Real-time Automated Construction Worker Location Tracking for Spatio-Temporal Safety Analysis and Feedback

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Abstract

Emerging sensing technologies offer significant potential to advance the construction safety 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 such emerging technology, effectively impeding widespread adoption. This paper evaluates a commercially-available Ultra Wideband (UWB) system for real-time, mobile resource location tracking in construction environments. A focus of this paper is to evaluate the performance of technology for tracking mobile resources in real-world construction settings. The paper provides case studies of resource tracking for analysis of safety worksite operations and demonstrates its applicability for the design of construction safety management support tools.

Keywords: 3D, location tracking, proximity, safety, sensing and safety technology, visualization, workers.

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 (Navon and Berkovich, 2006). Recent developments in remote sensing and automated data acquisition technology promise to improve upon existing material management strategies (Song, et al., 2006, 2007; Akinci et al., 2008; Grau, et al., 2009). 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 – but are not limited to – the risk of failure during the initial implementation phase and the high cost of implementation. When these risks are combined with the lack of demonstrated benefits, adoption of emerging technology can be non-existent. The penetration of emerging technology is thus limited to scattered implementations in various engineering subfields until more precise cost-benefit valuations are determined (Bohn et al., 2010). It is therefore highly imperative to understand the benefits of promising real-time location tracking technology so as to increase adoption and to advance production control procedures in the construction industry. Two key areas closely tied to the economics of construction projects are productivity and safety (Tuchman, 2009); 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 (Lundberg and Beliveau, 1989; Goodrum et al., 2010). For example, material handling and transport has been identified as a critical work task in construction (Nasir et al., 2010). Recent studies report significant amounts of time spent on materials searches in lay down yards (CII, 2010). 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 (Navon and Sacks, 2006).

Within the context of safety, significant time and economic resources are lost when workers are injured or killed by loads during work tasks (Teizer et al., 2010; Hinze and Teizer, 2011). Current construction best practices in material handling prescribe the foremen 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 (Teizer et al., 2009).

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’ (Borcherding, 1976; Wang et al., 2009; and CII 2010). 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 (Navon and Goldschmidt, 2003, and Eastman and Sacks, 2008).

Wireless, non-destructive, and reflector-less sensor technologies applied to construction have been identified as key breakthroughs (Nasir et al., 2010) 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 in context to safety, 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 capabilities are available for use in construction and infrastructure projects (Akinci, 2008). 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 (Teizer et al., 2007 and 2010; Cho et al., 2010). These characteristics must be weighed against the benefits provided.

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 below:

- 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 (Teizer, 2007, 2010, Cho, et.al., 2010, Saidi, et al., 2010; Fontana et al., 2002) and first responder tracking applications (Khoury and Kamat, 2009). Recent research has shown the use of UWB in construction potentially offers a solution to the above 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.

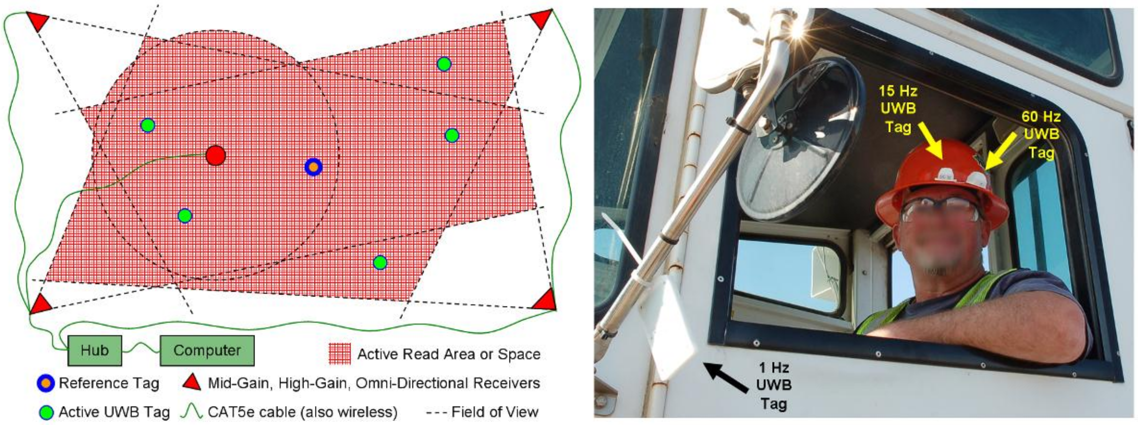


Figure 1: Triangulation of UWB tags using UWB receivers that overlap the coverage area/space and application to construction assets (yard dog and construction worker) inside a lay down yard.

3. Objectives and Scope

The goal of this research is to evaluate the performance of a commercially-available Ultra Wideband (UWB) system when used for assessing the safety aspect of 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 safety monitoring 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. 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.

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 Figure 1. More details to the experimental setup can be found in (Cheng et al., 2010). 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 UWB receivers to cover maximum observation space.
4. Utilize a total station to measure the receiver locations and register them.
5. Attach 1 Hz, 15 Hz, 30 Hz, or 60 Hz UWB tags on assets, e.g., workers, equipment, and materials.
6. Utilize Robotic Total Station (RTS) to measure the ground truth location of assets.
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.

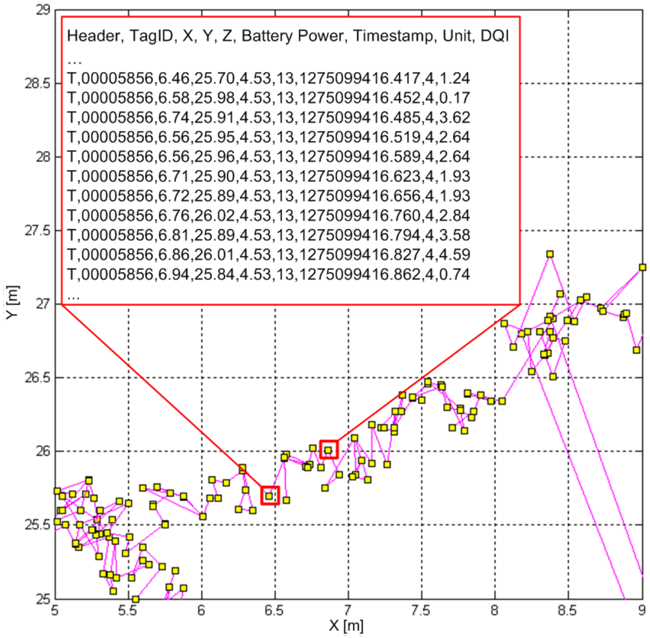
5. Evaluation of Ultra Wideband Data Error

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 sensed tag, status information regarding the receivers, and reference tag information. The data packet associated to tag position data is of the form:

<Data Header>,<TagID>,<X>,<Y>,<Z>,<Battery Power>,<Timestamp>,<Unit>,<DQI>

Each position data packet represents a triangulated position from an 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 Figure 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.

Since the UWB signal are noisy with occasional outliers, the UWB signal was filtered with a Robust Kalman filter (Durovic and Kovacevic, 2009). In addition to signal smoothing, the robust Kalman filter rejects outlier measurements so that the outliers do not corrupt the filtered signal estimate. Further details to the method of signal synchronization and error analysis can be found in (Saidi et al., 2010).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Header, TagID, X, Y, Z, Battery Power, Timestamp, Unit, DQI
...
T,00005856,6.46,25.70,4.53,13,1275099416.417,4,1.24
T,00005856,6.58,25.98,4.53,13,1275099416.452,4,0.17
T,00005856,6.74,25.91,4.53,13,1275099416.485,4,3.62
T,00005856,6.56,25.95,4.53,13,1275099416.519,4,2.64
T,00005856,6.56,25.96,4.53,13,1275099416.589,4,2.64
T,00005856,6.71,25.90,4.53,13,1275099416.623,4,1.93
T,00005856,6.72,25.89,4.53,13,1275099416.656,4,1.93
T,00005856,6.76,26.02,4.53,13,1275099416.760,4,2.84
T,00005856,6.81,25.89,4.53,13,1275099416.794,4,3.58
T,00005856,6.86,26.01,4.53,13,1275099416.827,4,4.59
T,00005856,6.94,25.84,4.53,13,1275099416.862,4,0.74
...
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Figure 2: Sample and format of raw UWB data.

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 are assessed from a safety perspective.

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 Figure 3). 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 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.

Figure 3: Layout of experiments: Construction pit (left), lay down yard (middle), and UWB tag and RTS prism on helmet (right).

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 meters). 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). Unlike industrial site environments, the open field provides the ideal environment for UWB sensing as there were no obstructions.

Construction Pit. This experiment was conducted in a confined work area of approximately 2400 m^2. The registered 3D point cloud of the as-built conditions at the time of the experiment can be seen in Figure 4. 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°).

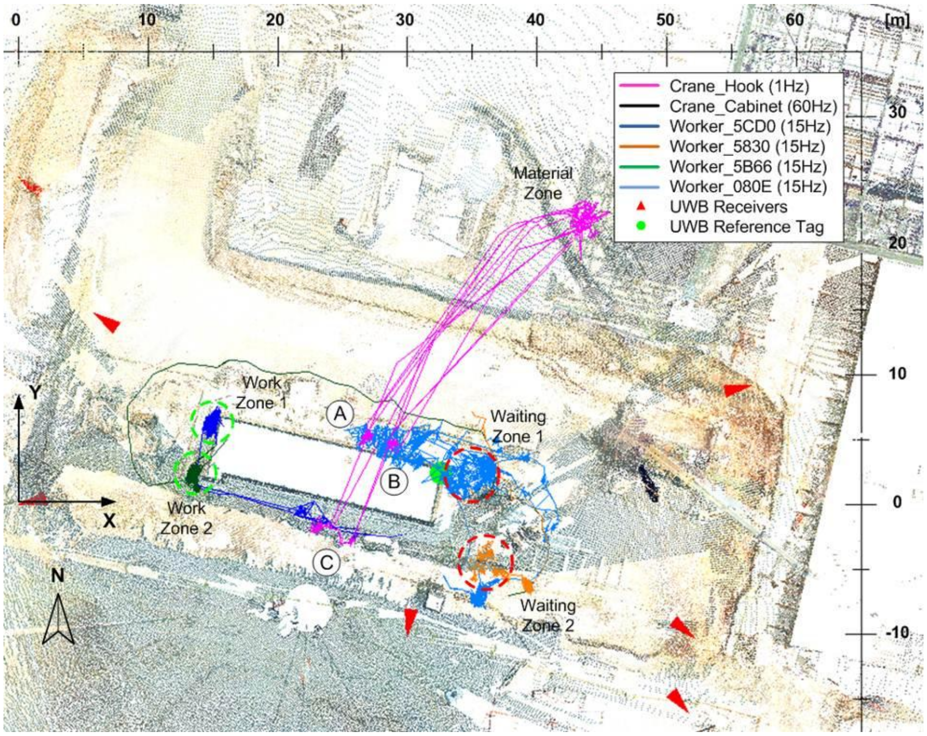


Figure 4: Plan view of construction pit: UWB resource trajectory data mapped on the registered range point cloud from a 3D laser scanner.

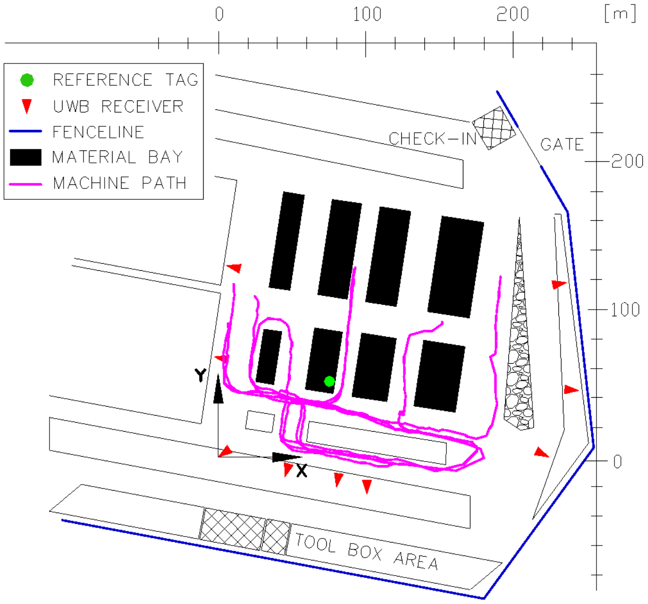
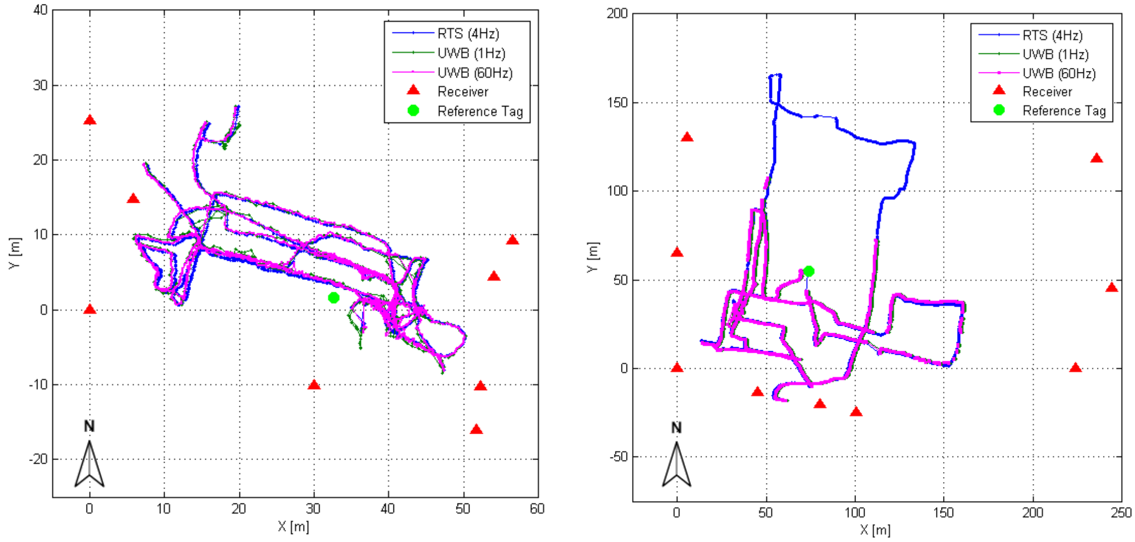


Figure 5: Lay down yard with overlaid sample of the UWB trajectory data of a yard dog (a construction vehicle to transport material).

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 minutes and 22 seconds) of the entire UWB data set will be analyzed. The data sample includes events linked to the crane unloading rebar into the pit.

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 65000 m^2. 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 (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 installments 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 Figure 5. 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.



(a) Construction pit. (b) Lay down yard.

Figure 6. Synchronized UWB and RTS trajectories.

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 materials discovery in large lay down yards, those surveyed identified the ability to "quickly locate materials within a two meter radii" 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 (Song et al., 2007; Grau et al., 2009).

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 Figure 6(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 0.35m/0.20 m for 1 Hz/60 Hz, respectively, means that real-time location tracking utilizing UWB technology in similar construction environments is feasible.

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 Figure 6(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.

Safety Analysis in the Construction Pit

Since 25% of all construction fatalities relate to too close proximity of pedestrian workers to equipment (Teizer et al., 2009, 2010), 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 Figure 7. The rebar load was attached to the hook of the mobile crane at "C1", in Figure 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 seconds before the crane swung back to its original load location "C1". This one material delivery cycle lasted approximately 10 minutes.

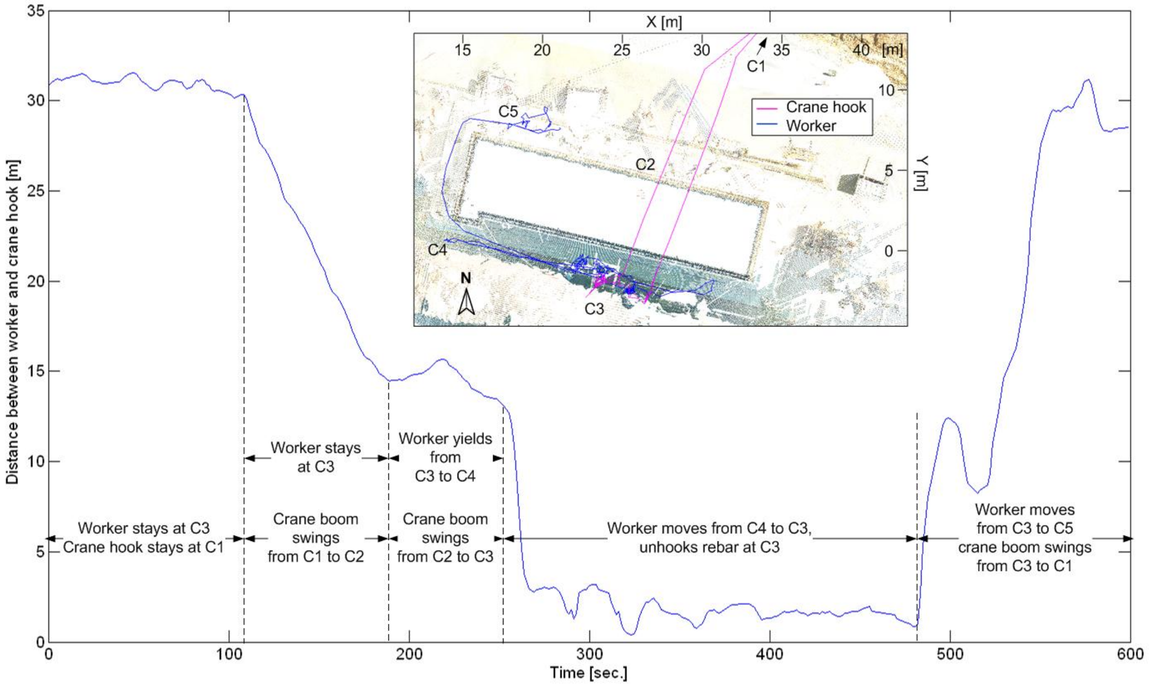


Figure 7: In-depth look at worker-crane interaction (distances) during a material hoist.

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 meters to 13.4 meters. 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 Figure 7, a safe distance of about 14 meters 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 three meters. After completion, the crane swung back using path "C2" and the worker moved to another work location "C5".

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 location tracking system (UWB) 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 being able to collect reliable spatio-temporal data from job sites, it is also highly imperative to understand the benefits of promising real-time location tracking technology so as to increase adoption and advance production control procedures in the construction industry. 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 (Teizer, 2010).

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 management of job sites and other areas requiring monitoring and control.

Acknowledgements

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