Advanced Engineering Informatics 25 (2011) 535–546

Contents lists available at ScienceDirect

Advanced Engineering Informatics

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

Performance-based evaluation of RFID-based indoor location sensing solutions for the built environment

Nan Li, Burcin Becerik-Gerber *

Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, United States

ARTICLE INFO

Article history:
Received 19 July 2010
Received in revised form 15 February 2011
Accepted 18 February 2011
Available online 23 March 2011

Keywords:
Indoor
Location sensing
RFID
Built environment
Accuracy
Affordability

ABSTRACT

Indoor location information is of great value to the building industry in improving the utilization and maintenance of facilities. The paper identifies previous academic accomplishments of radio frequency identification (RFID)-based indoor location sensing (ILS) solutions. The paper summarizes the major location sensing methods used in previous RFID-based solutions, and provides a review of 21 research projects, with their algorithm design, devices, test setup, and performance evaluation presented in detail. Based on this review, the paper summarizes the intensive use of the proximity method in RFID-based ILS, and analyzes the underlying rationale. The findings point out that no single solution satisfies all criteria for widespread implementations, and that the adaptability of these solutions to built environments need to be further justified. Finally, the paper outlines the gaps for future research, including modifying ILS solution design, developing a seamless outdoor/indoor location sensing solution, and building a context-aware information delivery mechanism for the building industry.

1. Introduction

Location information is crucial to a variety of standard and personalized applications in a wide range of industries such as transportation, manufacturing, logistics, and healthcare, and it is the basis for delivery of personalized and location-based services [1]. Examples include applications that show drivers their vicinity and guide them to their destinations [2], applications that enable the user to search for published services within his/her immediate vicinity [3], and applications that monitor the user's indoor location, and adjust the music played in rooms based on user preferences [4].

While global positioning system (GPS) technology has well met the need for outdoor location sensing (OLS), so far no single solution to the indoor location sensing (ILS) problem has been universally adopted. Various technologies have been proposed and tested for ILS, among which are indoor GPS, motion and rotation sensors, infrared, ultrasound, ultra wide band (UWB), wireless local area network (WLAN), and radio frequency identification (RFID).

Indoor location information is also of great value to the building industry, and has potential to improve the utilization and maintenance of facilities. For example, occupants unfamiliar with a built environment, ranging in scale from a building to a neighborhood to large-scale civic surroundings, could be provided with location information to navigate around and find their destinations; facility management (FM) personnel could be provided with locations of building components or equipment they need to maintain or repair; locations of tools and on-site FM personnel and the length of time they spend at each location could be analyzed to monitor the work procedures and improve productivity; changes in building occupancy could be detected in real time through location sensing, and energy conservation measures, such as adjustment of lighting and air conditioning, could be automated. Moreover, ILS also lays the basis for context awareness within the built environment, which relies on automatic recognition of both the user's location and activity [5]. Context-aware information can automate the delivery of spatial information to on-site mobile personnel, with which targets, including building components, equipment, tools and people, can be easily located and target-specific information can be accessed on-site.

This study focuses on ILS solutions that are built on RFID technology. Prior research has proven RFID technology's capability of providing accurate and cost efficient indoor location information. Moreover, RFID technology is applicable to the built environment because of its non-line-of-sight characteristic, wireless communication and on-board data storage capacities, and its wide use in the building industry [6–8]. However, the focus building industry researchers currently place on the development of an applicable RFID-based ILS solution could be further strengthened. The reasons are the research efforts in this area have been mostly concentrated in electrical engineering (EE) and computer science (CS) fields, with a focus on solutions' technical improvement. However, the

* Corresponding author.
E-mail address: becerik@usc.edu (B. Becerik-Gerber).

1474-0346/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.aei.2011.02.004

collaboration of multiple disciplines including civil engineering (CE) is required to identify RFID-based ILS solutions' value in practice, increase their adaptability to the built environment, and develop extended applications built on the ILS solutions. Besides, future research directions are needed and they may drive technical and methodological development to support a wider and more sophisticated adoption by the building industry.

In order to address these challenges and provide a comprehensive review of research in this area, 21 RFID-based ILS solutions are included in this paper. Algorithm design, devices, test setup, and performance evaluation of these solutions are described in detail. In addition, the potential value of these solutions and of services built using them are analyzed, and future research directions are presented.

2. Overview of RFID technology

A typical RFID system consists of two components, a reader and a tag, and operates at a certain frequency, as shown in Fig. 1. A tag contains a microchip and an internal antenna. Attached to an object, a tag stores a specific ID and other object-related data, and sends the data to a reader upon its request. Tags can be distinguished as passive or active, according to their power source. Passive tags need to be activated by the electromagnetic energy the reader emits and depend on that for power to operate. Therefore, they have shorter read ranges and smaller data storage capacities. Active tags rely on internal batteries for power supply, which enhances the read ranges significantly and enables additional onboard memory and local sensing and processing capacities. However, using a local power source also limits active tags' lifetime to 5–10 years [9] and increases the cost. To bridge the gap between passive and active tags, a third type of tag, battery-assisted passive (BAP) tags or semi-passive tags, has been introduced; these tags use internal batteries to power the chips, but they are only activated when in the reader's read range.

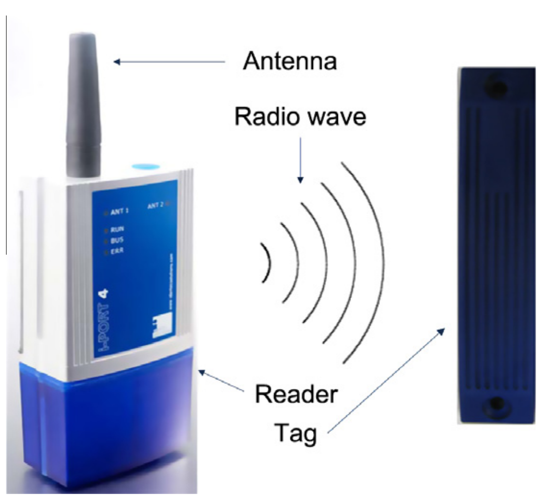

Fig. 1. RFID system components.

An RFID reader, composed of a transceiver and an antenna, reads data from and writes data to tags, and transfers the collected data to a host computer for future retrieval and analysis. The antenna establishes the communication between the transponder and the transceiver, and its shape and dimensions determine the performance characteristics such as the frequency range [10]. Larger antenna loops tend to yield wider coverage areas, but the signal-to-noise ratio decreases at the same time; therefore a careful balance in reader design must be attained between the coverage area and reception reliability [11].

The frequency on which the RFID system operates is another important element, which determines the characteristics of the signals traveling between reader and tags. Available frequencies include low frequency (LF), high frequency (HF), and ultra-high frequency (UHF) [12]. Super-high frequency (SHF) or microwave is also used. Presently UHF is the most widely used, because UHF passive tags offer simple and inexpensive solutions, and most active tags operate on UHF. Characteristics of each frequency are summarized in Table 1.

Choices of tags, readers, and frequencies and their combinations offer users flexibility in building customized RFID systems to meet their requirements. Jaselskis and El-Misalami [14] provided detailed guidelines with 37 steps to help contractors and owners in the building industry determine the configuration of the RFID systems that best fit their applications.

As the RFID technology gains wider adoption and is used throughout the supply chain or across industries, the level of compatibility becomes an important issue, which has given birth to various worldwide technical standards. The International Organization for Standardization (ISO) has created standards for data structure (ISO 11784) and air protocol interface (ISO 11785) of tags used in tracking animals. It also has standardized the air interface protocol of tags used in proximity cards for access control and payment systems (ISO 14443) and in vicinity cards that can be read from a greater distance (ISO 15693). Also have been established are the standards for testing the conformance and performance of tags and readers (ISO 18047, ISO 18046). As the use of RFID technology for goods tracking becomes prevalent, ISO has also developed relevant standards to cover related air interface protocol (ISO 18000 series) [15].

Table 1
Characteristics of radio frequencies.

	LF	HF	UHF	Microwave
Frequency range	125–135 kHz	13.56 MHz	400–960 MHz	2.45–5.8 GHz
Read range	<0.5 m (passive)	<1.0 m (passive)	<10 m (passive), >10 m (semi-passive and active)	>100 m (active)
Standards	ISO 11784/5, 14223, 18000–2	ISO 14443, 15693, 18000–3	ISO 18000–6/7, EPCGen1 and 2	ISO 18000–4/5
Metal/fluid impact	Very low	Low	High	High
Data transfer rate	Low	Medium	High	High
Power and data transmission for passive tags	Inductive coupling[a]	Inductive coupling[b]	Propagation coupling	N/A
Typical industry	Farming, security, brewery	Pharmaceutical, health care	Manufacturing, logistics, construction	Army, shipping, airlines

[a] Tag draws power from the electromagnetic field that reader creates, and changes the electric load on the antenna, which influences the electromagnetic field and is sensed and analyzed by the reader.
[b] Tag uses electromagnetic power that reader emits, changes the load on the antenna, and reflects back an altered signal. Also called backscatter [13].