Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments

T. Cheng a, M. Venugopal a, J. Teizer a,⁎, P.A. Vela b

a School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA, 30332–0355, United States
b School of Electrical and Computer Sciences, Georgia Institute of Technology, Atlanta, GA, 30332, United States

A R T I C L E   I N F O

Article history:
Accepted 2 May 2011
Available online 31 May 2011

Keywords:
3D
Accuracy
Error analysis
Laser scanning
Location tracking
Ultra wideband
Robotic Total Station
RFID
Safety
Visualization

A B S T R A C T

Emerging wireless remote sensing technologies offer significant potential to advance the management of construction processes by providing real-time access to the locations of workers, materials, and equipment. Unfortunately, little is known regarding the accuracy, reliability, and practical benefits of an emerging technology, effectively impeding widespread adoption. This paper evaluates a commercially-available Ultra Wideband (UWB) system for real-time, mobile resource location tracking in harsh construction environments. A focus of this paper is to measure the performance of the UWB technology for tracking mobile resources in real-world construction settings. To assess tracking accuracy, location error rates for select UWB track signals are obtained by automatically tracking a single entity using a Robotic Total Station (RTS) for ground truth. Furthermore, to demonstrate the benefits of UWB technology, the paper provides case studies of resource tracking for analysis of worksite operations. The work demonstrates the applicability of UWB for the design of construction management support tools.

1. Introduction

The dynamic nature of construction activities, in comparison to the manufacturing industry and its mostly stationary fabrication plants and assembly environments, presents a significant challenge towards realizing the goal of understanding construction site activities. Hindering this understanding is the fact that production control protocols in the construction industry are labor intensive, manual, and error prone [1]. Recent developments in remote sensing and automated data acquisition technology promise to improve upon existing material management strategies [2–7]. Similar benefits are anticipated for process management strategies.

To date, many barriers exist that prevent owners and contractors from deploying data acquisition technology in construction. These include the risk of failure during the initial implementation phase and the high cost of implementation. An additional barrier is the lack of demonstrated benefits associated with emerging technology, e.g., the inability of the owner and/or contractor organization to exploit the information collected. When faced with known costs but unknown returns on investment, adoption of emerging technology can be non-existent. Utilization of the technology is then limited to scattered implementations in various engineering subfields until more precise cost-benefit valuations are determined [8]. It is, therefore, important to investigate how promising real-time location tracking technology may advance construction practices and enhance production control procedures in the construction industry. Two key areas closely tied to the economics of construction projects are productivity and safety [9]; lapses in both are responsible for significant losses in the construction industry.

With regards to productivity, one key area identified as a critical need is the localization and tracking of assets that are linked to work tasks, including workforce, equipment, and materials [10,11]. For example, material handling and transport has been identified as a critical work task in construction [11,12]. Recent studies report significant amounts of time spent on materials searches in lay down yards [13]. The material flow for a steel erection process at industrial job sites may involve the delivery of the material component from the fabrication plant to a temporary lay down yard. A lay down yard is an important temporal space in the assembly process of material components, as it allows for storing and sorting the components in the correct order, and provides a healthy temporal buffer to ensure parts availability when needed. Prior research has shown that the current process of material handling on large industrial job sites is inefficient [14].

Within the context of safety, significant time and economic resources are lost when workers are injured or killed by loads during work tasks [15,16]. Current construction best practices in material handling prescribe the foreman to blow a whistle or the equipment
operator to activate the horn of a crane at the beginning of a material lift. Such manually activated signals are effective in alerting the surrounding workers to pay attention to where the load is swinging. Many workers or crane operators have difficulty, though, in relating their own location to the position of the load. Incorrect spatial awareness could lead to accidental injury. The importance of spatial awareness is emphasized by the fact that 25% of all construction fatalities relate to the unsafe proximity of ground workers and equipment [17].

To more concretely understand worker behavior and activities for improving the understanding of construction site operations, it is necessary to analyze observations of construction work in progress. For example, one way of improving current work practices is by observing work tasks and generating manual evaluations. This practice is commonly known as ‘work sampling’ [18–20].

Any technology that can reliably, accurately, and automatically record the location of construction resources for work sampling could significantly simplify previously conducted manual assessments and improve confidence in the measurements. Likewise, technological systems that track project critical resources (e.g., people, equipment, material) and provide information on resource utilization can enhance current work practices. Such systems are popular in robotics and telecommunications by the name of context aware systems. The existence of a context aware system in construction that tracks the location of construction resources, and identifies and measures the status of work tasks, would improve project performance [21,22].

Wireless, non-destructive, and reflector-less sensor technologies applied to construction have been identified as key breakthroughs [12] for both construction practitioners and researchers in terms of reducing non-value-added activities, responding quickly to safety hazards, and automating and rapidly generating as-built and project documentation. In both cases, technological adoption is lagging due to uncertain benefits. Further investigation and control is needed to improve on these fronts.

This paper presents research findings on the evaluation of a commercially-available Ultra Wideband (UWB) system, which is a radio-frequency based real-time location tracking technology, in several harsh construction environments. The error rate of the real-time location tracking technology is measured and evaluated. Results of experimental field validation studies are presented, along with technology application scenarios analyzing the field data.

### 2. Remote construction resource location tracking

Arguments in favor of using automated remote tracking technology in construction are to increase tracking efficiency, to reduce errors caused by human transcription, and to reduce labor costs. A variety of sensors and sensing technologies with automated tracking capabili- ties are available for use in construction and infrastructure projects [5]. Selection of one particular technology depends on the application, the line-of-sight (LOS) access between sensors and sensed objects, the required signal strength, the data provided, and the calibration requirements. Moreover, the prevailing legal framework regarding the permitted bandwidth and associated availability, and the implementation costs associated with each technology add further constraints [23–26]. These characteristics must be weighed against the benefits provided.

Many existing technologies for localization and tracking fall within the broader category known as sensor networks (SNs) or wireless sensor networks (WSNs). Sensor networks consist of a collection of sensing nodes used to compute position from location-based measurements via triangulation. When a resource is tagged with an electronic tag capable of generating the necessary signals, a sensor network provides location information of the tagged resource. The three predominant location-based variables of a wirelessly transmitted signal are the received-signal-strength indicator (RSSI), the angle-of-arrival (AoA), the time-of-arrival (ToA), and the time-distance-of-arrival (TDoA). Given measurements of one of these variables by a collection of distributed sensor nodes, triangulation leads to estimates of the associated signal source position.

In RSSI models, the effective signal propagation loss is calculated based on the power of received signals at the nodes. Several theoretical and empirical models are implemented to translate this loss into distance [2–4,27]. However, the disadvantage of this technique is that convergence from data collection to information may take time, which leads to post real-time positioning [28].

In AoA models, sensor nodes estimate the angle direction from which the signals originate. Based on simple geometric relationships it calculates the position of the nodes. Studies show that high accuracy can be achieved by several advanced approaches [29,30]. Implementation of an AoA-based sensor network requires antenna arrays with directional antennae for triangulation. Deployment of the antennae for complete coverage can be costly for many temporary projects and for object cluttered environments, such as those found in indoor construction environments [31,32].

In ToA and TDoA models, the propagation time of a signal is translated directly into distance if the propagation speed is known. The most popular localization system using ToA techniques is Global Positioning Systems (GPS), which relies on communication with Earth orbiting satellites for triangulation. Cost and size make high-precision GPS prohibitive for tracking every asset on a construction site [2,3,6,7]. An alternative emerging TDoA technology is active RFID, which employs an on-board power source for the signaling electronics, together with locally installed antennae. One form of active RFID is Ultra Wideband RFID, which was initially developed for military use in the 1960s. FCC approval led to UWB being explored for monitoring of civil applications [33–35], including construction in 2007 [24].

Several case studies exist in construction applications that describe the successful use or combination of more than one of these principles in association of technology such as GPS, RFID, bar codes, laser scanning, ultrasound, etc. [7] and [36] experimented successfully fusing active RFID and GPS technology to predict the location of metal pipe spools and other industrial construction assets. [37] leveraged passive RFID technology to track construction assets in a high-rise renovation project. [38] focused on radio frequency in combination with ultrasound signals in a wireless sensor network.

Alternative (non-sensor networked) tracking technologies include Robotic Total Station (RTS) and vision-based technologies. An RTS can only track single entities, thus its utility is limited to specific scenarios. Tracking construction resources using vision cameras can make work sampling more objective by automatically recording and reviewing the performance of selected work tasks. Although recent progress has been made in automated vision data processing [39–42], fully automated vision tracking of multiple resources in dynamic environments is far from being solved.

Although any of the previously offered tracking principles and their associated data gathering devices could be selected to monitor the trajectories of construction resources, few studies have focused on evaluating technology that is capable of simultaneously monitoring multiple, mobile resources at high data collection rates. To be of interest to the construction industry, the tracking technology should meet as many of the criteria listed as follows:

- **Cost and maintenance:** Low implementation and maintenance cost, while rugged enough to withstand a harsh environment and project lengths of up to several years;
- **Device form factor:** Small enough to fit on any asset (as needed) without interrupting the completion of work objectives;
- **Scalability:** Robust in a variety of site layouts (open, closed, and/or cluttered space(s), and small to large spaces);
- **Reliability:** Capable of accurately and precisely recording the activities that are associated to monitored work tasks;
• Data update rate: High data frequency provided in real-time (greater or equal 1 Hz); and
• Social impact: Less invasive technology, but providing highest possible safety and security standards for all project stakeholders while at work (in particular workers that face risks directly).

Existing UWB research in construction applications has focused on evaluating real-time resource location tracking of workers, equipment, and materials in outdoor and indoor environments [24,25,31,32] and first responder tracking applications [26]. Recent research has shown the use of UWB in construction potentially offers a solution to the aforementioned requirements. Compared to other technologies like RFID or ultrasound, UWB has shown to possess unique advantages including: longer range, higher measurement rate, improved measurement accuracy, and immunity to interference from rain, fog, or clutter. This study focuses on the performance capabilities of UWB in real world settings while also demonstrating the operations analysis possible with UWB track signals from multiple project entities.

3. Objectives and scope

The goal of this research is to evaluate the capabilities of a commercially-available Ultra Wideband (UWB) system to record work tasks that occur frequently on construction and infrastructure sites. The first objective is to measure the performance of the real-time tracking technology for mobile resources in realistic job sites. The second objective is to illustrate work tasks that would benefit from such real-time location data. Both research objectives include technology performance testing in live construction environments. The environments were a large and relatively flat lay down yard for handling large pieces of steel material and a construction pit that was classified as a confined space by construction safety professionals. Both had multiple workers, pieces of equipment, material, and other obstructions present at the time of the experiments. Typical scenarios that were observed included heavy construction equipment operating in close proximity to workers. The location measurement error rate of UWB technology in these environments is computed, while the utility of UWB technology is included heavy construction equipment operating in close proximity to workers. The location measurement error rate of UWB technology in these environments is computed, while the utility of UWB technology is discussed and brought into context to existing best work practices with regards to a specific safety or productivity task.

Since extended UWB performance evaluation in the various construction environments has not been performed in previous research, the particular scope of the remainder of this paper is to explore and test the technical feasibility of operating the UWB system in large-scale open construction environments. This paper does not address the social, legal, or behavioral impacts on workers using UWB technology, the sensor node layout and its effect on measurements, nor the comparison of commercially-available UWB systems. The following sections present the methodology, experiments, and results of performance measurements of tracking the real-time location of assets (workers, equipment, material), in open (lay down yard) and dense (object cluttered and confined spaces) construction environments. Demonstration of the UWB signal for safety metrics and work sampling follows.

4. Methodology

This research utilized a commercially-available UWB localization system consisting of a central processing unit, called the hub, which triangulates the positions of incoming Time-Distance-of-Arrival (TDoA) streams from multiple UWB receivers deployed in the construction environment. The UWB signal receivers connect to the hub via shielded CAT5e cables. The TDoA streams originate from actively signaling UWB tags, which are attached to construction resources of interest (worker, equipment, material). In addition, the UWB system requires the placement of a static reference tag in the scene to improve the position measurements of UWB tags. A typical UWB setup and installation with tags on construction assets, including workers, equipment, and materials, is shown in Fig. 1.

The accuracy of the distance measurements will depend on the geometric configuration of the reference point and the receivers deployed in the field. Best practices were followed to ensure a functional setup. The methodology to evaluate the performance of UWB technology in live construction environments included the following tasks:

1. Coordinate field trial with field personnel and construction schedule prior to test day and identify test location.
2. Perform a laser scan of test site to capture existing as-built conditions.
3. Install mid-gain (60° field-of-view) or high gain (90° field-of-view) UWB receivers to cover maximum observation space, while maintaining maximum distance from each other, and facing as few obstructions as possible (at least three receiver TDoA measurements are needed in one plane to measure two-dimensional (2D) tag locations readings, at least 4 receivers are needed at different elevations to measure three-dimensional (3D location readings).
4. Utilize a total station to measure the receiver locations and register them in the UWB hub. Define the RTS and UWB coordinate systems with reference to a common frame.
5. Attach 1 Hz, 15 Hz, 30 Hz, or 60 Hz UWB tags on assets, e.g., workers, equipment, and materials. Choose higher frequency tags for highly dynamic assets, e.g., workers. Document the material, the piece of

Fig. 1. Triangulation of UWB tags using UWB receivers that overlap the coverage area/space and application to construction assets (yard dog and construction worker) inside a lay down yard.
equipment, or the worker’s trade and work task that each tag is attached to.
6. Utilize a Robotic Total Station (RTS) to measure the ground truth location of one asset.
7. Gather real-time UWB and RTS location data.
8. Visualize the information in real-time using a 2D user interface.
9. Use data in post-processing analysis, e.g., for error and proximity analysis.

The first two tasks are part of the ‘preparation phase’, which should occur in advance of the actual experiment. Tasks three to five describe the ‘installation and registration phase’, which should occur immediately prior to the experiment. Tasks six and seven are the ‘data collection phase’, which is the experiment proper. Tasks eight and nine form the ‘data visualization and analysis phase’. As one focus of this paper is the performance evaluation of a commercially-available UWB system in live construction environments, emphasis in the next section is on explaining of the steps associated to task nine.

5. Evaluation of ultra wideband data error

This section describes the procedure followed to assess UWB tracking performance. The default data output stream provided by the UWB system consists of data packets of three types which are differentiated by their packet headers: position data associated to a tag, battery power level information. The data packet associated to tag position data is of the form:

\[
\text{<DataHeader>, <TagID>, <X>, <Y>, <Z>, <BatteryPower>, <Timestamp>, <Unit>, <DQI>}
\]

Each position data packet represents a triangulated position from a unique tag identification (ID). In addition to the tag identification number and the time-stamped spatial data (x, y, z, t) for the UWB tag, the UWB system (a Sapphire DART, Model H651) collects additional status information regarding the tag. Status information includes the battery power level, a message unit, and a Data Quality Indicator (DQI). Sample data and its corresponding path are illustrated in Fig. 2.

The data header “T” of each row means that two-dimensional data is collected. The time stamp is in the UNIX timestamp format. The tag, whose ID is 00005856, has variable X and Y coordinates, and a fixed Z coordinate. The battery level is 13 out of 14 (14 means full). In general, low DQI value means higher data quality.

Previous experiments have shown that the data quality indicator provides values that are insufficient when estimating the error rate of a UWB system in construction environments [25,31,32]; they do not correlate to error. For this reason, a commercially-available 1° construction Robotic Total Station (RTS) was selected to provide real-time ground truth location data. A 360° (mini-) prism was mounted on a worker’s helmet, which was also tagged with UWB tags. The relative height distance between the center of the RTS prism and UWB tag was less than 3 cm and subsequently insignificant for practical tracking applications in a construction environment. Both RTS and UWB systems record real-time spatial and temporal data to prism and tags, respectively. Since the UWB signal are noisy with occasional outliers, the UWB signal was filtered with a Robust Kalman filter [43]. In addition to signal smoothing, the robust Kalman filter rejects outlier measurements so that the outliers do not corrupt the filtered signal estimate. Fig. 3 depicts a UWB track signal filtered by the Robust Kalman filter. Once the temporal correspondence between the two data series is established, the UWB is interpolated and the measurement error is computed with RTS data as the reference.

5.1. Signal synchronization

The UWB system was set up in the same Cartesian coordinate system as the RTS, but operated at different measurement rates, thus comparison of the two signals required signal synchronization. The procedure first consists of resampling the two signals to the same frequency. The frequency chosen was that of the UWB sensor since it required upsampling of the RTS signal (and, consequently, no loss of information). Time synchronization consisted of maximizing the cross-correlation, where the cross-correlation is a measure of the similarity between two signals as a function of a time-shift applied to one of the signals. When the features of both data series (UWB and RTS) match, the cross-correlation is maximized at the time-shift aligning the two signals. Because the cross-correlation can be sensitive to missing or incorrect signal segments, the time synchronization shifts were computed for several signal subsets.

The two data series from both tracking technologies were divided into several signals, each with different time intervals. The cross-correlation and maximizing time-shift were computed for each interval. The cross-correlation computation process for one UWB and RTS interval is

\[
C(\tau_j) \overset{def}{=} R(U | \tau_j) = \sum_{i=1}^{n} R(\tau_j | U[t_i + \tau_j])
\]

where the \(C(\tau_j)\) denotes the similarity between two data streams at time lag \(\tau_j\), while \(R(\tau_j)\) and \(U(t)\) denote the RTS and UWB data respectively. After the time lag, maximizing the cross-correlation for each data subset is found, the average time lag \(\tau_j\) is implemented as the synchronization time lag for the complete data series.

5.2. Error analysis

Once synchronized to the ground truth signal (here, the RTS signal), the UWB measurement error is computable through comparison with the ground truth data. Rather than compare the UWB signal directly to the resampled RTS signal, the method from [44] is used to generate the signal error. In this method, the error associated to a given ground truth location measurement is computed through a weighted average of several UWB measurements (recall that the UWB tag operates at a higher frequency). Given the i-th RTS
measurement occurring at time \( t_i \), define \( t_{i-1/2} \) to be the time halfway between \( t_i \) and \( t_{i-1} \), and similarly define \( t_{i+1/2} \). The index set \( J(i) \) consists of all indices of UWB measurements occurring between \( t_{i-1/2} \) and \( t_{i+1/2} \), e.g., \( J(i) = \{ j | t_j \in \left[ t_{i-1/2}, t_{i+1/2} \right] \} \). All of the measurements associated to the index set are valid measurements to compare against the \( i \)-th RTS measurement. Rather than compare one of the UWB measurements to arrive at the error, a weighted average of the UWB errors of elements in the associated index set is computed,

\[
\text{Error}_{t_i} = \sum_{j \in J(i)} W_{ij} \text{Error}_{t_i}(t_j)
\]

where

\[
\text{Error}_{t_i}(t_j) = ||U[x,y,t_j] - R[x,y,t_i]||
\]

and

\[
W_{ij} = \frac{4t_j - 4t_i + 2}{\Delta T^2}
\]

with

\[
\sum_{j \in J(i)} W_{ij} = 1.
\]

At the time \( t_i \), the RTS data can be directly retrieved from the records, while the error of UWB measurement is computed by the weighted average of the errors between the UWB data found within one RTS data collection period \( \Delta T \) to the RTS data at the time \( t_i \). The weight factor \( W_{ij} \) is a function of time, with a greater contribution to the average error when the UWB data is recorded at the time closer to \( t_i \). Fig. 4 depicts the error computation with the weight factors represented by circles of differing radii.

6. Experiments and results

This section consists of four major subsections. The first details the experiments performed and their overall characteristics. The second collects the experimental data and examines the expected error rates of UWB when deployed for real-time tracking. The last two demonstrate practical benefits of having the real-time UWB track data for analysis. In particular, the coordinated activities of workers moving a load is assessed from a safety perspective, and the time trajectories of a worker are analyzed to demonstrate automated work sampling.

6.1. Description of the experimental environments

There were a total of three experimental environments, one controlled and two real-world construction areas. The controlled area was an open field. The two construction areas were located on a large industrial job site (see Fig. 5). They were a construction pit (classified as a confined space by construction safety professionals) and a lay down yard for temporarily placing steel materials. To understand resource flow visually and connect the trajectories to their surrounding

---

**Fig. 3.** Raw UWB data (left) and sample of Robust Kalman Filtered UWB data (right).

**Fig. 4.** Schematic of error computation: UWB location track signal and visualization of comparison with RTS signal.
environment, a commercially-available laser scanner gathered the three-dimensional (3D) point cloud and a camera documented the as-built conditions prior to the experiments. The focus of data capturing was on recording resource location from naturally occurring work tasks in harsh (i.e., resource rich, spatially challenging, object cluttered, metal) construction environments. Thus, the experiments lasted several days to make the workforce familiar with the presence of UWB, RTS, and laser scanning technology.

Each resource entering the work zone was tagged. Here, a resource refers to either a worker, a piece of equipment, or material. Available UWB tags varied from low to high frequency (1 Hz to 60 Hz) and from low to high power (5 mW to 1 W). The decision on which tag type was applied to each of the resources was made based on the resource, its velocity, and its operational environment. For example, a badge-type UWB tag was attached to steel material as the form factor (length/width/height = 7.4/4.2/0.7 cm) and high power (1 W) were best suited for attachment to the metal material. High frequency tags were (15/30/60 Hz) were attached to the helmets of workers as their movements required more frequent location monitoring. In some cases, multiple tags were attached to a single resource. All UWB tag locations were simultaneously tracked at update rates of at least 1 Hz. A 1 Hz tag was designated to be the static reference tag for the UWB receivers. As previously described, a commercial 1° Robotic Total Station (RTS) measured the ground truth (x, y, z, and timestamp) of UWB tag(s) using a 360° mini-reflector-prism that was installed on the helmet of one worker or on a prism rod (see Fig. 5).

6.1.1. Open field

In order to provide a more complete picture of the tracking performance characteristics associated to UWB as a function of the site diameter, several controlled experiments were conducted in an open field. Four UWB receivers were placed in a square configuration. Within the primary sensing zone (where there were at least three receivers within the field-of-view), a person equipped with UWB tags and an RTS prism (all helmet mounted), was tasked to walk in a rectangular pattern. The same experiment was repeated for four UWB receiver diameters (20, 40, 60, and 70 m). The trajectory of the person was scaled accordingly with the receiver configuration diameter (the diameter is the maximum pair wise distance between two installed receivers when considering all possible receiver pairings). Fig. 6 depicts the square UWB receiver layout and the location of the reference tag. Unlike industrial site environments, the open field provides the ideal environment for UWB sensing as there were no obstructions.

6.1.2. Construction pit

This experiment was conducted in a confined work area of approximately 2400 m². The registered 3D point cloud of the as-built conditions at the time of the experiment can be seen in Fig. 7. The red triangles represent the location and orientation of the UWB receivers (short edges indicate the direction), while the green circle represents the location of the static reference tag. UWB trajectory data for a few of the tracked resources are overlaid in the image. Of note, two access points (ramps for equipment and workers) allowed entry into the confined space. The south side of the pit was specified as a confined space (a 20 meter long, three meter wide, and five meter high space, with unstable walls and a repose angle of greater than 45°).

The work crew consisted of several workers (six carpenters, ten rod busters, eight form workers, 2 foremen, and one crane operator) and equipment (one mobile crane, one tractor and two material hauling trailers). Although location data of the entire crew was collected, the following observations include (for illustration purposes) data to one carpenter erecting formwork, two rod busters tying rebar, one foreman supervising, and crane operator hoisting materials with the crane. The work task of the day was to erect formwork and rebar to all sides of a four meter tall rectangular reinforced concrete structure (close to the center of the excavated pit). Although the work activities and locations of resources were recorded for the entire work day, only a sample (43 min and 22 s) of the entire UWB data set will be analyzed. The data sample includes events linked to the crane unloading rebar into the pit.

6.1.3. Lay down yard

The second field trial environment included monitoring resource locations in a large lay down yard which had significant quantities of metal steel pipe and girder objects present. The size of the lay down yard and available UWB receivers limited the observation area to approximately 65,000 m². The major material bays comprised mostly of custom fabricated steel pieces, which were well laid out for workers and equipment to move around. At the time of the experiment, equipment and ground workers had only one access point available to the yard and one tool and restroom area. Nine UWB receivers were set up at the boundaries (fences) of the lay down yard. A reference tag

---

Fig. 5. Layout of experiments: construction pit (left), lay down yard (middle), and UWB tag and RTS prism on helmet (right).

Fig. 6. Open field receiver layout.
(green circle) in the line-of-sight of all receivers was placed on a 2.5 m high pole overlooking all steel materials. The location of important control points such as material bays, fence, road, and other installations in the lay down area were recorded using the RTS. These measurements were used to develop an approximated plan view of the lay down yard. The plan view of the lay down yard, access gate, work and tool box areas, and other facilities, including the UWB receiver locations (red triangles) are illustrated in Fig. 8. The dark areas are the material bays where material was frequently placed or picked up. A 34 minute subset of the data was elected for analysis.

6.2. Tracking performance analysis of ultra wide band

This section analyzes the error between the ground truth RTS signal and the UWB signal. We must first acknowledge that different tasks require different levels of accuracy. For the tasks being examined here, high fidelity (on the order of centimeters or millimeters) is not necessary. What is essential is that personnel utilizing the track data can effectively use it for analysis and operations purposes. With this in mind, an opinion based worker survey was taken. For material discovery in large lay down yards, those surveyed identified the ability to “quickly locate materials within a two meter radius” would assist in the efficiency of their work. This is consistent with other research indicating that meter accuracy is sufficient for the majority of work tasks [4,6,32].

6.2.1. Performance in the construction pit

The track signals of a worker fitted with a 60 Hz UWB tag and the RTS prism are plotted in Fig. 9(a). The observation period collected 603 synchronized samples for the 1 Hz tag and 2654 synchronized samples for the 60 Hz tag. The average error of the 1 Hz tag was 0.48 m for raw data and 0.41 m for the filtered data. The average error of the 60 Hz tag was 0.36 m for raw data, and 0.34 m for the filtered data. The low average error coupled with a standard deviation of 0.35 m/0.20 m for 1 Hz/60 Hz, respectively, means that real-time location tracking utilizing UWB technology in similar construction environments is feasible.

6.2.2. Performance in the lay down yard

The track signals of a worker fitted with 1 Hz and 60 Hz tags, and he RTS prism are plotted in Fig. 9(b). The observation period led to 1023 synchronized samples for the 1 Hz UWB tag and 4370 synchronized samples for the 60 Hz UWB tag. The average error of the 1 Hz tag was 1.82 m for raw data, and 1.26 m for the filtered data. The average error of the 60 Hz tag was 1.64 m for raw data, and 1.23 m for the filtered data. In this experiment, the larger covered area required to separate the UWB receiver distances to the upper limits of the suggested receiver configurations for some of the receiver pairings. Given that
the error rates were within the suggested range for locating materials, and low standard deviations of 0.72 m/0.66 m for 1 Hz/60 Hz, respectively. UWB localization technology in large, open, outdoor areas is feasible. Detailed results are shown in Tables 1 and 2.

6.2.3. Performance as a function of UWB receiver diameter

The data from the open field experiments and the two site experiments was collected and plotted in the form of several error box plots and organized by increasing diameter (see Fig. 10). The box diagram shows the lower quartile, median and upper quartile of the computed tracking errors. The lowest and highest errors within a factor of 1.5 of the inter-quartile range lie are demarcated by the horizontal bars below and above the box. The “+” symbol marks outliers.

Up to the 70 m diameter measured, the error rates are well within the tolerances expected by workers for the majority of their work tasks. Note further, that the construction pit scenario (diameter of 65 m) lies between two best-case, controlled scenarios (45 m and 70 m). Comparison of the error rates shows that performance does not degrade significantly, thus construction environments similar to the construction pit should lead to similar performance. When the diameter increases to 270 m, as in the case of the lay down yard, the error rate grows, however it is low enough to perform materials search. Importantly, for the 270 m distance setup 99.9% of reported UWB data lies within 4 m of associated the RTS measurement, while over 75% of the reported UWB data lies within 2 m.

6.3. Safety analysis in the construction pit

Since 25% of all construction fatalities relate to too close proximity of pedestrian workers to equipment [15,17], a particular emphasis in the experiment was to study the interaction of workers with equipment. To demonstrate how UWB tracking could assist, consider one of the hoisting operations. The last of the three hoists (“A”, “B”, and “C”) is associated with the drop-off zone labeled by a “C” in Fig. 7. The rebar load was attached to the hook of the mobile crane at “C1”, in Fig. 11. The crane and its attached load started swinging toward the drop location “C3” at timestamp 108 (seconds) and arrived at timestamp 267 (seconds). Detaching the load from the crane hook took the worker (5CD0) 224 s before the crane swung back to its original load location “C1”. This one material delivery cycle lasted approximately 10 min.

A spatio-temporal analysis of the worker assisting the process provides clues into the worker’s behavior. For safety purposes, the worker should maintain a safe distance from the moving load until it has been safely lowered. While the crane boom was swinging, the worker (5CD0) originally occupied the drop location “C”. As the crane was swinging toward him, the worker-to-crane hook distance decreased continuously from over 30 m to 13.4 m. Being warned by the horn of the crane and realizing the load was getting closer to the worker, he stepped outside the potential path of the crane load and moved temporarily to “C4”. As shown in Fig. 11, a safe distance of about
14 m was maintained between the worker and the crane hook. As soon as the crane stopped swinging, the worker approached the load to unhook it from the crane. The worker-to-crane hook distance then dropped to less than 3 m. After completion, the crane swung back using path “C2” and the worker moved to another work location “C5”.

### 6.4. Automated work sampling

Another application example demonstrating the utility of UWB location tracking data is for automated work sampling. Based on pre-defined work and wait areas, which will be called zones, location tracking data can be used to decompose a worker’s presence in the zones versus time. The sampling of zone proximity and travel times on a more detailed level and over longer temporal durations becomes feasible when it is automated. Typically, the data is obtained manually, which places an upper limit on the frequency and duration of data collected, while also placing limits on accuracy given the subjective nature of the measurements [11,45].

Ten minutes of trajectory data of a worker (08C6) are illustrated in Fig. 12. The graphs in Fig. 13 show the traveling speed of a worker and his distance to two work related zones and one wait zone. The dashed lines represent thresholds below which the worker is presumed to not be moving or within the confines of a defined zone in the case of a distance threshold. Assuming a worker traverses at a velocity similar to the walking speed of a human.

<table>
<thead>
<tr>
<th>Raw data</th>
<th>Filtered data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average error (1 Hz) [m]</td>
<td>1.82</td>
</tr>
<tr>
<td>Standard deviation (1 Hz) [m]</td>
<td>1.67</td>
</tr>
<tr>
<td>Average error (60 Hz) [m]</td>
<td>1.64</td>
</tr>
<tr>
<td>Standard deviation (60 Hz) [m]</td>
<td>1.23</td>
</tr>
</tbody>
</table>

**Fig. 10.** Error box plots of UWB signal as UWB configuration diameter increases.

**Fig. 11.** In-depth look at worker–crane interaction (distances) during a material hoist.

---

<table>
<thead>
<tr>
<th>Summary of construction lay down yard</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWB data points collected (1 Hz) [No.]</td>
</tr>
<tr>
<td>Duration [mm:ss]</td>
</tr>
<tr>
<td>Synchronized data pairs (1 Hz) [No.]</td>
</tr>
<tr>
<td>UWB data points collected (60 Hz) [No.]</td>
</tr>
<tr>
<td>RTS data points collected [No.]</td>
</tr>
<tr>
<td>Synchronized data point pairs (60 Hz) [No.]</td>
</tr>
</tbody>
</table>

**Table 2**

Statistical results of experiment in lay down yard.

---

### In-depth look at worker–crane interaction (distances) during a material hoist.

- The crane hook stays at C1
- The crane boom swings from C1 to C2
- The worker moves from C4 to C3
- The worker moves from C3 to C5
- The worker moves from C5 to C1

---

Error box plots of UWB signal as UWB configuration diameter increases.

---

The graphs in Fig. 13 show the traveling speed of a worker and his distance to two work related zones and one wait zone. The dashed lines represent thresholds below which the worker is presumed to not be moving in the case of a velocity threshold, or within the confines of a defined zone in the case of a distance threshold. Assuming a worker traverses at a velocity similar to the walking speed of a human.
speed of pedestrians which is about 1 m per second [46], similar or
greater speeds can account for changing the work position, while
slower speeds (in combination with absolute location position over
time) imply a constant work position. Thus, a speed threshold of
0.5 m/s is defined. For work/wait zones, a radius of 3 m defines the
work area given a coordinate location for the zone.

Fig. 12. Job site zone depictions for automated work sampling analysis.

Fig. 13. Automated work sampling for a worker based on UWB track signal: (a) worker traveling speed and distances to work/wait zones, and (b) activity decomposition based on pre-defined work zones.
In this example, the worker started in “Work Zone 1” and traveled to “Work Zone 2”. After staying in “Work Zone 1” for about 170 s, the worker moved within 30 s to the “Waiting Zone”, where he spent more than 200 s. The worker then returned to “Work Zone 2” within 30 s and remained there for 130 s before the observation period ended. The pie-chart in Fig. 13 illustrates the results of automated work sampling as determined automatically from the data in Fig. 12.

Even with complete information regarding the work process and product such as would be provided in a building information model [47], location based monitoring of construction work activities can only be conclusive concerning the amount of time spent in a given zone. Additional inspection is required to estimate the work completed, and thereby the value added. Combining automated work sampling with additional (possibly occasional) inspection would enable productivity analysis [11,13,18].

7. Conclusions

Rapid technological advances have made it possible to implement Ultra Wideband (UWB) real-time localization and tracking systems in construction applications. While possible, the capabilities and benefits of UWB deployment require further study, which is the aim of this investigation. This paper demonstrated, in field trials, that a commercially-available UWB system is able to provide real-time location data of construction resources thereby resolving the capability question. Validation occurred through performance measurements utilizing a Robotic Total Station (RTS) for ground truth measurements. Aside from validating the ability to collect reliable spatio-temporal data from job sites, it is also important to demonstrate automated information extraction from the data. Thus, limited field data was analyzed from safety and work sampling perspectives. The safety application demonstrates the benefits of applying location tracking data for better documenting, analyzing, understanding, and correcting best safety practices as they are executed in the field. In this particular case, successfully computing the distance between two dynamic construction resources (worker and crane hook) allows analyzing for too-close proximity of resources, and eventually preventing struck-by incidents [15]. The work sampling application exposed the benefit of applying location tracking data to automate conventional work sampling techniques. Automated work sampling, however, may demand more details than the location tracking data provides; for example, is the worker carrying a tool (productive task) or not (unproductive task)? Automated location tracking data and work sampling has tremendous utility for productivity analysis of long term work tasks involving multiple resources that possibly traverse the job site. Future research has to address these issues.

In summary, UWB technology in large open space construction environments achieves sufficient accuracy as to be practical for many open environment construction application areas. Overall, the presented work showed that real-time location tracking has potential construction applications in assisting the safety and productivity management of job sites and other areas requiring monitoring and control. Further, construction engineering and management concepts would benefit from the real-time location tracking data that UWB, and other, technologies provide.

Acknowledgements

This research was partially funded by the National Science Foundation (NSF) under grant CMMI-CS #08000858 and the Construction Industry Institute (CII) under grant RT269. Their support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of others.

References


