Evaluation of Time-Difference-of-Arrival Error of Acoustic Beacons Caused by Velocity of Microphone Array

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Abstract. In this paper, we described a criterion of estimating the quality of time-difference-of-arrival (TDOA) estimation with a moving microphone array. The microphone array was supposed to receive a known signal from an acoustic beacon which transmitted a binary code with binary phase shift keying (BPSK). The movement of the microphone array may cause two kinds of error on the TDOA estimation: physical change of TDOA caused by the movement, and apparent change caused by the lower correlation values of Doppler-shifted signals. For evaluating the latter error, we employed the peak to average power ratio (PAPR) of the cross correlation function. The Doppler effect on TDOA error were evaluated with a computer simulation. The microphone array was moved at -2 to 2 m/s, covering the velocity range of indoor mobile robot. Besides the velocity, following three parameters of the sound were investigated. The types of the code for evaluation were chosen as M-, Gold and Kasami sequences, carrier frequencies were 0-40 kHz, and chip rates of the binary code were 0.5 - 20 kHz. As the results, it was confirmed that if PAPR is lower than a certain value, 40 in this simulation, the peak detection of the cross correlation is difficult and it results in high and unpredictable TDOA errors. Higher chip rates and lower carrier frequencies showed better resilience against the Doppler effect. The proposed criterion may infer the maximum velocities at which TDOA can be estimated without any measure against the Doppler effect for realistic parameters. This criterion would contribute to the on-line evaluation of the quality of TDOA, which may be beneficial for estimating sound direction of arrival.

1. Introduction
Self-localization of mobile robots are one of the essential functions for intelligent tasks. Especially in indoor environments, there is no chance to use GNSS/GPS (Global Navigation Satellite Systems / Global Positioning Systems) because the satellites are not observable. Under these conditions, there are some possible methods for estimating locations of the mobile robots. One of the conventional methods is wheel-based or IMU (inertial measurement unit)-based odometry, which accumulates velocity and angular velocity of a mobile robot[1, 2]. Although it is quite easy to implement, the accuracy cannot be guaranteed owing to accumulation of measurement errors. Contrarily, there are localization methods which use not only the sensors above, but also
sensors to acquire information about the surrounding environment. The typical methods are camera-based or LIDAR (Light Detection and Ranging)-based SLAM (simultaneous localization and mapping) [3]. This type of the localization method can acquire information of surrounding environment and correct localization error according to the information. However, it is usually a costly calculation that extraction of plenty of feature points (>500) to be tracked from measurement and tracking them over time robustly. Also, the LIDARs or cameras for practical use themselves are expensive.

To overcome these problems of calculation cost and expensive equipments, acoustic localization methods have been proposed. There are several types of acoustic localization. One is multi-transmitter single-receiver type. This type of the localization method uses TDOA for each sounds from different but known locations. Although it is possible to estimate the location, the pose of receiver cannot be obtained, as single receiver does not provide enough information. It is critical for applications such as mobile robot localizations, which the pose is quite important as well as a location for movement.

Our research group has proposed a self-localization method using acoustic beacons in surrounding environment and microphone array on mobile robot [4, 5, 6], as multi-transmitter and multi-receiver type. This method can estimate time-difference-of-arrival (TDOA) between the received signals of each microphone element of the microphone array, and conduct self-localization based on TDOA. This method does not require time synchronization, and can estimate not only position, but also the pose of mobile robots.

For these acoustic localization methods, the Doppler effect on the sounds used for localization is one of the major problems. In this problem, there are studies to evaluate the effect on cross-correlation values [7], localization [8], communication of sound emitters and receivers [9]. However, these studies are only for single receiver and not intended for array signal processing. Therefore, TDOA of the receiver microphones were not evaluated.

In this paper, we evaluate the effect of the Doppler effect on TDOA error for binary phase shift keying (BPSK) of acoustic beacons. There are mainly two ways that the Doppler effect affects TDOA. One is the apparent change of sound speed caused by the microphone movement, which causes actual TDOA changes on microphone signals. This change can be predicted by theoretical analysis. The other one is change of cross-correlation characteristics of received and transmitted signals. TDOA of the BPSK signals are usually detected as a time at which the maximum value of cross-correlation function of receiving signals and replica signal of transmitting signal was observed. The Doppler effect may affect to this characteristic, and deteriorates both the peak time and the peak height. This change is not easy to predict theoretically. Our aim of this paper is to evaluate the TDOA error from these two aspects focusing on TDOA error. This observation may make a criteria to predict a velocity range that TDOA estimation can be done for realistic parameters of BPSK signal.

2. Computer simulation of localization
2.1. Conditions of simulation
Computer simulations were performed assuming movement of a mobile robot along a straight line in certain velocities. Figure 1 shows a description of simulation condition. The mobile robot had two microphones which were placed in distance of 1 m, and the microphones were unidirectional and synchronized. A loudspeaker was placed on 5 m apart from the microphones in order to assume a far sound field. The loudspeaker emitted BPSK-modulated signal repeatedly. The generation polynomials, the initial conditions of each sequence and other common conditions of the emitted signals are described in Table 1. Different BPSK-modulated signals for various carrier frequencies, $f_c$, and chip rates, $f_b$, were examined. Signals of the microphones were recorded for a period of BPSK-modulated signal, namely $n/f_b$ (s), at a sampling rate of 400 kHz. The TDOA of recorded signals were calculated by cross-correlation method, which estimates
Figure 1. Simulation condition and description of TDOA estimation method

Table 1. Common parameters of simulation

| Sequence type | M, Gold, and Kasami |
|---------------|---------------------|
| Sequence length $n$ | 255 (8th order) |
| Generation polynomials |  |
| M sequence | [8, 7, 6, 5, 2, 1, 0] |
| Gold sequence | [8, 7, 6, 5, 2, 1, 0] |
| Kasami sequence | [8, 4, 3, 2, 0] |
| Initial conditions | $m = 1$ |
| Sampling rate | 400 kHz |

TDOA as the time at which the cross correlation function of the recorded signals takes the maximum value. The window length of the cross correlation $w$ was set to be $n/f_b$ (s) in order to calculate for 1 period of a signal. Following two variables were evaluated to evaluate the effect of BPSK signal parameters on resiliency against the Doppler effect:

(i) Different carrier frequencies, $f_c$, under condition of a constant chip rate $f_b = 5$ kHz.

Higher carrier frequency would result in a larger frequency shift by the Doppler effect. To evaluate the effect, practical carrier frequencies were chosen from 0 Hz (base band signal) to 40 kHz (common in ultrasonic localization systems).

(ii) Different chip rate, $f_b$, under condition of a constant carrier frequency $f_c = 20$ kHz.

Higher chip rate widely spread spectrum and would have resilience against the Doppler effect. To evaluate the effect practically, a chip rate range of 0.5–20 kHz was simulated.

For each condition, the theoretical TDOA error $\Delta \bar{\tau}$ caused by the apparent sound speed change was calculated as following equation using variables shown in Fig. 1:

$$\Delta \bar{\tau} = \frac{d \sin(\theta)}{c - v} - \frac{d \sin(\theta)}{c}.$$  \hspace{1cm} (1)

The first term represents TDOA with movement at a velocity of $v$, and the second term represents TDOA without movement.

Also, it is important to evaluate characteristics of cross correlation functions that how easily the maximum peak can be found. This characteristic was evaluated with peak to average power ratio (PAPR) with variables shown in Fig. 2. PAPR was calculated as following equation:

$$p = \frac{\max f_{i,k}^2}{\mu},$$  \hspace{1cm} (2)
where $\mu$ denotes the mean of power value except values around the maximum peak. $\mu$ is calculated as:

$$
\mu = \frac{1}{\arg_t \max(f_{i,k}) - g/2 + w} \int_{t=-w}^{\arg_t \max(f_{i,k})-g/2} f_{i,k}^2 dt + \frac{1}{w - (\arg_t \max(f_{i,k}) + g/2)} \int_{t=\arg_t \max(f_{i,k})+g/2}^{w} f_{i,k}^2 dt.
$$

(3)

The variable $g$ denotes a guard bandwidth for ignoring the maximum peak and values around it of the cross correlation function. Eq. 2 holds high value if the peak value is higher than values of other region. Higher $p$ indicates easier to detect the maximum peak, and lower $p$ indicates more difficult to find out the correct peak of the cross correlation function. In the simulation, $g$ was set to 10% of window length $w$.

2.2. Results and Discussions

The results of computer simulations are shown in Fig. 3. Figures 3(a)–(j) show the results under different $f_c$. Figures 3(a)–3(e) and Fig. 3(k)–3(o) show results of TDOA estimation error, and Fig. 3(f)–3(j) and Fig. 3(p)–3(t) show corresponding PAPR, $p$. From the figures, a trend can be observed that TDOA error depends on $f_c$ even at the same velocity. Also, shown as the shaded area, the TDOA error was drastically increased if the velocity exceeded a certain amount. This drastic increase from theoretical TDOA error can be explained by PAPR changes. For example, the cross correlation function at P1, $v = -1$ m/s, and P2, $v = 0$ m/s, in Fig. 3(e) are shown in Fig. 4(a) and Fig. 4(b). As shown in Fig. 4, the peak of the cross correlation function is obvious if $p$ takes higher value. These results may indicate that when PAPR take lower values, corresponding TDOA may be quite inaccurate. The threshold of $p$ for accurate or inaccurate TDOA was approximately 40 in this case as seen in Fig. 3. One exception is Fig. 3(f), which takes exceptionally low values without drastic change on TDOA. This is because its condition is $f_c = 0$, namely there is no carrier energy on the PAPR where all other conditions have.

Figures 3(k)–(t) show the results under different $f_b$. From the figures, a trend can be observed that $f_b$ affected TDOA error and lower $f_b$ resulted in higher TDOA error at the same velocity. Also, this drastic change from theoretical TDOA error can be explained by PAPR changes, as a range at which PAPR is less than approximately 40 is corresponding to inaccurate TDOA ranges. The lower $f_b$ means narrower spectrum spreading in frequency and shorter signal period. Lower chip rate $f_b$ cause lower cross correlation peak at higher velocity because of the longer signal period and narrower spectrum, and affects the TDOA error. With higher $f_b$, the period of the signal was shortened, and the frequency was spread widely. The shorter signal period and
Figure 3. Velocity $v$ vs. error of time difference of arrival $\Delta \bar{\tau}$ and velocity $v$ vs. PAPR $p$ for different $f_c$ and $f_b$. Shaded areas represent inaccurate TDOA.

widely spread spectrum makes resilience to the Doppler shift, and results in good correlation characteristics as $p$ indicates. From the simulation, there are velocity ranges for each $f_b$ where TDOA can be estimated correctly. Under condition of $f_c = 20$ kHz, the velocity range of -0.1–0.1 m/s for $f_b = 0.5$ kHz, -0.2–0.2 m/s for $f_b = 1$ kHz, -0.6–0.6 m/s for $f_b = 5$ kHz and 10 kHz, and more than -2–2 m/s for $f_b = 20$ kHz. Especially under the condition of $f_b = 20$ kHz, TDOA would not become inaccurate without any measure against the Doppler shift. Also, it can be confirmed with PAPR shown in Fig. 3(t), as the PAPR is enough high to estimate the peak of the cross correlation function. This can be a criteria to determine $f_b$ and whether measure against the Doppler shift is needed.
Figure 4. Normalized cross correlation functions $f_{i,k}$ of Kasami sequence for each highlighted points in Fig. 3. (a) P1, $f_c = 40$ kHz, $f_b = 5$ kHz, $v = -1$ m/s, (b) P2, same condition to (a), $v = 0$ m/s.

3. Conclusion

In this paper, we described a criterion of estimating the quality of time-difference-of-arrival (TDOA) estimation with a moving microphone array. The microphone array was supposed to receive a known signal from an acoustic beacon which transmitted a binary code with binary phase shift keying (BPSK). Within the Doppler effect, we focused on the apparent change of TDOA by the lower correlation values of Doppler-shifted signals. For evaluating this error, we employed the PAPR of the cross correlation function. The Doppler effect on TDOA error were evaluated with a computer simulation. The microphone array was moved at -2 to 2 m/s, covering the velocity range of indoor mobile robot. Besides the velocity, following three parameters of the sound were investigated. The types of the code for evaluation were chosen as M-, Gold and Kasami sequences, carrier frequencies were 0-40 kHz, and chip rates of the binary code were 0.5 - 20 kHz. As the results, it was confirmed that if PAPR is lower than a certain value, 40 in this simulation, the peak detection of the cross correlation is difficult and it results in high and unpredictable TDOA errors. Higher chip rates and lower carrier frequencies showed better resilience against the Doppler effect. The proposed criterion may infer the maximum velocities at which TDOA can be estimated without any measure against the Doppler effect for realistic parameters. This criterion would contribute to the on-line evaluation of the quality of TDOA, which may be beneficial for minimizing TDOA error caused by the Doppler effect by processing the received signals to maximize the PAPR. As future work, experimental results are needed.

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