2012 International Conference on Indoor Positioning and Indoor Navigation, 13-15th November 2012

Indoor Positioning for Moving Objects Using a Hardware Device with Spread Spectrum Ultrasonic Waves

Yuya Itagaki
Akimasa Suzuki
and Taketoshi Iyota
Faculty of Engineering
Soka University
Hachioji, Tokyo 192-8577, Japan
Email: e11m5203@soka.ac.jp

***Abstract*— Moving objects, especially autonomous mobile robots, require information of indoor self-location with high accuracy to reach their destination safely and correctly. In this study, we aimed to measure the indoor position of a moving object using SS (spread spectrum) ultrasonic waves, and we discussed the accuracy of the moving distance measured using a newly developed hardware device. In the case of static object, we showed that because of the noise tolerance of SS waves, a distance up to 20 [m] could be measured between a transmitter and a receiver on cm-order. To detect the SS ultrasonic signals, correlation calculations were carried out between a range of received waves and same range of replica signals; the replica signals were the same as the transmitted SS signals. Popular positioning systems using SS electrical waves employ signal acquisition to calculate coordinates of objects from correlation values and signal tracking to measure the relative shift of distances of moving objects. It is difficult for the system using SS ultrasonic waves to continue tracking because of the decrease in the self-correlation value due to the Doppler effect that acted on a moving object. To solve this problem, we proposed a tracking method for keeping correlation values by limited range of correlation calculations. In this study, for obtaining real-time updates of positional information from the relative shift, an experiment of distance measurement was also conducted using a newly developed hardware device that was used to carry out signal acquisition and the proposed tracking method. The results show that real-time signal tracking with our method could be realized, same as existing software between +/- 0.5 [m/s]. This paper reports that we can expect self-localization of robots using this system.**

Keywords: Indoor Positioning, Spread Spectrum Ultrasonic waves, TOF, Signal Tracking;

I. INTRODUCTION

Localization is required for a robot and a person to navigate to their destinations. GPS can be used to guide when robots and persons who are outdoors. However, this positioning system cannot be used indoors, because it would be difficult for the GPS signal to reach the robot and the person indoors. Therefore, various positioning systems (e.g., using ultrasonic waves [1] and radio waves [2]) have been investigated to find a better method for navigation indoors. Among these systems, the positioning system using ultrasonic waves has an advantage that the multipath of the ultrasonic waves is more distinct because ultrasonic waves are slower than other waves. On the other hand, these waves are weak in terms of noise resistance. To overcome this drawback, positioning systems with spread spectrum (SS) ultrasonic waves have been investigated in [3], [4], [5], [6].

Improving measurable distance for moving objects has not been investigated extensively. Generally, the system using SS ultrasonic waves measures the target's position by signal acquisition, which is a method for obtaining the absolute coordinate of the target. In other cases of positioning systems using SS radio waves (e.g., GPS), signal tracking, which is a method for obtaining relative movement, is also utilized. By signal tracking, we can obtain a moving distance from the previous position at each interval of the cycle of an SS ultrasonic signal. We can expect to reduce the measurement interval by employing signal acquisition and signal tracking together. Therefore, the positioning method involuving signal tracking can be effective for measuring an object's moving distance, such as a robot.

However, if we employ signal tracking directly, measurement is difficult for an object moving at a speed of 0.10 [m/s], because the Doppler effect causes the frequency of SS signals to vary. A larger range of correlation calculation results in a further decrease in the correlation value due to the Doppler effect. To solve this problem, we have proposed a tracking method for keeping correlation values by limited range of correlation calculations. In this study, the effectiveness of this method was experimentally investigated via software simulation; signal tracking was realized within an average error of 50 [mm] via an experiment with a robot moving at a speed of under 0.2 [m/s]. We also constructed hardware, which was used for signal acquisition and tracking, and conducted an experiment for measuring distance. From this experiment using the hardware mounted on static object, we could measure distance up to 7.0 [m] within an average error of 100 [mm] via the tracking method.

This paper is organized as follows. In section 2, positioning environment and positioning methods are explained. In section 3 and 4, I present a proposed method and discuss an effectiveness on the proposed method. In section 5, I explain experiment of measurement distance using the proposed method and show the experimental result. In section 6, there is the

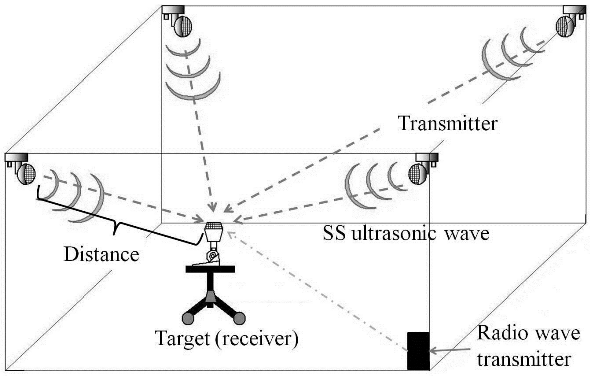

Fig. 1. Positioning environment for indoor positioning using SS ultrasonic waves.

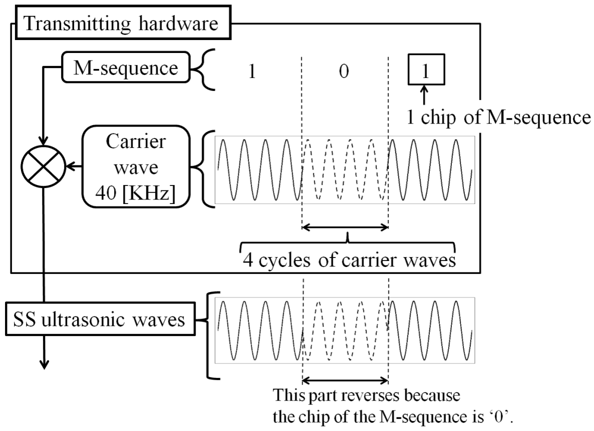

Fig. 2. Procedure in transmitting hardware.

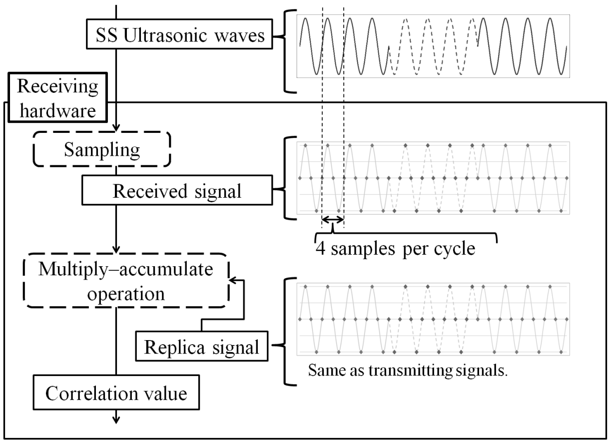

Fig. 3. Procedure for calculating a correlation value at a receiving hardware.

conclusion.

II. INDOOR POSITIONING METHOD USING SS ULTRASONIC WAVES

A. Positioning environment for indoor positioning system using SS ultrasonic waves

An indoor positioning system using SS ultrasonic waves for measuring the position of a static target (e.g., people and robots) in 3-D space has been investigated in real time. Fig. 1 shows the positioning environment for the system. As shown in Fig. 1, three or more transmitters are installed in a room, and the position of a receiver mounted on a target is measured. To measure the position, the distances between the transmitters and the receiver are calculated by multiplying the time of flight by ultrasonic speed. The time of flight is measured from the start of transmission to signal detection.

B. Generation of SS ultrasonic waves in a transmitting hardware

The SS ultrasonic waves used in the positioning system consist of carrier waves and maximal-length linear shift register sequence (M-sequence), which is a type of pseudo-random binary sequence. M-sequence can be generated easily by a shift register in the transmitting hardware, and it is periodic. Its period can be determined from the length of the shift register. In our system, an M-sequence with a length of 511 chips generated by a 9-bit shift register is employed. It also has a self-correlation characteristic; a high correlation value, defined as the peak value, is obtained from the multiply-accumulate operation for identical M-sequences without phase shift.

Fig. 2 shows the procedure for generating SS ultrasonic waves in the transmitting hardware. In Fig. 2, one part of the SS ultrasonic waves is produced by multiplying four cycles of carrier waves by 1 chip of the M-sequence. The carrier waves are used at a frequency of 40 [kHz] and are modulated by binary phase shift keying. If 1 bit of M-sequence is 1 (0), straight (reverse) carrier waves, plotted as a solid (dashed) line in Fig. 2, are generated as SS ultrasonic waves.

C. Correlation calculation in a receiving hardware

Correlation values are required for distance measurement. The correlation value is calculated in the receiving hardware. Fig. 3 shows the procedure for measuring the distance between the transmitter and the receiver at the receiving hardware. Transmitted signals are obtained as digital sampling data at the receiving hardware, as shown in Fig. 3. One cycle of carrier waves includes 4 samples; the sampling frequency becomes 160 [kHz]. The digital sampling data are referred to as the received signals. In the receiving hardware, a replica signal, which is identical to the signal generated in the transmitting hardware (Fig. 2), is produced with a sampling frequency of 160 [kHz]. The correlation value is obtained by the multiply-accumulate operation between replica and received signals within a range. This multiply-accumulate operation and this range are referred to as the correlation calculation and the correlation range, respectively.

D. Signal acquisition in positioning using SS ultrasonic waves

To obtain a distance, signal acquisition and signal tracking can be applied. However, signal tracking requires the result of

978-1-4673-1954-6/12/$31.00

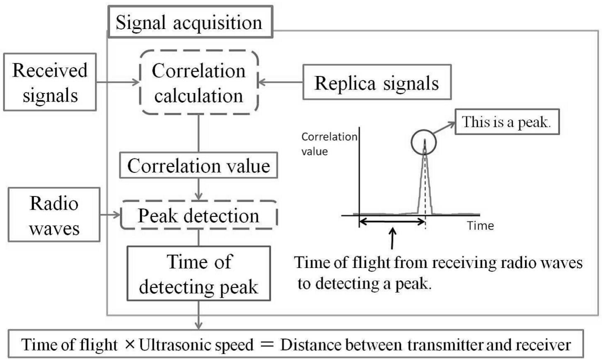

Fig. 4. Signal acquisition for measuring distance

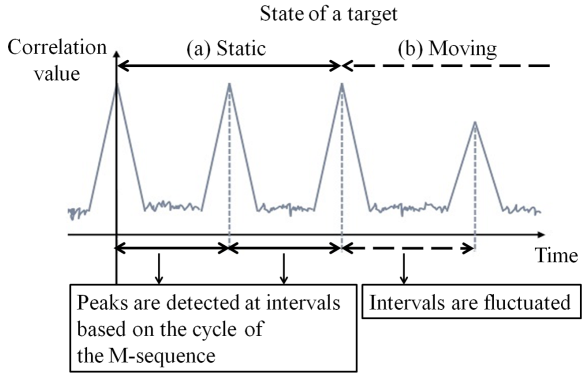

Fig. 5. Distribution of correlation values in case of using (a) static target and (b) moving target.

signal acquisition for initialization. In signal acquisition, the distance between the transmitter and the receiver is measured. Phases of received signals can be also detected via signal acquisition. If signal acquisition is applied for the initialization of signal tracking, a method for measuring time of flight should be improved from conventional method which use a time at start of transmission, because signals are keep transmitting. The procedure of signal acquisition with the proposed method for obtaining the time of flight is explained in Fig. 4. Correlation calculation is carried out between received signals and replica signals within 1 cycle of the M-sequence, as shown Fig. 4. In signal acquisition, correlation values have to be calculated for each sampling instant; therefore, a large amount of computation is required. From this calculation, peak values are detected by the self-correlation characteristic of the M-sequence. Signal acquisition yields the time of flight from the time of receiving radio waves to the time of peak detection.

E. Signal tracking method for SS ultrasonic waves

Signal tracking is done when signal acquisition results in peak detection. In signal tracking, a relative movement is measured in terms of distance on the basis of the phase shift between the received signals and the replica signals. Fig. 5 shows the distribution of the correlation values obtained by signal acquisition in the cases of (a) a static target and (b) a moving target. In this figure, the correlation value and the correlation time are represented on the vertical axis and the horizontal axis, respectively.

In the case of measurement for a static object (shown in Fig. 5(a)), peaks are detected at an interval based on the cycle of the M-sequence [7]. In the case of measurement for a moving target (shown in Fig. 5(b)), the interval fluctuates. The peak values shown in Fig. 5(b) are smaller than those shown in Fig. 5(a), because the frequency of the received signals from the moving target changes because of the Doppeler effect, and the received signals are also phase-shifted. The phase shift is compensated for by feedback control using signal tracking. In the case of large Doppler effect, signal tracking is difficult because of the small peak.

Fig. 6 shows the procedure for signal tracking. In Fig. 6(a), the time when the next peak of the correlation value is to be obtained is estimated from the correlation range and the previous time of peak detection, which is obtained via signal acquisition or signal tracking by used the periodicity of the M-sequence. Herein, this time is referred to as the estimation time. In Fig. 6(b), 17 replica signals are generated. The phase of the M-sequence of the replica signals is shifted by one sample interval from estimation time to ± 8 samples. Replica signals shifted by +8 and -8 samples are referred to as Early code and Late code, respectively. In Fig. 6(c), correlation calculation is carried out using these replica signals and received signals within the correlation range. In Fig. 6(d), the difference is calculated by subtracting a correlation value of Early code (early correlation value) from that of Late code (late correlation value). Delay locked loop shown in Fig. 6(e) calculates the current phase shift from the previous peak of correlation values and the difference given by Fig. 6(d). In Fig. 6(f), a current peak or correlation value, selected from 17 correlation values, is obtained from this phase shift, and the current peak is used for calculating the phase shift. From the current phase shift of the M-sequence, a relative distance depending on the moving target can be calculated by multiplying the phase shift by ultrasonic speed because the time difference between the estimation time and the time of current peak detection is calculated by the phase shift (Fig. 6(g)).

III. PROPOSED METHOD WITH LIMITED CORRELATION RANGE

Even if we employ the tracking method, indoor positioning with a mobile object is difficult because of the Doppler effect. Therefore, a method with a limited correlation range is proposed. Let us explain the proposed method using Fig. 7. Fig. 7 illustrates the correlation calculation between received signals influenced by the Doppler effect and replica signals, when a peak is detected, for both (a) the conventional method using the full-length correlation range and (b) the proposed method using a limited correlation range, respectively. In case of the conventional method, shown in Fig 7(a), the correlation range becomes a cycle of the M-sequence. The phase shift,

978-1-4673-1954-6/12/$31.00

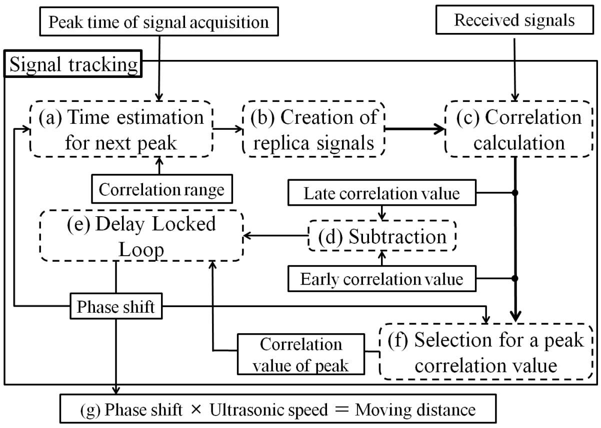

Fig. 6. Procedure of signal tracking hardware for measuring distance of moving object.

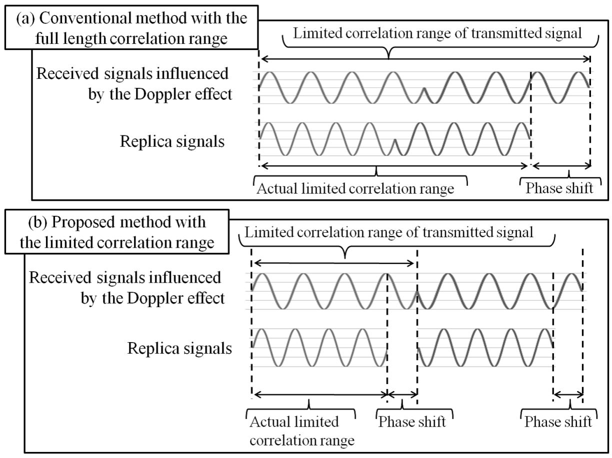

Fig. 7. Comparison of signal tracking for measuring a moving distance between (a) conventional method with the full-length correlation range and (b) proposed method with the limited correlation range.

shown in Fig. 7(a), increases, and the peak of correlation values decreases because of the large correlation range. In the case of the proposed method, shown in Fig. 7(b), the limited correlation range results in a decrease in the phase shift; therefore, a robust peak against the Doppler effect can be obtained.

In the case of the proposed method for signal tracking with a limited correlation range, the correlation values obtained by calculation are small because the number of samples in the received signals is small. The S/N ratio of the signal also decreases; therefore, in measuring the position of a static object, signal acquisition has an advantage over the proposed method. However, in the case of measuring a moving object, the proposed method can be expected to measure the position stably because the correlation values do not decrease; the correlation values obtained from the proposed method are robust against the Doppler effect. Therefore, hardware for real-time distance measurement was constructed. This hardware could be used for distance measurement of a static object and a mobing object, and for this, it switched seamlessly between signal acquisition and the proposed signal tracking, respectively.

IV. Effectiveness of the Method with the Limited Correlation Range by Software Simulation

A. *Software simulation for signal tracking using the pseudo-signals based on static transmitter and receiver*

To discuss the effectiveness of the tracking method with the limited correlation range for the SS ultrasonic waves, software simulation of signal tracking with the proposed method was conducted using recorded sound data, which was obtained by an experiment for distance measurement. In this experiment, the distance between a transmitter and a receiver is fixed at 30 [cm]. Pseudo-signals influenced by the Doppler effect at a pseudo-speed were generated from the sound data via off-line processing in software. M-sequences were generated from a 10-bit shift register and had a correlation range of 64 chips (i.e., $1/16$ of full length).

The robustness of our method was discussed in terms of variations in the peaks of the correlation values using the pseudo-signals. Fig. 8 shows the ratios of the peaks of the correlation values. Fig. 8(a) and (b), showing solid and dashed lines, represents the ratios with the full-length correlation range and the limited correlation range, respectively. In this graph, the ratios connected by lines are plotted with height as the vertical axis and the pseudo-speed of the receiver as the horizontal axis. Here, for comparing Fig. 8(a) and (b), the ratio of peaks, obtained by pseudo-signals on the static object with the full-length correlation range and the limited correlation range, respectively, was defined as 100 [%].

From the experimental result, in the case of Fig. 8 (a), the ratio of the peak of correlation values at 1.0 [m/s] was decreased to under 10 [%]. The ratio at the same speed of 1.0 [m/s] in Fig. 8 (b) shows about 40 [%]. The peaks of correlation values using the proposed tracking method are greater than those using the normal signal tracking with the full-length correlation range. Therefore, the effectiveness of the proposed method using the limited correlation range is shown.

B. *Software simulation for signal tracking using a moving robot*

As another discussion, the performance of the proposed tracking method was evaluated using recorded data obtained for a robot moving up to a speed of 0.4 [m/s]. Fig. 9 illustrates the outline of this experiment. The experimental sysytem consists of a static transmitter and a receiver mounted on the moving robot. Signal tracking when the receiver is moving away from the transmitter is more difficult than when the receiver is moving forword the transmitter. The farther is the distance between the transmitter and the receiver, the lesser is the peak of correlation values. In this experiment, the distance was measured for the mobile robot moving away from the position of the transmitter. As shown in Fig. 9, the initial

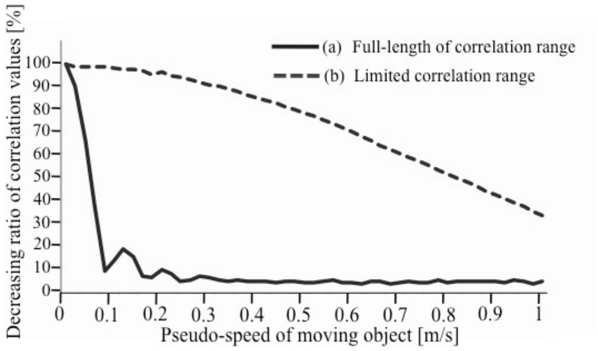

Fig. 8. Decreasing ratio of peaks of correlation values with (a) full-length of correlation range and (b) limited correlation range for each pseudo-speed obtained by simulation.

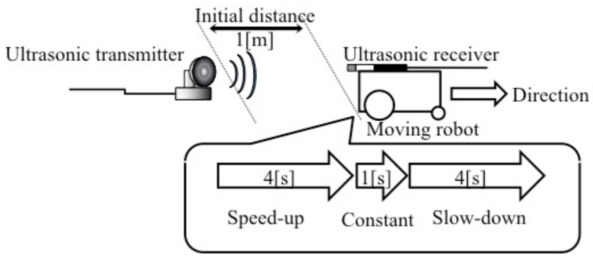

Fig. 9. Experimental environment for signal tracking using moving object.

TABLE I

MEASURABLE DISTANCE USING THE TRACKING METHOD WITH (A) FULL-LENGTH CORRELATION RANGE AND (B) LIMITED CORRELATION RANGE

	measurable distance [m]	
maximum speed of the object [m/s]	(a) full-length of correlation range	(b) limited correlation range
0.05	0.25	0.25
0.1	0.45	0.5
0.2	0.2	1.0

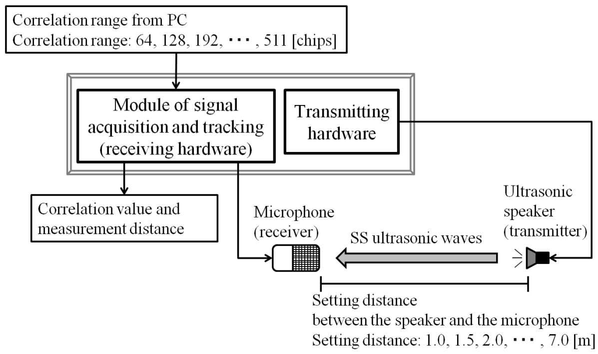

Fig. 10. Experimental environment for the distance measurement using hardware with signal tracking

distance was fixed at 1 [m]. From the initial distance, the robot speeded up in 4 [s], moved with a constant velocity for 1 [s], and slowed down in 4 [s]. As a parameter, the maximum speed of the robot was set to 0.05 [m/s], 0.1 [m/s], 0.2 [m/s], 0.3 [m/s], and 0.4 [m/s], and the signals used were the same as those in the experiment shown in Fig. 8.

The experimental results for an object moving up to a speed of 0.2 [m/s] are given in Table I. Table I presents the maximum distance, which was measured using the signal tracking method with (a) the full-length correlation range and (b) the limited correlation range for different maximum speeds of the robot.

For the maximum speed of 0.05 [m/s], Table I indicates that distance could be measured until 0.25 [m] for both ranges, where the robot had completed its movement. At the maximum speed of 0.1 [m/s] for the full-range values, signal tracking was impossible over the distance of 0.45 [m], where the robot was slowing down. At the maximum speed of 0.2 [m/s] for the full-range values, the signal tracking was also impossible over a distance of 0.45 [m], where the robot was speeding up. However, if the proposed method (i.e., signal tracking using the limited correlation range) was utilized, the signal tracking was possible, even though the robot moved at a speed of 0.4 [m/s]. This experiment was conducted via off-line simulation using software; however, the proposed method could be realized for measuring distances between a moving receiver and a stable transmitter.

V. MEASUREMENT DISTANCE USING THE PROPOSED METHOD MOUNTED ON HARDWARE

A. Experimental setting

We conducted an experiment for measuring distances using the hardware of signal tracking in order to discuss the measurable distance and the measurement error if we employed the proposed method. Fig. 10 shows the experimental environment for distance measurement. In the hardware, signal acquisition, tracking, and generation modules are installed. The signal generated by the hardware is transmitted by an ultrasonic speaker and is received by a microphone. The received signals are processed in the signal acquisition and tracking modules. The distance between the speaker and the microphone is referred to as the setting distance. The setting distance was fixed at 0.5 [m] intervals from 1.0 [m] to 7.0 [m]. A correlation range for the proposed method of the signal tracking is configured beforehand using a PC. We used a 9-bit shift register for signal acquisition, so the maximum correlation range became 511 [chip]. In the experiment, we used the correlation range at 64 [chip] intervals from 64 [chip] to 511 [chip]. When peaks are detected three times, signal tracking is performed. We carried out 30 measurements at each distance. On the basis of the distribution of the correlation values and the average error for distance measurement at the end of signal tracking, the measurable distance of our signal tracking method was discussed.

978-1-4673-1954-6/12/$31.00 © 2012 IEEE

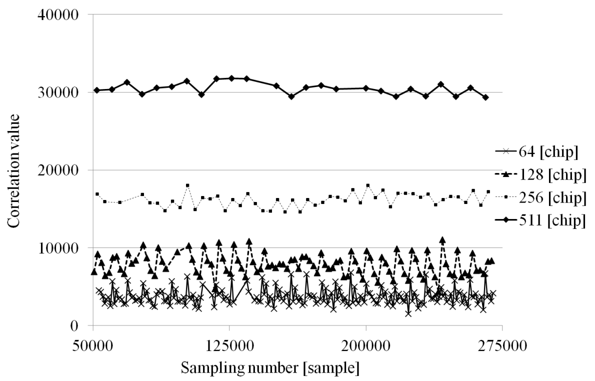

Fig. 11. Transition of correlation value for each correlation range.

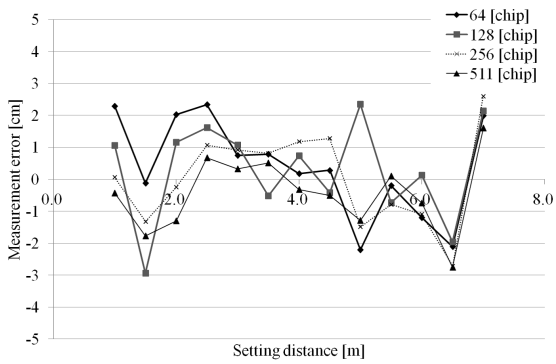

Fig. 12. Measurement errors for each setting distance.

B. Experimental result with the proposed signal tracking method

From the experimental results, we could measure distance up to 7.0 [m] within an average error of 50 [mm]. Fig. 11 shows the distribution of the correlation values for each correlation range in case of the least correlation values in the distance measurement, which was fixed at 7.0 [m] between a transmitter and a receiver. In this figure, the correlation values connected by lines are plotted with height as the vertical axis and sample number as the horizontal axis. From Fig. 11, we found that dispersion is greater for a smaller correlation range. However, as shown in Fig. 11, signal tracking for 64 [chip] can be realized.

Fig. 12 shows measurement errors for each setting distance. In this figure, the measurement error connected by lines is plotted with height as the vertical axis and setting distance as the horizontal axis for correlation ranges of (1) 511 [chip], (2) 256 [chip], (3) 128 [chip] and (4) 64 [chip]. From Fig. 12, we could measure distance up to 7.0 [m] within an average error of 50 [mm]. The experimental results shown in Fig. 11 and Fig. 12 shown that distance measurement can be realized using our signal tracking method with SS ultrasonic waves.

VI. Conclusion

In this paper, we proposed a signal tracking method for measuring the distance traveled by a moving object by using SS ultrasonic waves, and the effectiveness of the method was discussed through two experiments: software simulation using a signal under the Doppler effect and signal tracking with hardware using a static object. This tracking method realizes to keep correlation values under the Doppler effect by a limited range of correlation calculations. In the simulation, we found that signal tracking with a moving object that was limited to a speed of 0.2 [m/s] could be realized within an average error of 50 [mm]. We could also measure distance up to 7.0 [m] within an average error of 50 [mm] via the tracking method using the hardware; therefore, we can say that this signal tracking method is effective.

References

[1] Andy Ward, "A New Location Technique for the Active Office,": IEEE Personal Communications, 1997.

[2] Dinesh Manandhar and Hideyuki Torimoto, "Development of IMES Installation, Setup and Management System,":The Institute of Navigation, 2011.

[3] Akio Yamane, Taketoshi Iyota, Yongwoon Choi, Yuzuru Kubota and Kazuhiro Watanabe, "A Study on Propagation Characteristics of Spread Spectrum Sound Waves using a widely used Band-limited Ultrasonic Transducer," :Journal of Robotics and Mechatronics, 2004.

[4] Hazas,M. and Hopper,A, "Broadband Ultrasonic Location Systems for Improved Indoor Positioning,":IEEE Transactions on Mobile Computing, 2006.

[5] Omar A.M. Aly and A.S. Omar, "Spread Spectrum Ultrasonic Positioning System,": WPNC/UET, 2005.

[6] A. Suzuki, T. Iyota, A. Yamane, Y. Choi, Y. Kubota, K. Watanabe, Measurement Accuracy on Indoor Positioning System Using Spread Spectrum Ultrasonic Waves Proc. of the 4th International Conference on Autonomous Robots and Agents (ICARA 2009), Feb. 10-12, Wellington, New Zealand.

[7] Pratap Misra and Per Enge, "Global Positioning System :Signals, Measurements, and Performance,"

978-1-4673-1954-6/12/$31.00 © 2012 IEEE