Advanced Engineering Informatics 30 (2016) 660–671

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei

A people-centric sensing approach to detecting sidewalk defects

Hyunsoo Kim, Changbum R. Ahn *, Kanghyeok Yang

Construction Engineering and Management, Charles Durham School of Architectural Engineering and Construction, University of Nebraska–Lincoln, W113 Nebraska Hall, Lincoln, NE 68588, United States

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 12 August 2016
Accepted 2 September 2016

Keywords:
Sidewalk defects
People-centric sensing
Wearable sensing
Infrastructure management

ABSTRACT

A defective sidewalk inhibits the walkability of a street and may also cause safety accidents (slips, trips, and falls) for pedestrians. When a pedestrian walks along a sidewalk, his/her behaviors may vary according to the condition of the sidewalk—e.g., whether the surface is normal, holed, cracked, tilted, or sloped. As a result, the pedestrian's stability may also change according to the built environment's conditions. Accordingly, this paper examines the feasibility of using pedestrians' physical behaviors to detect defects in a sidewalk. Pedestrians' physical responses and paths over a sidewalk are collected using an inertial measurement unit (IMU) sensor and a global positioning system (GPS). Then, after aggregating the pedestrians' bodily responses and locations, the irregularity of multiple pedestrians' responses are calculated in relation to their locations. The locations that show irregularities in the pedestrian-response patterns present a high correlation with the existence of a defect. The results of this study will help improve the continuous diagnosis of defects in sidewalks, thereby enhancing these built environment systems' serviceability.

1. Introduction

Built environments, including civil infrastructure and buildings, are designed to provide specific services to users [1]. Maintaining a sufficient service level for users is thus critical for achieving each built environment's designed objectives [2–4]. Of the numerous types of built environments, the sidewalk is one of the most influential infrastructures for humans since it is an integral part of sustainable transportation, and supports pedestrian travel as well as healthy physical activity [5]. What is more, the quality of sidewalks is a significant indicator of the perceived safety and quality of the pedestrian environment [6].

Correspondingly, injuries from defective sidewalks have become a crucial problem. In the city of New York, more than thirty million dollars per year was paid out for settlements and judgments resulting from defective sidewalks from 2008 to 2012. During this period, the cost per defective sidewalk claim was over fifteen thousand dollars. Besides the cost of settling these claims, the detection of defective sidewalk is important for enhancing the safety of pedestrians, including disabled and elderly persons. According to the Americans with Disabilities Act of 1990 (ADA), pedestrian infrastructure is legally considered part of the "public right of way," and governmental agencies can be liable for injuries resulting from inadequate maintenance of infrastructure, including sidewalks. For these reasons, addressing the problems caused by defects in sidewalks is valuable not only for pedestrians, who deserve access to safe sidewalks, but also for those who are legally responsible for defects, such as governments or owners. Governmental agencies in the United States have thus taken various approaches to addressing such issues, including performing periodic inspections using experts [7,10] and transferring liability of sidewalk maintenance from the city to property owners. Nonetheless, claims related to defective sidewalks continue to grow in terms of both frequency and payout amounts [8,9]. Thus there is a clear need for identifying and locating sidewalk defects in a continuous and automated fashion.

To this end, this paper investigates the feasibility of harnessing pedestrians' bodily responses to their environment as a means of detecting defects in a sidewalk. According to several studies [10–13], humans physically respond to the changes in their physical environment. For example, when a pedestrian walks along a sidewalk that includes a defect, his balance or gait stability changes at the moment of stepping on or over the defect. Therefore, human responses to the surrounding environment may offer information that lets us estimate the condition of the environment. To examine the feasibility of such a people-centric sensing approach, we collected data from inertial measurement unit (IMU) sensors to measure pedestrians' bodily responses and data from global

* Corresponding author.
E-mail addresses: hkim13@unl.edu (H. Kim), cahn2@unl.edu (C.R. Ahn), kyang12@huskers.unl.edu (K. Yang).

http://dx.doi.org/10.1016/j.aei.2016.09.001
1474-0346/

positioning systems (GPS) to locate pedestrians; these data are used to analyze pedestrians' bodily responses to their location.

The paper is organized as follows: first, we review current practices and related techniques. Next, we introduce challenges in detecting sidewalk defects using pedestrians' bodily responses, and then propose a hypothesis for the relationship between pedestrians' bodily responses and defect existence. To examine the suggested hypothesis, an outdoor experiment is performed on an actual sidewalk. The discovered relationship between the pedestrians' bodily responses and the defect's existence is expected to provide a basis for developing a proactive monitoring system that empowers the stakeholders who are responsible for injuries caused by defective sidewalks to be able to continuously monitor and maintain the quality and the function of their sidewalks.

2. Background

2.1. Current efforts for defective sidewalk detection

Although there are many people who use vehicles as a transportation method, walking is still the best method of moving short distances, making sidewalks an integral component of human movement. According to [14], there are several objectives for sidewalks, including linking buildings, setting up facilities, and providing an emergency escape route. To fulfill these objectives, sidewalk defects should be well managed. A management process for sidewalks includes several steps, among which the detection of defects is the first step. A common practice for detecting a sidewalk defect is a user survey that focuses on a user's evaluation/satisfaction with a particular facility [15]. A user reports detected defects to a governmental agency, and then the agency checks the status of the defect and manages it. However, outcomes of surveys and reports are often affected by respondents' temporary emotions, recent experiences, and familiarity with the facility. Surveys are also not efficient in terms of time and cost, nor are they very effective in providing detailed analysis of defect existence, which ultimately causes a decrease in sidewalk quality [16].

Consequently, many governmental agencies rely on visual inspections to identify violations of pre-defined regulations that may degrade the quality of a sidewalk (see Table 1). Visual inspections are quite labor-intensive and often inaccurate due to the limited set of pre-defined defects [17]. In addition, the governmental regulations that provide guidelines on defects are often very outdated; for example, the regulations on defective sidewalk elements used in several states in the US (e.g., Iowa, Nebraska, and California) originated from engineering studies conducted before 1902 [18] and do not take the dynamic nature of human-physical system interactions into consideration. Even for the same defect, the impacts of a defect are greatly affected by users' individual characteristics (e.g., users' physiological conditions) and usage patterns (e.g., user traffic). For example, regulations for pedestrian sidewalks in Iowa define a sloped sidewalk of more than 2″ in an 8–10′ length as a defective sidewalk, but the risk level of the sidewalk slope will vary by users' physiological conditions (e.g., agile or disabled), user traffic, and weather (e.g., snowy, icy, etc.). Furthermore, the defective sidewalk standard for each state is different. Although this difference parallels the different conditions of each state, the variability highlights the fact that there is no universal regulation for defects in sidewalks. Therefore, inspections based on current, predefined defective sidewalk regulations may not be sufficient to guarantee the quality of a sidewalk.

2.2. People centric sensing

Considering the fact that sidewalks are meant for pedestrian use, the involvement of actual users is very important when evaluating the quality, function, and defects of sidewalks. Recent efforts have sought to transform human users into sensors—a concept called "people-centric sensing." This approach mainly focuses on collecting targeted information about users' daily patterns and interactions [24,25]. Although the sensory coverage of spaces [21], events [19], health [22,23], and social interactions [24–26] is beneficial for people or citizens [20], people-centric sensing is an immature research area for detecting built environment system defects because most current people-centric sensory research has focused on humans or the interaction between humans, not on the interaction between users' responses and external systems. One representative method that estimates external system conditions using user responses is pothole detection on a motor vehicle road. This method detects potholes using a vehicle response, such as the abnormal vibrations observed when driving over a pothole [27]. Additionally, there are other, similar studies utilizing bicycles [28] and wheelchairs [29,30]. Although these prior works provide evidence of the viability of detecting unstable conditions [27,31–33] from wheel-based equipment, to the best of the authors' knowledge, no one has attempted to detect sidewalk defects through pedestrian responses. Furthermore, while the approach of mounting an IMU on wheeled equipment would provide more reliable measurements for the levelness and evenness of sidewalk surfaces, it may not directly represent the effect of sidewalk defects on pedestrians' walking patterns. Human behaviors are more complicated than mechanical equipment usage, and are thereby difficult to measure due to variability. Therefore, humans' response variability should be considered before adopting a people-centric sensing technique, and thus we chose to focus on pedestrian behavior in this study.

Table 1
Defective-sidewalk regulations.

Description of Defective-Sidewalk Standard	IA (Dubuque)	NE (Omaha)	CA (San Francisco)
Vertical or horizontal separations equal to or greater than a *specific range*	3/4″	1″	1/2″
Holes or depressions equal to or greater than a *specific range*	3/4″	3/8″	1/2″
Spalling over fifty (50%) percent of a single square with a depression equal to or greater than a *specific range*	3/4″	3/8″	1/2″
A single square cracked into more than three (3) pieces OR sections distorted equal to or greater than *specific range*	3/4″	1/2″	1/2″
Sidewalk is raised (or depressed) more than a *specific range* from the normal grade of the sidewalk	2″ in an 8–10′ length	2″ in an 8′ length	1/2″ per foot of transition
Water stop box is raised or lowered equal to or greater than a *specific range* and/or lid is cracked or missing	3/4″	None[a]	None[a]

[a] No specific regulation.