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Sound based indoor and outdoor environment detection for seamless positioning handover☆

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Abstract

In this paper, we propose a sound-based indoor and outdoor environment detection method to realize seamless positioning handover for in-and-outdoor integrated positioning systems. The proposed method uses a special chirp sound probe which is propagated by a speaker of a mobile device and collected back through a microphone of the device. The indoor and outdoor environments are detected by analyzing the reverberation patterns of the retrieved probe. When we tested the proposed method at 46 indoor and outdoor locations, roughly 95% detection accuracy was achieved.

Keywords: Environment detection; Sound; Reverberation; Positioning

1. Introduction

With the advent of GPS [1], the satellite-based outdoor positioning system has been penetrating into our daily lives for our safety and convenience. However, GPS cannot be used indoors as the walls and the ceiling block GPS signals. A number of studies have been conducted to develop indoor positioning systems (IPSs) using various signals such as 5G wireless networks [2], RFID [3], infrared (IR) [4], GSM [5], Bluetooth [6] and wireless LAN (WLAN) [7].

If the IPSs were successfully constructed and popularized, someday it will be integrated with GPS for in-and-outdoor integrated positioning systems. The integrated positioning systems need to switch between GPS and IPS. The switching should be made promptly and accurately for the convenience of users. Only a few handover schemes have been developed to detect the changes of the surrounding environment and automatically switch between GPS and IPS [8,9]. The methods can be classified into two approaches. The first approach uses the availability of positioning systems [10]. It decides whether the environment is indoor or outdoor under the assumption that GPS is not available indoors and IPS outdoors. Thus, this approach has limitations at the places where both GPS and IPS are available. In the second approach, sensing data obtained from embedded or external sensors are used. Light intensity [11], geomagnetic field intensity [11], and ambient temperature [12] have been utilized in previous studies.

Although the studies focused on developing prompt indoor and outdoor environment detection, both approaches have drawbacks in accuracy and delay of the detection. They require tens of seconds to detect indoor and outdoor environments, and the detection is not accurate enough to be practically used in the field.

This paper presents a sound-based indoor and outdoor environment detection method. The method utilizes an acoustic feature that generates different reverberation patterns depending on the surrounding environment. The indoor reverberations usually show distinguished patterns from outdoors. The proposed method consists of three steps in large. In the first step, a special sound probe, so-called chirp signal, is generated by a speaker and retrieved by a microphone of a mobile device. In the second step, the reverberation patterns of retrieved signal are analyzed. Finally, in the third step, indoor and outdoor are classified based on the reverberation patterns.

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2. Adaptive hybrid filter

To develop an effective and practical sound-based indoor and outdoor environment detection method, a unique and easily detectable sound probe is required to be generated. We have selected chirp signal as the sound probe because it can be efficiently generated, retrieved, and processed [13]. Noises included in retrieved signals also can be efficiently suppressed with appropriate signal filters [13]. The chirp signal has widely been used in many fields such as spread spectrum communications and sonar/radar systems. The frequency of chirp signal is unique in that it steadily increases or decreases with time. As sweeping a range of frequencies, the retrieved signal will contain the reverberation features of all frequencies in the range.

For a sound probe, we generate a chirp signal whose instantaneous frequency $f(t)$ increases linearly with time. The frequency function of the chirp signal is given by Eq. (1), where f_0, f_1, and k represent the starting frequency, final frequency, and the rate of linear frequency changes, respectively.

$$f(t) = f_0 + kt, \quad \text{where } k = \frac{f_1 - f_0}{t_1}. \tag{1}$$

Using the function a linear chirp sound probe is generated and propagated. The propagated sound probes are retrieved by simply recording the sounds using a microphone embedded in a mobile device. When the sound probes have the duration of γ ms, the recording process starts γ ms before the propagation of the probe to record ambient noise of the environment, and lasts for a while after the end of the propagation to include all the reverberations of the probe. It is known that reverberation arrives in less than approximately 100 ms.

Once the chirp signal is retrieved by the microphone, the degree of reverberation of the chirp signal is measured for the detection of indoor and outdoor environments. Ambient noise reduction, original chirp signal detection, envelope extraction, and reverberation score calculation are the steps constituting the analysis process.

Ambient noise reduction is the first step of the analysis. A special band-pass filter was used to remove the ambient noises from the retrieved sound using fast Fourier transform (FFT) [14]. Then the original chirp signal was extracted from the noise-removed signal by applying cross-correlation, which is a function of a time lag applied to one of waveforms to measure the similarity of two waveforms. Since the reverberation of the retrieved sound has similar characteristics to its original sound in frequency range, the reverberation of a chirp signal still remains in the retrieved sound after the ambient noise reduction and the cross-correlation calculation. The reverberation of a chirp signal is measured by analyzing the results of the cross-correlation between the chirp signal and its retrieved sound.

Although the degree of reverberation can be computed with the cross-correlation values, an envelope of the cross-correlation values was used for more convenient and correct measurement. The envelope of fluctuating signals is a smoothing curve which outlines the peaks of amplitude. The envelope can be obtained by applying a smoothing filter to the abstract cross-correlation values. Fig. 1 shows the envelopes extracted from the indoor and outdoor reverberations of a sample chirp signal, respectively. As can be seen in the figure, the reverberations appear more conspicuously indoors than outdoors.

With the envelope, the degree of reverberation can be measured by computing its integral value, the reverberation score. The range of integration is critical to make the score calculation reliable because the range defines the end of the reverberant tail. All reverberation features can be included in the score calculation if a generously wide range of integration is used. However, a wide range exceeding the end of a reverberant tail will introduce noise into the calculation. The lengths of reverberant tails are diverse depending on the characteristics of indoor spaces such as the heights of ceilings, the widths of aisles, and the types of wall materials. Therefore, the integration range should be carefully determined through experiments for the optimized detection result.

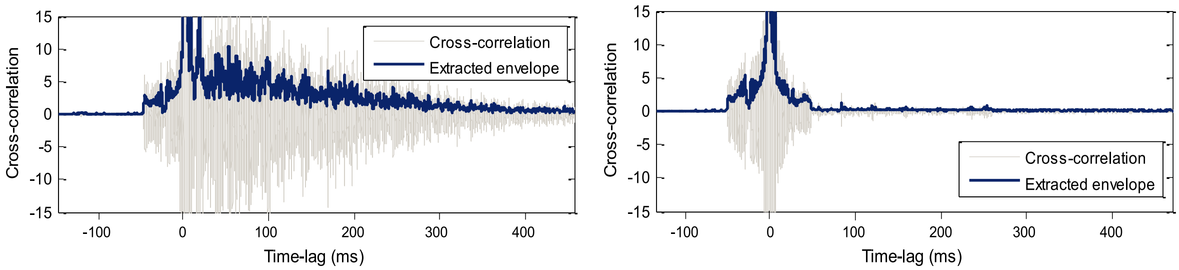
A binary classification method can be used to determine indoor or outdoor environment based on the set of reverberation scores. There are many binary classification methods to classify a set of calculated reverberation scores into indoor or outdoor environment. Static threshold value is one of choices for the classification. The threshold value should be carefully decided based on a variety of training data. Once the threshold value is decided, the classification is rather simple and straightforward. All we need to do is to compare the observed reverberation score with the threshold value. Machine learning technique can be another choice to analyze reverberations in a more sophisticated fashion for a more accurate classification. In this paper, however, we apply the static threshold-based method because it is enough to demonstrate the usefulness of sound probes in indoor and outdoor environment detection.

3. Experimental results

To confirm the effectiveness of the proposed method, we measured indoor and outdoor environment detection accuracy of the proposed method. The experiments were conducted at KAIST campus located in Daejeon, South Korea. In the experiment, we set a path between the centers of two buildings at the campus and collected test data while a user was walking back and forth 10 times along the path. Sound probes were continually generated, and collected every 3 s. In total, 540 sound probes and 40 indoor/outdoor transitions were collected for the test data. The experimental area included variable indoor and outdoor environments, such as narrow corridors, lobbies, open outdoors, near-entrances, etc., as illustrated in Fig. 2.

Samsung Galaxy S3, which runs Android 4.3 (Jelly Bean), was used for the data collection. During the data collection, the sound volume was set to the maximum level, and collectors held the devices naturally in one hand. A linear chirp signal lasting 50 ms was generated as sound probes. The frequency of the chirp was in the range from 1 kHz to 3 kHz.

The environment detection accuracy was measured for 540 probes. Also, we evaluated delay and accuracy of transition detection for 40 indoor/outdoor transitions. We used the proportion of true results in the population as detection accuracies for environment and transition respectively.



(a) Envelope of a probe retrieved in an indoor space.

(b) Envelope of a probe retrieved in an outdoor space.

Fig. 1. Comparison of envelopes extracted from sound probes collected at indoor and outdoor locations.

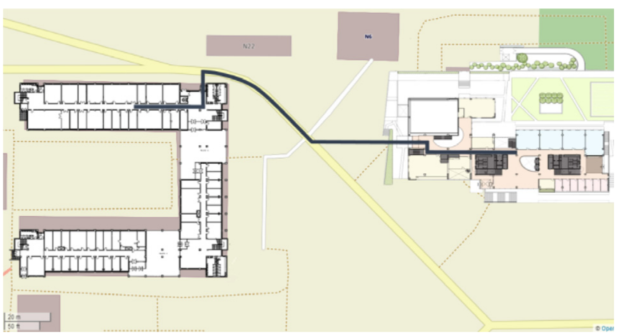


Fig. 2. A data collection path for transition detection test.

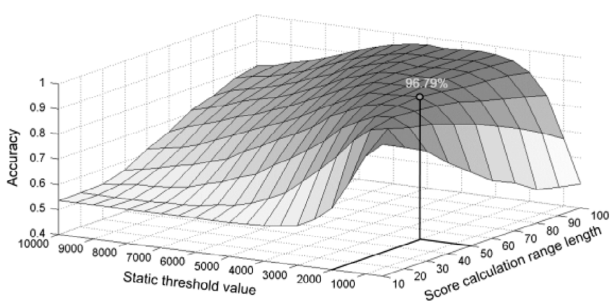


Fig. 3. Environment detection accuracy with various threshold values and score calculation ranges.

Static threshold was used for the classification. The threshold value was varied from 1000 to 10,000 by 1000. The range of integration for the score calculation was increased from 10 to 100 by 10. Fig. 3 shows the environment detection accuracies. As discussed in the previous section, the score calculation range defines the range of reverberation in collected sound streams. The best accuracy (96.79%) was achieved at the marked point in Fig. 3, where the score calculation range was 50, and the threshold value, 2000.

With these settings, we compared the detection delays and accuracies of indoor/outdoor transitions with two previous methods proposed by R. Hansen et al. [10], which utilize both GPS and Wi-Fi Positioning System (WPS). As the application of WPS requires Wi-Fi radio maps to be prepared [10], we constructed Wi-Fi radio maps of the buildings shown in Fig. 2. We also collected Wi-Fi and GPS signals along with the collected sound probes for the test of WPS-based and GPS-based transition detections.

Fig. 4 shows the cumulative accuracies of transition detections in a given time for the three methods. As illustrated

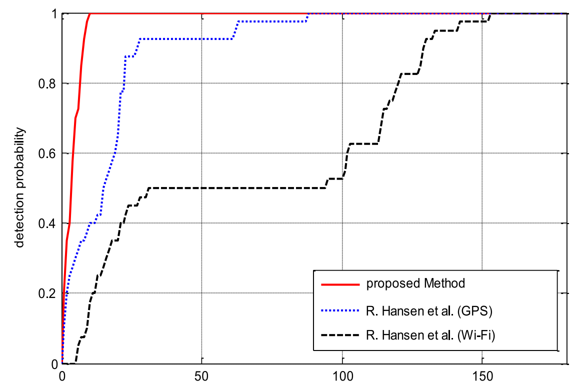


Fig. 4. Transition detection error comparison (CDF).

in the figure, the proposed method reduced the average transition detection delays by more than 80% compared to the previous methods. The detection time of the proposed method took only 3.81 s in average, whereas Hansen's methods required 16 s with GPS, and 67 s with Wi-Fi for the transition detection.

4. Conclusion

This paper presented a sound-based indoor and outdoor environment detection method for the seamless indoor and outdoor positioning handover. Chirp signal was used for the first time to detect indoor and outdoor environments. The performance of the method was outstanding compared to existing methods. Although the method was developed to detect indoor and outdoor environments for positioning systems, it can be used for other applications as well. For example, the awareness of indoor and outdoor is important for some context-aware applications. Since this paper showed the feasibility of the proposed method with a simple experiment, further studies are required with variable experimental settings for applying the method to the real-world applications.

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