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A low-cost centimeter-level acoustic localization system without time synchronization

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ABSTRACT

In this paper, we present a range-based localization method without time synchronization. It uses only a speaker, a microphone, and some forms of device-to-device communication such as WIFI radio; thus, it is easily applied in most commercial off-the-shelf mobile devices such as cell phones. The localization scheme is composed of two stages. We obtain the initial distances between the moving object and the anchors in the first stage using a BeepBeep ranging system, in which they both send and receive sound signals. In the second stage, which is the main localization stage, the difference distances between the moving object and the anchors can be obtained using a OneBeep ranging system. Only the located object must emit sound signals periodically, and all of the anchors including the located object should receive the sound signals in the OneBeep system. The distances between the moving object and all the anchors can be obtained by adding the difference distances to the initial distances, and then, the moving object can be located. A localization experiment was conducted in a 6×9 m room with weak reflection, and the localization can reach centimeter-level accuracy in 5 min.

1. Introduction

Many range-based localization algorithms have previously been proposed, of which the Time of Arrival (TOA) and Time Difference of Arrival (TDOA) are popular. In the TOA method, the sender–receiver distance is the product of the propagation time and the propagation speed, and given the speed, the distance can be obtained by measuring the propagation time [1,2]. Time synchronization between the sender and receiver is required in TOA [3]. To compute the distance between the transducers (speakers) and the object to be localized (microphone), TOA measurements of acoustic signals that consisting of Binary Phase Shift Keying modulated Gold sequences are performed as in [4]. A previous paper [5] presented an acoustic localization system for indoor use that was based on the TOA and fingerprinting technique. Experimental results showed that the location system generally provide an accuracy of less than 10 cm.

TDOA is generally known as the method that obtains the difference distances between the sender and different receivers by measuring the time difference of the signal arriving to different anchors. At least three receivers are needed in the two-dimensional position program. Given the difference distance between the sender and two of the receivers, the sender should be in a hyperbolic curve due to the difference distance and the given position of the receivers. With the addition of a second hyperbolic curve, an intersection can be formed, that is the position of the sender. Time synchronization between the sender and receiver is not needed in TDOA, but the time synchronization between the receivers is required. TDOA is widely used to locate sound sources [6–9].

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Because time synchronization is usually required in TOA and TDOA, more hardware and software components are necessary and accordingly affect the localization accuracy. Therefore, research on localization without time synchronization is of interests [10–16].

Whistle, a TDOA-based localization method, was proposed in [15]. Time synchronization between the receivers was not needed because of the addition of a reference anchor that also sent signals. The distances between the reference anchor and other receivers were known, and the time arrival difference between the signals from the sender and the reference anchor could be obtained according to the local clock of each receiver. Then, the difference time of the signal from the sender to different receivers could be obtained. Whistle was implemented on commercial off-the-shelf cell phones with acoustic signals and generally reaches a localization accuracy of less than 30 cm.

The sender–receiver difference distance can be obtained by measuring the time arrival difference between two time nodes when the signal is sent. Given the initial sender–receiver distance, the distance at any time node can be obtained by adding the sender–receiver difference distance to the initial distance. This method is called the inter-node time difference-of-arrival (ITDOA) [13]. The inter-node sending difference time can be obtained based solely on the sender, and the corresponding inter-node receiving difference time can be obtained based solely on the receiver. If the distance between the sender and receiver remains unchanged, then the two difference times should be the same. Otherwise, the difference in the two difference times multiplied by the signal propagation velocity is the sender–receiver difference distance between the two time nodes. We observed that time synchronization is not needed at this time. Simulations for the ITDOA method have been studied, but few real experiments have been conducted [13,14].

The BeepBeep ranging system without clock synchronization between devices is proposed in [16], and it achieves approximately 1 or 2 cm of accuracy within a range of more than 10 m. As shown in Fig. 1, A sends the signal at time t_{As}, and B receives the signal at time t_{Br}; if A and B are time synchronized well, then the distance can be obtained using the TOA method. In the case without time synchronization, B sends a signal after B receives the signal from A at time t_{Bs}, and A receives the signal from B at time t_{Ar}. The distance can be obtained by multiplying the propagation speed by half of $[(t_{Ar} - t_{As}) - (t_{Br} - t_{Bs})]$, which is called the elapsed time between the two time-of-arrivals (ETOA), where $(t_{Ar} - t_{As})$ is based solely on the clock of A, and $(t_{Br} - t_{Bs})$ is based solely on the clock of B; clock synchronization between the devices is no longer required. However, the distance obtained using the BeepBeep ranging system is uncertain if either device moves during the gap between the times that they send their signals, namely, t_{As} and t_{Bs}. Moreover, if the distance between more than two devices must be measured, then each device should send the sound signal once successively, thus, the measurement cycle is too long. The BeepBeep system can be used as a ranging scheme but is not suitable for locating a moving object.

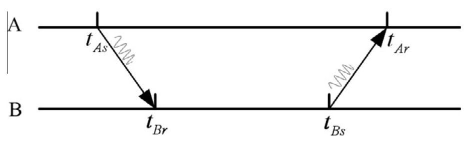

Fig. 1. Event sequences in the BeepBeep ranging procedure.

We proposed the OneBeep ranging system, which is a kind of ITDOA method, to help locate a moving object. As shown in Fig. 1, only the moving object A is required to emit the signal periodically. The initial distance should be given in ITDOA and can be obtained using the BeepBeep ranging system. Thus, we realized that to locate a moving object both the BeepBeep and OneBeep systems must be used. We performed our experiments using laptops. Because the microphone and loudspeaker for each laptop are not close, the distance between them in the BeepBeep ranging system should be accounted for, which is not discussed in [16]. The localization scheme including the BeepBeep and OneBeep systems is a pure software solution and uses only a speaker, a microphone, and some form of device-to-device communication, such as WIFI radio. This approach is easily applied to robots, smart phones and other devices.

The remainder of this paper is organized as follows: We review the related audio ranging work in Section 2. The overall ranging mechanism of our work is presented in Section 3. In Section 4, we present the detailed OneBeep ranging mechanism. The error of the OneBeep ranging system is analyzed in Section 5. We review and supplement the BeepBeep ranging mechanism in Section 6. The localization experiments using the BeepBeep ranging system and OneBeep ranging system are described in Section 7. Section 8 concludes the paper.

2. Related work

Many range-based localization algorithms using acoustic signals have been proposed recently. There are basically four types of measurements of acoustic signals among the existing works: TOA [4,5,17], TDOA [6–9,18,19], direction of arrival (DOA) [20], and received signal energy [21].

In the cricket systems [17], TOAs of ultrasound signals from the emitters at known positions to the receiver to be located are measured. The RF signals are employed for synchronization of TOA measurements. TOA measurements of acoustic signal consisting of Binary Phase Shift Keying modulated Gold sequences are performed in [4]. A reference microphone at a fixed location is used for determining the delays for each speaker. Because the fixed speakers and the microphone to be located share a CPU or clock, time synchronization is not a prominent problem here. A classic sound source localization method based on TDOA estimation is presented in [18] using 8 microphones. The work in [19] deals with the problem of localizing and tracking a moving speaker using a microphone array consisting of four omnidirectional microphones. The proposed algorithm is based on estimating TDOA by maximizing the weighted cross-correlation function in