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An Information Addition Technique for Indoor Self-localization Systems Using SS Ultrasonic Waves

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***Abstract*—In this paper, we propose an information addition technique for a 3-D indoor positioning system using spread spectrum (SS) ultrasonic waves, and evaluate its effectiveness. The system can position a target with high resolution, noise tolerance, and an ability of implementing CDMA by SS code using a limited number of transmitting channels. An M-sequence is employed as the SS ultrasonic code. Our aim is a positioning system for self-localization of people and robots; the location of a receiver installed on a target can be measured with SS signals from transmitters mounted in the positioning area. To evaluate the effectiveness of the proposed technique, an experiment to measure the distance from transmitter to receiver was conducted with the original hardware used with this technique. In this experiment, 4-bit information in a period of the M-sequence, generated by an 8-bit shift register, was applied. The result showed that the distance from transmitter to receiver and the added information can be detected at the same time. This experiment demonstrated the effectiveness of the information addition technique for SS ultrasonic waves.**

Keywords: Spread spectrum, Ultrasonic waves, Indoor positioning system, Information addition

I. INTRODUCTION

Indoor positioning systems have been recently required for self-localization of people and robots for navigation in a building with many large rooms. Therefore, indoor positioning systems such as GPS (Global Positioning System) or infrared rays are being investigated. 3-D indoor positioning systems such as Active Bat and Dijk's method [1,2] have a simple structure and can measure a position with high precision. However, many systems using ultrasonic waves are generally weak in terms of noise resistance. In addition, the measurement time is increased owing to an increase in input from the targets; these systems generally measure some target positions via time division multiplexing (TDM). Therefore, a positioning system using spread spectrum (SS) ultrasonic waves has been investigated as a noise-tolerant system that does not use TDM. Hazas et al. have reported that such a positioning system can be realized using custom-designed transmitters and receivers in analogy with GPS [3,4]. We too have also proposed a real-time indoor local positioning method using SS ultrasonic waves, and evaluated the performance of noise tolerance and Code Division Multiple Access (CDMA) using all-purpose transmitters and receivers [5].

In this proposed system, the time of flight (TOF) is measured between more than four transmitters functioning as a pseudo-satellite located within the environment and the receiver. In this case, in a large positioning area with many transmitters, the system should contrive to acquire the position of each transmitter because the arithmetic processing in a receiver will be prohibitively costly and the kind of SS ultrasonic waves allotted for each transmitter is limited. In large areas, the temperature fluctuates, which changes the sound speed frequently, and therefore, we can expect an improvement in positioning precision by estimating the speed of sound corresponding to the temperature changes. We propose a new method in which information is added to SS ultrasonic waves for identification of transmitters and temperature information in a large positioning area.

In the process of designing a positioning system for people and robots, the amount of information transmitted should be considered for real-time positioning. In analogy with GPS, information signals are directly applied, and a 1-bit information signal is added to several periods of SS ultrasonic waves. In this case, the amount of information transmitted in the proposed system is less than that in the GPS method because SS ultrasonic waves have lower transmission velocity and carrier frequency than electrical waves. Masuda et al., in a study on a system conducting measurement and communication at the same time, proposed a method for modulating a 1-bit information signal within two periods of SS ultrasonic waves [6].

In our study, we improved the amount of information transmitted for realizing real-time positioning and the detection of transmitters and temperature, simultaneously. To improve the amount of information transmitted, an experiment for detecting the error rate of the information and measuring the error of distances was conducted via the proposed method, in which 4-bit information was added to a period of SS ultrasonic waves. Our experimental results demonstrate that real-time positioning and detection of information are realized simultaneously in our technique, thus confirming its effectiveness.

II. THE POSITIONING SYSTEM WITH SS ULTRASONIC WAVES

A. *The positioning method with SS ultrasonic waves*

In the case of indoor positioning using SS ultrasonic waves, the position of a target is obtained from the distances between transmitters installed in the environment and a receiver mounted on a target. Fig. 1 shows an overview of the indoor

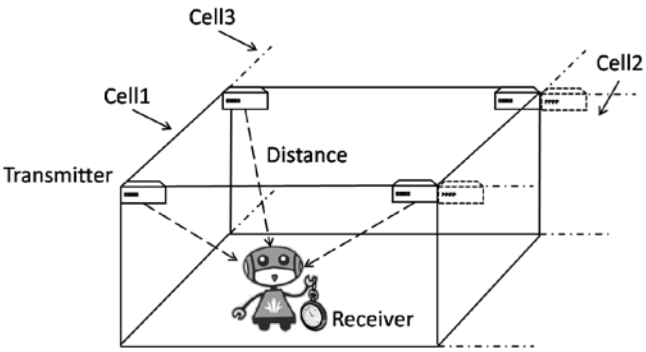


Fig. 1 Outline of our positioning system

positioning system using SS ultrasonic waves. In this system, transmitters are located on the wall and ceiling, and a cell of the positioning area is structured from four transmitters. The indoor area is divided into many positioning areas, such as cell 1, cell 2, and cell 3. A different kind of M-sequence is allotted to each transmitter, and the M-sequence is multiplied by carrier waves to generate transmission signals of SS ultrasonic waves. As shown in Fig. 1, the position is calculated from the distances between the three transmitters and the receiver.

In the receiver, to detect SS signals, replica signals are generated using the same carrier waves and M-sequence as those in the transmission signals. The SS signals are detected from product-sum operation between replica and received signals as a correlation operation. This procedure for signal detection is called *code acquisition.* The TOF of SS ultrasonic waves between a transmitter and a receiver is calculated with code acquisition. The distance is measured by multiplying the TOF by the speed of the ultrasonic waves.

B. Code acquisition with M-sequence

An M-sequence is a pseudo-random code sequence that consists of 0s and 1s. In our system, an M-sequence is generated by an 8-bit shift register, as shown in Fig. 2. Figs. 2(a) to (d) show the values of the shift register, the values of the tap selector, the results of the AND operation, and the input values to the shift register, respectively. In Fig. 2(a), the initial value is inputted to each bit of the shift register. In Fig. 2(b), the tap selector decides the next input value to the shift register. The values in Fig. 2(b) correspond to the M-sequence channel, which is generated by selecting low cross-correlations from among these values. In Fig. 2(c), the results of the AND operation between Figs. 2(a) and (b) are outputted. The output of the exclusive-OR (Fig. 2(d)), calculated from the selected values (Fig. 2(c)), is inputted into the LSB of the shift register

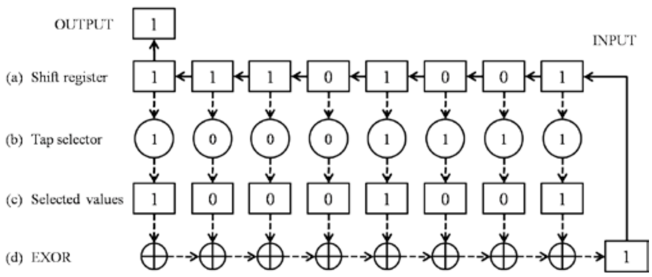


Fig. 2 Hardware for generating M-sequences by using an 8-bit shift register

(Fig. 2(a)). After each bit of the shift register is shifted left, only one bit and the value in Fig. 2(d) are inputted to the LSB, and the MSB of the shift register is outputted. The output of the MSB is the M-sequence. As shown in Fig. 2, the M-sequence generated from the n-bit shift register has $2^n - 1$ bit (chip) periods.

The self-correlation characteristics of the M-sequence change because of a phase shift in the chip. Fig. 3 shows the self-correlation characteristic transition of the M-sequence for a stationary target. In Fig. 3, the correlation values connected by lines are plotted with height as the vertical axis and chip period shift as the horizontal axis. In Fig. 3, the variables *T* and *N* show the length of an M-sequence period and the maximum value of the self-correlation characteristic, respectively. Fig. 3 shows a high correlation when there is no phase shift of the positioning code. The peak coincides with the M-sequence period. The ratio of the peak and other correlation values with phase shift is equal to the inverse of the maximum correlation value.

In our positioning system, the TOF between a transmitter and receiver is measured from the time signals are emitted at transmitter to the time of peak detection. In the case of the stationary object shown in Fig. 3, the interval *T* between two adjacent peaks is equal to an M-sequence period because of the characteristic of the M-sequence.

III. THE TECHNIQUE OF INFORMATION ADDITION IN SS ULTRASONIC WAVES

A. The technique of information addition in GPS

The information addition technique for SS ultrasonic waves can be considered as an application of GPS. The GPS signals consist of carrier waves in the gigahertz band, the measurement code for generation of SS signals, and satellite navigation data. The positioning code is allotted for the constant factor period of the carrier waves, and information signals are added to the positioning code period. The positioning code period used in GPS is 1 ms, and the baud transmission rate of information is 50 bps. The navigation data correspond to information signals in our positioning system. If the GPS method is applied to SS ultrasonic waves, 1-bit information is added to 20 periods of the positioning code. When the information signal “1” is added, the signals are emitted after 20 periods of the code are multiplied by “1.” When the signals are emitted after 20 periods of the positioning code are multiplied by “-1,” the SS

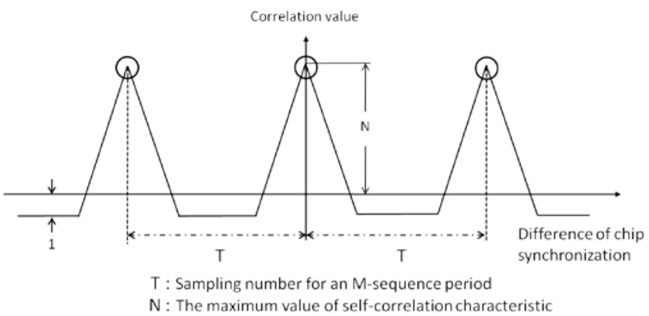


Fig. 3 Self-correlation characteristic of the M-sequence for a stationary target

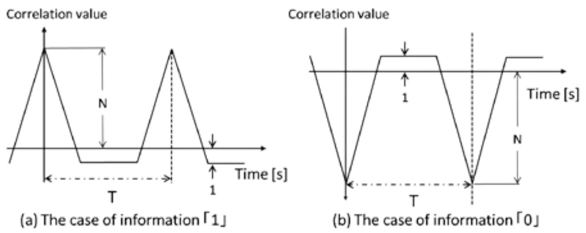


Fig. 4(a) Self-correlation characteristic in the case of an M-sequence with information "1," (b) self-correlation characteristic in the case of an M-sequence with information "0"

signal's phase is inverted by 180°. Fig. 4 shows the self-correlation transition when the conventional method for ultrasonic waves is directly used. "1" or "0" is added as 1-bit information to more than one period of the M-sequence. If an information signal is added to the M-sequence, the peaks of the correlation values obtained from the code acquisition become positive and negative as shown in Figs. 4(a) and (b), respectively. In the receiver, information signals can be detected from the positive or negative correlation values if a peak is detected.

B. Information addition for SS ultrasonic positioning in the transmitter

The transmission speed and carrier frequency of SS ultrasonic waves are lower than for electrical waves, so that the baud transmission rate decreases to about 2 bps. In this paper, we propose adding some bit information to a period of the M-sequence. Fig. 5 shows the transmit and receive system of SS ultrasonic waves using the proposed method. As shown in Fig. 5, SS ultrasonic waves are generated in the transmitter by multiplying carrier waves by the M-sequence. The information signals are added to the generated waves. In the receiver, all received signals, including those received during the past periods of the M-sequence, are saved in memory. The two operation circuits of Calculator0 and Calculator1 calculate a correlation value using the saved data in the memory. A correlation value and information signal are detected by comparing and accumulating the results of the operation at Calculator1 and Calculator0. Fig. 6 describes the method of 4-bit information addition in the transmitter. Figs. 6(a) to (d) show the range of information addition, SS ultrasonic waves generated by multiplying carrier waves by the M-sequence, information signals, and transmission signals, respectively. As shown in Fig. 6(b), SS ultrasonic waves are generated by multiplying carrier waves by the M-sequence. The subscript of the variable CM_1 in Fig. 6(b) shows the signal generated from the first chip of the M-sequence. The signals in Fig. 6(b) are divided on the basis of the amount of information. The range for adding information signals is called the information addition range. As shown in Fig. 6(a), the information addition range is four because the information signals are 4-bit signals. The transmission signals shown in Fig. 6(d) are generated by adding the values in Fig. 6(c) to each information addition range. The subscript of the variable S_1 in Fig. 6(d) is shown as the chip number of the M-sequence as well as the subscript of the variable CM_1.

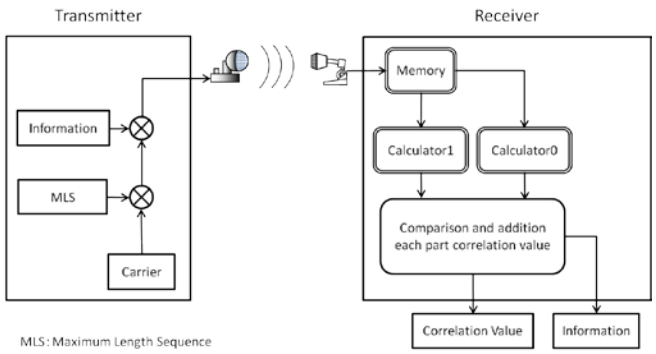


Fig. 5 Transmit and receive system with the proposed method

C. Information extraction in receiving

Fig. 7 describes the procedure in the receiver. The replica signals are generated for the correlation operation at each operation circuit Calculator0 and Calculator1 (see Fig. 5). Figs. 7(a) to (d) show the correlation range, replica signals,

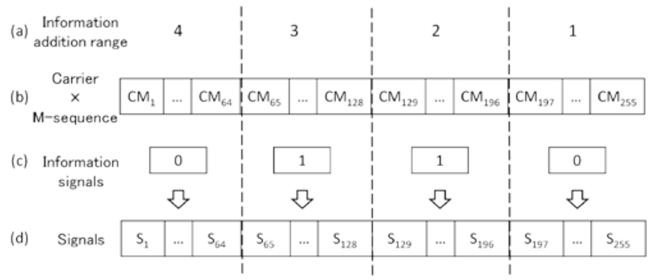


Fig. 6 Procedure for adding 4-bit information to SS ultrasonic waves in the transmitter

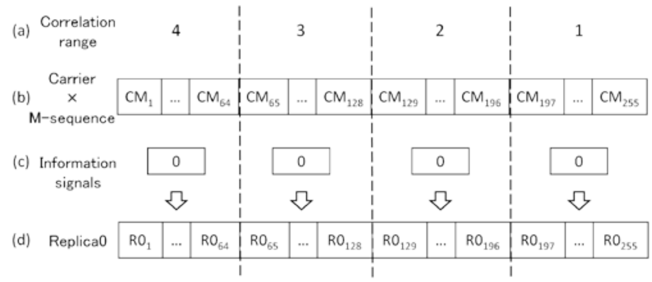


Fig. 7 Procedure for adding "0" as information signals to the replica signals at Calculator0

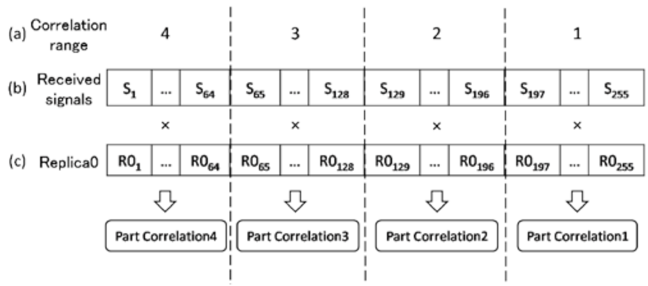


Fig. 8 Procedure for calculating part correlation values from the correlation operation at Calculator0

information signals, and replica signals with information signals, respectively, at Calculator0.

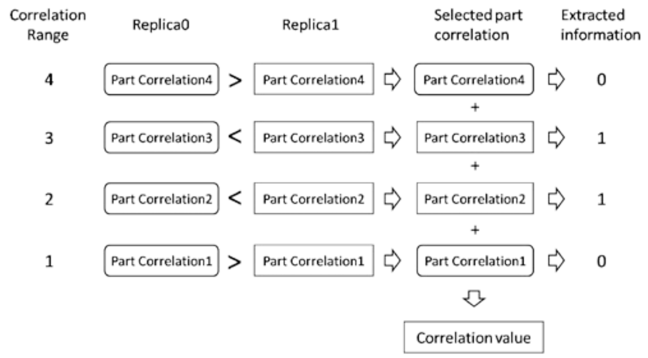
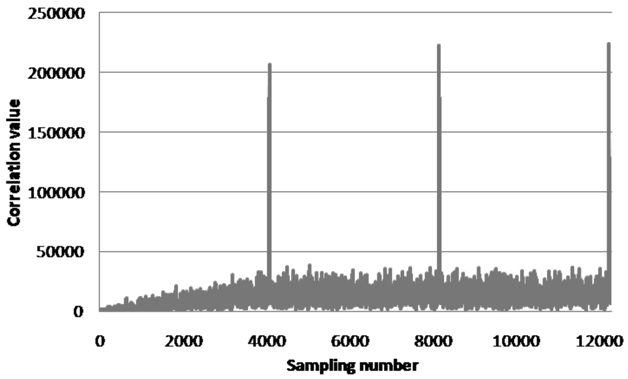


Fig. 9 Procedure for calculating correlation value and generating the extracted information

As shown in Fig. 7(b), the replica signals are generated in the receiver using the same carrier waves and M-sequence as those in the transmission signals, as well as information addition at the transmitter. The values in Fig. 7(c) are added to each correlation range in Fig. 7(a). As shown in Fig. 7(d), Replica0 is generated by adding “0” as an information signal to the replica signals. In the same way, Replica1 is generated by adding “1” to the replica signals at Calculator1. The received signals and Replica0 are used for the correlation operation. Figs. 8(a) to (c) show the correlation range, received signals, and Replica0, respectively. Fig. 8 describes the correlation operation at Calculator0. As shown in Fig. 8(b), the received signals are read from memory. The correlation operation between the received signals and Replica0 in Fig. 8(c) is performed in each correlation range. The four values are called *part correlation values* in this case. At Calculator1, the four part correlation values are calculated by performing the correlation operation between the received signals and Replica1 in the same way. The part correlation values generated at each operation circuit are compared and accumulated at the “Comparison and addition of part correlation values” stage in Fig. 5.

Fig. 9 describes the procedure “Comparison and addition of part correlation values.” The square of a solid line and a broken line shows the part correlation values obtained from Replica0 and Replica1, respectively. As shown in Fig. 9, the part correlation values are compared at each correlation—range4, range3, range2, and range1—and the largest value is selected as the Selected Part Correlation in Fig. 9. The extracted information signal and part correlation values are outputted at each operation circuit. In Fig. 9, the Part Correlation obtained from Replical0 and the “0” obtained as Extracted Information are outputted where the number of correlation ranges is 4 and 1, respectively. In the other ranges, the values obtained from Replica1 and “1” as Extracted Information are outputted. The part correlation values obtained at each correlation range are accumulated sequentially and outputted as the correlation value. If the correlation value is a peak, the Extracted Information is detected as information signals added in the transmitter.



(a)

IV. THE RESULTS OF THE EXPERIMENT

A. *Experiment: information transmission with audio cable*

1) *Experiment outline*

A transmission/reception experiment is conducted to confirm the hardware behavior. In this experiment, both transmission and reception circuits, shown as the transmitter and the receiver in Fig. 5, are structured in an FPGA (Cyclone, Altera) using Verilog HDL. The experimental environment is structured with no noise. The signals generated in the transmitter are carried to the receiver over a D/A convertor, audio cable, and A/D convertor, in that order. The M-sequence shown in Fig. 2 for this experiment has a period of 255 chips.

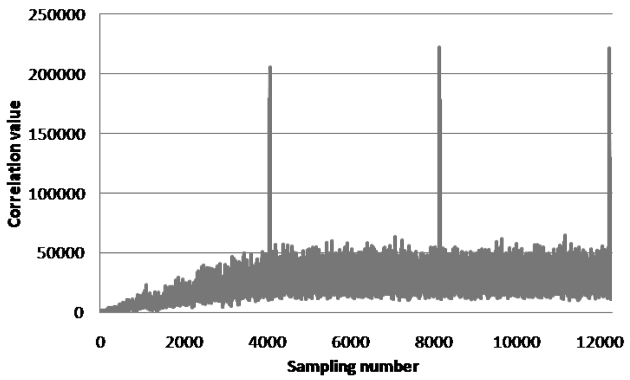
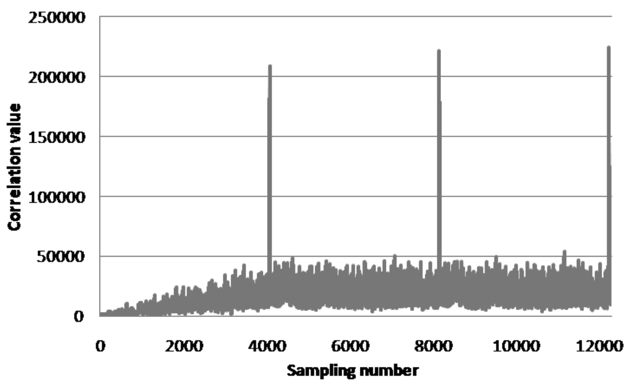


Fig. 10 The transition of the correlation value for (a) 4-bit, (b) 8-bit, and (c) 16-bit information signals



(b)

In the receiver, SS ultrasonic waves are also captured at a sampling frequency of 160 kHz. The information signals are 4-bit, 8-bit, and 16-bit. In this experiment, it is confirmed that the information signals obtained in the receiver at the time of peak detection are equal to the information added in the transmitter.

2) The results of the experiment and explanation

It was experimentally confirmed that information signals can be detected in the receiver. Figs. 10(a) to (c) show the correlation values for each type of information signal (4-bit, 8-bit, and 16-bit, respectively). In Fig. 10, the correlation values connected by lines are plotted with height as the vertical axis and sampling number as the horizontal axis. As shown in Figs. 10(a) to (c), a peak correlation value is detected in the receiver for each information signal. From Fig. 10, the first peak is smaller than the others because the received signals are disturbed. The top of the signal was damped during transmission. However, the correlation values on the first peak are obtained with a large enough S/N ratio to measure a position and to detect information signals as well as other peaks. Figs. 10(a) to (c) show that the noise level increases with an increase in the amount of information; the largest part correlation value is selected at each correlation range, and the number of accumulating part correlation values increases as the amount of information increases.

It was confirmed that the information signals can be transmitted to the receiver in a noiseless environment.

B. A positioning and information transmission experiment in real space

1) Experiment outline

A transmission/reception experiment was conducted to test the measuring precision and the error rate of information detection. The experiment, on measurement and information transmission, was conducted in a real space in a noisy environment using the same hardware as the experiment for a noiseless environment. In this experiment, the signals generated in the transmitter are carried to the receiver over a D/A converter and A/D converter, in that order. Eight types of information signals are used, from “0000” to “0111,” and the MSB of the signals is “0” as a fixed value. These ten signals are generated randomly and added to SS ultrasonic waves. Fig. 11 illustrates the experimental environment. As illustrated in Fig. 11, the distance between the transmitter and receiver is installed at one meter intervals from 1 m to 6 m. The transmission experiment is conducted 100 times at each distance.

The information transmission is termed successful if an obtained information signal, when a peak is detected in the receiver, equals the information signals added in the transmitter. The distance is measured based on the peak detection time, and the average and maximum of measurement error are discussed.

2) The results of the experiment and explanation

The information signals can be detected at the trial of one hundred times at all installation distances. Fig. 12 shows the transition of installation distances and measurement errors. In Fig. 12, the measurement errors connected by lines are plotted with height as the vertical axis and installation distance as the horizontal axis. The plot in Fig. 12 shows the average of the measurement error for each installation distance. As shown in Fig. 12, the maximum value of the measurement error increases if the installation distance is more than 4 m. Fig. 13 shows the transition of the correlation value as the vertical axis

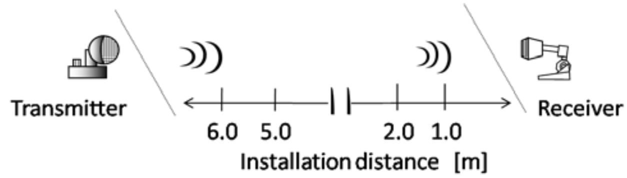


Fig. 11 Outline of an experimental environment in real space

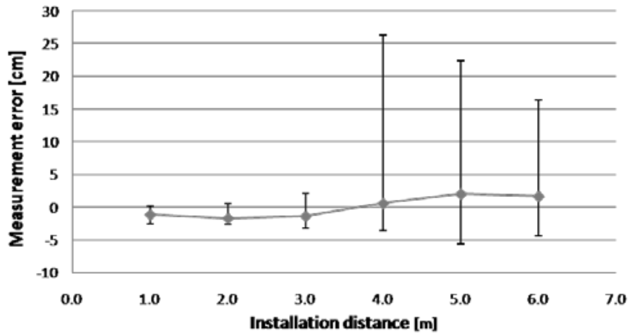
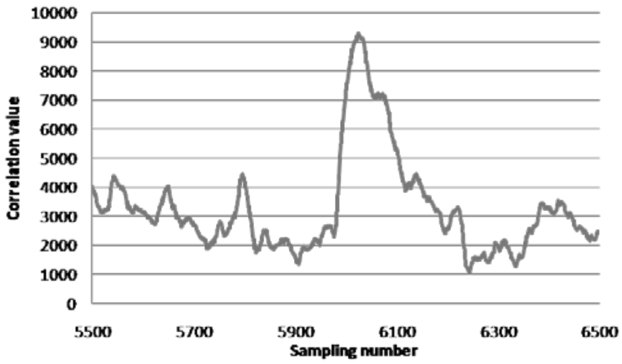


Fig. 12 Measurement error of distance at each installation distance



(a)

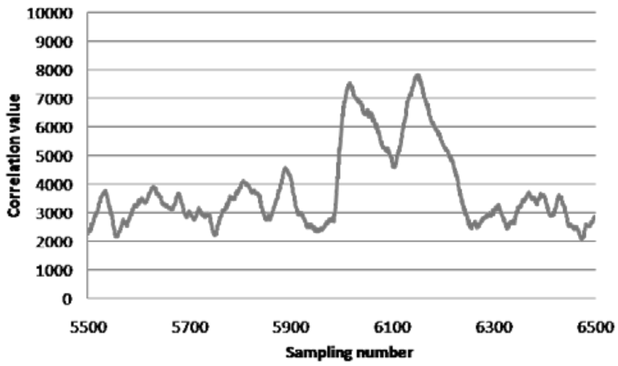


Fig. 13 Transition of correlation values for the (a) average measurement error and (b) the maximum measurement error at 4 m

and the sampling number as the horizontal axis. Figs. 13(a) and (b) show the transition of the correlation value when the measurement error is approximately average and maximum, respectively. In Fig. 13(a), there is only one peak, but there are two peaks in Fig. 13(b); the multipath waves interfered with the direct waves, amplifying the received signals. In the current peak detection, the maximum of the correlation values is detected as a peak for a period of SS ultrasonic waves. The measurement error occurs when the later peak is larger than the earlier peak. However, if the multipath waves interfere with the direct waves, the information signals can be detected.

Therefore, the effectiveness of this proposed method is confirmed by the measurement precision and information detection in the case of the 4-bit information signal.

V. Conclusion

In this study, for identification of transmitters and temperature information, the technique of adding information signals to SS ultrasonic waves was employed in an indoor positioning system for self-localization of people and robots, and the hardware behavior implementing this proposed technique was evaluated. In this proposed technique, information signals are added to the information addition range at the generated signals in the transmitter and are emitted. In the receiver, two kinds of replica signals are generated, and the correlation operation is conducted between received signals and replica signals at each operation range. The correlation value is outputted after the part correlation values are compared at each correlation range and are accumulated. At the same time, the extracted information signals are also generated. In the receiver, the extracted signals are detected as information signals added in the transmitter in the case of peak detection.

In the experiment of information transmission with an audio cable, 16-bit information addition is realized for a period of the M-sequence by using this proposed method. It is confirmed that the distance can be measured and that information signals can be detected within 6 m in real space when 4-bit information signals are added to a period of the M-sequence. The measurement error occurs because of a peak detection procedure on the measuring precision. However, the position of people and robots can be measured sufficiently accurately because the average of measurement error is less than 2.5 m at each installation distance. The experimental results thus confirm the effectiveness of the proposed technique.

In future, the information signals added to a period of the M-sequence will be increased, and the capability of addition is discussed based on comparison with this experiment. The error rate of information detection will also be discussed at the maximum distance that can be measured using SS ultrasonic waves.

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