Use of Ultra-Wideband Sensor Networks to Detect Safety Violations in Real Time

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Abstract –

Safety is the highest priority for most construction professionals. However, enforcing the safety requirements and self-regulation of construction jobsites can be difficult. Often, one safety manager is responsible for multiple jobsites and must split their time appropriately depending on the type of work and size of job. This, coupled with large jobsites, makes consistent monitoring of safe working practices a challenge. This paper summarizes a preliminary study that examines the feasibility of utilizing Ultra-Wide Band (UWB) sensors for continuous monitoring of safety violations on a construction job site by placing UWB sensors on personal protective equipment (PPE) and common jobsite equipment. Laboratory experiments were conducted to test the feasibility of current system capabilities by developing a prototype system utilizing known algorithms for sensor localization with an application of relational parameters to test the systems capability of correctly identifying safe and unsafe working conditions. These preliminary experiments revealed the limitations of the current body of knowledge. This paper discusses the concept of continuous monitoring and the identified benefits that UWB sensor networks may be able to provide for construction safety monitoring. The preliminary prototype development and experiments are also discussed with an explanation of the identified limitations. Lastly, future research steps on how to overcome the identified limitations is discussed.

Keywords –

Ultra-Wide Band Sensors; Safety; Construction; Network Sensors; OSHA; fall protection

1 Introduction

Safety on a construction job site is a very high priority. A safe jobsite can lead to lower insurance rates, completing jobs more efficiently, and most of all allow everyone to go home safe at the end of the day. To help increase the safety monitoring capacity of a site, Ultra-Wide Band (UWB) Sensor Networks are being explored as a method for offering continuous safety monitoring in ensuring construction workers are following safe working procedures for common tasks.

UWB sensing is a promising new technology for tracking objects without requiring line-of-sight. Unlike cameras, which require the objects to remain within the field-of-view in order to be tracked, UWB signals propagate through walls and objects and allow non-line-of-sight tracking.

On a construction site, it may be feasible to track pieces of safety equipment and working equipment as they move around. The limitation of the technology is that UWB position measurements are noisy. Depending on the time resolution and spatial precision required, UWB position tracking may be suitable for detecting some safety violations. This research is a preliminary investigation of this area.

This paper summarizes the preliminary study that examines the feasibility of utilizing UWB sensors for continuous monitoring of safety violations on a construction job site. A prototype monitoring system, preliminary laboratory experiments, and identified limitations to the current body of knowledge are also discussed.

2 Background and Literature Review

Construction projects are very dynamic in nature. The dynamic work environment is inherently dangerous, making safety of those who work in construction a priority for those involved. Each company is responsible for safety on the job-site and most have a formalized safety training program. A site superintendent or safety officer, for larger jobs, is usually responsible for enforcing safety protocol. Because of job size and other job duties, these personnel can only observe a fraction of the activities each day so continuous monitoring by personnel is next to impossible and would be very costly. This research suggests that sensor networks may be utilized to help jobsite superintendents and safety officers identify possible unsafe working practices by personnel without having to witness it themselves. The UWB sensors can offer a continuous monitoring of site and worker conditions, especially for those who are working at height and have a risk of falling.

2.1 Safety in Construction

In 2014, OSHA reports that there were 8 million worksites with 130 million workers on them. During this same year there were 4,679 workers killed on the job. The construction industry makes up approximately 21% of these fatalities with 12 workers on average not making it home to their families every week [1]. It has been estimated that the cost of fatal and non-fatal injuries in the construction industry exceeds $11.5 billion annually [2]. Most of the construction fatalities involve what OSHA refers to as the “Focus Four” which include Falls, Electrocutions, Struck by Objects and Caught-in Between. Of these four, falls are by far the most significant accounting for 40% of all construction related fatalities. Despite Fall Protection (29 CFR 1926.501) being the most frequently cited standard by OSHA, it is clear that more can be done to protect the American work force [1]. It is for this reason that this research is examining the use of UWB sensors to help monitor conditions where fall is a risk in the preliminary study.

2.2 Ultra-Wide Band (UWB) Sensors

Ultra-Wideband (UWB) sensor networks use short pulse radio frequency waveforms over a large bandwidth for precise localization of tagged elements within an environment [3] and does not require line of site between the sensor and tag, allowing it to work both inside and outdoors [4]. UWB technology has its origins with time-domain electromagnetics or specifically base-band pulse technology of the early 1960s [3]. Baseband-pulses are short duration pulses concentrated between zero frequency and the microwave spectrum [5]. Early research was originally focused on understanding microwave networks and intrinsic material properties which then lead to the development of target-signature analytics in the time domain [5]. The term “UWB” originated with the Defense Advanced Research Project Agency (DARPA) in the early 1990s as a means of distinguishing between more traditional radar technologies and that of low probability of detection (LPD) (covert) radar systems [6]. UWB systems have primarily been used in LPD radar; however, is now more frequently being researched for civilian applications.

One of the areas that UWB is being studied, and is the topic of this paper, is in precise 3D object localization in real time. With these systems, short-pulse waveforms are transmitted by mobile tags and received by three or more stationary receiving boards. The receiving boards transmit the data to a central processing hub via standard CAT-5 cable (tethered) or wireless gateway signal (untethered). The time of arrival (TOA) to each of the receivers is used to triangulate the tags to specific spatio-temporal locations. Depending on the commercial system used, the angle of arrival at each receiver board may also be used to determine the spatial location of the tags. Algorithm smoothers and filters are applied at the processing hub to filter out incomplete and noisy data [7]. UWB technology has several key advantages to other spatial location alternatives such as RFID tags, 3D video range camera and GPS. These advantages include immunity to multipath cancellation, low interference to legacy systems, high communication security and extended battery life with low pulse rate and short duty cycles tags [5,6,8]. While these advantages are important, what makes UWB particularly relevant for applications on a changing construction jobsite is that it has high signal fidelity inside the building (where satellite signal can be disrupted for GPS systems), where there is a high degree of variability in the density of the obstructions in the environment and when line of sight is difficult to maintain [7,9]. Past studies suggest that these advantages coupled with the relatively low costs of the tags may offer a high return on investment for UWB technology in the construction industry specifically in the areas of work zone safety, job site monitoring and resource tracking [7,8,10].

While the literature suggests that UWB sensor networks show promise in the construction industry, there are several limitations inherent with current technology. Under the best conditions, where the tags and receiving boards are in line of site, the tags are static and all receiver boards are tethered (hard wired), the accuracy is approximately 10 cm [7]. In a field trial at the University of Nebraska-Lincoln (UNL), the UWB inaccuracy increased to 59 cm as interferences were added [7]. Although not addressed in the UNL study, it has been suggested that there could be mutual interferences between UWB sensor tags reducing the fidelity of the network [11]. The UNL field trial also confirmed an experiment by Welch et al. which concluded that the human body interacts with the UWB antenna creating a sharp and pronounced null in the signal [9]. The Welch et al. [9] experiment concluded that the system performance when using UWB sensors near human targets will depend significantly on the signal angle of arrival; however, the effect was reduced in a dense multipath environment common with active construction jobsites. Welch et al. notes that in dense multipath environments where more traditional communications system struggle to perform, UWB systems excel further suggesting that UWB systems have a niche in asset location in the construction industry.

3 UWB Safety Monitoring System

This research is looking at the feasibility of using UWB sensor networks for tracking the position for critical equipment and personnel to identify potentially unsafe conditions. The proposed system would be designed to assist safety officers and superintendents in monitoring safe and unsafe working habits of their employees. The idea is to place UWB sensor tags at strategic locations on equipment and on personnel protective equipment worn by workers to identify safe and unsafe conditions based on the proximity, location, and movement of the tags.

The research set out with three specific aims: (1) examining the feasibility of UWB sensor networks use in constructions safety, (2) based on those tests, generate a list of applicable safety violations that can be monitored using the sensor networks, and (3) identify limitations and barriers of the sensor networks that need further examination.

3.1 Mock-up Testing

The mock-up testing was used to test the feasibility of the UWB sensor networks use in construction safety. The laboratory based experiment utilized the simple equipment and work activities related to the “falls” risk. Specifically, working on a bakers-style scaffold (an easily moveable elevated platform) and a-frame ladder were used.

Basic activities and violations for the bakers scaffold and ladder were identified. For the bakers scaffold, a common violation would be the worker not locking the wheels to prevent it from moving every time they needed to move the scaffold. This also commonly leads to the worker being able to pull the scaffolding along the ceiling when placing ductwork or ceiling panels. This is a clear safety violation and fall risk, however many workers may be tempted to do this in order to speed up their productivity because getting on and off the scaffolding and properly locking the wheels can take significant time if shorter, simpler tasks are required at height over a large area. For the ladder, a fall risk is present when the worker steps on the last rung or top of the a-frame ladder. This causes the worker’s center of mass to be higher than the ladder can safely support.

3.1.1 Bakers Scaffold Violation

To test the violation of the bakers scaffold, a UWB tag was placed on a boot of the actor who is simulating the movement of the worker and another tag is placed on the scaffold (Figure 1). Scripted testing included walking around on the floor pushing the scaffolding as well as standing on the stationary scaffolding and walking on top of it. Lastly, taking the boot off with the sensor and placing it on top of the scaffolding and pushing the scaffolding around was tested. This was done in order to test for the “unsafe condition” without actually putting the actor in danger of falling.

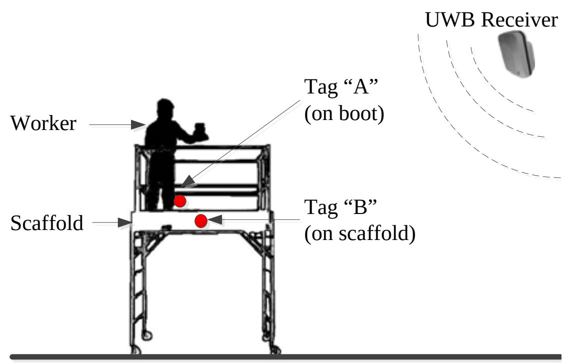

Figure 1. Safety Violation Mock-up

3.1.2 Ladder Violation

When working on a ladder it is important for the worker to not step on the top or next to top rung of the ladder. In order to script this scenario and test the UWB feasibility a UWB tag was placed on the rung of the ladder that should not be stepped on. The other tag was left on the actors boot. The test was then run to see if the UWB sensors could detect when the boot was on the rung with the tag, thus signally a violation.

3.1.3 Mock-up Testing Goals

The goal of these mock-up tests is to identify if conditions can be detected by the UWB sensor network that would signal to a superintendent or safety officer that a problem has occurred which could signal additional safety training is needed by an employee. The goal of the system is to offer a tool for those in charge of safety to better understand the habits of the workers and potentially offer additional training. It is not intended to be used as a means for enforcing violations through punishment. The recorded information can then potentially be used one of two ways depending upon the processing time needed for the system to adequately and accurately detect unsafe conditions. The first method would be to send out an immediate alert via text message or email that will notify the superintendent or safety officer that an unsafe condition is present. This would require a close to real time calculation and notification that the event is occurring. Alternately, the system could take readings over a longer period of time, thus offering a larger lag of notification but potentially higher accuracy because of the use of more data. This would allow for a log to be created over a time period, for instance the course of one day, which can then be reviewed by the safety officer or superintendent. Since the system is to be used as a tool to notify the superintendent and safety officer that additional training is needed or someone may need to be observed, and it is not intended to be a method for automatic reprimand to workers committing the potential violation, the system log could be a better indicator of an employee's actions over a period of time and highlight actual trends of behaviour instead of one incident that has the potential to be a false positive.

3.2 Laboratory Experiment Setup

The testing laboratory is equipped with a UWB tracking system manufactured by Ubisense, Inc. Figure 2 shows a UWB transmitter, commonly referred to as a tag, and a UWB receiver. Transmitters are encased in small rugged plastic containers. Eight receivers are distributed around the lab and are mounted above ceiling tiles. Positions of tags are measured by how long the UWB signals take to propagate from the transmitters to receivers. The Ubisense system uses the 5 receivers that measure the strongest signal strength for each position calculation.

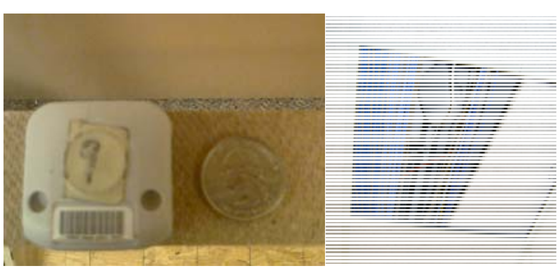

Figure 2: UWB transmitter (left) and receiver (right).

Figure 3 shows a ladder and scaffolding that were used for testing. A tag was mounted below the top surface of the scaffolding and another tag was mounted below the highest step on the ladder. A tag was placed on the boot of a person to track their motion to determine if they were using the ladder or scaffolding in an unsafe manner. Each tag has a unique identifier in the system allowing for the equipment and the person interacting with the equipment to be distinguished from each other. Each piece of equipment is linked to a specific set of parameters defining safe and unsafe conditions (based on sensor location, proximity, and movement).

Figure 3 shows a floorplan and image of the laboratory space.

Figure 4 shows an overview of the algorithm. There are four stages. In the first stage raw UWB position measurements are taken for each tag. In the second stage the raw measurements are smoothed using a Kalman filter. In the third stage we developed a custom algorithm to determine if a tag is stationary or in motion. In the fourth stage, safety violations are detected depending on the relative positions and stationary/motion conditions of the tags related to their movement and proximity to the "actor" tag. The following provides the details for each stage.

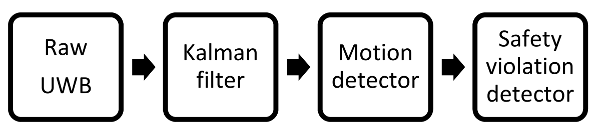

Figure 4: Overview of algorithm.

Given a set of N UWB tags we denote each tag using a subscript i where i=1…N. Let the raw position measurement for a UWB tag to be denoted $(\tilde{x}_i, \tilde{y}_i, \tilde{z}_i)$. These are sampled at 10 Hz. On occasion samples are missed due to the UWB receivers not receiving sufficient power to detect a tag and thus make a measurement. This can happen when a tag is obstructed by large amounts of dense materials that diminish the power received. In such a case, the tracked position of the tag does not change until a new measurement is received.

The purpose of the second stage is to smooth the raw measurements. Raw UWB measurements have an average error of 30 cm but the noise distribution is non-Gaussian [12]. Sources of noise include the transmission of signals through materials obstructing the direct line-of-sight path, reflections of the signals causing non-line-of-sight estimates, and changes in the sets of receivers obtaining the strongest signal strengths [13,14]. To smooth the data we apply a Kalman filter [15]. Our filter uses a constant velocity model. The state is defined as

$$X_t = \begin{bmatrix} x \\ y \\ z \\ \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix}$$

where (x, y, z) gives the position and $(\dot{x}, \dot{y}, \dot{z})$ gives the velocity. The velocity is assumed to be constant and accelerations are modeled as dynamic noise using the state transition equation

$$X_{t+1} = \Phi X_t + A_t$$

where Φ is the state transition matrix

$$\Phi = \begin{bmatrix} 1 & 0 & 0 & \Delta T & 0 & 0 \\ 0 & 1 & 0 & 0 & \Delta T & 0 \\ 0 & 0 & 1 & 0 & 0 & \Delta T \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and A_t is the dynamic noise matrix

$$A_t = \begin{bmatrix} 0 \\ 0 \\ 0 \\ N(0, \sigma_d) \\ N(0, \sigma_d) \\ N(0, \sigma_d) \end{bmatrix}$$

Observations are denoted as

$$Y_t = \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix}$$

and are modeled by the observation equation

$$Y_t = MX_t + N_t$$

where M is the observation matrix

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

and N_t is the measurement noise matrix

$$N_t = \begin{bmatrix} N(0, \sigma_n) \\ N(0, \sigma_n) \\ N(0, \sigma_n) \end{bmatrix}$$

Using these matrices, the standard Kalman filter algorithm is applied. The values σ_d and σ_n determine the amount of smoothing. We set $\sigma_d = 0.001$ and $\sigma_n = 1$. This tuning of the filter provides a large amount of smoothing so that the jitter-like Gaussian noise is completely eliminated and the occasional outlier causes only a small bump. This reduces the speed at which actual changes in velocity can be detected. However, the intent is not to provide instant real-time tracking, but to detect periods of time during which a piece of equipment is being used in a non-safe manner. Thus it is important to smooth out false detections that may be caused by the large measurement noise at the cost of not detecting violations caused by motion that occurs for a brief period of time (e.g. 1 second).

The purpose of the third stage is to determine if each tag is in motion or stationary. Let the motion state for tag i be defined as $m_i = 0$ if the tag is stationary and $m_i = 1$ if the tag is in motion. A buffer of the most recent 10 filtered measurements is kept for each tag:

$$\begin{bmatrix} x_t & y_t & z_t \\ x_{t-1} & y_{t-1} & z_{t-1} \\ \vdots & \vdots & \vdots \\ x_{t-9} & y_{t-9} & z_{t-9} \end{bmatrix}$$

The average $(\bar{x}, \bar{y}, \bar{z})$ of the values in the buffer is calculated. If the tag is stationary, its position is tracked as $(\bar{x}, \bar{y}, \bar{z})$. If the tag is in motion, its position is tracked as (x_t, y_t, z_t) which is the most recent filtered measurement in the buffer. The effect is to provide even more smoothing while a tag is considered stationary but a quicker response to motion if the tag is considered in motion. To change state from stationary to in motion, the count of positions within the buffer that are greater than 20 cm from $(\bar{x}, \bar{y}, \bar{z})$ must be greater than 6. This allows for a few outliers without triggering a state change. Similarly, to change state from in motion to stationary, the standard deviation σ_{buffer} of the values in the buffer must be less than 15 cm. This allows for a small amount of motion in an area without triggering a state change.

The purpose of the fourth stage is to check the positions and motion states of the tags for safety violations. The algorithm checks each tag mounted on a boot against each tag mounted on a piece of equipment. For each type of equipment, a separate set of conditions is tested. Two examples are detailed below. If the conditions fail, then a counter is increased; if the conditions pass, then a counter is decreased. A warning for a safety violation is triggered if the counter rises above a threshold. The up/down operation of the counter helps prevent false alarms by requiring unsafe conditions to persist for a period of time.

For experimental purposes, two types of violations were tested. The first occurs when a person stands too high on a ladder. The second occurs when a person stands on scaffolding while it is in motion. The ladder violation is detected by comparing the position of the tag mounted on a boot to the position of the tag mounted on a ladder. If the z coordinate of the boot is higher than the z coordinate of the ladder, and if the x,y coordinates of the boot are within 40 cm of the x,y coordinates of the ladder, then a violation is detected. The scaffolding violation is detected by checking the motion state of the scaffolding and comparing the position of the tag mounted on a boot to the position of the tag mounted on the scaffolding. If the scaffolding tag is in motion, the z coordinate of the boot is above the z coordinate of the scaffolding, and the x,y coordinates of the boot are within 50 cm of the x,y coordinates of the scaffolding, then a violation is detected.

Upon initialization, all the relevant position variables are set to the center of the tracking area. It takes a few seconds for the filtered estimates and motion variables to settle to their actual values. All the motion states are initialized to in motion and safety violation counters are initialized to zero.

4 Findings and Limitations

The experiment findings identified two areas related to the use of UWB sensors to construction safety monitoring. This includes that the protocols for identifying safety violations, though relevant for self-regulations and personal supervision, are not definitive enough for defining appropriate computer based algorithms for monitoring. Another issue is that the accuracy of sensor localization is directly linked to the period of time that the data is collected, so certain movements may be hard to detect if the collection period is increased to gain a more accurate location. The short movements may be seen as outliers in the data instead of short, legitimate movements.

4.1 Future Research

In order to more clearly define the parameters, the researchers are proposing a four step grounded theory methodology to identify better tracking with the UWB system. This includes (1) video documentation of workers performing typical tasks. This will be a combination of scripted activities in the lab that will include scripted violations or errors in methods. (2) Data analysis of the videos that will include coding of the workers movements, times, length of movements, etc. (3) System Coding based on parameters identified with the video coding. (4) Prototype validation through the monitoring of scripted activities in the laboratory to identify the system's ability to positively identify safety violations. (5) Finalize protocol for documenting and coding additional violations for easy inclusion in an expanded safety monitoring system. Activities related to fall protection will be the focus of the next research steps.

5 Discussion

In studies conducted in other fields, employee performance, when they know they are monitored has increased [16]. This leads to others also identifying benefits of electronic monitoring systems [17]. However, electronic monitoring can also have negative effects on job attitude and satisfaction especially when using close monitoring techniques such as camera recording, data entry, and chat/phone recording that lead to the employees feeling as if they lose control [17]. Attitudes also go down when monitoring is focused on individuals and unpredictable [17]. Monitoring can also be seen as an invasion of privacy, but McNall and Stanton [18] identified within a study that employee control over monitoring, such as providing areas where monitoring does not take place, can help those being monitored feel more comfortable. The study also stated there might be a link to reasons for monitoring and transparency of monitoring being a factor but could not definitively say.

The fact of the matter is that employees' concerns will need to be addressed and they will need to be comfortable with the technology. There are clear applicable benefits to the contractor in terms of ensuring a safer work environment and monitoring safe work practices that can lead to improved safety training, however it can also lead to employers taking advantage of the system to monitor productivity and utilize it as a disciplinary tool. A positive, transparent environment, focusing on improvement and not discipline may help overcome potential challenges of employee acceptance of the technology.

The benefits of better trained employees in terms of safe working practices can have a large impact on the company's bottom dollar. If safety incidents onsite decrease, insurance rates and worker's compensation payments will also decrease, this will provide a monetary savings to the company. Safety also helps with a company's reputation. The use of an electronic monitoring system such as a UWB sensor network for continuous safety monitoring can be a positive tool within the construction industry.

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