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Exploring approaches to improve the performance of autonomous monitoring with imperfect data in location-aware wireless sensor networks

Xiaowei Luo [a], William J. O'Brien [b,*], Fernanda Leite [b], James A. Goulet [c]

[a] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong
[b] Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1752, Austin, TX 78712, United States
[c] Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA 94720, United States

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ABSTRACT

In recent years, information and sensing technologies have been applied to the construction industry to collect and provide rich information to facilitate decision making processes. One of the applications is using location data to support autonomous crane safety monitoring (e.g., collision avoidance and dangerous areas control). Several location-aware wireless technologies such as GPS (Global Positioning System), RFID (Radio-frequency identification), and Ultra-Wide Band sensors, have been proposed to provide location information for autonomous safety monitoring. However, previous studies indicated that imperfections (errors, uncertainty, and inconsistency) exist in the data collected from those sensors and the data imperfections have great impacts on autonomous safety monitoring system performance. This paper explores five computationally light-weight approaches to deal with the data imperfections, aiming to improve the system performance. The authors built a scaled autonomous crane safety monitoring testbed with a mounted localization system to collect location data and developed five representative test cases based on a live construction jobsite. Seven hundred and sixty location readings were collected at thirty-eight test points from the sensors. Those location data was fed into the reasoning mechanisms with five approaches to generate the safety decisions at those thirty-eight test points and evaluate system performance in terms of precision, recall and accuracy. The results indicate that system performance can be improved if at least ten position readings from sensors can be collected at small intervals at any location along the moving path. However, by including additional data such as velocity and acceleration that may be read from devices mounted on workers, localization error may be significantly reduced. These findings represent a path forward to improve localization accuracy by mixing imperfect data from the sensed environment with supplemental input.

1. Introduction

This paper reports the results of using five computationally lightweight approaches to improve system performance with imperfect data from location-aware sensors. The analysis indicates that promising results can be obtained using simple approaches, suggesting that viable systems may be developed to remedy common imperfections in data monitoring and support robust applications. The approaches detailed in this paper build from the literature detailing the inaccuracy of sensed data; however, they do not require prior calibration of the sensor network to support flexible deployment.

The motivating context for this research is autonomous job-site safety monitoring – crane safety, in particular. Cranes can perform a great variety of tasks on construction jobsites to increase efficiency and productivity of the construction sites. However, a crane can be very dangerous piece of equipment. CPWR [25] has examined crane-related deaths in construction from 1992 to 2006 and identified there were total 632 crane-related deaths, an average of 42 deaths per year. The study also showed that cranes not only pose risks to construction workers but also to the public since there were approximately 7% of the total crane-related deaths were innocent bystanders. CPWR's findings do not only show the magnitude of the problem but also analyze the possible explanations for the causes of crane-related deaths and injuries,

* Corresponding author.
E-mail addresses: xiaowluo@cityu.edu.hk (X. Luo), wjob@mail.utexas.edu (W.J. O'Brien), Fernanda.Leite@austin.utexas.edu (F. Leite), james_goulet@berkeley.edu (J.A. Goulet).

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for example lack of safety training, inspections, safety plans and traffic control. In addition, OSHA's study identified boom/crane contact with the energized power line (nearly 45% of crane-related accident) and dropped crane loads as some of the major causes of crane accidents [17]. Although there are a large number of safety procedures designed and safety management systems developed for reducing crane-related accidents, the number of injured rate remains high, which further clearly indicated that the existing safety procedures and safety management systems are not effective enough in preventing accidents. Recent advances in sensing and computing technologies offer a potential solution to automate the crane safety monitoring process. Our research envisions an autonomous crane safety monitoring system, which utilizes location data and other information from various sources (e.g., location-aware wireless sensors, accelerometers, building information models). According to CPWR's studies, there were four main types of cranes associated with crane-related fatalities, mobile or truck crane, overhead or gantry crane, tower crane and floating or barge crane, our research will focus on developing tower crane safety monitoring system. The research is divided into three phases: (1) knowledge elicitation, which is a process of extracting safety knowledge and information requirements to serve as a foundation for autonomous safety monitoring system development; (2) development and deployment of the autonomous safety monitoring system in a distributed computing environment; and (3) exploring the impacts of data imperfections situations (e.g., erroneous or missing data) on the safety monitoring system together with approaches to reduce the impacts of the imperfections on the safety system. Prior research has reported on the first two phases [6,12,13,16]. The authors' recent paper [14] has reported the impacts of data imperfections on autonomous jobsite safety monitoring. The working paper indicates that the autonomous jobsite safety monitoring system based on the raw data collected from location-aware sensors is not satisfactory and approaches to deal with imperfect data should be investigated.

The paper is organized as follows: Section 2 summarizes current approaches to autonomous crane safety monitoring and the impacts of data imperfections on such systems; Section 3 describes the implemented autonomous crane safety monitoring system, the scaled testbed, the process of data collection and processing, and the metrics to evaluate the crane safety monitoring system's performance; Section 4 describes the modeling approaches to improve the system performance; Section 5 reports the results of what improvement can be achieved with those approaches; and Section 6 summarized the results and proposed the future research directions.

2. Research background

Tower crane safety monitoring is important on construction jobsites for preventing serious injuries and fatalities. To overcome limitations of manual systems, sensing technologies have been proposed for autonomous crane safety monitoring. One of the most important pieces of information used for construction safety applications is location data. There have been several different technologies available to obtain location information, including GPS, Radio Frequency (RF) sensors, Ultra Wideband (UWB), Ultrasonic, LADAR, laser scanner, Infrared, and video/image-based tracking [24]. For example, Yang [27] used image processing techniques on video streams from surveillance cameras to track if a crane enters predetermined blind lifting areas. Electric field monitoring sensor [18] was also used to monitor if the crane component is getting too close to the power line but it required calibration and the environment might affect the system's performance. Among the techniques mentioned above for the safety alert system, RF-based technology is one of the most promising applications for construction safety. Different RFID technologies have been used to prevent blind lifting for crane operators [10,22] and prevent workers from getting to close to a stationary mobile crane [23] or under the crane [7], and crane collisions [5,28].

The applications demonstrate promising benefits of introducing sensing technologies for autonomous safety monitoring; however, the applications were developed under the assumption that the collected information is perfect, which is not true due to the imperfect nature of sensing devices. Previous studies [1,15,20,21] indicated that imperfect (missing, erroneous, and uncertain) data is common and the imperfect data collected from sensors adversely impacts safety monitoring system performance.

In the authors' recent paper [14], imperfect information in the autonomous safety monitoring system was studied and the results show that imperfect information results in unsatisfactory system performance in terms of precision and recall to the point where commercial implementation is likely non-viable without improvement. The authors' working paper indicates that future research should be conducted to explore potential approaches to deal with imperfect data for improving the safety monitoring system's performance in a realistic world.

Razavi and Haas [20] have recognized that the acquire date from sensing devices are imperfect and found there are five major frameworks to deal with imperfect data: probabilistic, evidential belief reasoning, soft computing, optimization-based, and hybrid methods. They modified a data fusion model based on the JDL model with the integration of the five major farmworkers for tracking onsite materials among multi fusion levels (low for location detection, high for relocation detection and meta-process for project state). Since safety management requires near real time decision making based on sensed data, dealing with imperfect data for safety monitoring in this paper focuses at the low level (location detection) based on Razavi and Hass's work. In machine learning-based approach, the number of training set data points used for localization is usually very large and the computing time would be large even based on linear computing complexity. To reduce the burden to the system and speed safety decision making, the computing complexity issue needs to be addressed. In this paper, the authors use Bayesian approach based on few data points for safety situation decision making to reduce the processing burden of the system. Besides location information, this paper includes non-location information (velocity, and acceleration) to assist location prediction modeling. Both soft computing and evidential belief reasoning are adopted for improving the system's performance with imperfect data.

3. Autonomous crane safety monitoring system testbed and data collection

In the autonomous crane safety monitoring system, the dangerous areas under a crane load are divided into three areas based on different risk levels, arranging from the high risk to low risk: the red zone, the yellow zone and the green zone [13]. The target is considered to be in dangerous situations when falling in the red zone, to be close to the dangerous situation when falling in the yellow zone and safe in the green zone. Based on the three types of control areas, the autonomous crane safety monitoring system has two derivatives: (I) Red–Yellow–Green (R/Y/G) system, which contains both warnings and alerts and (II) Yellow–Green (Y/G) system, which only contains warnings. In system I, an alert is triggered if the target is in the red zone and a warning is triggered if the target is in the yellow zone. In system II, a warning is triggered if the target is in the yellow zone or the red zone. The purpose of a Yellow–Green system is to place emphasis on entering a warning