Development of a Sensor Network Protocol for Non-invasive Detection of Mobile Plant Operation in Construction Sites

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Abstract:

Tracking and monitoring techniques proposed for construction sites in the past have limitations and gaps. One is the privacy concerns associated with tagging and tracking of personnel or equipment on a site. Second is the practical limitation of tagging, as tagging the objects may not always be possible. Third is that tagging can lead to additional costs, as tags have to be maintained and repaired when damaged. To the best of authors' knowledge, to date no non-invasive method has been developed that identifies on-site hazards in real time and links real-time hazard situations with building information models' (BIM) site activity schedules. The authors aim to fill this gap through a relatively large project, of which the first phase work is presented in this paper.

The proposed technique uses a wireless radio frequency based non-invasive detection technique to detect mobile plants in operation to identify risk exposure. It has the potential to determine risk profiles of 'mobile plant in operation' by detecting construction activity on site zones. This paper reports the development of the underlying IEEE 802.15 Zigbee based mesh network. The details related to the design and development of the communication protocol, sensor network configuration and preliminary testing are discussed. The network will be used on a construction site to detect the mobile plant operation non-invasively.

This research is expected to contribute to improve safety of inherently dangerous construction industry, which globally reports relatively high accident rates compared to other industries.

Keywords: wireless sensing, tag-free detection, tracking, safety, mobile equipment

1. INTRODUCTION

Globally, construction is a dangerous industry. Unsurprisingly, due to the industry's poor records in fatalities and serious compensation claims, the Australian Work Health and Safety Strategy 2012-2022 has identified the construction industry as one of the priority industries for safety improvement.

Among the recorded fatalities, vehicle incidents accounted for 15% and being hit by moving objects accounted for 10% (Safe Work Australia 2012). A major reason for these incidents is the absence of a systematic mechanism to monitor risk exposure of 'mobile plant' on site. Definition of mobile plant from the work health and Safety Regulation 2011 (Work Health and Safety Act, 2011) is adopted in this study as '*any plant that is provided with some form of self-propulsion that is ordinarily under the direct control of an operator, and includes: earthmoving machinery (e.g. rollers, graders, scrapers, bobcats), excavators, cranes, hoists, elevating work platforms, concrete placement booms, reach stackers and forklifts.*' This project proposes a novel approach of monitoring risk exposure on site. The proposed non-invasive mechanism monitors mobile plant in operation on site which will support safety improvements.

2. BACKGROUND

2.1 Hazard Recognition and Safety Planning

Every resource on a construction site introduces its own set of safety hazards and is itself exposed to safety risks. Advances in the area of information and knowledge management allow for representation of and reasoning about construction information, for example by leveraging databases of project information, such as Building Information Models (BIM), to support site safety management. Sulankivi et.al. (2013) have reported on "integrating safety into BIM as an effective and practical method for detecting and eliminating fall-related hazards" prior to construction. Wang and Boukamp (2011) developed an ontology-based reasoning framework to support job safety analysis. Zhang et.al. (2012) later extended this framework and integrated it with Building Information Models to support "automated Jobsite Hazard Analysis (JHA) using safety ontologies in BIMs."

The new framework allowed for an improved identification of hazard zones in work areas using BIMs (Zhang et.al. 2014).

These and other hazard recognition and safety planning approaches, however, relied on construction operation information being provided prior to the construction activity happening on site. Marks and Teizer (2013) highlight that approaches such as these “do not generate feedback during performance of the work task and are unable to provide alerts in real-time to construction personnel.” This is an important concern, as construction sites are highly dynamic environments and context changes on the site lead to new hazards. It is thus necessary to track on-site activities to enable a frequent re-evaluation of the safety situation on site.

2.2 Tracking and monitoring

Tracking and monitoring has been trialed in the construction industry for different purposes. Video technology has been used to track personnel on site (Khosrowpour et.a. 2014, Teizer et.al. 2009). Radio Frequency Identification (RFID) has been used for tracking tools (Goodrum et al. 2005), materials (Jeselskis et al. 2003), labour (Woo et al. 2001) and for context/location awareness (Elghamrawy and Boukamp 2010). RFID has been integrated with other technologies, such as 'GPS' to improve blind lifting and loading crane operations (Li et al. 2013) and 'Zigbee', a low-cost, low-power wireless technology, has been used to track near-miss incidents (Wu et al 2010). An Ultra-Wide Band (UWB) based virtual fencing system was proposed to improve Work Health and Safety (WHS) on construction sites (Carbonari et al. 2011). GPS-based tracking for site operations (Pradhananda and Teizer 2013) and fusion methods to combine multiple technologies for labor tracking to monitor productivity (Cheng et al. 2013) and ergonomics analysis on construction sites (Migliaccio et al. 2013) were also trialed.

However, the previous research on tracking and monitoring techniques have limitations and gaps including: (1) privacy concerns may hinder the tagging and tracking of personnel or equipment on a site when applying in the construction domain; (2) the need to tag the object being detected, which can lead to additional costs and to practicality concerns, as tagging objects may not always be possible and/or tags have to be maintained and may be damaged. To date no non-invasive method has been developed that identifies on-site hazards in real time and also links real-time hazard situations with building information models’ site activity schedules.

Edirisinghe et al. (2014) proposed a device-free detection technique with risk profiling to detect risk exposure on construction sites. This device-free detection technique establishes a unique wireless signal in an area and analyses signal propagation effects triggered by objects moving through the area. This way, the introduction of objects to the area can be identified through changes in the wireless signal propagation. Depending on the effect of the object on the wireless signal, the object can also potentially be classified with 100% accuracy, but it can never be *identified* with 100% accuracy. Thus, this approach avoids the privacy concerns that are usually associated with other tracking methodologies, such as the ones mentioned before. It also eliminates the maintenance concerns related with active tracking techniques that use object tagging to identify and track objects, as no tags have to be attached to the objects and maintained.

The signal propagation effects that this approach analyses are sensitive to a number of variables, including the environment to which it is applied. Due to the highly dynamic nature of construction sites, a significantly high effect of multi-path fading (noise) of the wireless signal can be expected. Hence, it is required to adjust the approach to construction site characteristics. By taking site characteristics into account and leveraging construction site and activity information for classification of the identified objects and conducting testing on a simulated site environment, the herein proposed research is expected to lead to an innovative, privacy sensitive object identification and tracking mechanism.

As a vast variety of moving objects on a site can be expected of which some will have similar effects on the wireless signal propagation on site, the classification of the sensed objects is expected to be a special challenge. Boukamp’s construction information classification and ontological modeling approaches (e.g. Elghamrawy and Boukamp 2010, Wang and Boukamp 2011, Zhang, Boukamp and Teizer 2014) will be leveraged to improve the identification accuracy of the wireless sensing approach through intelligent mapping of signal propagation effects to construction information classes and concepts.

3. METHOD

3.1 Device-Free non invasive detection

Device Free Localization (DFL) (Patwari and Wilson, 2010) allows locating an object without tagging the object being located. Radio signal measurements of a Radio Frequency (RF) network can be represented using set of parameters of Received Signal Strength Indicator (RSSI) of each link. The effect called multi-path fading is caused when various components of the original signal arrive via multiple directions at the receiver due to various effects and interactions from various sources such as vehicles, people and vegetation in the surrounding environment. This multipath signal propagation effect can be a useful source of information for detecting and locating obstructions (Edirisinghe et al., 2013). By using a "fingerprint" method, the changes caused in the radio network representation due to the obstruction/the object being tracked can be analysed. Most of the RF fingerprinting techniques are hindered by an effect called multi-path propagation which causes frequent fluctuations of the radio signal. The most commonly used technique for removing Radio Signal Strength Indicator (RSSI) fluctuations due to multi-path is simple time averaging. A novel approach for extracting a robust signal feature from RSSI measurements in indoor wireless LAN environments was investigated by Feng et al. (2008). This method uses a signal processing technique to mitigate the multi-path effect and it is composed of a robust feature extracted from RSSI measurements by eliminating the variations due to multi-path effect. The approach was applied to detect vegetation (Feng et al. 2008) and to detect elephants (Edirisinghe et al, 2013) in the past. Edirisinghe et al. (2014) proposed using this technique in a construction site to detect risk exposure to improve safety. This technique is expected to mitigate multi-path effect in highly dynamic construction sites in order to detect/locate workers.

3.2 Sensor Network

To establish the required wirless mesh network, we used the sensor network platform called TelosB. A TelosB mote has an IEEE 802.15.4 radio with an integrated antenna, a low power MCU, and a 250kbps data rate. The mote has an embedded 8MHz TI MSP430 microcontroller with 10kB RAM. The mote runs the TinyOS operating system.

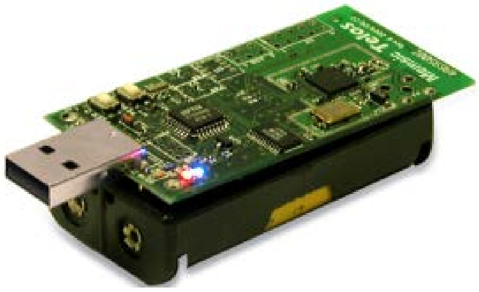

Figure 1. TelosB sensor platform
(source: http://www.memsic.com/userfiles/files/Datasheets/WSN/telosb_datasheet.pdf)

The mesh network configuration is illustrated in Fig. 2. The test network is composed of six TelosB motes including one mote that acts as the central co-ordinator of the sensor network. The Coordinator (NODE 0) of the network is connected to a central server. The Universal Serial BUS (USB) connection is used for this connection. The Coordinator communicates with the server via a C# program. The other nodes (NODE 1, NODE2, NODE 3, NODE 4 and NODE 5) report the RSSI values of the network links upon requested the by the coordinator.

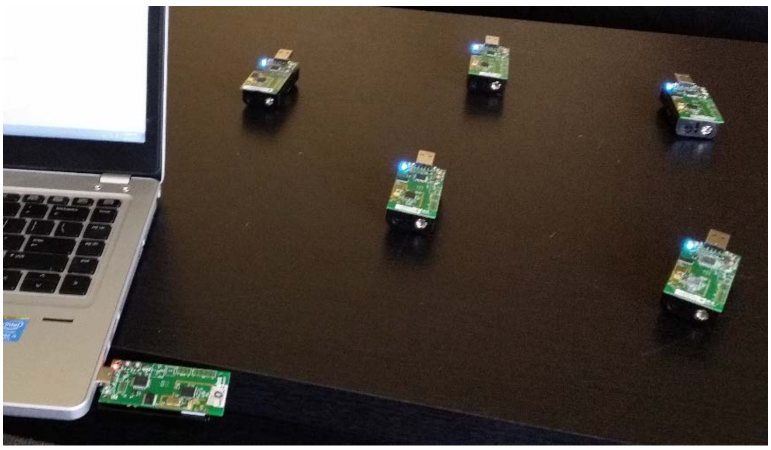

Figure 2. IEEE 802.11 Mesh Network

The number of motes required depends on the size of the area in which the network shall be deployed, static obstacles on site affecting the network (e.g. walls and columns) and the required accuracy of fingerprint. Thus, it is expected that different sites will require different numbers of motes.

The communication protocol is designed to capture the RSSI values of all the available links in the network. I.e. there is no configuration required to inform the system of the number of motes or their location. RSSI of all available links in the network are measured and recorded in the server together with the reference time. The communication protocol is discussed in the next section.

3.2 Programming the Motes and Configuring the Sensor Network

The motes were programmed using TinyOS installed on Ubuntu 14.04. TinyOS configuration on Ubuntu includes interfacing for MSP430 microcontroller which allows communication with the microcontroller of the motes. The communication protocol was designed for two programs: one for the coordinator; and one for the nodes. The algorithms for these two programs are shown in Figure 3. The message receipt is "interrupt" event driven.

Coordinator

```
Initialization
Initiate a timer for one cycle to complete
For node 1 to 5 {
    Unicast a Wakeup message
    if all rssiResponse messages not received
            {
                If(Wait timer expired) {
                        Error reporting
                }
            }
}

If receive rssiResponse message
{
            Write Data
            Update message count
}
```

Node

```
If receive Wakeup message
{
    Get RSSI of the Wakeup message
    Send rssiResponse message to
        Coordinator with RSSI
    Send getRSSI message to other
        neighboring nodes
}

If receive getRSSI message
{
    Get RSSI of the getRSSI message
    Send rssiResponse message to
        Coordinator with getRSSI details
        and RSSI value
}
```

Figure 3. Communication Protocol Algorithm

As shown in the Figure 3, the coordinator initiates the communication with the nodes via a general "Wakeup" message. Upon receiving the "Wakeup" message, the nodes then send the RSSI value of the received "Wakeup" message back to the coordinator. This is the measure of the signal strength of the communication link from the coordinator to the node. The coordinator receives the "rssiResponse" message and records the RSSI data and source node. The nodes also send an "getRSSI" message to other nodes nearby. Nodes receiving the "getRSSI" message respond with the RSSI information of the received "getRSSI" message. The source node then forwards this information back to the coordinator. This creates additional data points useable for the fingerprint method. Additionally, this allows extending the mesh network easily. As not every node on a site may be sufficiently near to the coordinator, or the direct link between the mote and the coordinator may be blocked by a moving piece of equipment crossing the signal path, the node to node communication allows all RSSI information to be propagated through the network to the coordinator.

A node thus has multiple links. For example, let us consider the link between NODE 1 and NODE 2 in our test network: The RSSI values of the link "1,2" is recorded both from NODE 1 as the transmitter by NODE 2 (the receiver) as well as a link "2,1" where NODE 1 is the receiver and NODE 2 the transmitter. Hence, transmitter NODE 1 in our network has five links which are: (1,0), (1,2), (1,3), (1,4) and (1,5). Similarly, NODE 01 as the receiver, has five links which are: (0,1), (2,1), (3, 1), (4, 1) and (5, 1). For all these links, RSSI data is recorded which contribute to the generation of signal fingerprints in our fingerprint method.

The mesh network configuration flexibility allowed for by the developed communication protocol grants the required flexibility for establishing a sufficient number of data points. In our targeted construction industry context, this flexibility will be critical to easily create more data points for the sensing approach and to develop a clearer fingerprint of the network for the different objects that pass through the area covered by the network.

4. RESULTS

Preliminary testing of the network found that the message flow was optimal when the timer of the coordinator was set for 3S interval to complete one cycle of communication successfully in the given set-up. This tie interval can vary in the real site set-up based on the distance covered by the network or any other dynamics on the site. The scalability of the system to larger number of nodes can affect the duration of each cycle because the number of nodes in the network can impact the speed of the coordinator as well as the time needed to complete one cycle in the communication protocol effectively (without flooding the network). Error handling at the coordinator (based on a timer as discussed in the previous section) can take care of any bottleneck nodes or broken links in the network.

RSSI of the links were captured in real-time using the C# program. It captured the coordinator output written to the terminal and displays in the Graphical User Interface (GUI) shown in Figure 4. The program can start capturing data at a given time and stop at a given time. In addition to that, the GUI facilitated recording the time between significant external events that can be entered by the user. This feature enables recording significant events during site testing to help establish the fingerprints for equipment moving on the site. Further, the GUI allows visualizing the RSSI variations of a particular link. As shown in Figure 4, the left panel updates the RSSI data of all the links in the network.

The graph in Figure 4 illustrates the variation of RSSI values of a given link. For example, RSSI values of (2,0) link is illustrated in the figure, where the NODE 02 is the transmitter and coordinator (NODE 0) is the receiver. The RSSI data of the links together with the reference time and the events data are recorded for further processing and to analyze the multipath mitigated RSSI values.

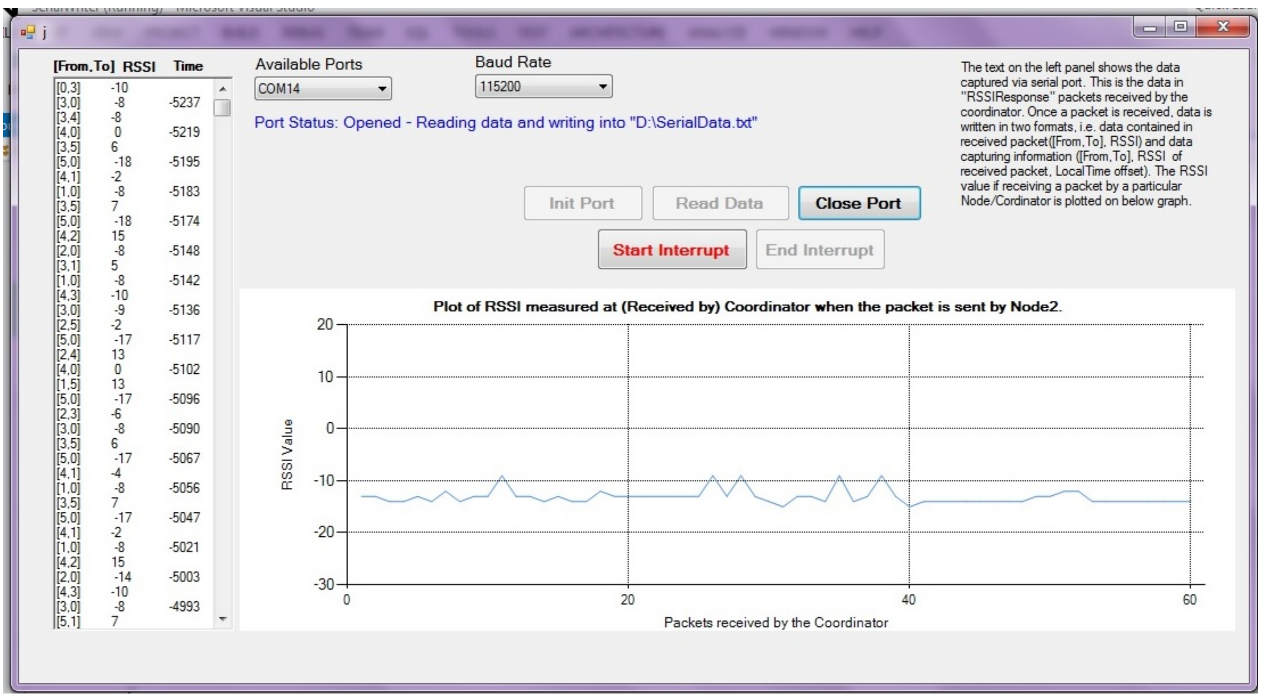

Figure 4. Graphical User Interface

5. CONCLUSIONS

Construction as a dangerous industry has recorded relatively high accident rates compared to other industries. Statistics show that these have significant social and economic consequences. The proposed project aims to support improve safety by identifying risk exposure of construction workers by detecting the mobile plant operation on site.

The paper presented the first phase of the project which is design, development and initial testing of the sensor network. Communication protocol was designed to address the issues and challenges in the network and its application context including: coordinating nodes, and creating sufficient data points for a good fingerprints while using as few nodes as possible. Future work includes using the network for site testing of the multipath mitigation to detect mobile plant operation and linking the system with scheduling information from BIM. Sensitivity and accuracy of the proposed method in the dynamic construction site will also be investigated in comparison with previous applications of the method.

The proposed project, while also intellectually contributing to the field, is expected to have the potential to make a significant social contribution in identifying the risk exposure of construction workers, reducing the number of workers who are harmed and to improve safety while maintaining privacy.

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