Ultra-Wide Band technology applications in construction: a review

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This paper explores the state-of-the-art research and development of UWB applications in many sectors, including the construction industry. This paper will provide insights into the technology for the uninitiated reader without involving detailed technological and arithmetic aspects of UWB. To do so, this paper first introduces the key concepts behind UWB and provides a brief historical perspective. It then summarizes the UWB's technical features which enable it so popular in industry. Finally, a number of UWB application examples in many sectors, including construction, are presented to analyze and highlight the impact on the industry performance. UWB technology is expected to become a very important component and have profound impact in ubiquitous computing in the near future.

INTRODUCTION

This paper provides an introduction to UWB technology. It presents UWB system's principles which characterize the function and composition of UWB system and brief history of UWB technology. Moreover, the UWB's technical features are summarized to facilitate profound understanding UWB's popularity. Specific emphasis is given to the UWB technology's applications in various industries including the construction industry.

Definition of use of UWB systems

UWB wireless communications offers a radically distinct approach to wireless communication compared to traditional narrow band systems. According to the FCC, UWB is any signal that has a fractional bandwidth equal to or greater than 0.20 or has a bandwidth equal to or greater than 500 MHz (Breed 2005).

UWB technologies can transmit extremely short and low power electro-magnetic pulses. The radio spectrum spreads over a very wide bandwidth (Shen et al. 2008). Due to its short pulse radio frequency (RF) waveforms and large bandwidth, UWB provides fine time resolution and provides good potential for application in ranging and positioning and well immunity to multipath effects.

The tags in UWB tracking system decide the localization dimensionality, reception by three or more receivers permits accurate 2D localization, while reception by four or more receivers allows for precise 3D localization. If only one or two receivers can receive a tag transmission, proximity detection can also be readily accomplished (Khoury et al. 2009).

Commercially existing ultra-wideband systems (see principle layout illustrated in Fig. 1) include the following (Teizer et al. 2008; Giretti et al. 2009):

- Processing computer and hub including a graphical user interface;
- Minimum of four UWB receivers at different height levels to record real-time three-dimensional signal data in a field of view of 90° (mid-gain), 60° (high gain), and omni-directional;
- CAT-5e shielded wires (wires potentially to be replaced with a wireless signal transmission); and
- Low- and high-powered UWB tags (approved for safe use by FCC: 5 mW, 1 W) with different emitting signal refresh rates of 1, 15, 30, or 60 Hz, including one reference tag.

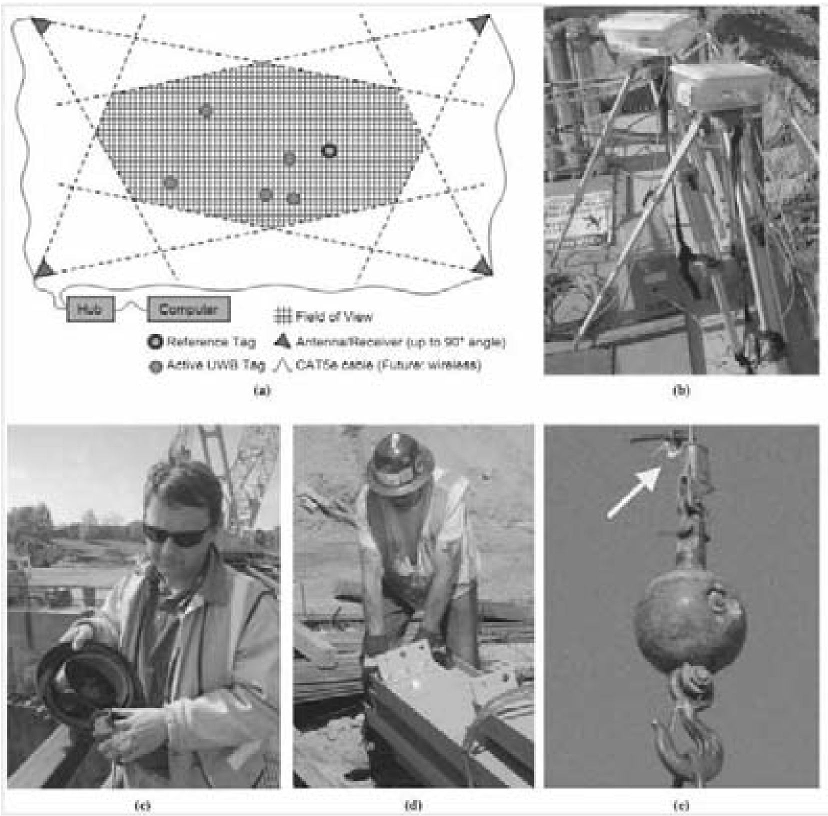

Figure 1. **UWB receiver and hub configuration and sensor field setup (Teizer et al. 2008)**

The UWB system operates as follows: a set of 3 or more receivers are positioned at known coordinates about the periphery of the area to be monitored. Short-pulse RF emissions from tags are subsequently received by either all, or a subset, of these sensors and processed by the central hub's CPU. A typical tag emission consists of a short burst, included a set of data for ID purposes, repeated at a given frequency (limited between 1 and 60 Hz). Time differences of arrival (TDOA) of the tag burst at the various receivers are measured and sent back to the central processing hub. Calibration (i.e. signal speed measuring) is performed at system start up by monitoring data from a reference tag, which has been placed at the known location. Every receiver obtains its power from the central processing hub via standard CAT-5 cables, which are also used to carry data back to the hub for subsequent processing (Giretti et al. 2009)

A brief history of UWB

Although recently concerned extensive research interest, UWB technology's origin can date back to work in the early 1960s on time-domain electromagnetic wave propagation. Bennett and Ross summarized UWB's early application in a seminal paper (Bennett et al. 1978). Ross was the first researcher to demonstrate an UWB communication system in 1986. The first (1973) fundamental landmark patent on UWB communications systems simply referred to the technology as "base-band pulse" (Ross 1973; Barrett 2000). The term "UWB" originated with the Defense Advanced Research Projects Agency (DARPA) in a radar study undertaken in 1990, serving as a convenient means for discriminating between conventional radar and those utilizing short-pulse waveforms having a large fractional bandwidth (Fontana 2004).

The early UWB systems were designed for military, low probability of detection radar, and communications applications (Fontana 2004). Until 1994, the majority of the work was performed under US government programs. With the rulings of the FEDERAL Communications Commission (FCC) under the U.S. government, after 1994, there has been an increase in nongovernmental-related research and an increase in the number of UWB government agencies and companies that are greatly accelerating the development of UWB technology (Breed 2005) (Teizer et al. 2007). In 2002, the FCC approved the unrestricted use of low-powered UWB systems and tags [5 milliwatts (mW)]. By far, as one of the earliest civilian applications of UWB, Fontana et al. [(Fontana et al. 2003)] utilized UWB for accurate assets localization. First time of arrival (TOA) measurement was adopted to achieve the position accuracy of better than one foot. Other early research included Fontana (Fontana 2004) and Park et al (Park et al. 2004). Fontana discussed recent techniques for the generation and reception of short-pulse electromagnetic waveforms and examined a number of recently developed UWB systems in the communications, radar, and precision-positioning fields. Park et al developed a UWB GPR system for detecting small objects buried under ground.

Owing to the consideration about potential interference to existing and future planned services, the process of establishing rules of UWB frequency range is usually time-consuming. At present few countries and areas, such as USA, Europe, have established the rules, however in many other countries, UWB devices have yet to be approved (Allen et al. 2005; Teizer et al. 2008).

In the U.S.A., the Federal Communications Commission (FCC) has mandated that UWB radio transmission can legally operate in the range from 3.1 GHz to 10.6 GHz (Fontana 2004) (FCC NEWS)(Ingram et al. 2004).

European rules for license of UWB permit operation between 3.4 GHz to 4.8 GHz and between 6 GHz to 8.5 GHz bands, respectively (Rueppel et al. 2008).

UWB's technical features

There are some distinctive advantages of short-range high-bandwidth UWB which are summarized below (Bensky 2004) (Fontana et al. 2003; Teizer et al. 2008; Giretti et al. 2009) (Khoury et al. 2009):

- high immunity to interference from other radio systems;
- high multipath immunity, due to the use of very short UWB pulses, capable of discriminating between direct and time-orthogonal reflected waves;
- high data rate;
- high localization accuracy (for both 2D and 3D), due to the reliability of the TDOA (time difference of arrival) algorithm implemented;
- extremely low duty cycles, which translates into low average prime power requirements allowing tags to work autonomously for year, ideal for battery-operated equipment and without frequent recharging needs;
- can track multiple resource at the same time, real time and three-deimensionally;
- can work in indoor and outdoor environments at the same time, reducing the installation cost of multiple sensing units to a minimum;
- longer indoor range than other high rate communications systems, due to the high peak-to-average power ratio;
- lighter weight, the weight for each tag is less than 12 g;
- update rate of RF signal of each tag can be up to 60 Hz;
- needn't calibration.

Applications of UWB in industry

Since UWB technology has shown to possess unique advantages for precision localization applications, a number of scientific and technical domains have benefited from UWB's successful application, such as military affairs, medical treatment and engineering.

UWB technology is very useful for military application. Because a very short duration pulse implies a large band, the power is spread over numerous frequencies instead of being concentrated. The resultant power spectral density is very low and the probability of detection and interception is very low.

In the field of high power UWB technology (electromagnetic detection) for military application, an impulse UWB radar have the following features:

- Ability to detect through obstacles and in dense media;
- Improvement of the radar range resolution;
- Improved clutter rejection;
- Improved detection of low flying targets;
- Improved detection of (stealth or not) target;
- Improved recognition (or even identification) of targets;
- Target imagery made possible, using a Synthetic Aperture Radar mode (SAR), which gives a high cross-range resolution added to the high range resolution;
- Access to low pulse repetition frequency mode without range-velocity ambiguity.

An experimental UWB radar was developed, called PULSAR, to assess the benefit of UWB concerning the detection of targets masked by vegetation, or anti-tank mines.

In the field of low power UWB technology for military application, wireless communications and localization-identification are two major application fields. Two technical approaches can be investigated in wireless communications. The first approach is utilizing UWB as radio link between body and weapon/head devices to transmit data or video between the camera on the weapon system and the video display of the soldier, the second approach is the use of impulse radio UWB in the intra-squad communication system. In the field of localization-identification, UWB can also provide localization and identification functionalities for the soldier (Colson et al. 2005).

In medical applications, non-invasive imaging with UWB makes it possible to get very accurate in-body information from patient. UWB radar is much safer than X-ray due to the great difference in the emission power levels. UWB is one transmission technology to be adopted in wearable sensors to support real-time or frequent vital parameter measurement for elderly or after surgery patients to remain independently living in their own homes as long as possible (Hamalainen et al. 2008).

UWB technology is also appropriate for detection of unknown or known small and shallow objects buried underground. A new application of UWB ground penetrating radar (GPR) is reported in this project for the detection of buried gas pipelines. The UWB GPR is used to draw a map of buried gas pipelines by connecting a global positioning system (GPS) to the GPR. Usually the gas pipelines are buried within 3m and made of metal, thus the system's maximum target depth of 3m is decided upon. The whole system is set up and tested in a real environment. Compared to conventional radar systems, the complexity of the system is reduced, but its performance is better. The developed system has a good ability to detect underground metal objects, even small targets of several centimeters (Park et al. 2004).

Maintaining an efficient train-to-wayside communication for communication-based-train-control (CBTC) poses major problems, due to the increasing amount of exchanged data for the supervision, the automatic train control, operation and protection, the increasing demand on video transmission and multimedia services. The difficult conditions related to the operation in tunnels, the main operation environment urban guided transport, generate constraints resulting on performance limitations of existing communication systems. The propagation phenomena characterize this environment, such as frequency selectivity and distance and frequency dependent pathloss. UWB-impulse radio technology is an efficient alternative solution to these problems because it allows simultaneously high data rate communication and high resolution train location and obstacle detection as well as robustness to multipath environments (Saghir et al. 2009).

Applications of UWB in construction industry

In recent years, UWB technology has been applied in construction industry successfully. Application examples from both research and industry are as follows.

Automated Real-Time Three-Dimensional Location Sensing for construction resource Positioning and Tracking

Successful construction projects are often dependent on the ability to assess resource status or work task performance efficiently and effectively, readily available information on these factors has inherent value for real-time or near real-time decision making. Technology can become more attractive for implementation if it have the potential to automate real-time workforce, equipment, and material positioning and tracking at the same time remotely, three-dimensionally because of facilitated site productivity analysis and control of work task schedules, increased return on investment and overall construction performance(Teizer et al. 2008).

Real-time 3-D location sensing requires at least four receivers that preferably are located at different height levels. In this research, the receivers and antennas are connected via shielded CAT-5e cables to the hub either in-line or parallel. Each cable powers the connected receiver(s) as well as transmits the tag identification and time readings back to the hub. A reference tag in line of sight of the receivers or of receiver subgroups is placed preferably in the center of the space observed. All hardware components (receivers, cables, hub, and processing unit) are preferably located at the boundary of the observation area. Before measuring the tag locations, the three-dimensional position of receivers and reference tag is determined by using a total station. The performance of the UWB system was tested in several field experiments using the outside and inside space of a steel erection site. The first field experiment was to position a worker who carried a UWB on his helmet and walked a "figure eight" inside the steel structure. The second field experiment was to track the steel beams during the steel erection process for a three-story research building. The conducted experiments were well in line with observed results of other research efforts in different application disciplines (Teizer et al. 2008).
Experiments for obstacle avoidance and field personnel tracking are shown in Fig. 2.

On-site real-time safety management

Construction industry remains one of the industries with the poorest safety records and the issue of construction worker safety has become a major concern of construction industry worldwide. Intelligent approach is always called for to check for risky events before they occur and to timely relay warning signals to workers, in order to prevent possible consequences and a context aware system should be deployed over all construction site (Oloufa et al. 2002). Due to its positioning accuracy and real-time tracking capability, UWB technology can be very suitable for safety management. To facilitate on-site real-time health and safety management, it's critical to continuously check the workers' behavior and prevent possible dangerous situations by equipping workers with wearing a special tag, which is small enough so not to interfere with ongoing activities (Giretti et al. 2009).

A proactive advanced system developed by Giretti, Carbonari et al. is composed mainly of 2 parts: the first performs real-time position tracking, while the second provides real-time prediction of risky events by virtual fencing of dangerous areas based on the position information provided by UWB system. Position tracking is performed through the use of UWB technology, shown to be capable of providing the required accuracy for path monitoring

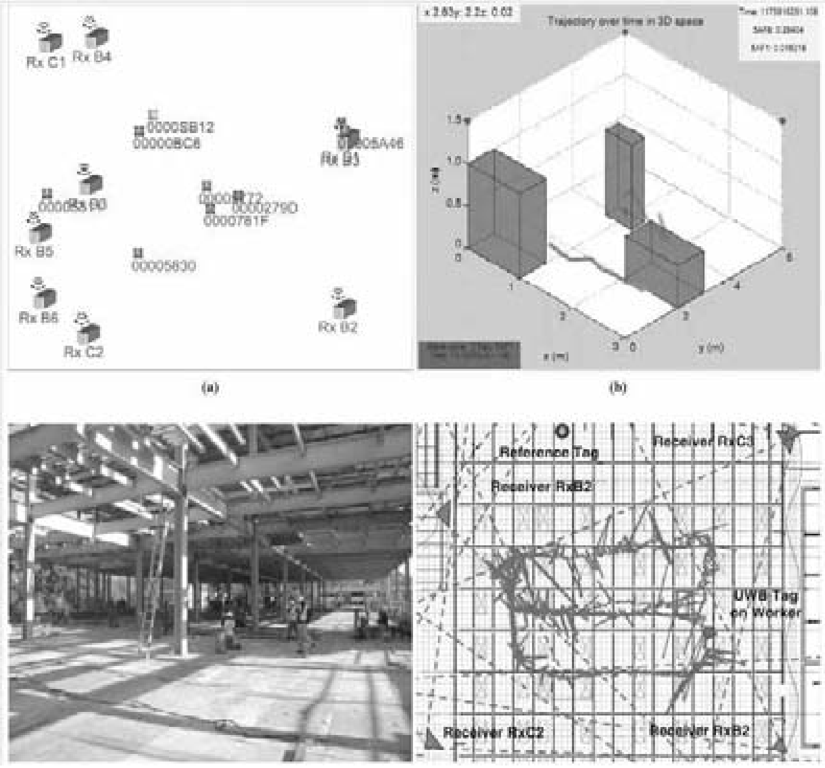

Figure 2. **Experiments for obstacle avoidance and field personnel tracking(Teizer et al. 2008)**

of humans and equipment within the site. Workers present on the site are requested to wear a special tag, capable of sending acoustical, vibrational or light-flashing warnings to their bearers, when dangerous situations are involved. The UWB localization system tested in this paper consists of a set of active tags (0.3 W and 1 W powered tags), four UWB "mid-gain" type receivers and one central processing hub, manufactured by MultispectralTM Inc. In the used configuration, the tags work at 1 Hz, in order to exploit their lifespan as long as possible. To infer how the UWB localization system works during several construction stages, representative of the vast part of the entire process, three tests were carried out, i.e. performance tests of excavation works, after the completion of the building's concrete frame and after the walls' erection on a 5 storey block of flats respectively. Experimental results indicate that UWB behavior is rather constant during most part of the construction progress. The same system setup may be used from the start of the construction up until the erection of walls. At the last stage, it's necessary to have a higher number of receivers per unit area. Comparison between measured and actual positions of a worker's movements throughout the construction site in the test stage after the completion of the building's concrete frame is shown in Fig. 3. Laboratory tests showed the performance of virtual fencing system is very reliable (Giretti et al. 2009).

The accurate, real-time information about the location, speed and trajectory of construction resources can lead to important information regarding travel patterns and safe construction operations. Teizer, J., U. Mantripragada, et al. developed algorithms to locate and identify obstacles and determine their dimensional values on the basis of analyzing spatial data of the trajectory of construction workers provided by Ultra Wideband technology, then the new information can be used for safe path planning efforts (Teizer et al. 2008). Plan view of circular travel path is shown in Fig. 4.

Application in emergencies

The requirements for emergencies will be very variable, but will generally include: good radio penetration through structures, the rapid set-up of a stand-alone system, tolerance of high levels of reflection, and high accuracy. The accuracy should be better than 1 m, and locations should be in three dimensions. UWB is the preferred solution in emergencies (Ingram et al. 2004).

When in an emergency, it's very important to improve the orientation and safety for rescuers within complex buildings. In this project, reliable indoor real-time positioning system consists of multi-method-approach (including UWB, WLAN and RFID) and a building information model (BIM)-data-export are developed to provide spatial context building information, e.g., gas pipes or high voltage panels. Each rescuer, such as fire-fighters, will use a mobile device (PDA or other mobile computer) equipped with indoor positioning, routing, and important building information will be displayed in the rescuer's spatial context to enable indoor navigation (positioning and route calculation). Because UWB is less influenced by metals and high humidity than other radio communication technologies, UWB is used for position sensing in passenger and baggage halls (Rueppel et al. 2008).

UWB-based sensor networks for localization in mining environments

Underground mining operations are considered as hazardous industrial activity because of the poorer ventilation/ visibility, the dangers of rock falls, and the presence of toxic gas. In emergencies, wireless communication may become vital for survival, for example, during a disaster, the conventional wired communication system may become unreliable, necessitating a wireless radio system. In

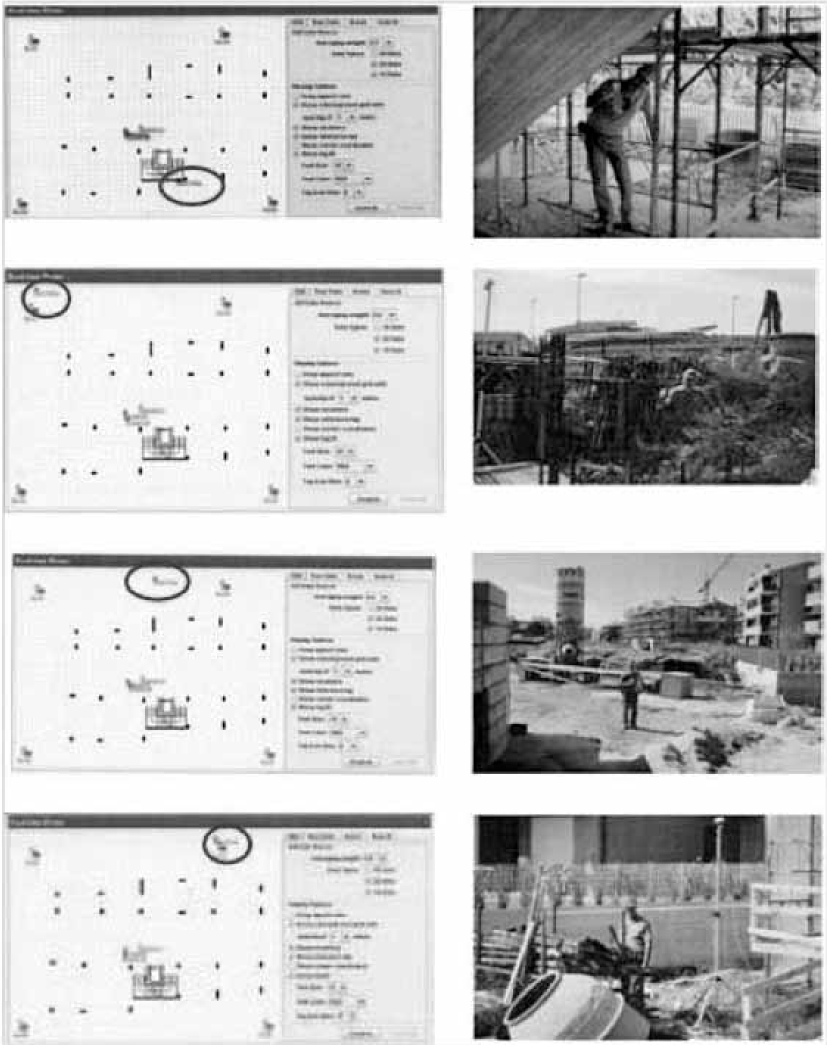

Figure 3. **Comparison between measured and actual positions of a worker's movements throughout the construction site (Giretti, Carbonari et al. 2009)**

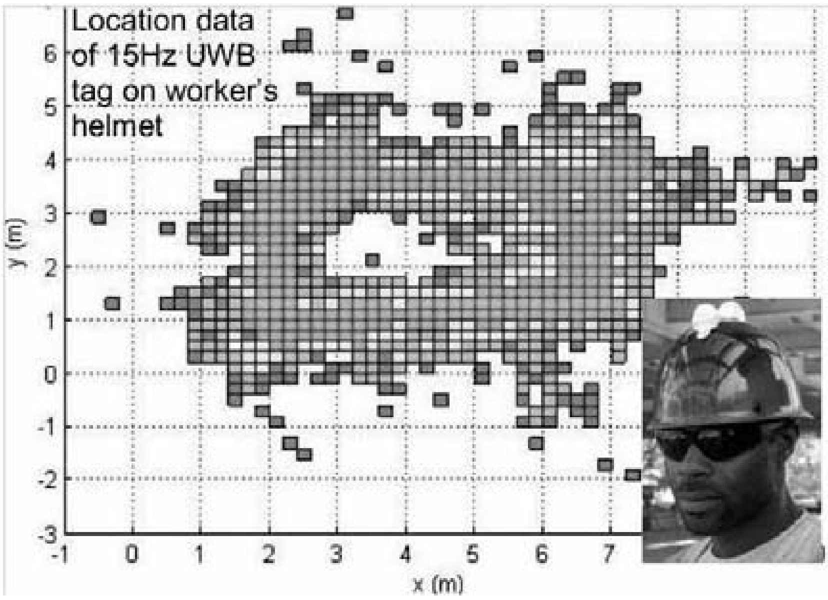

Figure 4. **Plan view of Circular Travel Path (Teizer et al. 2008)**

this case, UWB was selected owing to its asset in ranging accuracy, pre-eminently in cluttered environments and its ability to penetrate obstacles, UWB based-wireless sensor network (WSN) as solution for localization the equipments and miners in underground mines is described and analyzed (Chehri et al. 2009).

Nondestructive Evaluation of Pavements and railroad track substructure combined UWB with GPR

Pavement structures need to be evaluated nondestructively, a novel, compact, low-cost, impulse ground-penetrating radar (GPR) system with UWB sampling receiver is developed with good range resolution and penetration depth. Performance of this system has been verified through the measurements of relative permittivity and thicknesses of various samples, and a good agreement between the experimental and theoretical results has been achieved (Lee et al. 2004).

Ballast fouling may jeopardize the ballast layer in railroad track system, so an UWB GPR non-destructive system is designed to detect the trapped water and scattering pattern, measure the thickness of clean ballast, predict air void volume in railroad ballast. Because electromagnetic energy attenuation is highly frequency dependent, the frequency sub-bands of the reflected UWB GPR signal can be analyzed separately to quantify the fouling material and moisture content (Al-Qadi et al. 2010).

SUMMARY

With the rapid development of wireless monitor and tracking technology, ubiquitous computing has changed the scenario of industry greatly. UWB is a new kind of radio signal and can provide precise positioning over longer ranges or throughout buildings in a number of fields due to its unique technical features. Research on the UWB technology continues very vigorously today and many countries are engaging to establish their own UWB frequency range. UWB is used successfully in a variety of industries, such as military affairs, medicine and engineering. As for construction industry, UWB is used for automated real-time three-dimensional location sensing for construction resource, on-site real-time safety management, emergency application, localization in mining environments, nondestructive evaluation of pavements and railroad track substructure. With more countries specify their frequency range of UWB system and reduce system cost by mass production, it's expected that UWB technology will produce more profound impact in most industrial sectors.

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