Indoor Positioning System using Ultrasonic Sensors as a Position Information Infrastructure for a Wide Area

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Abstract

This paper describes an indoor positioning system that uses ultrasonic signals and can cover a wide area. This indoor positioning system can be used in many practical applications, for example, detecting the location of moving objects, such as a person or a wheelchair, and navigation within a wide indoor area such as an underground shopping mall or a large hospital. The authors have previously proposed a solution for indoor positioning using ultrasonic sensors. However, the previous prototype had a shortcoming when it came to expanding the positioning area. An ultrasonic receiving unit that includes an amplifier, detection circuits and a one-chip microcomputer has now been developed and these units may be connected in a cascade style configuration, so making it easy to expand the positioning area. In a static test performed to evaluate the positioning accuracy, the offset positioning error was about 22mm and the standard deviation of the positioning results was about 2mm. In a dynamic test, 34 ultrasonic receiving units were installed in the ceiling and about 30.4m model railway track was laid on the floor, and the ability to identify the moving position of a model train on the railway track was confirmed. The proposed system configuration, its effectiveness and its accuracy were verified by these experiments.

Keywords: Position Information, Positioning, Ultrasonic Sensor, Information Infrastructure

1 Introduction

The global positioning system (GPS) is widely used for determining position in outdoor areas. It has become a universal system and the location information provided by GPS is widely used in navigation devices and many other service systems. However, for indoor positioning applications, no common system has yet been established and various possibilities are being investigated such as using wireless LAN systems. Position information is an indispensable requirement for the realization of “smart space”.

Indoor positioning information can be made use of by many applications. The size of usage area and required positioning accuracy for some of these are shown in Fig.1. Some applications require a higher accuracy than can be satisfied by using wireless LAN systems. The authors have been investigating a positioning system that uses only ultrasonic sensors (without radio frequency transmissions) to satisfy accuracy requirements [1]. The previous prototype suffered a shortcoming in covering the positioning over a wide area due to the cable connections. The system configuration has been investigated and changed to use a simple cable connection which makes it easy to expand the area covered by the positioning system, hereafter called the positioning area. The positioning accuracy and the validity of the new system configuration have been evaluated by using a new prototype model and a model railroad train moving on tracks on the floor.

Figure 1. Application region and required accuracy
2 Positioning Principle and System Architecture

2.1 Positioning Principle

The system configuration involves the use of ultrasonic receiving sensors embedded in the ceiling and an ultrasonic transmitter attached to a moving object below. The basic positioning principle is shown in Fig.2. The clock of the transmitter unit is independent of the receiving part in the proposed system. Therefore, the propagation time cannot be obtained and only the relative delay times at each receiving sensor can be detected. Here, the delay time refers to the amount of time that has elapsed after the first receiving sensor detects the ultrasonic signal. Three delay times \( t_1, t_2 \) and \( t_3 \) can be obtained from four receiving sensors as shown in Fig.2. The synchronization of all receiving sensors is maintained, since they are all connected to a PC which governs the timing, as described in section 2.2.

\[
\begin{align*}
\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} &= ct \\
\sqrt{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} &= c(t+t_1) \\
\sqrt{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} &= c(t+t_2) \\
\sqrt{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} &= c(t+t_3)
\end{align*}
\]

Figure 2. Basic positioning principle

The following mathematical equations can be derived by considering the distance and propagation time. Here, \( x, y, \) and \( z \) are the positions of the receiving sensors and are determined when they are embedded in the ceiling. The constant, \( c \), is the ultrasonic signal velocity (dependent upon temperature). The variable, \( t \), is the propagation time from the transmitter to the receiving sensor that is the first of all the receiving sensors to receive the ultrasonic signal (an unknown value). The variables \( t_1, t_2 \) and \( t_3 \) are the delay time at each receiving sensor (determined as described above). The variables \( x, y, \) and \( z \) are the coordinates giving the position of the moving object that is attached to the transmitter (these values need to be obtained). Since there are four unknown quantities \((x, y, z \text{ and } t)\), at least four receiving sensors are required in order to solve the following equations:

2.2 System Architecture

The prototype system for lightening the workload of cable connection is shown in Fig.3. The upper diagram shows the previous prototype configuration [2] and the lower shows the new prototype. With the earlier configuration, the many cables from the detection must all be connected to the Receiver FPGA, which detects the timing of ultrasonic reception. As the positioning area expands, the load of cable laying works increases. The new configuration shown in the lower diagram uses RS-485, in which each unit is connected to others in cascade. This configuration results in a decrease in the work of running cables and makes it easy to expanding the positioning area.

In this prototype, the amplitude and detection circuit for the ultrasonic signal and a one-chip microcomputer (PIC16F1823), to capture the timing of the received ultrasonic signals, are implemented as a single receiving unit, which makes it easy to connect a number of units in a cascade configuration. An overview of the receiving unit is shown in Fig.4. The temperature sensor is used for compensation because the ultrasonic propagation velocity changes with temperature. In addition, the crystal oscillator (EPSON MA505) is used for accurate clock generation instead of using the oscillator implemented in the PIC microcomputer. The ultrasonic receiving sensor and transmitter are Murata MA40S4R and MA40S4S, respectively.
3 Evaluation Experiment
3.1 Static Test for Evaluation of Accuracy

The positioning accuracy of the prototype system was confirmed by experiment. The measurement target was set up on the floor \((x=2300, y=1695)\) and its position was measured for accuracy evaluation. 100 measurements were carried out in order to evaluate variability as well as accuracy. The results are shown in Fig.5. The offset errors were about 23mm and 10mm for the x and y axis, respectively, and the standard deviation was about 2mm for both axes. This accuracy should be sufficient for the application shown in Fig.1.

![Figure 5 Results of static test for positioning accuracy](image)

3.2 Dynamic Test for Moving Object

The practical usefulness of positioning system for a moving object was confirmed by experiment. Figure 6 shows a picture of experimental area. In this system, a model train, with an ultrasonic transmitter attached, was used as the moving object on a model railway track. The railway track formed a continuous loop with a total length of about 30.4 m. A total of 34 ultrasonic receiving sensors were installed in the ceiling. The height of the ceiling from the floor was 2.6 m. The experimental results obtained using this test configuration are shown in Fig.7, which illustrates the shape of the railway tracks, the positioning results and also the position of ultrasonic receiving sensors. These results were obtained as the train made two complete circuits of the railway track. Therefore, repeatability was also confirmed by this result. It was confirmed that the positioning error was within 100 mm in the xy plane. This should be sufficiently accurate to monitor the location of a moving person or, for example, a moving electrical wheelchair in an indoor area. Although abnormal numerical answers were obtained with a low probability (less than about 5%) in the positioning calculation, such results can be identified and omitted by taking account of the realistic position and velocity of the moving object and the propagation time of ultrasonic waves, etc.
4 Conclusions

We have proposed a new architecture for an ultrasonic positioning system for indoor use over a wide area. The authors’ developing ultrasonic positioning system requires neither synchronization between the transmitting and receiving units nor radio frequency signals. In this prototype, the amplitude and detection circuit for ultrasonic signal and a one-chip microcomputer (PIC16F1823) to capture the timing of the received ultrasonic signals are implemented as a single receiving unit so making it easy to connect a number of receivers in a cascade configuration. This configuration makes it easy to expand the positioning area. For an evaluation, receiving sensors were installed to cover an area of about 34m². In a static test carried out to confirm the positioning accuracy, the average offset error was less than 22mm and the standard deviation was about 2mm. This is considered to be sufficient accuracy for the assumed applications, such as navigation or position detection in an indoor area. In addition, a dynamic test for a moving object was carried out using a train on a model railway track. The accuracy in tracking a moving object was also confirmed by this experiment. The development and demonstration of an application system using the proposed positioning system is an area planned for further studies. The authors are now investigating the architecture of a cost effective positioning system which makes use of an inertial positioning using the acceleration sensor and gyro sensors built into smartphones.

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References