Journal of Applied Geodesy 4 (2010), 23–32 © de Gruyter 2010. DOI 10.1515/JAG.2010.003

A case study on the feasibility and performance of an UWB-AoA real time location system for resources management of civil construction projects

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Abstract. The application of integrated satellite and modern wireless positioning technologies for ubiquitous real-time resources management in large scale civil engineering projects can greatly optimize the time and cost in the construction process, and is now the trend for modern construction project management. As the outdoor conditions of most civil construction sites are open to sky, satellite positioning with the popularly used Global Positioning System (GPS) has been proved to be very efficient and effective. However, the condition in indoor and underground construction site is very complicated due to the fact that different construction activities would be carried out in different congested areas, involving heavy construction plant, equipment, professionals and technical personnel. Nowadays different emerging technologies such as Wi-Fi and ZigBee can be adopted for position and tracking in indoor environments. Nevertheless, under the very complicated construction site conditions these technologies may fail due to movement of human resources and construction plant, variation of metrological conditions, and serious multipath effects of signals. It is considered that Ultra Wide Band (UWB) technology is more suitable for indoor construction site environments. In this paper, a case study on the attempt of integrating GPS with Ubisense Real-time Location System (RTLS) for resources management in an underground railway construction site is discussed. Laboratory and field tests have shown that the RTLS can provide better resources management capability in terms of positioning accuracy and stability than Wi-Fi and ZigBee technologies under complicated construction environments. The test results show that the system can normally achieve better than 15 cm accuracy, and better than 1 m under adverse geometrical site condition. However, the high instrumental set up cost and the requirement for high quality data transmission cable for high precision time synchronization between sensors may deter wide application of similar system for resources management in construction sites.

Keywords. GPS, Ultra Wide Band, resources management.

1. Introduction

Applications of wireless positioning technologies for real time resources management include, but not limited to, for example, asset and personnel tracking, work flow monitoring of manufacturing processes, logistics and supply chain, and security management. In a large scale civil engineering project, resources are moving or allocated either within a project site or at various site locations, in both indoor and outdoor environments. To effectively optimize manpower, construction plant and equipment, and to facilitate rescue in case of emergency, it is necessary to understand the distribution of different resources in real time. The application of integrated satellite and modern wireless positioning technologies for ubiquitous real-time resources management in large scale civil engineering projects can greatly optimize the time and cost in the construction process, and is now the trend for modern construction project management. Global Navigation Satellite Systems (GNSS) have been widely used for high precision engineering surveying applications such as control point establishment, deformation monitoring, and setting out using static, rapid static, or real time kinematic methods. Besides these high precision positioning applications, low-cost high sensitivity GPS receivers able to achieve meter to sub-meter level positioning accuracy suitable for location based applications are readily available on the market. Civil construction sites generally have good receiver-satellite visibility in outdoor environments, hence GPS plays a significant role in outdoor positioning. Nowadays different emerging technologies such as Wi-Fi and ZigBee (Mok 2007 and Mok, Lau and Xia 2007) can be adopted for positioning determination in indoor environments. These technologies rely very much on the signal strength in the positioning algorithms, therefore under very complicated indoor site conditions when the area has frequent movement of human resources and construction plant, or rapid change of surrounding objects, the instability of signal strength pattern may lead to failure or big error in the positioning solution. The increasing demand for high speed wireless transmission of multimedia information and precise geolocation positioning in indoor environments have led to specific interests on UWB, a radiocommunication technology originally developed for military applications in 1960. UWB transmission which is predicted to have ample applications from computer and home peripherals to mobile and handheld devices, and high precision positioning, has the following advantages: (i) With the large bandwidth, the signal is very difficult to be detected and tracked, therefore signal transmission is highly secured. Moreover, large bandwidth implies less time measurement uncertainty and more precise range data can be obtained, (ii) Extremely low transmission powers make less or no interference to other radio signals, (iii) The bandwidth of waveform pulse signals are narrow, therefore signals are more robust to multipath effect. Moreover, multipath effects can be more easily controlled by a well-designed filter. The Ubisense Real-time Location System (URTLS) is one of a few UWB positioning systems available on the market. This system is claimed to be able to achieve 15 cm 3-D positional accuracy in real-time. Industrial applications include tool tracking in vehicle manufacturing, tracking of attendees in larger conference venue, and proximity detection between objects. The objectives of this research are (i) to explore how Ubisense RTLS and GPS positioning data may be integrated for ubiquitous resources management, and (ii) to assess the feasibility of applying such an integrated system for large scale civil construction projects that involve resource monitoring in both indoor and outdoor environments. These will be discussed in the following sections.

2. Ultra Wide Band positioning

UWB systems operate very differently compared to traditional systems (Hulbert and Streeton, 2003). First, to be qualified as a UWB channel, the corresponding signal needs to occupy a bandwidth of no less than 500 MHz, which is substantially higher than those of other commonly used wireless systems. Second, instead of transmitting at dedicated, interference-free frequency bands, UWB systems transmit in bands which are already occupied by other wireless systems. For example, within the UWB frequency band, i.e., 3.1 to 10.6 GHz, the following wireless systems have already existed: wireless local area network 802.11a operating at 5 GHz, fixed microwave links operating at 6 GHz and satellite links at 4/6 GHz. In other words, when the UWB systems are in close proximity with other wireless systems, the UWB signals may interfere with existing wireless signals in the band which in turn may interfere with the UWB signals. To minimize its interference to others, UWB signals keep the power density of its transmission signal to no more than −41.3 dBm/MHz. Two main streams of UWB systems are being developed: high speed data transfer of up to 480 Mbps within a few meters versus low power consumption, and low data-rate, longer distance for sensors/distance measurement. For high speed communications, UWB makes use of MB-OFDM (Multi-Band Orthogonal Frequency Division Multiplexing) (Zhou and Lau, 2007) or DSSS (Direct Sequence Spread Spectrum) modulations whereas in low data-rate applications, impulse radio is used (Gaffney, 2004). The American Federal Communications Commission (FCC) was the pioneer organization who gave definitions and rulings of UWB technology. To avoid interference to the existing radio services, they published the First Report and Order in (FCC, 2002) to limit the UWB radiation and also permitted the technology commercialization. The document defines the radiation masks as shown on Figure 1. The Ubisense RTLS tested in this project is modulated with OFDM, has the maximum tag-sensor range of 50 m, and the positioning area can cover up to 400 m^2 with four sensors (Ubisense, 2010).

An important feature of UWB is the high standard requirement for clock synchronization between transmitter and receiver. Therefore, the Time of Arrival (TOA) or Time Difference of Arrival (TDOA)

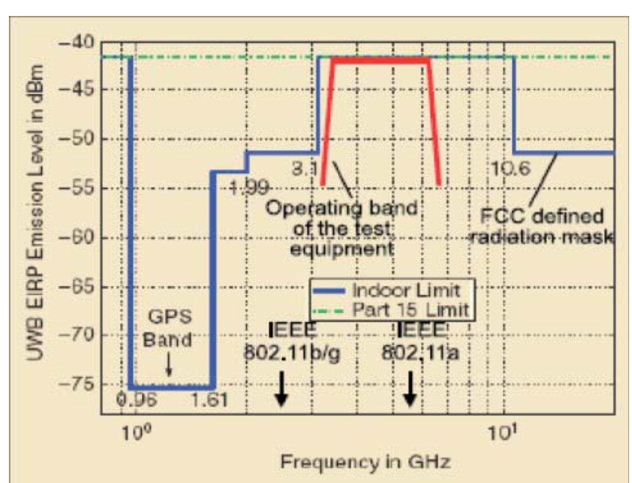

Figure 1: UWB Radiation Mask Defined by the FCC and the Operating Spectrum of the Equipment in Use.

technique (Kolodziej and Hjelm, 2006) are suitable to acquire accurate range data for position fix. In practice, the TDOA technique is preferred, since between-sensor differencing will result in the elimination of clock bias of the positioning tag, therefore it only requires synchronization of sensors.

3. The Ubisense Real-time Location System

Figure 2 shows the architecture of the RTLS. According to specification, the system adopts 2.4 GHz for telemetry and 5.8 to 7.2 GHz for UWB transmission, and is able to achieve better than 15 cm accuracy in horizontal position as well as height components. Similar to other sensor network systems, the hardware includes sensor and tag components. Each sensor contains an array of antennas for determining azimuth and elevation angle of the signal from positioning tags, and hardware to receive UWB signal. With this hardware configuration and data collection capabilities the system can perform three-dimensional position fixing by Angle of Arrival (AoA), TDOA, or their combination. With the TDOA approach, the tags are not required to synchronize with the sensors, where time synchronization between sensors is achieved by connecting a high quality timing cable to a port at the back of the sensor, as shown in Figure 3. This RTLS should be more precisely described as a hybrid angular (AoA) and UWB (TDOA) positioning system.

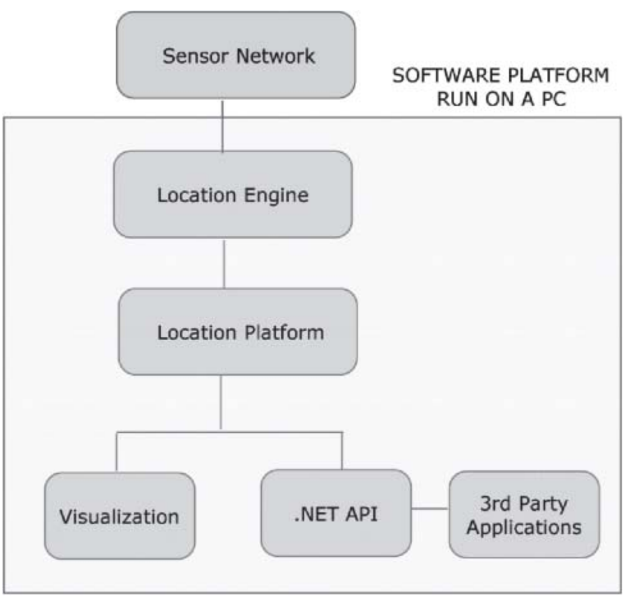

Figure 2: Schematic diagram of the Ubisense RTLS.

The Location Engine is a software that runs on a PC platform. The software is able to tune the sensor network to its optimum performance, carry out real time position tracking, and allow extraction and transfer of data to an external program through the .NET API. The Visualization component provides visual aid to the RTLS by displaying the whereabout the tags are in real time. The Location Platform is a software platform to gather data from positioning sensors as well as from other non-location sensors installed in the system, such as temperature and motion detectors. The Location Platform also allows users to define location based responses in the visualization component, for example, highlighting an object when the tag has entered a defined zone.

4. Integration of GPS and the Ubisense RTLS

Figure 4 shows how the integration of GPS and RTLS positioning results is achieved. As discussed above, the Ubisense RTLS has the flexibility for third-party application development by using the .NET API. An external program can be readily developed for transmitting the tracking positions to a data center through the TCP/IP internet protocol. Nowadays, low-cost GPRS communication enabled

Figure 3: Ubisense UWB-AoA sensors (left) and a typical UWB-AoA tag (right).

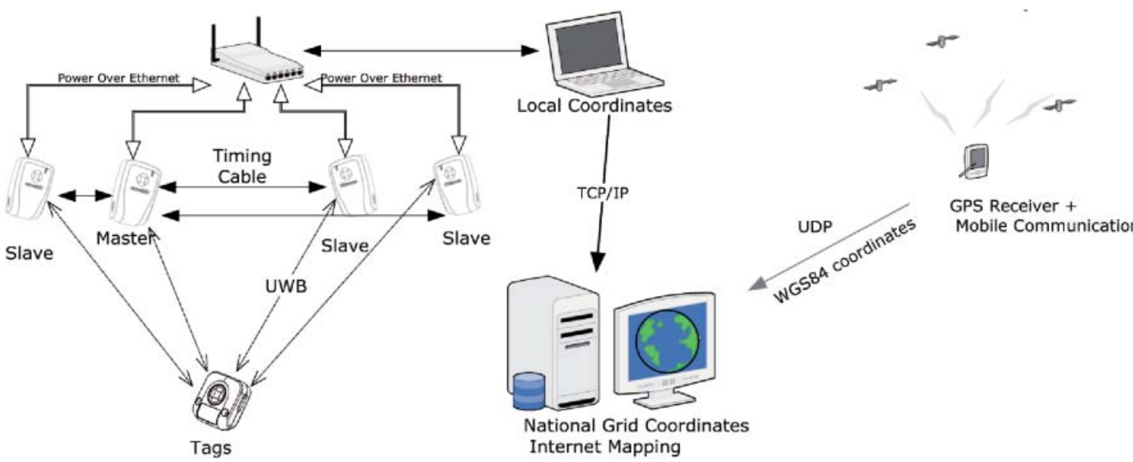

Figure 4: Integration of GPS and the Ubisense Real Time Location System.

Figure 5: An example of low-cost GPRS enabled GPS tracker.

GPS trackers are readily available on the market. This type of GPS tracker contains the functionality of transmitting the NMEA data stream to a specific Internet Protocol (IP) Address, hence at the data center a User Datagram Protocol (UDP) client program can be developed to monitor the incoming GPS NMEA data. At the data center, a coordinate transformation is performed to convert the local coordinates of RTLS positions and WGS84 coordinates from GPS results to the national coordinate system, before the integrated results can be used in an application. Figure 5 shows an example of the GPRS enabled GPS tracker. The IP Address setting and GPRS Access Point Name (APN) setting can be achieved by sending an SMS command to the tracker with the format shown below:

APN setting:	command number#password #APN
IP Address setting:	command number#password #IPAddress#Port Number

Different mobile service providers have their unique APN, of which information can be obtained from the subscribed company. The following examples are used to illustrate the APN and IP address settings for the mobile service provided by for example, PCCW in Hong Kong.

APN setting:	600#8888#pccwdata
IP Address setting:	999#8888#203.169.211.100 #4001

5. Laboratory test

Before the RTLS was actually set up for field test in a construction site, a laboratory test was carried out to assess its performance under good geometrical and environmental conditions. Eight sensors were set up in an electronic equipment testing laboratory of the Hong Kong Polytechnic University. Two positioning cells were set up, each with a rectangular area formed with four sensors, covering the overall positioning area of about 11×7 m, and a local coordinate system was defined. It should be noted that, in such a small area only one zone is sufficient to provide the positioning service in real practice.

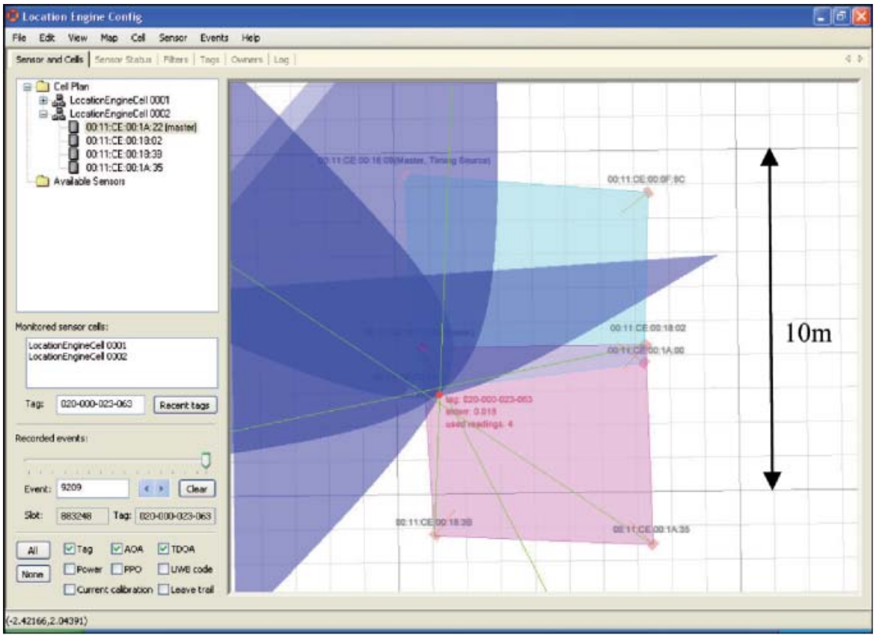

Figure 6: Eight UWB sensors forming two positioning cells in the laboratory.

Such network design was deliberate in order to test the performance of the system when the tag is crossed from one zone to another. The sensors were communicated through the LAN router, each sensor being assigned an IP with a unique MAC address, and synchronized with other sensors by high quality timing cable connection. Figure 6 is a snapshot of the positioning process, extracted from the visualization platform. The green lines are AoA measurements, and the hyperbolic blue zones are generated from TDOA data. The computed position is shown as a red dot in one of the positioning cells.

After system calibration, the positioning tag was placed at each of the total 73 known points separated at 0.5 m grid intervals. The tag's positions determined by the combined AoA and TDOA mode were then compared with the known values. The mean deviation for the X, Y and Z components are 0.12 m, 0.17 m and 0.18 m respectively. Deviation of each sampling point in the X, Y and Z components are shown in Figure 7.

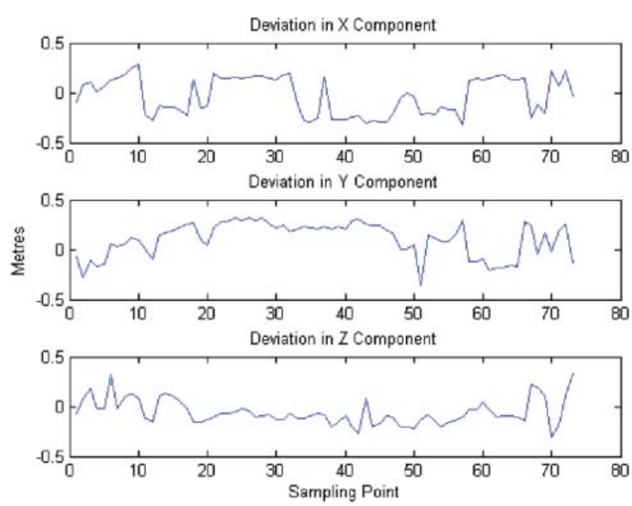

Figure 7: Deviation of X, Y and Z components of each sample point from the known value.

6. Field test in underground construction site

A typical resource management application that requires GPS and RTLS integration is underground railway construction which involves site management in both outdoor and indoor environments. The Guangzhou MTR construction is managed by Guangzhou Metro Corporation. At present, about 35 km of metro lines have been completed and operational, and extension lines to other cities such as Guangzhou-Foshan section are now under construction. A field test was carried out in a section of MTR construction site in Guangzhou China, with

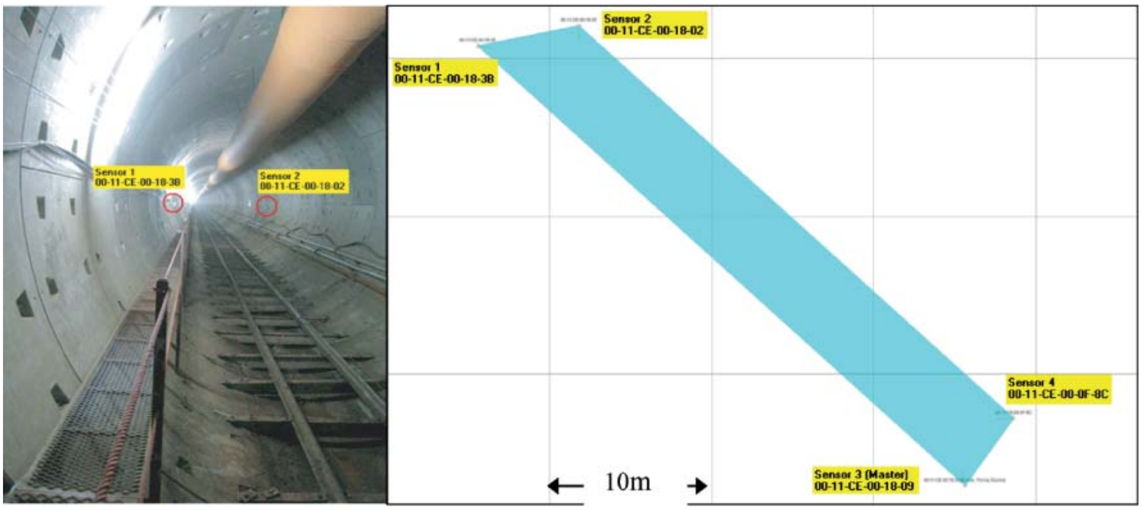

Figure 8: Four UWB-AoA sensors installed in a 5 m by 30 m section of the tunnel.

the aim to assess the performance of such a system under poor geometrical and metrological conditions. Such conditions are typical in most tunnel construction sites. Figure 8 shows a section of newly constructed underground railway line where the field test was carried out. The 5-meter diameter tunnel with the railway line at the middle has restricted the flexibility of sensor installation. Near the test site is the drilling area, therefore the test area was actually quite dusty, noisy, with occasional traffic for transporting excavated materials, high temperature as well as high humidity.

Four sensors were placed at the side of the safety walkway that covers about 30 m in length of the test area as shown in Figure 8. The geometrical and resource movement constraints, as well as the limited time that allowed us to carry out the test has restricted us to install the sensors permanently on site. Test in static mode was carried out by placing the tag near the middle of the test area, then started to log the positioning results for about 60 minutes at one second interval. The purpose of this test was to evaluate the positioning stability under the adverse metrological conditions inside the tunnel. The test result in Figure 9 shows that the position determination with the RTLS under the high temperature and humidity tunnel condition was fairly stable. The deviation from the mean value was about 3 cm for the horizontal positions, and 4 cm for the height component.

A kinematic test was then carried out by placing the tag at the top of the helmet of an assistant who walked forward and backward along the railway track in the defined area (see Figure 10). As shown in Figure 10, most of the successful fixes were around the middle area. For other locations where positions cannot be displayed, it indicates either the positions were not successfully determined, or that they were outside the defined area. It should be noted that, although more successful positioning results could be found around the middle area, only around 50 points in total were successfully determined out of about 250 fixes.

The reasons for the unsuccessful positioning were suspected to be due to the following three reasons. Firstly, the pitch, roll and yaw orientation of sensors are important in the calibration process. Although special attention was paid on the orientations, restriction of fixing the sensors on concrete wall did cause some degrees of discrepancy in precise orientation. Secondly, the geometrical strength is weak for optimum calibration and position determination of the system. Advice was sought from Ubisense after this test, and suggestion was given that two more sensors to be set up as shown in Figure 11 to improve the geometrical strength and redundant measurements under such poor geometrical condition. Thirdly, the system would only record the computed positions which fall within the defined project area. Any positions which fall outside the defined area would be filtered and would not be shown in the log file.

With the above experience and expert advice of the product company, another construction site in

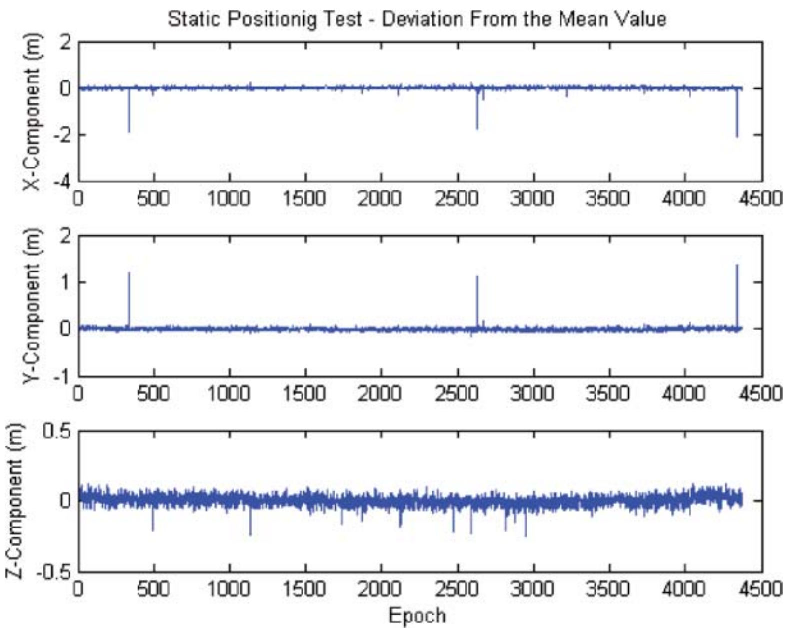

Figure 9: Result of Static Positioning Test using Hybrid AoA and TDOA Method.

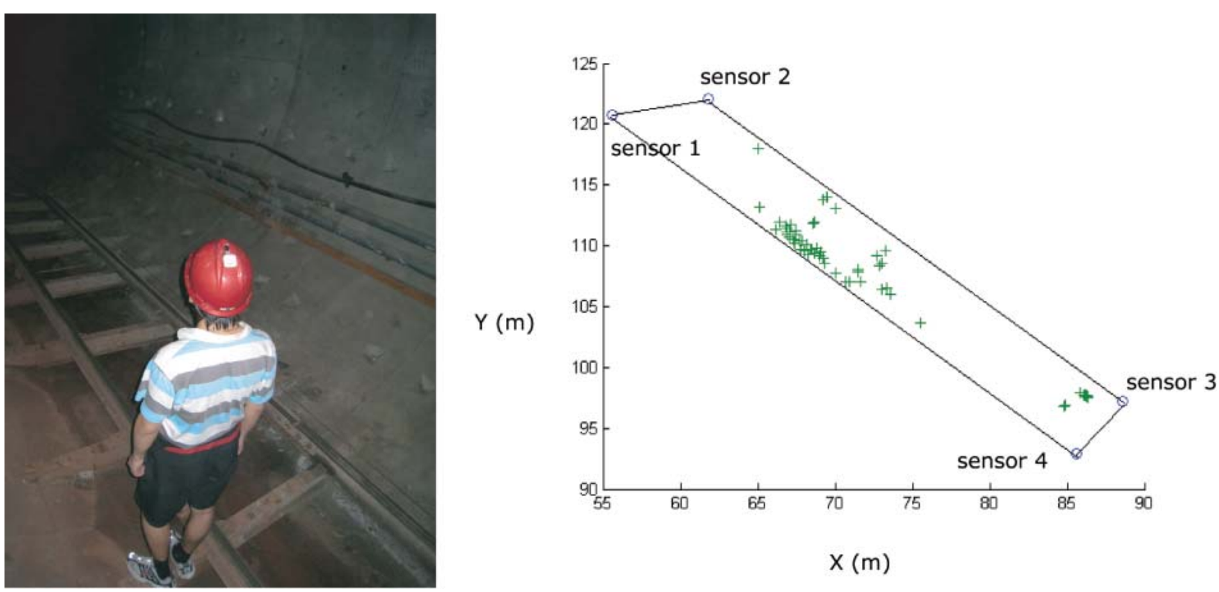

Figure 10: Positioning tag fixed at top of helmet for static kinematic positioning (left) and the positioning result (right).

Figure 11: Sensor configuration suggested by Ubisense for UWB-AoA positioning in weak geometry areas.

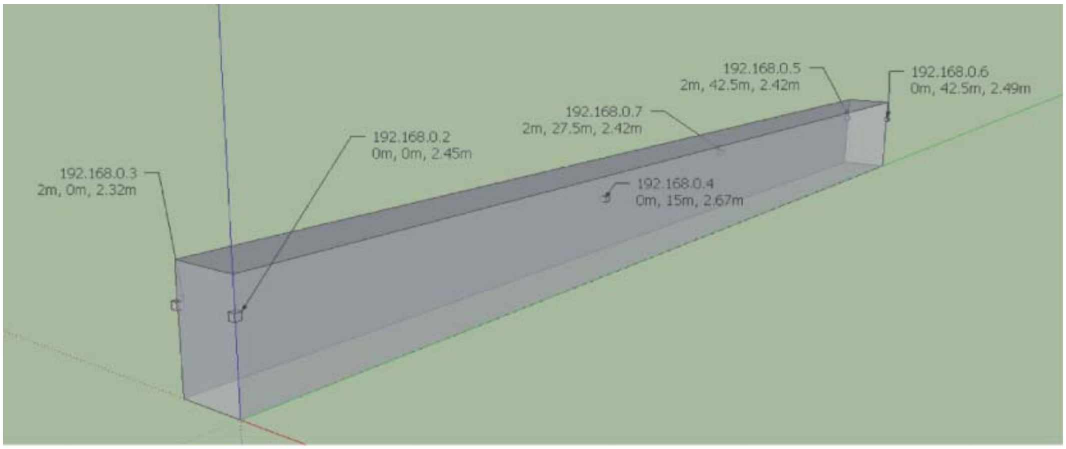

Figure 12: Test area in a building construction site in Hong Kong.

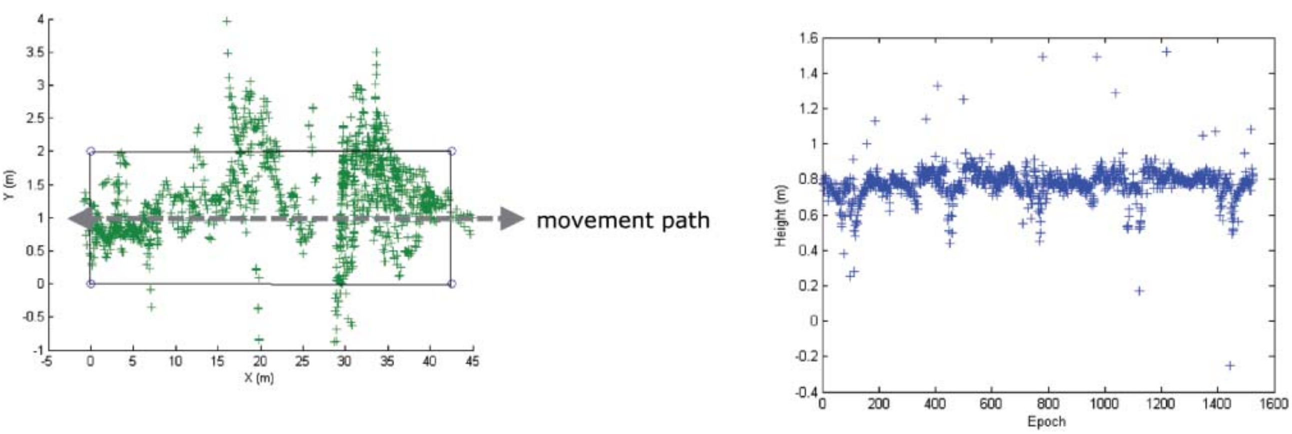

Figure 13: Scatter plot of positioning results of the second field test in the building construction site.

Hong Kong with similar geometrical condition was sought for further testing of the system. With support of Paul Y Construction, a major building construction company in Hong Kong, a suitable area inside the construction site of the teaching hotel of the Hong Kong Polytechnic University located about 100 m away from the university campus, was used to permanently set up the sensors on steel piles, following the suggested configuration shown in Figure 11, and actual dimensions shown in Figure 12. This is a 2 m by 40 m corridor, with height of about 2.7 m. The geometrical strength of this corridor is worse than the test area in the Guangzhou MTR project site.

The tag was held at a constant height of 0.7 m and moved along the corridor. About 1500 data with 10 samples per location were collected for analysis. In order to acquire a more complete picture about positioning performance, the system was set to allow logging of those positions that fall outside the region. As evidence shown in the plots in Figure 13, there was significant improvement in the success rate of the second test. About 90% of fixes fell inside the test region at ±1 m accuracy. With regard to height, over 90% of the fixes were between the 0.6 m and 0.9 m region.

7. Conclusions

In this paper, the adoption of Ubisense UWB-AoA RTLS for resources management in an underground railway construction site has been investigated and tested. Based on the laboratory and field test results, it is evidenced that the system can normally achieve better than 15 cm accuracy, and better than 1 m under adverse geometrical site conditions. It can be seen, that the system performance was quite good in static tests. In this case, the positioning accuracy is in the range of a few centimeters only. However, in kinematic tests, the RTLS did not perform so well in the selected test site (i.e., a railway tunnel under construction). Out of 250 position fixes, only 50 points in total could be successfully determined. The main reason for the poor performance is the number of sensors used and their distribution in the long and narrow tunnel. With the addition of two more sensors in the network, the performance can be significantly improved. The improvement was shown in another test performed in a construction site of a large building along a narrow corridor. To summarize, it can be said that the hybrid AoA and TDOA UWB RTLS can provide better resources management capability in terms of positioning accuracy and stability than Wi-Fi and ZigBee technologies (Mok and Retscher 2007, Mok, Lau and Xia 2007, Retscher and Mok 2007) under complicated construction environments. The system set up in this test was based on the normally recommended wired cabling architecture. The disadvantage, however, is the requirement for establishing a high quality data transmission cable for high precision time synchronization between sensors, which is expensive and may not be feasible in complicated civil construction sites. Ubisense has recently developed another cabling approach by using additional combiner/splitter hardware to combine sensor network and timing signals, in order to reduce the cabling costs (Ubisense, 2008). Moreover, the authors were recently informed that the RTLS network can now be set up in wireless mode, but at the expense of reducing the achievable accuracy to about 2 m. These developments would significantly reduce equipment set up costs, and is more practical to implement in complicated engineering site environments, hence more feasible to be applied to everywhere resources management in large construction projects.

Acknowledgements

This research is fully supported by the UGC Research Grant (2006–2007) B-Q02F ‘‘Investigation into seamless Indoor and Outdoor Positioning Based on UWB-GNSS Integration’’.

The authors would like to thank Mr. Guoxin Peng, Chief Supervisor of Guangzhou Rail Transportation Management Ltd., and Mr. Peter C. T. Ng, Project Manager of Paul Y. Construction Company, Limited, for their assistance in the field test arrangements.

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Received: Mar 2, 2010 Accepted: Apr 12, 2010

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