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Comparative assessment of an indoor localization framework for building emergency response

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ABSTRACT

Building emergencies, especially structure fires, are threats to the safety of both building occupants and first responders. It is difficult and dangerous for first responders to perform search and rescue in an unfamiliar environment, sometimes leading to secondary casualties. One way to reduce such hazards is to provide first responders with timely access to accurate location information. To address this challenge, the authors have developed a radio frequency based indoor localization framework, for which novel algorithms were designed for two different situations: one where an existing sensing infrastructure exists in buildings and one where an ad-hoc sensing infrastructure must be deployed. This paper presents a comparative assessment of this framework under different situations and emergency scenarios, and between simulations and field tests. The paper first presents an assessment of the framework in field tests, showing that it achieves room-level accuracies above 82.8% and 84.6% and coordinate-level accuracies above 2.29 m and 2.07 m, under the two situations, respectively. Moreover, the framework demonstrates considerable robustness in the tests, retaining a room-level accuracy of 70% or higher when the majority of sensing infrastructure is damaged. This paper then synthesizes results from both simulations and field tests, and demonstrates how the framework can be adapted to different situations and scenarios while consistently yielding satisfactory localization performance.
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1. Background

Building emergencies especially structure fires are big threats to the safety of building occupants and first responders. For example, public fire departments across the U.S. attended 487,500 fires in buildings in 2013, which caused 2755 deaths and 12,200 injuries [1]. When emergencies occur, unfamiliar environments are difficult and dangerous for first responders to search and rescue, sometimes leading to secondary casualties. Statistics show that 87% of fire-related firefighter fatalities and injuries occur in structure fires [2]. A total of 159 firefighters died between 2000 and 2011 in the U.S. when responding to structure fires, one major cause of which was firefighters getting lost [3,4]. One way to reduce such hazards is to provide firefighters with timely access to accurate location information. Their increased awareness of own locations within the spatial context would significantly reduce the possibility of getting lost in buildings as well as the associated fatalities and injuries.

It is also of critical importance for an incident commander to know the locations of first responders in real time, so that decision-making processes are made faster and more informed. When an emergency happens, first response teams are sent to carry out search and rescue operations. In most cases, searching for occupants is a manual process and requires a complete inspection of all indoor spaces. Such blind search process is highly inefficient and could be prohibited by fire, smoke or structural damages. Reducing the time spent on searching for occupants has great potential to reduce chances of fatalities and injuries of trapped occupants, and it can be achieved by making the locations of trapped occupants more transparent to first responders at emergency scenes.

Access to location information during emergency response operations is far from being automated and efficient. Currently, after a size-up of an emergency, which evaluates the severity of an incident and estimates required resources based on visual inspections from outside a building, first response teams are sent in to the building, usually in groups of four, to perform various tasks such as fire attack, ventilation, and search and rescue. The deployed first responders communicate over radios with an incident commander outside the building, who marks tasks and locations of the deployed teams in a command post and updates this information based on vocal reports received from the deployed teams. However, it is challenging to keep this information organized and updated, considering the ever-changing situations inside a building, especially when multiple teams use multiple radio channels to communicate. Access to real-time location information, if made

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possible, would enable an incident commander to better monitor and guide the deployed first responders. This would lead to reduction of their chances of getting lost or trapped, and improvement of their efficiency in performing assigned tasks. On the other hand, search for trapped occupants is usually done in two rounds. During a primary search, first responders traverse the building, determine a rough number and location of trapped building occupants and rescue them. During a secondary search, first responders make sure all spaces are thoroughly searched, and rescue occupants who are still trapped. Although radios (and in some cases thermal cameras) are used to help detect the occupants at emergency scenes, the search process is generally low-tech and blind. First responders usually have little clue of how many occupants are trapped, where they are, and how to reach them. There is a need for an indoor localization solution that enables first responders to obtain real-time location estimations of both themselves and trapped occupants during emergencies, so that they can prioritize spaces that are more likely to have occupants when planning the search and rescue routes, and increase their own safety during emergency response operations.

2. A radio frequency based indoor localization framework

2.1. Need analysis

Given the significance of indoor location information at building emergency scenes, the authors have carried out the following research efforts that have led to the development of a novel indoor localization framework using radio frequency (RF) technologies.

First, the authors examined the relative importance of indoor location information among a list of nineteen information items that may be useful during building emergencies [5]. Interactive interviews were designed and conducted with first responders from the Los Angeles Fire Department (LAFD). During the interactive interviews, imaginary building emergencies were presented to the interviewees who were asked to command an emergency operation with the help of the provided information items. Based on the interview results, for each information item, its importance was examined from three perspectives including the order that it was requested during the interviews, the frequency that it was updated, and its overall value ranked by the interviewees. The importance of each information item was assessed in a quantitative manner, and it was found that indoor location information was one of the most important information items in all stages of building emergency response operations.

A survey was also carried out among first responders across the U.S. to examine the requirements for indoor localization at building emergency scenes [5]. The survey was motivated by the fact that, with the rapid adoption of various sensing tools, such as remote sensing [6–8], geographic information systems (GIS) [9–11], thermal imaging cameras [12], and mobile computing and communication devices [13,14], that are used in the emergency response practices, there is a need for an effective tool that can aid the search for victims and tracking of deployed first responders. Most existing indoor localization solutions for building emergency response operations, either proposed in the academia [15–23] or are available in the market [24,25], were developed in the absence of clear knowledge about the needs of first responders if an indoor localization solution existed. This problem is even more obvious with indoor localization solutions developed for general purposes using various technologies such as inertial navigation systems (INS) [26–28], assisted GPS (AGPS) [29–31], and infrared [32–34], as well as a couple of RF technologies including ultra wide band (UWB) [35–37], radio frequency identification (RFID) [38–41], wireless local area network (WLAN) [42–45], and wireless sensor networks (WSN) [46–48]. For example, most existing solutions predominantly emphasized their high accuracies; however, none of them argued what level of accuracy is sufficient to support emergency response operations while not becoming over demanding in terms of supporting infrastructure or prior data input, or to what extent an accuracy should be retained when a solution is challenged by hazards such as fire and structural collapses. In this survey, the respondents were asked to select the top five important requirements from a list of eleven requirements. Based on the survey results, the following requirements were identified as critical when designing or evaluating indoor localization solutions for building emergency response operations: accuracy (focus on room-level), ease of on-scene deployment (up to 2.25 min for ad-hoc network setup), robustness (against physical damages), computational speed (approximately 40 s for location computation), and finally size and weight of devices (up to 107 cm^3 and 1.15 kg).

2.2. Methodology

Based on the above requirements, the authors designed two localization algorithms, named the EASBL (Environment-Aware radio frequency beacon deployment algorithm for Sequence Based Localization) and the IMLE (Iterative Maximum Likelihood Estimation). Built on a sequence based localization schema [49], the EASBL was designed for situations, where ad-hoc sensor networks are needed at emergency scenes in the absence of existing sensing infrastructure. The algorithm has a dual-objective function that balances between localization accuracy and the deployment effort of ad-hoc networks. The likelihood of correct room-level location estimation is measured by location space quality, a metric that can be calculated based on geometries of the space and the deployment plan of devices. The deployment effort is measured by the number of devices to deploy, and the accessibility of locations to deploy the devices. The EASBL uses a Tabu search metaheuristic to improve the efficiency of searching for optimal plans for space division and device placement. The algorithm design and details as well as the mathematical formulation can be found in [50].

The IMLE was designed for situations, where existing sensing infrastructure can be accessed to collect RF data needed for location computation. Existing sensing infrastructure can be a network of any type of RF transmitters and transceivers installed in buildings for certain purposes, such as communications and security. This network of RF devices can be used for localization purposes during emergencies, provided that the information of its configuration, particularly the layout and specifications of the devices, is known. The IMLE integrates a maximum likelihood estimation (MLE) method for estimating the parameter values of a RF signal propagation model. Such ad-hoc estimation reflects the impacts of environmental factors on RF signal propagation. The model is then used to infer target locations from collected RF signals, which also adopts the MLE method. In addition, the IMLE introduces a novel iterative computational process, which integrates the spatial layouts and searches for room-level estimations that can lead to convergence after certain iterations or, if no converged estimations exist, estimations that are most likely to converge. This iterative process offsets the impact of wall-related RF signal attenuations on the localization accuracy. The details of the IMLE algorithm can be found in [51]. Both algorithms were evaluated extensively however, only under simulated building emergency scenarios, and reported promising results that demonstrated the potential of the algorithms in satisfying the aforementioned five requirements. It needs to be emphasized that both algorithms closely integrate building information modeling (BIM) as a source of indoor geometric information used in location computation, and a platform for user interaction and visualization of localization results.

As a continuous research effort, this paper further assesses the localization framework with two algorithms, in hopes of achieving the following objectives:

(1) Assess the performance of these two algorithms in field tests. Simulation based evaluation is advantageous in that the tests are easily repeatable, and that evaluations are carried out in a controlled environment so that the impact of a particular factor can be isolated and analyzed. However, simulation based

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