Effect of Movement on Positioning Accuracy in a Transponder-based Acoustical Positioning

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Abstract. A transponder-based positioning method using audible sounds for a large-scale area positioning has been proposed by the authors. The proposed method has two characteristics; it employs audible sounds instead of ultrasounds to measure long distance by using audible sounds, and it achieves positioning without clock synchronization among devices which is required additional equipment such as radio wave. However, positioning of the moving object (terminal) is still challenging because the proposed method requires longer measurement time than other methods since it measures the round-trip time of flight (TOF) among the terminal and the anchors (transponders). In this paper, we evaluated the effect of the terminal movement on positioning in simulations and experiments. From simulations and experimental results, it was found that the effect of Doppler and the terminal movement cause random error and offset in TOF/distance, respectively. Consequently, it was found that our proposed method is sensitive to the terminal movement.

1. Introduction
Indoor positioning is a technique to localize people/objects and it is utilized for various location services such as people navigation and robot automation. Generally, indoor positioning is achieved by using acoustical waves [1–6], laser light [7], radio waves [8], infrared light [9], geomagnetic field [10], and inertial measurement units [10]. Among them, acoustical positioning is cost effective, and it is used to achieve for small-scale area localization such as a corridor/room. These techniques commonly use ultrasounds higher than 20 kHz, and achieve accurate positioning by measuring time of flight (TOF) of ultrasound. However, ultrasound attenuates rapidly in air, and it is not suitable for large-scale localization. Hence, it is difficult to achieve positioning in large-scale area by ultrasound means. In addition, existing positioning methods commonly require clock synchronization among devices in the measurement of TOF, resulting in complicated system.

To achieve simple and cost effective large-scale localization, we have proposed a transponder-based positioning method using audible sounds lower than 10 kHz [11]. The proposed method is achieved as follows [Fig. 1(a)];

(i) A terminal transmits audible sounds (request signals) to transponders of known position.
(ii) The transponders detect the request signal from received sound. After a constant delay time, the transponders transmit response signal of audible sounds (response signal) to the terminal shortly.
Anchors (Transponders)

Loudspeaker
Microphone
Terminal

(a) Terminal without movement

(b) Terminal with movement

Figure 1. Transponder-based acoustical positioning.

(iii) The terminal receives the response signals and measures round-trip time of flights (TOFs) among the terminal and the transponders.

The proposed method has two characteristics; it employs audible sounds instead of ultrasounds to measure long distance, and it achieves positioning without clock synchronization among devices which is required additional equipment such as radio wave. We tested this method in experiments, and found that the proposed method can achieve accurate positioning (error: within 0.1 m).

However, positioning of a moving terminal is still challenging because the proposed method requires longer measurement time than other methods since it measures round-trip TOF among the terminal and the transponders [Fig. 1(b)]. Moreover, the terminal movement causes an effect of Doppler that may affect the measurement of TOF. Hence, the effect of the movement on positioning accuracy in the transponder-based positioning should be clarified.

In this paper, we evaluate the effect of the terminal movement on positioning in simulations and experiments. This paper consists of four sections. In section 2, we overview transponder-based acoustical positioning and analyze effects of the terminal movement on positioning. In section 3, we perform simulations and experiments. In section 4, we conclude our works.

2. Transponder-based positioning and effects of terminal movement

2.1. A overview of transponder-based positioning

The proposed method measures round-trip TOFs among the terminal and transponders. A schematic view of the measurement procedure of TOF is shown in Fig. 2 [11]. Firstly, the terminal transmits a request signal to the transponder #i at a specific time $t_{Ti}$. The request and response signals are modulated by maximum-length sequence (M-sequence) signals that have good cross-correlation property [6]. The unique code of M-sequence is assigned each transponder. Secondly, the transponder receives the request signal and calculates a cross-correlation function between the received request signal and the assigned request signal. When the cross-correlation function exceeds a threshold, the transponder detects the request signal and immediately transmits the response signal to the terminal. Note that a delay time $w$ (that is the transponder timing interval of recording the request signal and the response signal) is kept constant. Finally, the terminal receives the response signal and calculates the cross-correlation function between the received waveform and the assigned response signal. Then, TOF between the terminal and the transponder #i ($t_i$) is calculated by peak detection of the cross-correlation function. If the terminal received the response signal at $t_{Ri}$, $t_i$ is determined by the relationship among $t_{Ti}$, $t_{Ri}$, and $w$,

$$ t_i = \frac{t_{Ri} - t_{Ti} - w}{2}. \tag{1} $$

From the above method, the terminal can measure the round-trip TOFs. After the measurement of multiple TOFs, the terminal positioning is performed by using TOFs and the positions of the transponders. In following, we assume a case of three transponders existing at $x_i = (x_i, y_i, z_i)^T, (i = 1, 2, 3)$. In this case, the relationship of known information [position of transponder #i, $(x_i)$, and the
distance between the terminal and transponder \(i, (\rho_i)\) and unknown information [position of terminal, \(\mathbf{x} = (x, y, z)^T\)] is expressed as

\[
\begin{align*}
\rho_i &= c t_i, \\
\rho^2_i &= (x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2, (i = 1, 2, 3). 
\end{align*}
\]  

(2)

Because Eq. (2) is a nonlinear equation, the terminal solves Eq. (2) using iterative methods such as the Newton-Raphson method and obtains \(\mathbf{x} = (x, y, z)^T\), as well as existing positioning schemes.

2.2. Effects of terminal movement

The transponder-based positioning method assumes that the positioning is performed in a static/quasi-static environment. However, if we consider positioning in a dynamic environment, the following two problems may become an issue. The first problem is the increase of random error in the measurement of TOF. In detail, when the terminal transmits the request signal or receives the response signals, the effect of Doppler is caused in both signals by the terminal movement. Because the effect of Doppler stretches the request and the response signals in time, it brings deterioration on the cross-correlation characteristic. In other words, the peak-to-average-power-ratio (PAPR) of the cross-correlation function becomes small as the effect of Doppler increases. This means that the measurement of TOF becomes sensitive to the noise, so that the random error increases. Secondly, the terminal movement may cause offset in the measurement of round-trip TOF because the position of the terminal changes during the measurement of TOF. The TOF obtained from this measurement may be different from both of the transmission of the request time and the reception of the response time.

3. Simulations and Experiments

In this section, we tested the effects of the terminal movement on positioning accuracy in the transponder-based acoustical positioning by simulations and experiments. In detail, we firstly evaluated the effect of
Table 1. Parameters used in simulations and experiments.

| Parameter                  | Value         |
|----------------------------|---------------|
| Sampling frequency         | 50 kHz        |
| Carrier frequency          | 5 kHz         |
| M-sequence order 7         |               |
| Chip time                  | 0.2 ms        |
| Moving velocity            | 0 to 1.2 m/s  |

Figure 3. Simulations of velocity of moving terminal versus PAPR.

Figure 4. Schematic view of experiment set up.

Doppler on the measurement of TOF in simulations. Moreover, we also evaluated the effect of the terminal movement on the measurement of TOF in experiments.

3.1. Simulations

Table 1 shows parameters used in simulations. We generated a request signal by modulating carrier frequency of 5 kHz by M-sequence. We calculated the received response signal by resampling the transmitted request signal using the velocity information of the terminal. Then, we calculated a cross-correlation function between the original and resampled signals. The PAPR of the cross-correlation function becomes

$$PAPR = \frac{\max(f(\tau)^2)}{\text{mean}(f(\tau)^2)},$$

where $f(\tau)$ is the cross-correlation function and $\tau$ is the time lag between signals. Figure 3 shows the simulation results. In this figure, the horizontal axis shows the velocity of the terminal and the vertical axis shows PAPR. As shown in Fig. 3, as the velocity of the terminal increases, the cross-correlation function peak decreases. Hence, it is expected that the random error of TOF will increase as the velocity of the terminal increases.

3.2. Experiments

In the simulations, it was expected that the random error of TOF increases as the effect of Doppler increases. In the experiments, we also evaluate the effect of Doppler on the measurement of TOF.
Figure 5. Examples of signal processing; (i) transmitted response signal, (ii) received response signal, (iii) cross-correlation between (ii) and (i), (a) $v = 0.12$ m/s, (b) $v = 0.24$ m/s, and (c) $v = 0.96$ m/s.

Figure 6. Relationships between velocity of moving terminal and PAPR.

Moreover, we evaluate the effect of the terminal movement on the measurement offset of TOF.

Figure 4 shows the experimental set up in an anechoic chamber of 3 m (W) $\times$ 3 m (D) $\times$ 3 m (H) size. Loudspeakers (Fostex, P650K), omnidirectional microphones (DB Products Limited, C9767), A-D/D-A converters (National Instruments, USB-6221 and 6259), and personal computers (PCs) were used in both a terminal and a transponder. The terminal and the transponder were set on a linear actuator (Misumi, RSB2, 1.2 m). Transmitting signals and receiving signals were processed using a measurement software (National Instruments, LabVIEW) on PC. Acoustical parameters such as TOF and terminal position were calculated by a software (MathWorks, MATLAB) on PC. We used parameters shown in Table 1 as well as simulations. Using above parameters, ranging experiments were performed. The terminal approaches the transponder at various velocities $v$ (0.12 to 1.20 m/s, every 0.12 m/s) and transmits/receives signal 10 times from the fixed transponder.

Figure 5 shows examples of signal processing result. As shown in Figs. 5 (a-iii), 5(b-iii), and 5(c-iii), the cross-correlation functions between the transmitted and received response signals have a peak. However, as the velocity of the moving terminal increases, the PAPR tends to decrease as the velocity increases.

Figure 6 shows the relationships between the velocity of the moving terminal and the PAPR of the cross-correlation function obtained from the experiments. As shown in this figure, the velocity of the terminal increases, the PAPR also decreases as well as the simulation results. Hence, it is expected that the random error of TOF increases as the velocity of the moving terminal increases.

The relationships between the measured distance and the true distance is shown in Fig. 7. The horizontal axis shows the true distance between the terminal and the transponder (when the terminal transmits the request signal). The vertical axis shows the measured distance obtained from the
Figure 7. Relationships between measured distance and true distance in various velocity of terminal movement; (a) $v = 0.12 \text{ m/s}$, (b) $v = 0.24 \text{ m/s}$, (c) $v = 0.36 \text{ m/s}$.

measurement of TOF. Focusing on the random error, as the velocity of the moving terminal increases, the variance also increases. Focusing on the measurement offset of TOF, the velocity of the moving terminal increases, the offset value tends to large. From the above experiment results, we found that the both affect on the terminal movement.

4. Conclusion
To achieve simple and cost effective positioning in large-scale area, we proposed a transponder-based positioning. We evaluated the effects of the terminal movement on positioning in the simulations and the experiments. From the simulations, we found that the measurement error of TOF increases as the effect of Doppler increases. From the experiments, we observed same tendency as the simulations. Focusing on the random error of TOF, as the velocity of the moving terminal increases, the variance also increases. Focusing on the measurement offset of TOF, the velocity of the moving terminal increases, the offset value tends to large. The obtained results suggest that the proposed method can achieve positioning accurately when the velocity of the moving terminal is low. On the other hand, it was also found that as the velocity of the moving terminal becomes higher, additional signal processing that cancels the effect of the Doppler and offset of TOF may be required. Positioning experiments using multiple transponders in the large-scale indoor environment is one of our future work.

References
[1] Widodo S, Shiigi T, Hayashi N, Kikuchi H, Yanagida K, Nakatsuchi Y, Ogawa Y and Kondo N 2013 Robotics 2 36–53
[2] Priyantha N B, Miu A K, Balakrishnan H and Teller S 2001 Proceedings of the 7th annual international conference on Mobile computing and networking (ACM) pp 1–14
[3] Ogiso S, Kawagishi T, Mizutani K, Wakatsuki N and Zempo K 2015 ROBOMECH Journal 2 12
[4] Hashizume H, Kaneko A, Sugano Y, Yatani K and Sugimoto M 2005 Proc. TENCON 2005-2005 IEEE Region 10 Conference (IEEE) pp 1–6
[5] Mandal A, Lopes C V, Givargis T, Haghighat A, Jurdak R and Baldi P 2005 Proc. Second IEEE Consumer Communications and Networking Conference, 2005. CCNC. 2005 (IEEE) pp 348–353
[6] Hirata S, Kurosawa M K and Katagiri T 2008 IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences 91 1031–1037
[7] Quintana B, Prieto S A, Adán A and Bosché F 2016 Indoor Positioning and Indoor Navigation (IPIN), 2016 International Conference on (IEEE) pp 1–8
[8] Zhang W, Hua X, Yu K, Qiu W and Zhang S 2016 Indoor Positioning and Indoor Navigation (IPIN), 2016 International Conference on (IEEE) pp 1–5
[9] Sakai N, Zempo K, Mizutani K and Wakatsuki N 2016 Indoor Positioning and Indoor Navigation (IPIN), 2016 International Conference on (IEEE) pp 1–4
[10] Hostettler R and Särkkä S 2016 Indoor Positioning and Indoor Navigation (IPIN), 2016 International Conference on (IEEE) pp 1–8
[11] Iwaya H, Mizutani K, Ebihara T and Wakatsuki N 2017 Japanese Journal of Applied Physics 56 07JC07