Accuracy of Distance Measurements Using Signal Tracking of Spread-Spectrum Ultrasonic Waves with CDMA

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***Abstract*— Autonomous robots moving indoors require information about their position with high accuracy in order to reach their destination safely and correctly. To realize self-localization for such autonomous robots, we aim to measure the indoor position of a moving object by using signal tracking with spread-spectrum (SS) ultrasonic signals. In this paper we investigate the accuracy of distance measurements using signal tracking of SS ultrasonic signals using Code Division Multiple Access (CDMA). To detect the SS ultrasonic signals, we perform correlation calculations between a range of received waves and a similar range of replica signals identical to the transmitted SS signals. Conventional positioning systems using SS signals employ signal acquisition to calculate the coordinates of objects from correlation values and signal tracking to measure the relative shift of distances of moving objects. After investigating the signal acquisition method, we found that 3-D positioning with an error of 50 mm was possible, even when transmitting simulcast ultrasonic signals with CDMA. Other studies using our proposed signal tracking method for moving targets without CDMA have maintained correlation values using a limited correlation range for correlation calculations, though they have yielded reduced correlation values for unmoving targets. In this paper, we develop a signal tracking method using the simulcasting of multiple signals with CDMA and discuss its effectiveness. We conduct an experiment on distance measurements to determine the method's measurable range and measurement error. We perform ten measurements of distances from 1000 to 6000 mm between a transmitter and a receiver, in 1000 mm intervals, using 50% of the correlation range. The results indicate an average measurement error of 11 mm, which is less than that of conventional signal acquisition methods.**

I. Introduction

The fields of application of position information have expanded in tandem with the advancements in our information-driven society. Indoor position information is important to people and robots for navigating along a route. Furthermore, the position information is required to realize the self-localization of the robots. In these cases, the moving targets have to be measured with high accuracy at less than 10 cm by using a battery-powered device.

A positioning system which obtains coordinates for achieving self-localization of robots must also be able to easily interface with a virtual reality simulation, such as SIGVerse$^{\mathrm{TM}}$[1], although the infrastructure required for providing this position information. The indoor coordinates is also expected when cooperative work is conducted using multiple robots.

Therefore, we have investigated an indoor positioning system using spread-spectrum (SS) ultrasonic signals to satisfy these needs, (i.e., real-time indoor positioning with high-accuracy coordinates for robots). Here, we aim to develop a signal tracking method using the simulcasting of multiple SS ultrasonic signals with Code Division Multiple Access (CDMA). In both our proposed Newton-Raphson and signal tracking methods, the numbers of repeated calculations are reduced because the initial coordinates, which are near to a target, are obtained through signal tracking. In this paper, we perform an experiment on distance measurement to find the measurable range and measurement error of our proposed tracking method. We measure distances of 1000 to 6000 mm between a transmitter and a receiver, at 1000-mm intervals, and the results indicate an average measurement error of 11 mm, which is less than the error of conventional signal acquisition.

II. Relevant Studies and Previous Works

Various sensor systems have been investigated for indoor positioning purposes, including pseudolites [2] or radio wave sensor [3]. Of these, ultrasonic-wave-based systems have been found to have lower cost and greater accuracy. However, these systems generally have weak noise resistance and are slow to acquire data as they use the time-division multiplexing method with on-off keying, which grows increasingly cumbersome as the number of objects to be measured grows. Thus, Ureña et.al. have been also investigated the measurement system by simulcasting ultrasonic signals [4][5]. As more robust measuring systems for ultrasonic signals, the system using SS ultrasonic signals have been also investigated [6][7][8] to overcome these drawbacks.

Analogous to SS radio wave systems (e.g., GPS), we have proposed a real-time 3-D positioning system using SS ultrasonic signals with a band-limited transducer, low-power field-programmable gate array (FPGA), and a small micro-processor [9][10]. Furthermore, we have discussed factors

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such as positioning errors in indoor environments [11], and signal degradation with band-limited transducers [12]. These studies showed the measurement accuracy of the positioning system using SS ultrasonic signals. We have also proposed a calculation algorithm based on the Newton-Raphson method for continuous signals, rather than conventional pulse signals. As a result, 3-D coordinates can be obtained every 80 ms using CDMA with continuous signals [13].

Signal acquisition is a method for obtaining the absolute coordinate of an unmoving target, while signal tracking is a method for obtaining the relative movement of a moving target. In a positioning system that uses SS radio waves, coordinates are measured through a signal acquisition and tracking process. Meanwhile, in a system using SS ultrasonic signals, position is measured via signal acquisition for unmoving targets and signal tracking for moving targets; the latter of which has been investigated using a limited correlation range [14]. In this study [14], we examined the measurable range of our proposed tracking method, based on an experiment on distance measurements using single SS signals. We found that we could potentially measure a moving target with a speed of 0.5 m/s, though signals grew more diffuse with range than when a signal acquisition was utilized for unmoving target. Thus, we need to further investigate the measurable range and effectiveness of this signal tracking method using simulcasting with CDMA. Unfortunately, there have been few studies on the measurable distance and measurement accuracy of moving targets using simulcasting SS ultrasonic signals.

III. Indoor Positioning Method Using SS Ultrasonic Signals

A. Positioning Environment for Indoor Positioning System Using SS ultrasonic signals

An indoor positioning system using SS ultrasonic signals for real-time measurement of the 3-D position of an unmoving target (e.g., unmoving people and robots) has been developed using a signal acquisition method [11]. Fig. 1 shows the positioning environment for this system. Four transmitters are installed in a room, and the position of a receiver mounted on a target is measured.

Generally, a system employing ultrasonic waves is ineffective in near-far problems, because of signal attenuation by the air. However, it is robust around obstacles owing to the diffraction of ultrasonic waves, and even small and slow processors can be utilized with ultrasonic speeds. The positioning system using SS ultrasonic signals possesses these same properties, so we must consider the near-far problem when signals are transmitted by CDMA.

B. Production of SS Ultrasonic SIgnals in a Transmitting Hardware

The SS ultrasonic signals for the positioning system consists of a carrier wave and a Maximal Length Sequence (MLS), which is a type of pseudo-random binary sequence[12]. Chips of the MLS can be generated easily by a shift register and taps in the transmission hardware, as shown in Fig. 1 The

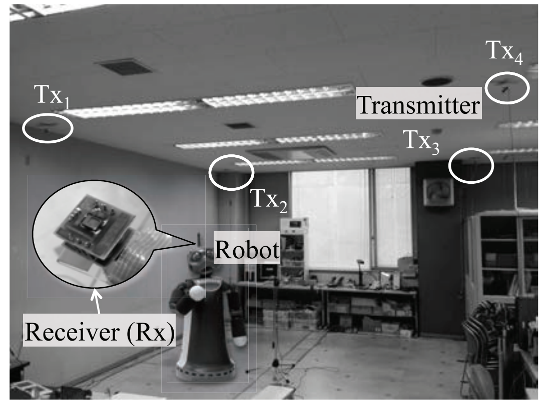

Fig. 1. A positioning environment for the self-localization of robots.

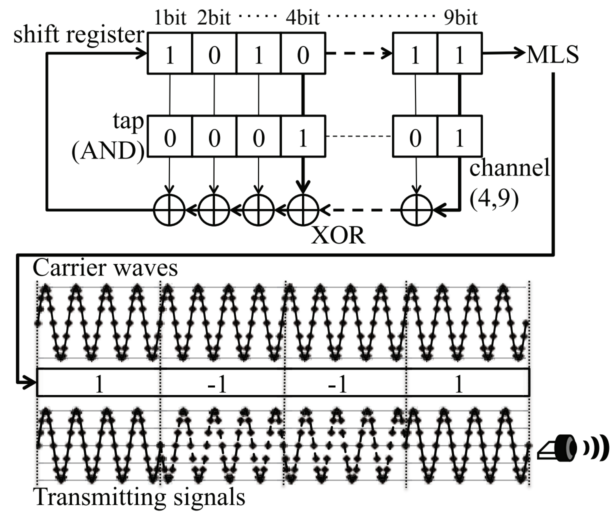

Fig. 2. Signal generation in our transmitting hardware by 9-bit shift register.

sequence has periodicity, which can be decided by the length of the shift register. In our system, we utilize an MLS with a length of 511 chips generated by a 9-bit shift register, as shown in the top of Fig. 2. By changing the value of the tap in Fig. 2, several sequences with low cross-correlation can be generated. In Fig.2, channel $\{4,9\}$ are selected. The MLS also has self-correlation characteristics. A high correlation value, defined as a peak value, is obtained from a multiply-accumulate operation with the same MLS without a phase-shift. Therefore, CDMA is achieved using several signals generated by different channels. Transmitted signals are generated using the MLS and carrier waves at 40 kHz. The sampling rate of the transmitted signals is 640 kHz, and the chips are modulated by 64 samples on the carrier waves, as shown in the bottom of Fig.2.

C. Signal Detection Using Continuous Ultrasonic Signals

We define the measurement distance as a certain distance between a transmitter and a receiver. Signal detection is performed in the receiver unit to obtain this distance. Fig. 3 describes the procedure for distance measurement via signal

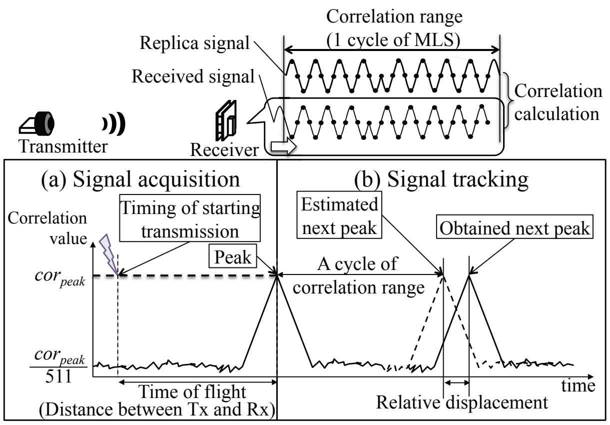

Fig. 3. The procedure for distance measurement using signal acquisition and signal tracking with SS ultrasonic signals.

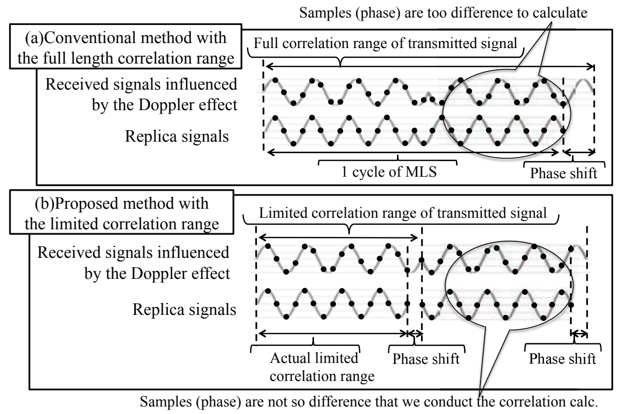

Fig. 4. The signal tracking method with a limited correlation range.

detection. The signals from the transmitter are detected from the calculated correlation values. The correlation calculation is typically performed between the received signals and the replica signals within one cycle of the MLS, as shown in the top of Fig.3. In the signal acquisition procedure, as shown in Fig.3(a), the correlation values are calculated for every unit of sampling time. The sampling time is 6.25 microseconds, because the receiving hardware in our system has a sampling frequency of 160 kHz. In Fig.3, we also plot the obtained samples on the replica and received signals. From this calculation, the peak values,cor_{peak} are detected via the self-correlation characteristics of the MLS when the transmitted signals are received. Otherwise, the correlation values are obtained at approximately $cor_{\mathrm{peak}}/511$. For signal acquisition, the signal detection procedure yields a time-of-flight (TOF) value, from the time when the beginning of the MLS is transmitted by the transmitter to the time of detection of the peak, as shown in Fig.3(a). The time at the beginning of the MLS is announced to the receiver via electrical signals, such as radio waves. The measurement distance between the transmitter and the receiver is calculated from the TOF. After obtaining the TOF, the peaks can be obtained at each period T as shown in Fig. 3, owing to the periodicity of the MLS. In our transmission system, the transmission timing is synchronized with 20 times this period. Thus, the TOF can be continuously obtained at $20T$ s intervals.

To measure a distance, the signal acquisition(Fig. 3(a)) and signal tracking(Fig. 3(b)) for the signal detection are conducted using the correlation values. aspects of the signal detection procedure are performed using the correlation values. The signal acquisition and tracking procedures measure the distance between a transmitter and a receiver for an unmoving target, and the relative distance for a moving target. However, the signal tracking procedure requires the result of the signal acquisition procedure for initialization. In our system, we first measure the position of the unmoving target. After signal acquisition is performed and the TOF is obtained, the positions of moving targets can be measured using the signal tracking procedure.

Following peak detection, if a peak is detected using an unmoving target, then the next peak will be detected after 1 cycle of the MLS, owing to the frequency of MLS, as shown by the solid line in Fig. 3(b). For a moving target, the shifted peaks are detected, as shown by the dashed line in Fig. 3(b). The relative moving distance to the previous position can be calculated by measuring the time between the estimated peak and the obtained peak. We compensate for the shifted peak of the replica signals by using feedback control in signal tracking. In the case of a large Doppler effect, however, signal tracking is difficult owing to the diffuse peak.

IV. Proposed Signal Tracking Method for SS Ultrasonic Signals

Even if we utilize a tracking method for a target moving at over 0.05 m/s, indoor positioning with a mobile object would remain difficult, owing to the Doppler effect on the SS ultrasonic signals[14]. SS ultrasonic signals from moving targets decrease more than SS radio waves in signal strength, such as in a Global Navigation Satellite System (GNSS), as the propagation speed of ultrasonic waves in air is much slower than that of radio waves. Therefore, we have proposed a method with a limited correlation range[14]. Let us explain the proposed method using Fig. 4, which illustrates the correlation calculation between received signals influenced by the Doppler effect and the replica signal, when a peak should be detected, for both (a) the conventional method using full-length correlation range and (b) the proposed method using a limited correlation range. Obtained samples are also plotted on Figs. 4(a) and (b) as black circles. In the conventional method in Fig 4(a), the correlation range becomes a cycle of MLS. The phase shift becomes large, and the peaks of the correlation values decrease because the long correlation range causes differences between the values in each received sample, as shown in the right side of Fig. 4(a). In the proposed method, shown in Fig.4(b), the limited correlation range decreases the phase shift and, therefore, a robust peak can be obtained despite the Doppler effect.

When using a method with a limited correlation range,

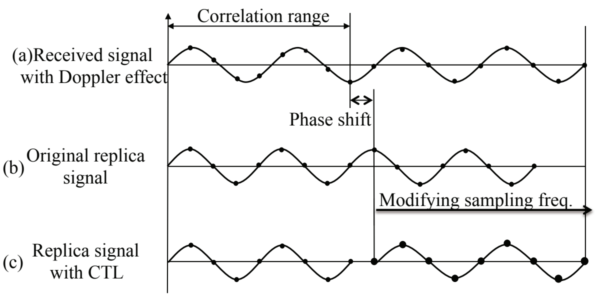

Fig. 5. Signal tracking using a CTL.

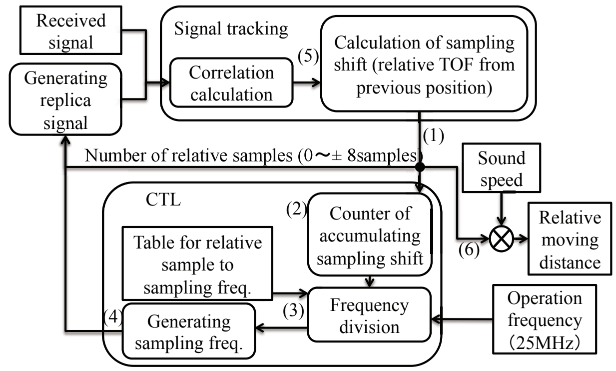

Fig. 6. Block diagram for signal tracking using CTL.

there is a trade-off between signal strength (i.e., peaks of the correlation values) for the unmoving target and measurement robustness for the moving target. The amount by which the maximum peak of the correlation values is decreased depends on the ratio of the correlation range to the full length of MLS. Therefore, we also apply a Carrier/Code Tracking Loop (CTL), which is expected to adjust the phase shift without significantly limiting the correlation range. This is a method for frequency tracking of carrier waves by measuring the difference in the phase between replica signals and received signals. This difference is obtained from code tracking using the proposed signal tracking method. Using this method, we can achieve a dynamic phase-shift corresponding to the expansion and contraction of the replica signals.

Fig.5 describes the method for the CTL used in our system. The obtained samples are plotted as black circles. Fig.5(a) presents signals received by an ultrasonic receiver. The signals received from a moving object have a different frequency to the original replica signals, as shown in Fig.5(b), because of the Doppler effect. The frequency of the received signals is therefore calculated based on the relative movement obtained through signal tracking, and the sampling frequencies of the replica signals are modified to match the frequencies of the received signals, as shown in Fig.5(c). Applying the CTL allows distance measurements to be made of moving targets with higher speeds than are possible in conventional methods, although these measurements are still limited by the acceleration of the moving target. Thus, we use acceleration to determine the limit of the correlation range. In this paper, we estimate the acceleration of the robots and utilize 50% of the full correlation range for our correlation calculation.

Fig.6 shows a block diagram for the hardware layout of our system for signal tracking with CTL. It includes a signal tracking component using the limited correlation range and a CTL component to detect the sampling frequency of the replica signals. Each component is able to track the code and carrier frequency of the received signals via feedback of the results of the other component. The CTL component measures and modifies the sampling frequency using the relative sample obtained through signal tracking with a limited correlation range. The signal tracking component utilizes modified replica signals from the CTL component.

In the CTL component, relative samples are inputted to stage (1). The relative samples are accumulated in stage (2). Frequencies of the replica signals are obtained using a reference table. This reference table memorizes the frequencies corresponding to the accumulated relative samples in stage (3). In stage (4), replica signals with this sampling frequency are generated. By using these replica signals and received signals, the next peak of correlation values is estimated in stage (4). From the difference between a peak obtained from the correlation calculation and the estimated peak, the next relative sample is measured in stage (5). In stage (6), the relative moving distance from the previous position is calculated by multiplying the relative sample by the speed of sound.

V. Positioning Calculation using the Newton-Raphson Method for Signal Tracking

In our signal tracking system, real-time positioning calculations are performed using the Newton-Raphson method [13], as described in Fig.7. First, the coordinates are initialized, as in Fig.7(a). The closer that these initials coordinates are to the true coordinates of the target, the smaller the calculation time will be. In the signal acquisition procedure in our system, coordinates are initialized at the center of the positioning environment. In the case of signal tracking, the previous position of the target is adopted for the initial coordinates.

We then use the Newton-Raphson method to find a more accurate set of coordinates. The distances from each set of coordinates of the transmitters to the pseudo-coordinates, such as the initial coordinates (shown as $d_1(0)$ in Fig.7), are calculated as in Fig.7(b), and the differences from the measured distance (such as $d_{1\mathrm{err}}(0)$ in Fig.7) are obtained. In the next calculation, the pseudo-coordinates are re-estimated to reduce this difference, and the calculation is repeated, as in Fig.7(c). The final set of coordinates that minimizes the sum of the differences using the least-squares method is the result of the positioning calculation.

VI. Hardware Architecture

To realize our positioning system, we utilized the hardware shown in Fig. 8. Our transmission hardware consists of an original transmission board, a PC, and transmitters. The transmission board is connected to the transmitters via audio mini

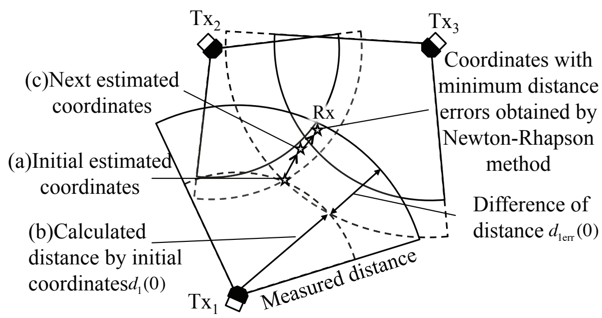

Fig. 7. Positioning method using Newton-Rahpson method.

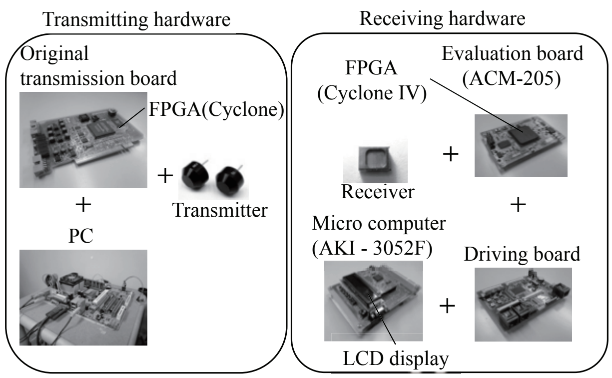

Fig. 8. Hardware devices for the positioning system.

plugs and a PCI bus in the PC. Signals for transmission are generated using a 9-bit shift register at the FPGA (Cyclone EP1C6Q240C6) in the board.

We constructed our receiving hardware using a receiver, a low-power FPGA (Altera Cyclone IV) on an evaluation board (ACM-205), an original driving board, and a microcomputer (AKI-H8 3052F) as a low-cost microcontroller. External Random Access Memory (RAM) is required to calculate correlation values [9], thus, SRAM is mounted on the original driving board and controlled by the evaluation board. The evaluation board is driven by an oscillator at 50 MHz. This evaluation board generates a replica signal and performs the signal acquisition and tracking with a CTL at a limited correlation range. The microcomputer, connected to the driving board, calculates the coordinates of the receiver mounted on the target and displays them using an LCD. This computer is a battery-powered device.

Table I presents the specifications for the transmitter and receivers employed in our positioning system. A transducer with a closed-aperture-type ceramic speaker (PR40-18S) made by Nippon Ceramics [15] is utilized as a transmitting device.

The directivity of the transducer is shown in Fig. 9. In this figure, we define the sound pressure at 0 degrees as 0 dB in terms of attenuation. The attenuation with angle is shown on the transmitter and the receiver. The directivity is also symmetrical about 0 degrees. This transducer has

TABLE I
SPECIFICATIONS OF THE TRANSMITTER AND RECEIVERS.

Type	Ceramic speaker (Close aperture type)	Si microphone
Directivity	Wide directivity half value half angle = 80[deg.]	Omni-directional
Frequency characteristics	40.0 ± 1.0 kHz	10 kHz to 65 kHz
Vender	Nippon ceramic	Knowles electronics

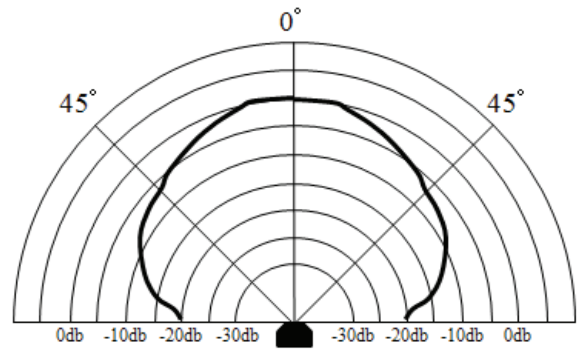

Fig. 9. Directional characteristics of the transducer (PR40-18S).

wide directivity, with a half-value angle at 80 degrees. The transmission power is 11 V peak-to-peak.

For the receiver, we employ a silicone microphone made by Knowles Electronics (SPM0404UD5) [16]. The frequency characteristics of the transmitter and receiver are 40 ± 1 kHz and 10 kHz to 65 kHz, respectively, as shown in Table I. The frequency characteristics of the transmitter and receiver are shown in Figs.10 and 11. In these graphs, the output or input sensitivity is on the vertical axes and frequency is on the horizontal axes. We observe that the transmitter can be used between 30 kHz and 53 kHz under 0 dBV/Pa, and that the receiver can be used up to 11 kHz with a flat response, and up to 50 kHz with over 0 dBV/Pa.

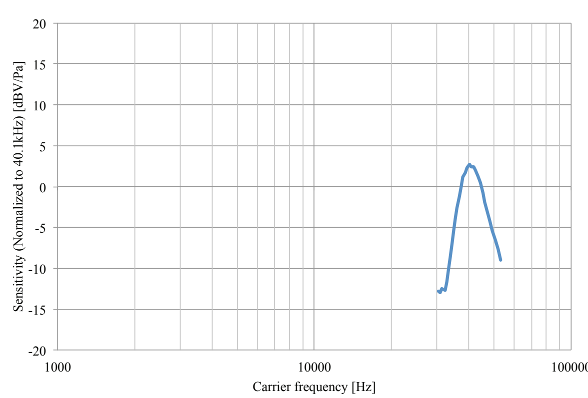

Fig. 10. Frequency characteristics of the transducer (PR40-18S).

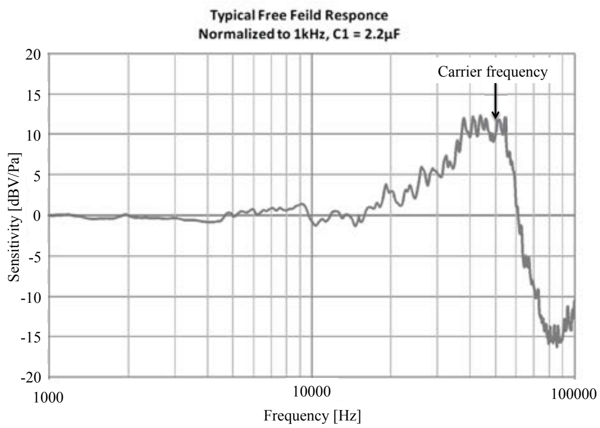

Fig. 11. Frequency characteristics of the microphone (SPM0404UD5).

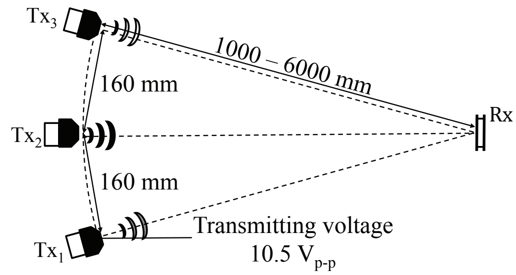

Fig. 12. Experimental setup for the distance measurement using the signal tracking method.

VII. Errors in Distance Measured with Signal Tracking

A. Experimental Parameters

The precision of measurement may be degraded in signal tracking, as compared to signal acquisition, because ultrasonic signals, i.e., the peaks of the correlation values, decrease with the limited correlation range. We therefore conducted an experiment to investigate the precision of the measurement using three channels simultaneously for signal tracking, as shown in Fig. 12. Three transmitters, Tx_1, Tx_2, and Tx_3, are installed along an arc line at intervals of 160 mm. The transmitters and the transmission unit are connected using a 3.5-mm mini-plugged phone connector cable, and the transmission volume is adjusted to 10.5 Vp-p. A receiver is mounted at the center of the arc where the transmitters are installed in order to equalize the distance between the transmitters and the receiver. The transmission timing is sent via cable to evaluate the effect of the errors induced by the CDMA. We measure distances of 1000 to 6000 mm at 1000 mm intervals using a receiver. In this experiment, continuous signals with three channels are utilized. These three channels are generated by tap positions of $\{4{,}9\}$, $\{4{,}5{,}8{,}9\}$ and $\{2{,}3{,}5{,}9\}$ in a shift-register, respectively, Distance between transmitter and receiver mounted on a staying target are measured by using signal acquisition with CDMA. A measuring distance by signal tracking with CDMA is renewed from the measurement distance by signal acquisition. The experiment was conducted 10 times at the each distance and the results were evaluated using the Root Mean Squared (RMS) of difference between the results and the installed distances. em_{rms} is defined as

$$em_{\mathrm{rms}} = \sqrt{(dm_i - d_i)^2} \tag{1}$$

where d_i and dm_i are the measured distance and the true distance between a receiver and i-th transmitter, respectively. The average value of the RMS measuring error is discussed in the following section.

B. Experimental Results for Distance Measurement by Signal Tracking with CDMA

Fig. 13 shows the measurement error when three channels of the CDMA are used. Figs. 13(I) and (II) show the error from using the signal acquisition and tracking methods, respectively. The vertical and horizontal axes correspond to the measurement error and measurement distance between the transmitter and receiver, respectively. The bars show the measurement error for the experiment using simulcast signals with three channels, and the diamonds on the dashed lines denote the averages of these errors. Generally, the measurement precision decreases when multiple channels are used, as compared to using only one channel, because of the near-far problem and cross-correlation of the CDMA [13].

Figs. 13(I) and (II) indicate that measurement accuracy using signal tracking is greater than that using signal acquisition, particularly when the distance between the transmitters and the receivers are small. The average error for all measurement distances when using signal acquisition was 18 mm, whereas the average error using signal tracking was 11 mm. The largest error measured using signal acquisition was 38 mm when Tx_1 was at a distance of 2000 mm, and that using signal tracking was 26 mm when Tx_3 was at a distance of 5000 mm. The measurement precision was below 30 mm for distances of 1000 to 6000 mm using signal tracking. Therefore, distance measurement of unmoving objects using our signal tracking method with a limited correlation range and a CTL could be accurate conducted as same as conventional signal acquisition method.

VIII. Conclusion

In this paper, we discussed an indoor positioning system that uses signal tracking by simulcasting multiple spread-spectrum (SS) ultrasonic signals with code division multiple access. For a positioning system that targets moving objects, such as robots, we also proposed a new signal tracking method with a carrier/code tracking loop using a limited correlation range.

However, measurement errors may occur when simulcasting signals by signal tracking, as the peaks of the correlation value decrease with the limited correlation range. Therefore, to examine the effectiveness of this method on an unmoving target, we conducted an experiment on distance measurements

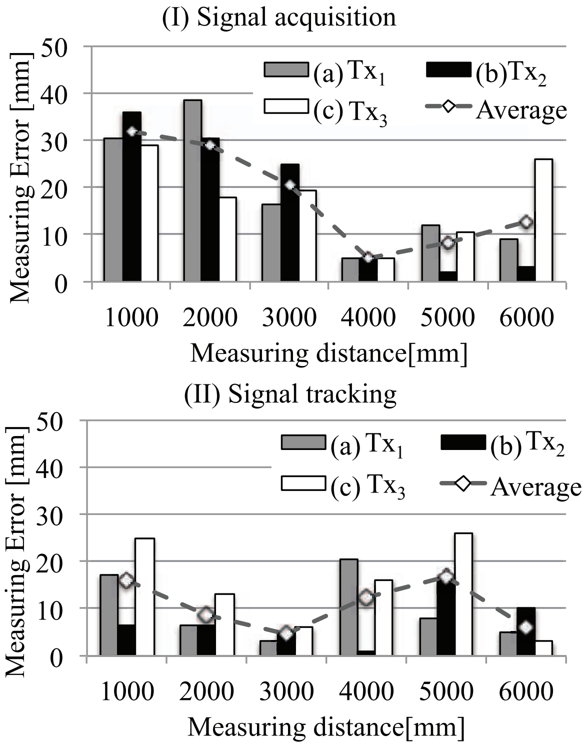

Fig. 13. Experimental results for distance measurements using the (a) signal acquisition and (b) signal tracking methods.

in order to measure the error involved in using signal tracking. The results indicated an average measurement error of 11 mm, which is less than that of conventional signal acquisition.

For future work, we will investigate the effectiveness of the indoor positioning system with simulcast SS signals and our signal tracking method using moving targets. We will also determine if our signal tracking method is effective for indoor positioning. We expect that the correlation values obtained from a moving target will be less than those from an unmoving one, in accordance with the results in this paper. Thus, we will investigate new peak detection methods for continuous signals that are robust against the near-far problem.

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