3D FDM–PAM: Rapid and Precise Indoor 3D Localization using Acoustic Signal for Smartphone

Masanari Nakamura
Hokkaido University
Kita 14, Nishi 9, Kita-ku
Sapporo, 060-0814, Japan
masanari@main.ist.hokudai.ac.jp

Masanori Sugimoto
Hokkaido University
Kita 14, Nishi 9, Kita-ku
Sapporo, 060-0814, Japan
sugi@ist.hokudai.ac.jp

Takayuki Akiyama
The Graduate University for Advanced Studies
2-1-2 Hitotsubashi, Chiyoda-ku
Tokyo, 101-8430, Japan
tak@nii.ac.jp

Hiromichi Hashizume
National Institute of Informatics
2-1-2 Hitotsubashi, Chiyoda-ku
Tokyo, 101-8430, Japan
has@nii.ac.jp

UbiComp'14 Adjunct, September 13-17, 2014, Seattle, WA, USA
ACM 978-1-4503-3047-3/14/09.
http://dx.doi.org/10.1145/2638728.2638758

Abstract

In this paper, we present an indoor 3D positioning method for smartphones using acoustic signals. In our proposed 3D Frequency Division Multiplexing–Phase Accordance Method (3D FDM–PAM), four speakers simultaneously emit burst signals comprising two carrier waves at different frequencies to enable the rapid calculation of the position of the smartphone. Through experiments, we show that 3D FDM–PAM can achieve a standard deviation of less than 2.8 cm at 7.8 measurements per second. The worst positioning error was 48.3 cm at the 95th percentile. We investigate the causes of error and discuss potential improvements to the localization performance.

Author Keywords

Indoor positioning; Acoustic signal; Smartphone; FDM

ACM Classification Keywords

Human-centered computing; Ubiquitous and mobile computing; Ubiquitous computing

Introduction

Smartphones have become popular personal devices and are now often used for indoor localization (e.g. [3, 4, 5]). The goal of this research is to identify the 3D position of a smartphone, thereby enabling the user's gestures or motions to be captured. In this paper, we propose 3D

Frequency Division Multiplexing–Phase Accordance Method (3D FDM–PAM), which can achieve rapid and precise 3D localization using TDoA (Time Difference of Arrival) trilateration. Experimental results show that 3D FDM–PAM can localize a smartphone to within a standard deviation (SD) of 2.8 cm at 7.8 measurements per second. However, because its worst positioning error can be 48.3 cm at the 95th percentile, we investigate the causes of error and discuss how they may be addressed.

3D FDM–PAM

For rapid and precise 3D positioning, we extend 2D FDM–PAM [1] devised by our group to 3D FDM–PAM. Trilateration methods based on either Time of Arrival (ToA) or TDoA can be used for localization, with ToA-based methods performing better than TDoA-based methods in general. However, we prefer to use TDoA because ToA requires high-precision time synchronization of transmitters and receivers, which is not easy for smartphones. We use four speakers in the experiments with our TDoA-based method.

In 3D FDM–PAM, a special burst pulse consisting of two sinusoidal waves of different frequencies is transmitted to create a beat wave called the "sync pattern," as shown in Fig. 1. The sync pattern can be expressed as:

$$s(t) = a_1 \sin(2\pi f_1 t + \phi_1) + a_2 \sin(2\pi f_2 t + \phi_2) \quad (1)$$

$$= a_1 \sin(\omega_1 t + \phi_1) + a_2 \sin(\omega_2 t + \phi_2), \quad (2)$$

where $\omega_i = 2\pi f_i$ $(i = 1, 2)$ is the angular frequency, a_i is the amplitude, and ϕ_i is the initial phase. In our experiment, four sync patterns, comprising $(f_1,\ f_2) =$ (14.75, 15.25), (15.75, 16.25), (16.75, 17.25), and (17.75, 18.25) [kHz], are assigned to different speakers. The sync pattern has an identified point, the "epoch," when the phase difference between the two constituent waves becomes a specified value. The epoch is used to identify the time of arrival at the receiver by accurately determining the phases ϕ_1 and ϕ_2 of the two constituent waves. An inner product of two time domain functions $f(t)$ and $g(t)$ is defined as:

$$< f(t),\ g(t) >= \frac{1}{T}\int_{-T/2}^{T/2} f(t)\overline{g(t)}dt, \quad (3)$$

where $\overline{g(t)}$ is the complex conjugate of $g(t)$.The inner product of $s(t)$ with $e^{j\omega_1 t}$ is calculated as:

$$< s(t),\ e^{j\omega_1 t} >= \frac{1}{2j}\big(a_1(e^{j\phi_1} - e^{-j\phi_1}\operatorname{sinc}\omega_1 T)$$

$$+a_2(e^{j\phi_2}\operatorname{sinc}\frac{\omega_2-\omega_1}{2}T - e^{-j\phi_2}\operatorname{sinc}\frac{\omega_2+\omega_1}{2}T)\big), \quad (4)$$

where T is the duration of a square window applied to the received signal $s(t)$ and $\operatorname{sinc} x = \sin x / x$ is the sampling function. In equation (4), ω_1 and ω_2 are large enough for $\operatorname{sinc}\omega_1 T \approx 0$ and $\operatorname{sinc}((\omega_2+\omega_1)T/2) \approx 0$ to hold. For $T = 2$ ms, $\operatorname{sinc}((\omega_2-\omega_1)T/2) = 0$ also holds. Therefore, ϕ_1 is obtained through equation (5).

$$< s(t),\ e^{j\omega_1 t} >\approx \frac{1}{2j}a_1 e^{j\phi_1}. \quad (5)$$

ϕ_2 can be calculated similarly. In our current implementation, we set the duration of the sync pattern to 4 ms, for which the epoch is located near the center of the square window, as shown in Fig. 1.

In 2D FDM–PAM, all sync patterns must be fully overlapped in the square window, as shown in Fig. 2. Thus, equation (4) can be approximated by equation (5), with all the phases of the constituent waves of the sync patterns then being correctly determined. In 3D FDM–PAM, partially overlapped sync patterns as shown in Fig. 3 are allowed, which makes its measurable coverage larger than 2D FDM-PAM. However, the approximation to equation (5) fails in Fig. 3, because $\operatorname{sinc}((\omega_2-\omega_1)T'/2) \approx 0$ in equation (4) does not hold in this case. This problem is discussed later.

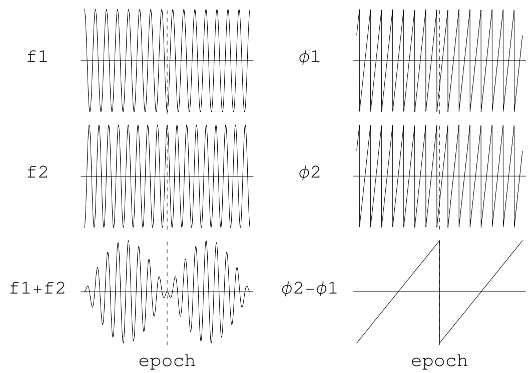
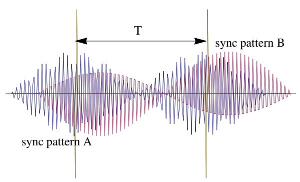


Figure 1: Two-period sync pattern and epoch



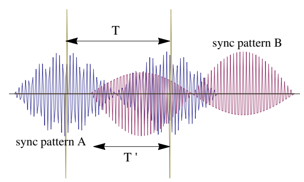


Figure 2: Fully overlapped sync patterns

Figure 3: Partially overlapped sync patterns

Experiments

Four off-the-shelf speakers (FOSTEX FT200D) were placed at $(x, y, z) =$ (0.0, 0.0, 0.04), (1.5, 0.0, 0.04), (0.0, 1.5, 0.04), and (0.0, 0.0, 1.54) [m]. A sync pattern was generated by a function generator (NF Corporation WF1948). The equipment characteristics dictated that a sync pattern be emitted from each speaker 7.8 times per second. A smartphone (Fujitsu Arrows F-02E) was located at (x, y, z)= (1.0, 1.0, 0.8), (1.0, 1.5, 1.3), (1.0, 2.0, 0.8), (1.5, 0.5, 1.3), (2.0, 2.0, 0.8), and (2.0, 2.0, 1.3) [m]. At each location, 100 measurements were conducted. Each sync pattern received by the smartphones was analog-to-digital converted and transferred to a PC (dual Xeon E5-2650, 64 GB memory) for the localization calculations.

The maximum SD for all the positions was 2.8 cm. The cumulative distribution function (CDF) in Fig. 4 shows that the 95$^{\text{th}}$ percentile errors for each of the six positions were 7.1 cm, 11.3 cm, 13.4 cm, 17.0 cm, 28.6 cm, and 48.3 cm, respectively. The results, especially the poor positioning results, can be partially explained by dilution of precision (DoP) [2]. The position calculations were confirmed to require around 78 ms. It is therefore possible to achieve around 12 localization measurements per second.

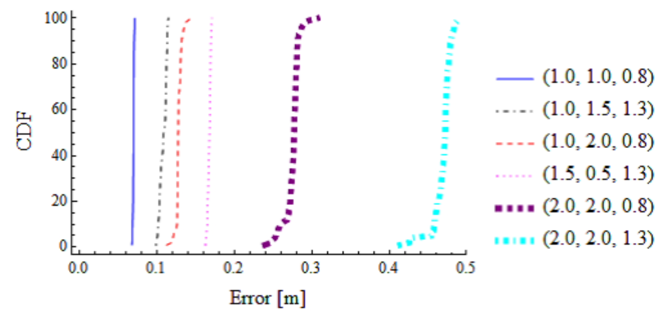


Figure 4: Experimental result

Discussion

Overlapped Signal Simulation

As mentioned above, 3D FDM–PAM may show localization errors that depend on signal overlap patterns (Figs. 2 and 3). Computer simulations were conducted that changed the overlap patterns by adding ambient noise. Fig. 5 shows that overlapped sync patterns may generate large errors at positions where the square window cannot capture all the received sync patterns.

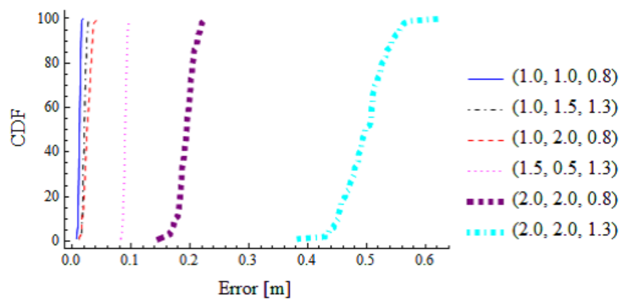


Figure 5: Simulation for overlapped sync patterns

Influence of Phase Characteristic

The phase characteristic related to the directivity of speakers and microphones is another cause of error. In an experiment to investigate the phase characteristic of a speaker, a standard microphone (Rion UC-31) was used to exclude any possible influence from the smartphone microphone. The distance between the speaker at a fixed position and the microphone placed at 9 (horizontal) $\times$ 9 (vertical) $=$ 81 different positions was measured (see Fig. 6). The angles to the microphone from the speaker ranged between $\pm$ 40 degrees. There were 100 measurements per position. The maximum SD of the measurements was about 3 mm. Fig. 6 shows a maximum error of 4 cm, which may lead to serious 3D positioning errors using TDoA trilateration for positions with poor DoP values.

Conclusion and Future Work

We have proposed 3D FDM–PAM for smartphone 3D localization and confirmed its precise and rapid localization performance. Our future work will aim to alleviate the positioning error problem by phase characteristic compensation.

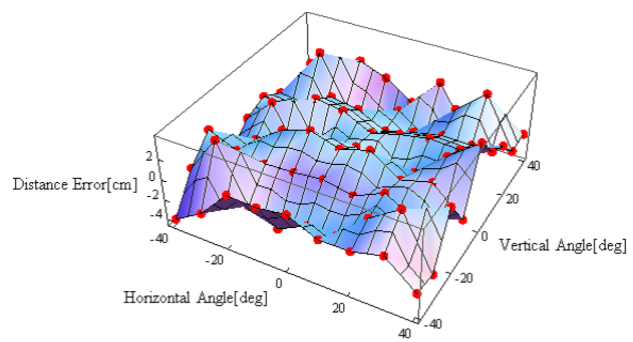


Figure 6: Speaker phase characteristic

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