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Indoor footstep localization from structural dynamics instrumentation

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ABSTRACT

Measurements from accelerometers originally deployed to measure a building's structural dynamics can serve a new role: locating individuals moving within a building. Specifically, this paper proposes measurements of footstep-generated vibrations as a novel source of information for localization. The complexity of wave propagation in a building (e.g., dispersion and reflection) limits the utility of existing algorithms designed to locate, for example, the source of sound in a room or radio waves in free space. This paper develops enhancements for arrival time determination and time difference of arrival localization in order to address the complexities posed by wave propagation within a building's structure. Experiments with actual measurements from an instrumented public building demonstrate the potential of locating footsteps to sub-meter accuracy. Furthermore, this paper explains how to forecast performance in other buildings with different sensor configurations. This localization capability holds the potential to assist public safety agencies in building evacuation and incidence response, to facilitate occupancy-based optimization of heating or cooling and to inform facility security.

1. Introduction

1.1. Research motivation

Advances in signal processing can provide new applications for existing sensor systems. This paper proposes measuring footstep-generated vibrations as a novel means for an indoor location service. The source of these measurements can come from existing accelerometers in a building's structural dynamics instrumentation system. Such sensors may have been previously installed for a smart building initiative or may be part of a structural health monitoring system. Once implemented, this technology could locate building occupants in circumstances where the capability would otherwise be unavailable. For example, although camera systems might address the technical needs for locating occupants, privacy concerns could preclude that choice. Some indoor localization techniques based on wireless technology would require the occupants to have body-worn devices to enable localization, a potentially intrusive requirement. It could be argued that the most compelling scenario is emergency response when public safety agencies need to know the locations of occupants moving throughout the building. Additionally, knowing the number and location of occupants throughout the building

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informs a more sophisticated heating and cooling strategy than current practices. This strategy, known as occupancy-based control, could offer an 18% savings over the present heating and cooling consumption according to a study funded by the U. S. Department of Energy [1]. The value of footstep localization for informing facility security was established for outdoor settings in [2,3], and holds a transformative value for the indoor setting too.

Locating the origin of footstep-generated structural waves is an instance of the broader problem of wave source localization and, more specifically, locating an impact source in a structure. Fundamental principles, from which many modern techniques are derived, estimate location from sensor measurements that have some known relation to wave properties. The measurements could be of the wave's angle-of-arrival (AOA), time-of-arrival (TOA), time-difference-of-arrival (TDOA), Doppler shift frequency-difference-of-arrival (FDOA), or received signal strength (RSS). Not all of these techniques are suitable for footstep localization from accelerometer measurements in buildings. AOA requires either a sensor that is sensitive to the bearing of the incoming wave or, in the case of beamforming (i.e., array) approaches, typically relies on a far field model so that the incoming wave can be approximated as a plane wave for the determination of suitable array weights. Neither of these characteristics holds for footsteps measured throughout a building by conventional accelerometers. FDOA is useful when a source continuously emits signals while in motion, but a person's footsteps generates building vibrations at the instant of each footfall. In the case of RSS it is well known—and in fact illustrated later in this paper—that seismic waves undergo superlinear power decay (e.g., exponential) as range increases between source and sensor assuming a fixed sensor surface area (aperture). Consequently, for a measurement error of $\mathcal{E}$ the implication is that the per sensor range error will have superlinear relation to $\mathcal{E}$. By contrast, TOA/TDOA approaches have range errors linearly proportional arrival time estimation error, thus favoring their adoption here.

In TOA-based localization with arrival time measurements, prior knowledge of the propagation speed and prior knowledge of wave origin time, one calculates the range from each sensor to the origin. Then, under ideal circumstances, the location estimate has the following geometrical interpretation. Placing a circle centered at each sensor with a radius corresponding to the sensor's computed range to wave source should produce an intersection of the circles at the wave origin. In practice, however, it is uncommon to know the originating time *a priori*. Instead, in the more common approach of TDOA, one sensor's reported arrival time serves as a reference from which the time differences of arrivals at other sensors forms the TDOA measurement set. These time differences correspond to range differences and form the basis of the *multilateration* relation that estimates location as the intersection of hyperbolic curves. The interested reader can refer to [4] for a comprehensive review of fundamental and modern algorithms on location estimation. Much of the early work applying these principles (e.g., [5–7]) presumed wave propagation in idealized environments. By contrast, waves in building structures can experience distortion due wave reflection, refraction or dispersion. As a consequence, attempts to apply existing localization techniques [5–7] within a building's structure will suffer significant errors, because these techniques do not account for wave distortion.

1.2. Prior work

1.2.1. Impact localization in structures

For the purpose of locating an impact point on a single plate, De Marchi et al. [8] crafted a dispersion compensation technique, the warped frequency transform, and then applied TDOA to the compensated measurements. To estimate impact locations in a plate with holes, Hensman et al. [9] applied a machine learning-inspired regression technique based on Gaussian process models; as with other types of supervised machine learning training was required. On a similar type of structure, Al-Jumaili et al. [10] extended the *Delta T* technique to generate a mapping from a coordinate grid superimposed on the structure to an expected time-of-flight delay (i.e., the “Delta T” values); here too some training was required. For active interrogation of a more complex structure by ultrasonic guided waves Haynes and Todd [11] proposed delay-and-sum beamforming. McLaskey et al. [12] also pursued beamforming-based localization in large concrete structures. For the task of footstep localization, however, drawbacks to the cited literature include reliance on prior information given or gained from training or requirements for a specific sensor geometry. Nonetheless, the literature does demonstrate the potential effectiveness of localization schemes based on TOA or TDOA measurements.

1.2.2. Machine learning and system identification methods

Many recent papers incorporate machine learning methods to advance the state-of-the-art for a variety of problems, and these papers might prompt one to ask if machine learning should be applied to the problem considered in this paper. Machine learning has a vast, burgeoning literature as evident from a lengthy review paper by Worden et al. [13] and a number of textbooks [14–21]; thus, it is not trivial to select a method well-suited to a new problem. Furthermore, it is instructive to observe that some of the impressive machine learning results reported elsewhere, particularly in computer vision [22], were greatly facilitated by an extremely large and comprehensive training corpus. For example, the ImageNet test corpus holds over 1 million images encompassing over 1000 categories [23]. Generating a large set of training and test data for footstep localization poses a logistical burden not encountered by computer vision researchers retrieving images from the Internet. Just as importantly, it is prudent to note that frequently the adoption of machine learning methods was motivated when a problem resisted solution by other, simpler methods. Indoor footstep localization is a nascent field with a small body of literature (reviewed in Section 1.2.3). For these reasons it is premature to incorporate machine learning techniques into the footstep localization process.