements. Calculated distances of all the measurements are close to their true values (3000 mm or 3 meters) and the distributions are also small. Note that the positional accuracy of the signal source in the experiment was not particularly high. The few-millimeter shift of the average distance value from 3000mm is due to the error of the phase accordance method. We thus need to do more experiments to examine the total accuracy. In the time being, we only state that the distribution of the measurement values is within a millimeter for these distances and angles.

V. Conclusions

We developed a new technique for positioning systems using ultrasounds. The new technique uses multiple ultrasonic waves (two, in this study) of different frequencies to correctly identify TOA and accurately estimate distances and orientations between transmitters and receivers. We built an experimental system and acknowledged the performance of the proposed technique is satisfactory, namely the error in estimated distance is within $\pm$ 1 mm when measuring a three meter distance and the orientation estimation error is less than 0.5 degrees when measuring zero-, ten-, twenty- or thirty-degree angles. In addition to the accuracy, the proposed method can estimate distances and orientations between devices by using an one-time ultrasonic burst wave. A positioning system based on the proposed technique is therefore especially useful for ubiquitous computing applications where people with mobile devices continuously change their positions in an indoor environment.

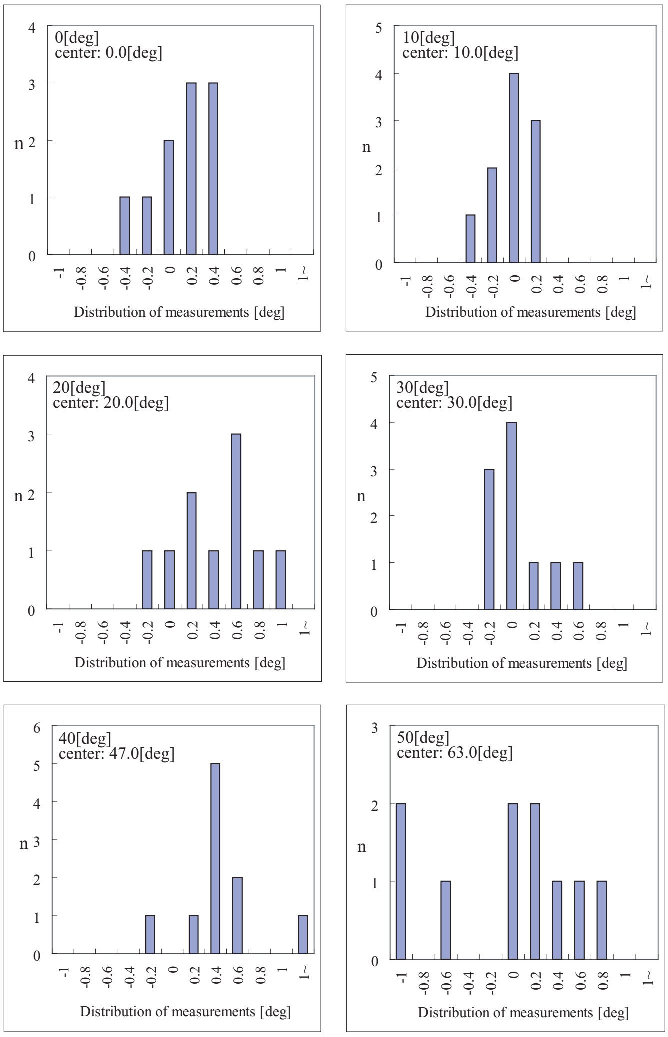

Fig. 8. Error distribution (angle)

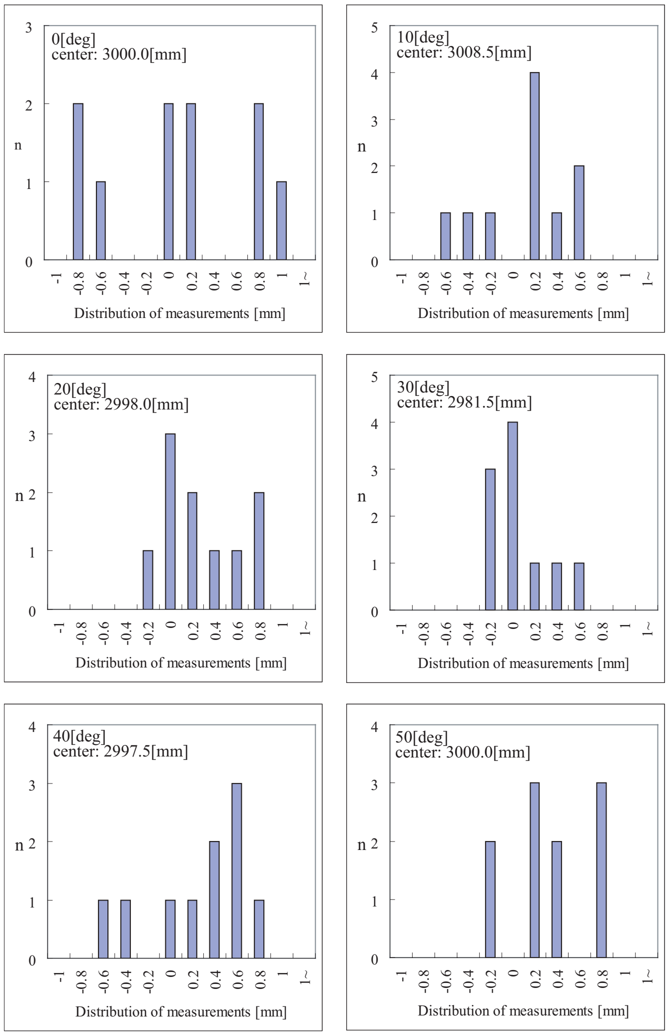

Fig. 9. Error distribution (distance)

Several issues still need to be investigated, for example, when measuring an angle of 40 degrees and beyond, the estimation is not accurate. We will try several methods for estimating correct orientations, such as choosing a wider perception angle device. We have not yet conducted intensive evaluations on how effective the proposed technique is for solving the multipath problem. We also plan to develop ubiquitous computing applications by using a positioning system based on the proposed technique. An example of the applications is *Toss-It* — which allows people with a mobile device to transfer data by a toss and a swing action [12].

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