Advanced Engineering Informatics 32 (2017) 126–138

Contents lists available at ScienceDirect

Advanced Engineering Informatics

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

Self-corrective knowledge-based hybrid tracking system using BIM and multimodal sensors

JeeWoong Park [a], Jingdao Chen [b], Yong K. Cho [a,*]

[a] School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA 30332-0355, United States
[b] School of Electrical and Computer Engineering, Robotics Institute, Georgia Institute of Technology, 777 Atlantic Dr. N.W., Atlanta, GA 30332-0355, United States

ARTICLE INFO

Article history:
Received 21 August 2016
Received in revised form 31 January 2017
Accepted 1 February 2017

Keywords:
Bluetooth Low Energy (BLE)
Building Information Model (BIM)
Inertial Measurement Units (IMU)
Location tracking
Mobile sensing
Data fusion

ABSTRACT

Researchers have recently devoted considerable attention to acquiring location awareness of assets. They have explored various technologies, such as video cameras, radio signal strength indicator-based sensors, and motion sensors, in the development of tracking systems. However, each system presents unique drawbacks especially when applied in complex indoor construction environments; this paper classifies them into two categories: absolute tracking and relative tracking. By understanding the nature of problems in each tracking category, this research develops a novel tracking methodology that uses knowledge of the strengths and weaknesses of various components used in the proposed tracking system. This paper presents the development of a hybrid-tracking system that integrates Bluetooth Low Energy (BLE) technology, motion sensors, and Building Information Model (BIM). The hypothesis tested through this integration was whether such knowledge-based integration could provide a method that can correct errors found in each of the used sensing technologies and thereby improve the reliability of the tracking system. Field experimental trials were conducted in a full-scale indoor construction site to assess the performance of individual components and the integrated system. The results indicated that the addition of map knowledge from a BIM model showed the capability of correcting improbable movements. Furthermore, the knowledge-based decision making process demonstrated its capability to make positive interaction by reducing the positioning errors by 42% on average. In sum, the proposed hybrid-tracking system presented a novel method to compensate for the weakness of each system component and thus achieve a more accurate and precise tracking in dynamic and complex indoor construction sites.

1. Introduction

The use of tracking technology to detect the movement of personnel, materials and equipment is vital in any construction operation. Effective implementation of tracking algorithms for resources such as labor [1,2] and materials [3] can lead to better decision-making for construction management applications [4]. These applications include context-aware information delivery [5], progress monitoring [6], proximity visualization [7], and productivity analysis [8]. According to the Health and Safety Executive [9], approximately 35% of accidents are directly/indirectly related to moving workers; 23% of accidents involving *moving workers* are caused by slips, trips, and falls, and 11% of worker accidents are struck-by accidents. In response to this, researchers have developed real-time tracking systems to monitor the indoor construction site safety condition with respect to identified potential safety hazards [10]. Furthermore, these tracking technologies are able to assist in collision avoidance [11], near-miss accident identification [2], proactive hazard signaling [12], and even building fire emergency response [13].

The nature of construction sites is, however, often complex and dynamic resulting from high volume of movement of both workers and materials as well as variability in building type, business type, and geographical location [14]. This can lead to many complications for tracking technology from both a hardware perspective and an algorithms perspective. From a hardware perspective, sensor setups used for tracking face several limitations in terms of range [15], measurement accuracy [16], signal strength fluctuation [17], interference [14], and cost [3] that prohibit their system deployment in actual construction environments, which are rapidly evolving. From an algorithms perspective, the tracking technique may need to combine data from multiple sensors [18], perform filtering on noisy data [19] and also take into account changes in the environment [20]. Moreover, certain tracking

* Corresponding author.
E-mail addresses: jpark463@gatech.edu (J. Park), jchen490@gatech.edu (J. Chen), yong.cho@ce.gatech.edu (Y.K. Cho).

http://dx.doi.org/10.1016/j.aei.2017.02.001
1474-0346/

techniques require a time-consuming offline phase for performing the initial system setup and require static environments for reliable tracking, such as the fingerprinting method [21–23].

To overcome these sensor limitations, recent research has explored hybrid-tracking solutions that combine multiple sources of positioning information under an integrated framework. These recent research studies have attempted to use multimodal sensors, that is, sensors that measure different physical quantities, in order to achieve a more accurate tracking solution. Despite these efforts, very few researchers has studied methods that explicitly use prior knowledge of sensor behavior in such integrated tracking systems. Identified behaviors of sensors form knowledge that can potentially correct errors in individual sensors when they are properly combined. To address this need for a more knowledge-intensive tracking system, this study develops a hybrid-tracking method incorporating Building Information Model (BIM) data, Bluetooth Low Energy (BLE) beacon signals and motion sensor measurements. This study takes advantage of knowledge of the nature of each source of tracking information: (1) BLE beacons provide absolute position information but are affected by high levels of noise, (2) motion sensors provide relative position information but are vulnerable to drift, and (3) building geometric information forms a new type of knowledge that can improve the tracking accuracy. This knowledge is utilized when integrating the different sources of tracking information under a probabilistic framework. The major hypothesis of this research is to test, by using knowledge-based error correction mechanisms, whether the integrated approach can correct errors developed in each of the sensors and thereby increase the overall reliability of the tracking system. The remainder of this paper will present, in order, the literature review, objective and scope, system design, case study and conclusion of the study.

2. Literature review

This section reviews the existing literature for the characteristics of different sensing technologies to build a knowledge base of the strengths and limitations of each type of sensor in terms of range, accuracy and reliability. The knowledge gained from prior work is critical to gaining an understanding the nature of each sensor component. In addition, the constructed knowledge base will be used as a source of information for designing error-correction heuristics in the integrated tracking framework.

2.1. Sensing technologies for positioning

In the field of non-RSSI based tracking technologies, researchers have explored video sensing by applying numerous computer vision algorithms such as cascade of Haar features, mean shift, and the Lucas-Kanade methods that perform personnel tracking and equipment tracking [1,8,24]. Video sensing is, however, vulnerable to occlusions when multiple objects need to be tracked and when objects move in and out of video fields of view [8]. Inertial Measurement Units (IMU) are also a popular research domain for personnel localization through handheld or waist-worn devices [25,26]. However, IMUs struggle with a problem of error accumulation that leads to significant drift over time [26]. Furthermore, in indoor environments, magnetic interference can also negatively affect the heading direction inference [25].

An example of RSSI-based tracking technology is RFID, which has been studied in material and tool tracking for improving productivity and control processes in indoor construction sites [27,28]. However, RFID technology faces issues such as metal shielding, chip sensitivity and limited read range that lower accuracy and reliability for tracking applications [15,29]. Although RFID is an effective inventory tracking tool on construction jobsites [27], it does not meet the requirements for accurate, real-time tracking of dynamic entities in complex environments [30]. UWB is used for material tracking and activity-based progress tracking with advantages in power consumption, read range, and ability to work both indoors and outdoors [20]. It is, however, known to have issues with multipath interference, material-dependent propagation, line-of-sight sensitivity, and difficulty in system deployment in changing environments [12,14,20,31].

A recent study used WLAN-based systems for performing labor tracking at a shield tunnel construction site by using a machine-learning technique called Fingerprinting [32]. It estimates positions using a pre-built map of approximate signal strength from each WLAN access point (AP) [21,32]. However, a major disadvantage of the fingerprinting technique is a lengthy offline phase where a site survey is carried out for hours or even days to build an RSSI fingerprints map [19,21]. Moreover, the fingerprint database represents the state of the site at the time of the database establishment, so this method may not operate properly in a changing environment, which is typical in a construction site.

BLE is a relatively new technology that was first released in 2010 and offers many advantages over traditional Bluetooth technology such as reduced power consumption, longer range, small form-factor, and lower latency [33–35]. BLE technology has the potential to overcome the previously highlighted problems in existing sensors for positioning. In comparison studies, BLE technology in the form of BLE beacons has been found to be more energy efficient and more flexible in terms of infrastructure deployment compared to the competing technologies [17,36]. As such, BLE technology can easily be integrated into hybrid-tracking frameworks alongside other sources of positioning information [37,38]. Similar to other wireless technologies, BLE is susceptible to fast fading and large Received Signal Strength fluctuations [17], but the lower cost and easier installation of BLE beacons allows the deployment of the system in larger numbers compared to UWB and WLAN. BLE technology has been researched in the construction domain in applications such as proximity sensing [36], but the full potential of the BLE technology in positioning has not yet been realized [32,33].

2.2. Integrated systems utilizing multiple system components

Recent research in tracking has also focused on integrated systems using multiple sensor technologies. Such hybrid systems can account for discrepancies in individual sensor readings through joint estimation methods; thus reducing tracking errors. For example, Li et al. [13] proposed a BIM-integrated localization system with Radio Frequency (RF) beacons. BIM information provided geometric context of the sensing area to minimize deployment effort and maximize localization accuracy for emergency response operations. Taneja et al. [39] developed algorithms to generate navigation models from industry foundation classes (IFC)-based BIM, and Taneja et al. [40] independently used an IMU sensor for relative tracking and Ekahau Wi-Fi sensors for absolute tracking, and combined each sensor with a map matching model to evaluate the performance of each system. Although they achieved forward advancement with this integration, their test results still present challenges such as a trap and drift from the IMU sensor and unreliable performance from the Wi-Fi sensor. Another recent study [41] used IMU with visual makers to improve the quality of indoor navigation. However, the placement of markers is a complicated task to perform in a busy, complex on-going construction site. Algorithmic studies [30,42] have also been conducted by exploring a combination of support vector regression/fingerprinting and Kalman filtering to achieve improved tracking. However, these systems may face practical issues in evolving construction sites.