Angular Dependence of Transducers for Indoor Positioning System Using SS Ultrasonic Waves

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

***Abstract*— For robot self-localization and navigation, we have investigated real-time indoor positioning systems using spread spectrum (SS) ultrasonic waves in conjunction with band-limited transducers as a low-cost and high-accuracy alternative with noise tolerance and CDMA. In indoor positioning, it is rare for the transmitter and the receiver to be arranged facing each other. In real-time measurements, improvement of angular dependence using SS modulation in conjunction with band-limited transducers has been not discussed thus far. Therefore, this study reviews the angular dependence from two viewpoints: strength of SS signals and distance measurement errors. To discuss the angular dependence, we conducted a distance measurement experiment using a transmitter and a receiver installed at a obtuse or right angle, respectively. In this experiment, we used a band-limited transducer with a closed-type aperture as the transmitter and one with an open-type aperture as the receiver, and the transmitter-receiver distance was set as 2 and 3 m. When the transmitter was titled at an angle, in the case of the SS, we could detect the signal within a 10-cm error even if the transmitter was oriented at a right-angle to the receiver. The experimental result was compared with a measurement using normal ultrasonic signals with on-off-keying. The result with SS modulation presents almost the same tendency as on-off-keying (OOK); however, the measurement accuracy and measurable range were improved. Therefore, in terms of accuracy, the SS modulation is more effective for indoor positioning than OOK.**

Keywords-spread spectrum ultrasonic waves, angular dependence, all-purpose transducer, measurable range, distance accuracy

I. Introduction

The fields of application of position information have expanded in tandem with advancements in our information-driven society. Indoor position information is important to people and robots for navigating along a route. Although the use of satellite-based outdoor position information systems (e.g., GPS) is widespread, it is difficult to directly use an outdoor positioning system indoors because signals from the positioning satellites seldom reach indoors. Therefore, systems that use sensors such as pseudolites[1], infrared rays[2], or ultrasonic waves[3] have been investigated for indoor positioning.

Compared to other methods, the systems based on ultrasonic waves have the advantages of low cost and comparatively high accuracy. However, generally, these systems have weak noise resistance and take a longer time to acquire data because they use a time-division multiplexed method with on-off keying (OOK), which becomes more cumbersome as the number of objects to be measured increases. To overcome these drawbacks, many systems using spread spectrum (SS) ultrasonic waves have been investigated[4]. Furthermore, we proposed a real-time positioning system with SS ultrasonic waves using a band-limited transducer[5], [6], [7]. In these papers, the ability of code division multiple access using SS ultrasonic waves has been shown. Furthermore, factors such as robustness to noise, positioning errors in indoor environments, and signal degradation with band-limited transducers have been discussed.

In the case of indoor positioning using ultrasonic waves, the signal strength decreases owing to the directional characteristics of the transmitters and the receivers, and a distance error occurs in the spatial relationship between the transmitters and the receivers (i.e., angular dependence). In our real-time measurement system, improvement of angular dependence through SS modulation using band-limited transducers has not been discussed thus far. Therefore, in this study, we conducted an experiment on distance measurements using ultrasonic signals attenuated because of angular dependence. From the results of this experiment, we discussed the measurable range and measurement errors under two modulation types (i.e., conventional OOK and proposed SS modulation); the results indicated that SS modulation was more effective.

II. Sensor system for distance measurement using ultrasonic waves

In the case of indoor positing systems using ultrasonic waves, position estimation is performed using three or more time-of-flight (TOF, between the transmitters and the receiver) values. For discussing the measurement error and measurable range, we used a sensor system for distance measurements. Signals were generated with the methods used in previous studies[8], [9]. The sensor system's architecture is shown in Fig. 1. The transmission unit contains a Digital / Analog (D/A) converter and a Field Programmable Gate Array (FPGA), which is used for generating carrier waves and M-sequences, respectively. The reception unit contains an Analog/Digital (A/D) converter and an FPGA, which is used for performing

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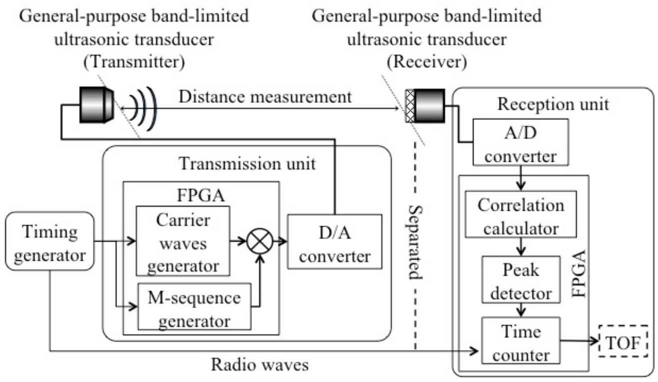

Fig. 1. System architecture for distance measurement using ultrasonic waves with OOK and SS modulation.

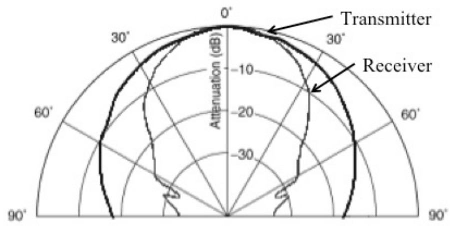

Fig. 2. Data sheet on directional characteristics of the transmitter (PC40-18S) and the receiver (R40-16). This figure shows the signal attenuation ratio for each angle.

correlation calculations, peak detection, and time measurements. In this experiment, a transmitter with a closed-type aperture (PC40-18S, Nippon Ceramic co., ltd.) and a receiver with an open-type aperture (R40-16, Nippon Ceramic co., ltd.) were used as general-purpose and band-limited transducers. The signal attenuation ratios for various transmitter and receiver angles are shown in Fig.2. In this figure, sound pressure at 0° is defined as 0 dB in terms of attenuation, and the attenuation depending on an angle is shown on the transmitter and the receiver, respectively. From Fig.2, it is observed that the transducers with closed- and open-type apertures have wide and narrow directional characteristics, respectively. In addition, the transducer with a closed-type aperture requires more electrical power than that with the open-type aperture.

In this system, an SS signal is generated for multiplication of carrier waves using M-sequences. The SS signal is dynamically generated by the transmission unit, shown in Fig. 1, and is outputted by a transducer, after D/A conversion. For measuring the TOF, the time counter is started at the same time as the transmission. Additionally, correlation values are calculated from the received ultrasonic waves using the correlation calculator and the A/D convertor, shown in Fig. 1, which constitute the on-line, real-time hardware processing component of our system. Thereafter, the peak detector, shown in Fig. 1, finds a peak from among the calculated correlation values. The time counter measures the TOF by counting the number of sampling times elapsed between the beginning of a transmission to the arrival of a peak. Thereafter, the 3D position of the receiver can be calculated from three or more

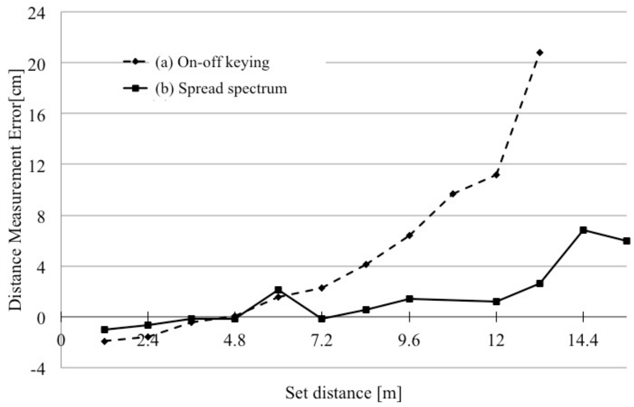

Fig. 3. Average measurement errors in distances modulated for (a) on-off-keying and (b) spread spectrum from 1.2[m] to 15.6[m].

distances using the measured transmitter–receiver TOF values. If the correlation calculation part can be installed onto the hardware, as shown in Fig. 1, real-time positioning would be possible because other processing activities such as position calculation using distances can be performed comparatively quickly using software and optimization expressions.

III. Distance measurement accuracy using a band-limited transmitter and receiver with SS ultrasonic waves

The measurable distance and measurement errors using SS modulation have been already compared[7] with OOK for long distances. In this study, to compare the measurable distance and the measurement error for OOK and SS modulation, we conducted distance measurement experiments using the sensor system shown in Fig. 1. In this experiment, distances were measured at every 5 trials, using a transmitter and receiver that are arranged facing each other.

Fig. 3 presents an experimental result for measurements at long distances. In Fig. 3, the measurement errors for SS modulation and OOK are represented by the solid and dashed lines, respectively. In addition, the set distance and the error of distance are arranged in an ascending order on the x- and y-axes, respectively. From Fig. 3 (a), it is found that in the case of OOK, the measurement error increased with distance. Furthermore, measurements were not possible beyond 13.2 m owing to noise and signal fade. In the other case with SS signals, shown in Fig. 3 (b), we could obtain the distance until 15.6 m except 10.4 m. In the case of the measurement for a 10.4 m receiver–transmitter distance, we could not find the peak correlation value automatically using hardware because of multi-path propagation.

The cause for the error when using OOK can be explained from Fig. 4. Fig. 4 shows the ultrasonic signal spread from a transmitter at the right to a receiver at the left. In this figure, the waveform at the head of an ultrasonic signal wavefront is described. In the case of OOK, a signal is detected using the threshold shown in Fig. 4. Therefore, if the high-frequency component of the signal attenuates, attacking time on envelope is also occurs, and signal detection is delayed from (a) the ideal

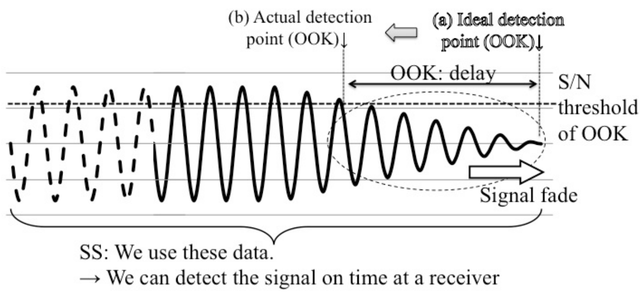

Fig. 4. Waveform of ultrasonic signals with signal fade.

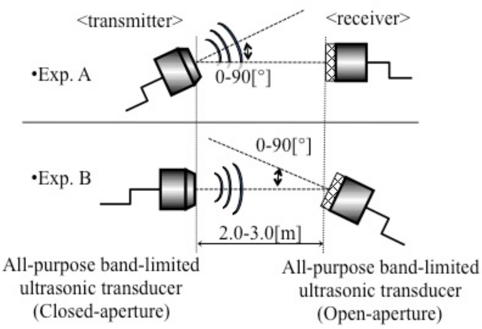

Fig. 5. Experimental setting for distance measurement using a (Exp. A) transmitter and a (Exp. B) receiver tilted at a certain angle.

detection point to (b) the actual detection point, as shown in Fig. 4, especially when the signals fade at long distances.

In another case of SS modulation, shown in Fig. 3 (2), a correlation value, calculated from all data in an M-sequence cycle, can be used for distance measurement. Signal detection is not delayed because we use long-cycle data, as shown in Fig. 4, and only the part of correlation values are decrease at the beginning of SS signals. Therefore, for long distances, measurement errors with SS modulation were smaller than those using OOK.

IV. Distance measurement considering angular dependence

A. Experimental setup for distance measurement between transmitter and receiver considering angles

In the case of OOK, positioning errors are obtained from angular dependence due to decreasing signal strength influenced by directional characteristics. In a conventional study[6], signal deterioration due to the directional characteristics of SS ultrasonic waves has been shown using broadband transmitters and a receiver. Therefore, to discuss the measurement performance for different modulation protocols under the same hardware and environment conditions, we conducted an experiment using a band-limited transmitter and a receiver set at an oblique angle relative to each other using SS modulation as well as OOK. We noted the differences in the measurement error and the measurable range. Fig. 5 shows the experimental overview. In this experiment, the transmitter–receiver distance was set to 2 and 3 m, and the distances were measured considering the angular variations of the transmitter as well as the receiver. We used a motorized rotation stage for varying the angle. Exp. A and Exp. B in Fig. 5 show the cases where the transmitter and the receiver were rotated, respectively. In both Exp. A and Exp. B of Fig. 5, the setting wherein the transmitter and the receiver were face-to-face and collinear was defined as 0°. The measurement error for a given distance was determined from the peak of the correlation values at 5-degree-intervals between 0 and 90° for rotation of the transmitter or the receiver.

B. Experimental result for distance measurement

The measurement distances obtained from the experiment shown in Fig. 5 are depicted in Fig. 6. In Fig. 6, the error for the face-to-face, collinear arrangement of the transmitter and the receiver is defined as 0 cm, and the amount of increase in error for each measured angle is presented. Further, each figure represents the differences in the measurement errors between Exp. A (rotating transmitter with closed-type aperture) and Exp. B (rotating receiver with open-type aperture). In these graphs, the distance measurement errors are plotted with height as the vertical axis and transmitter/receiver angle as the horizontal axis. In Fig. 6(a) and Fig. 6(b), the solid and dashed lines represent the distance errors under SS modulation and OOK, respectively.

In Exp. A, we could measure distances until 90° under (a) SS modulation and until 80° under (b) OOK owing to of the wide directional characteristics of the closed-type aperture transmitter. Let us discuss the measurement errors due to the two modulation types. In Fig. 6(a)(b), the distance measurement error increases with the transmitter angle. However, the extent of increase in the error was less with SS modulation as compared to that with OOK, and the measurable angle range was improved when using the proposed SS modulation. Signal detection was possible within an error of 10 cm, even if the transmitter was oriented at 90° relative to the receiver. In Fig. 6 Exp. B, owing to the narrow directional characteristics of the closed-type aperture receiver, only the signals under 30° could be detected using both (a) SS modulation and (b) OOK. Furthermore, the distance measurement errors using the SS modulation were lower than those using OOK, although to an extent lesser than that in Fig. 6, Exp. A.

These improvements in the measurement accuracy and the measurable angle range when using SS modulation can be verified from Fig. 6, Exp. A and Exp. B. The distance measurement errors shown in Fig. 6, Exp. A and Exp. B are similar to a previous experimental result for long distances[7], as shown in Fig. 3 and Fig. 4, and we can discuss the occasion of the error on Fig. 6 Exp. A and Exp. B by analogy to this study[7]. In the case of OOK, at the beginning of the signal, the high-frequency component attenuates. If the receiver and the transmitter are installed at an angle relative to each other, as shown in Fig. 5, the distance measurement error increases, because the amplitude attenuation delays signal detection, as is shown in Fig. 4. However, with SS modulation signals, a correlation value calculated from all data in an M-sequence cycle is used for distance measurement, as shown in Fig. 4. Therefore, even though the high-frequency component of the signal attenuates, a part of received waves at the beginning of

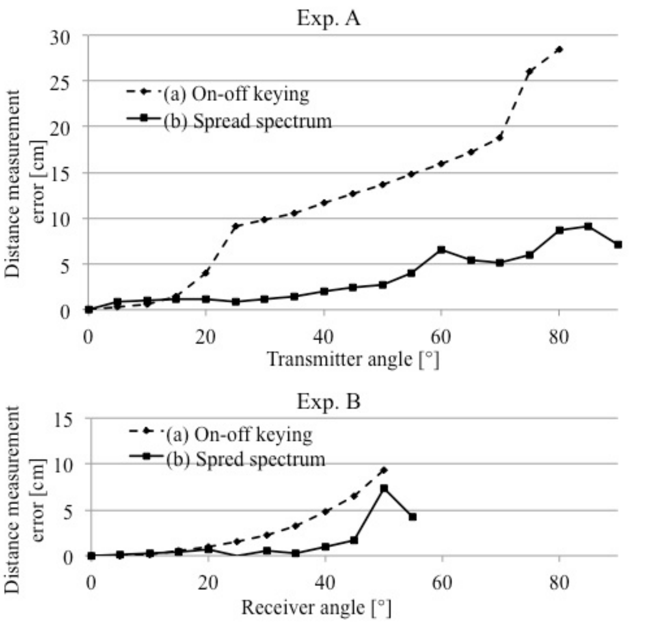

Fig. 6. Distance measurement error for angled transmitter and receiver obtained using (a) OOK and (b) SS modulation.

SS signals is decrease, and the peak of the correlation values can be detected without delay.

From the experimental result shown in Fig. 6, even when using SS modulation, the directions of the ultrasonic transmitter and receiver are important for ensuring full coverage in a three-dimensional, indoor positioning area, in particular, for hardware with narrow directional characteristics. However, the experimental results in the coverage area show that distance measurement using SS ultrasonic waves has an advantage in terms of the measurement error, even for transmitters and receivers oriented at oblique angles.

V. Conclusion

In this paper, we discussed the angular dependence between a band-limited transmitter and a receiver using SS ultrasonic waves for real-time indoor positioning systems. From the conducted distance measurement experiment, a measurable range and measurement error were determined using a band-limited ultrasonic transducer considering angle variation (between 0 and 90°). In addition, we compared the measurable range and the measurement error obtained using SS with those obtained using OOK, which is a simple modulation protocol for indoor positioning using ultrasonic waves. These comparisons were carried out for identical hardware, settings, and environmental conditions. The results show that the distance measurement errors when using SS ultrasonic signals are lower than those when using OOK, despite using a band-limited transducer and deteriorated SS signals. We found that the distance measurement error with OOK occurred because of the attenuation of the signal's high-frequency component; this result is in agreement with a previous study on the measurement of long distances. Thus, the effectiveness of the proposed SS modulation over OOK for indoor positioning was demonstrated.

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