

WIRELESS SENSOR TECHNOLOGIES FOR AUTOMATED TRACKING AND MONITORING OF CONSTRUCTION MATERIALS UTILIZING ZIGBEE NETWORKS

Won-Suk Jang¹ and Miroslaw J. Skibniewski²

ABSTRACT

This paper introduces automated material tracking (AMTRACK) system architecture. To overcome the limitations in previous RFID- and GPS-based technologies observed in current construction practices, a new ZigBee-based localization technique with two different types of query and response pulses is presented for more accurate tracking performance. Feasibility study shows that accuracy with combination of RF and ultrasound is better than the one that uses only RF signal. AMTRACK can provide ZigBee-based monitoring capacity by embedding specific transducers into the system for various purposes of monitoring applications. Optimization of router placement and cost benefit analysis are examined to present research direction in the future.

KEYWORDS: ZigBee Networks, Tracking and Monitoring, Localization, Construction Materials

INTRODUCTION

During several decades, many research efforts have been demonstrated to provide the effective materials management strategies for improvement in labor productivity and performance. Even though there was a growing awareness in the construction industry that materials management needs to involve a comprehensive and integrated coordination of management activity, previous research efforts could not clearly establish the impact of materials management practice on productivity. This might be attributed to the fragmented functions of materials management with minimal communication and unclear responsibilities among the owners, engineers and contractors (Bell and Stukhart 1986).

One of the keynotes presented in the workshop sponsored by National Institute of Standards and Technology (NIST) in May 2003 (Saidi et al. 2003), stated that “material tracking remains a very big problem on the current construction job site and how can it be addressed today.” This conclusion implies that the current practice of tracking materials in construction is still reliant on manual legacy systems. Thus, inefficiencies, reported to be 4-6% loss in labor cost related to the manual operation of reporting, recording and transferring field data in current tracking systems (Bell and Stukhart 1987), are still an important issue especially on large construction projects.

The paper introduces a new design framework of tracking and monitoring system architecture based on ZigBee™ networks, named as Automated Material TRACKing

¹ Ph. D. Candidate, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742-3021. email: wsjang@umd.edu

² Professor and A. J. Clark Chair, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD 20742-3021. email: mirek@umd.edu

(AMTRACK). An emerging technology introduced for industrial monitoring and controlling with better performance and cheap cost, the ZigBee™ protocol shows a potential for application as a tracking and monitoring tool in construction processes. In addition, we propose the ZigBee™-based combination techniques of radio frequency signal and ultrasound to improve positioning accuracy and associated cost benefits. Finally, feasibility and cost benefit have been examined to present the possible deployment framework in construction. Relating to tracking and monitoring the construction materials, real-time field data acquisition envisions a practical implication for providing up-to-date information in construction sites associated with the large scale project management systems.

RELATED WORKS

Tracking and monitoring of information flow on a construction job site is an important, yet commonly overlooked, aspect because timely information about the status of materials, equipment, tools and labors are directly related to the successful completion of project. Realizing the potential for cost savings and up-to-date information acquisition, the Construction Industry Institute (CII) funded a formal research project in 1987 to investigate the possible application of bar code in construction industry (Bell and McCullouch 1988). Bar code technology has the advantages in identifying and tracking the construction materials, tools, equipment and labor, but it presents several disadvantages: 1) short reading range; 2) manual operation to scan the information; and 3) limited capacity of data storage.

With advancement of radio frequency technology, RFID has received attention for possible tool for improved materials management such as tracking the construction materials, equipment, tools and labors. During several years, significant beneficial applications of RFID technology had been already found in retailing, manufacturing, transport and logistics industries, and security and access control (Song et al. 2006) due to its robust functionalities with inexpensive and non-labor intensive means of identifying and tracking products.

The basic functionality of RFID is to present remote identification and tracking of distributed RFID tags. Because of the fact that RFID was originally designed to replace the bar code technology, broader applications to wireless monitoring and localization are quite limited. Most of the RFID readers cost from \$2,500 to \$3,000 depending on the various features in the device (ABI Research 2005). Thus, it is prohibitively expensive to practically cover a scale construction site because the coverage range of communication for even active RFID tags is within 15 meters which does not provide enough reading range for practical use (Goodrum et al. 2006). Even though the global positioning system (GPS) can provide somewhat improved accuracy for locating the tags' position by combining them with RFID, GPS receivers are still expensive to track and monitor a large amount of materials in a typical construction project. In addition to high cost, localization systems based on GPS alone also suffer from the multipath and signal masking in highly dense areas, resulting in 20m errors in 40% of measuring points and even 100m errors in 9% of measuring points (Lu et al. 2004). Thus, it is unreliable to depend on the accurate localization data for material tracking and monitoring in a highly dense environment such as construction site.

AMTRACK ARCHITECTURE

Interference between two or more numbers of transmitted signals often incurs multipath in signal propagation. Reflection from ground, wall, and various objects that are not of interest is the major factor of multipath, and results in distributed amplitude, phases, and angles of arrival.

Thus, elimination of these multipath components is an important issue to achieve good of localization performance of distributed sensor networks. AMTRACK system is introduced to mitigate the unwanted components of signal propagation for accurate and reliable measurement of the location of distributed sensor devices. Additionally, the system also presents a new approach to a potential deployment of ZigBee network to the automated tracking and monitoring system in construction site.

This paper introduces two alternative approaches for estimating the distance of an object from the ZigBee router based on time-of-flight: one scheme includes the use of discretized signature pulse of radio frequency signal and the other uses the ultrasound pulse as a response pulse (see Figure 1). The discretized signature pulse of radio signal is designed to identify the unique characteristics of the original pulse, and an indicator located in front part of the radio pulse accounts for the measuring point in time-of-flight method.

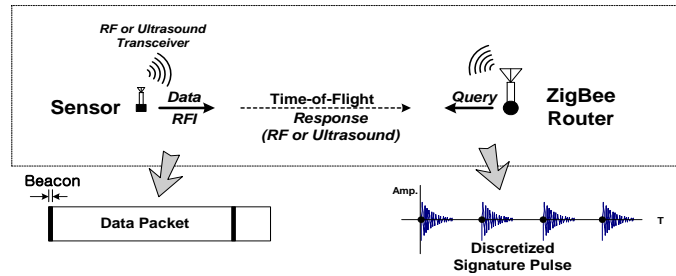


Figure 1: Description of combination of signature pulse: two alternative approaches (RF and ultrasound)

Once the RF transceiver in the sensor receives the original signature pulse transmitted directly from the router, it transmits as the same RF response pulse as the original one to the ZigBee router. Since frequency and signature shape will not be changed or distorted unless it is reflected or refracted, the sensor's distance can be measured by time-of-flight ensuring the elimination of multipath property of the radio signal without interference. On the other hand, ultrasound response pulse in sensor side with omni-directional antenna can be used for measuring the distance between them. First arrival of the ultrasound response pulse to the router is then used as unique pulse ID for measuring the distance with eliminating the unwanted waves that are reflected or refracted from the obstacles. Once the router recognizes the sensor's ID and distance (by query-response pulse), the geographic coordination of the sensors will be obtained by a trilateration technique that uses two or more ZigBee routers to determine the coordination of the sensors.

FEASIBILITY STUDY

In this section we study feasibility of location estimation of the objects by using a router and a ZigBee enabled sensor. We consider two scenarios in our feasibility analysis: Measurement of the distance by RF signal; and measuring of the distance by combination of RF and ultrasound technologies.

Measurement of the distance by RF signal

In order to make a detailed study of the potential performance of the system, assume that it is desired to estimate the distance from the router with an accuracy of 1 meter, and that the maximum distance of objects from the router is about 200 meters. As shown in figure 2(a), we assume that the timer is implemented by a counter with a fixed clock frequency f_c . The required resolution of 1 meter means that the timer needs to have the resolution of 200 divisions, which in turn means that it needs to have at least 8 bits. On the other hand, each increment happens in the

amount of time equal to $1 / f_c$ and accuracy of 1 meter is possible if $1 / f_c$ is smaller than the round-trip time of the RF signal for an object in distance of 1 meter. This will lead us to Equation (1):

$$f_c \geq \frac{3 \times 10^8 \text{ m/s}}{2 \times 1 \text{ m}} = 150 \text{ MHz} \quad (1)$$

Equation (1) shows that an increment of $1 / f_c = 6.6 \text{ ns}$ causes a 1 meter error in estimation of the distance from the router. One possible shortcoming is that if the undesirable errors and processing delays happen in scheduling of the sensors, it will cause increased error in measurement of the distance. All operations of a sensor are performed according to an on-board oscillator that generates timing of the internal processor of the sensor. For example, if the clock frequency of the microprocessor module of a sensor is $f_p = 50 \text{ MHz}$, then this means that the sensor can have the worst case delay of $1 / f_p = 20 \text{ ns}$ in responding the query of the router after receiving it. This is because the micorprocessor's operations can only be triggered on the rising and falling edges of the digital clock generated based on the oscillator frequency. A delay of 20 ns can generate up to 3 meters error in measurement of distance.

The error in estimation of distance of an object from the router based on the measurements of RF round-trip time delay is a result of fast speed of RF signals in space. In order to resolve this issue, we study a second scenario, in which an alternative ultrasound signaling is used to measure the distance between the sensors and the router.

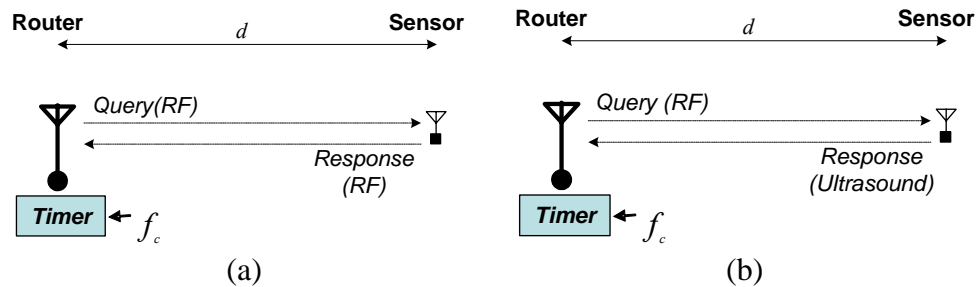


Figure 2: The schematic of the distance estimation from the router based on (a) the round-trip time of the RF signal only and (b) round-trip time of RF signal and ultrasound signals

Measurement of the distance by combination of RF ultrasound signals

In order to perform a similar calculation that presented in previous Section (1) and under similar assumption of measurement of distance up to 200 meters with the accuracy of 1 meter, we need the timer to be an 8-bit timer with the clock frequency specified by Equation (2):

$$f_c \geq \frac{340 \text{ m/s}}{1 \text{ m}} = 340 \text{ Hz} \quad (2)$$

In this case the signal travels with the speed of light in the forward direction and with the speed of ultrasound in the backward direction (Figure 2(b)). Since the speed of light is about one million times faster than the speed of ultrasound, we ignore the component of the delay introduced by the propagation delay of RF signal in the forward direction, or the small

processing or scheduling delay at the sensor. Therefore, the dominant component of the round-trip delay of the signal is the time of traveling the ultrasound signal from the sensor to the source.

It is useful to note that in this case a 1 meter increase in the distance of the object from the router results in about 3 ms increment in the length of round-trip time. This increment is significantly larger than the typical travel time of RF between the router and the sensor (about 1.3 μs for a maximum distance of 200 meters), or the typical processing and scheduling delays at the microprocessor of the sensor node (typically on the order of 10-100 ns). Therefore, we predict that the estimation of error based on combination of RF and ultrasound waves will result in a high performance and a very small error in estimation of the distance of the sensors from the router.

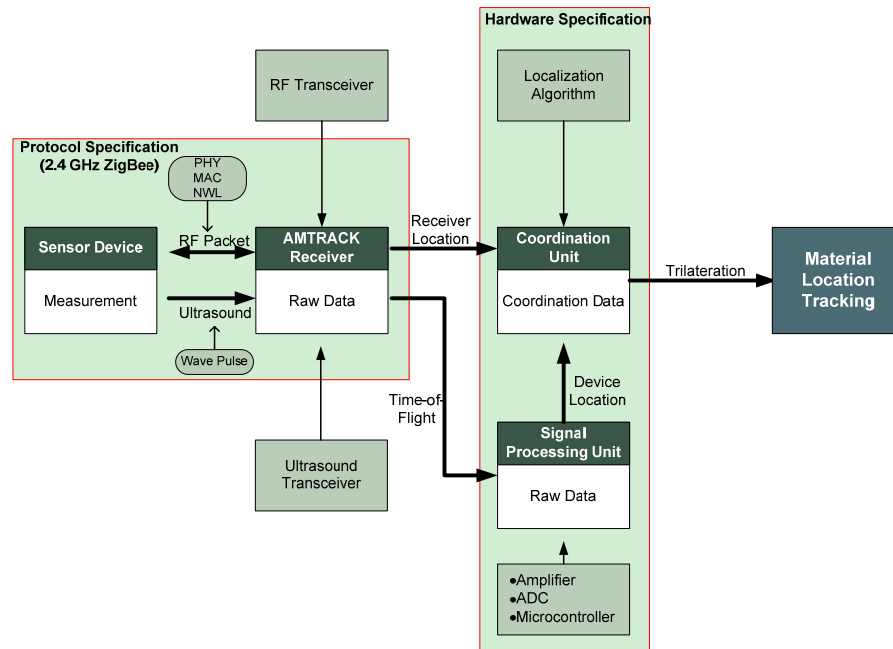


Figure 3: AMTRACK system block diagram

WIRELESS MONITORING ON CONSTRUCTION SITES

Possible applications utilizing ZigBee devices on construction sites are very promising. Based on the system architecture shown in figure 3, ZigBee routers are placed where they can cover the entire laydown yard within their trigger ranges (R_{tr}) to detect the events associated with the movement of distributed sensors. Ad hoc network will be used to transmit the sensory data to a base station, i.e. field office, through ZigBee routers with optimum network path. Since ZigBee has 16-channel allocation, one channel can be assigned to determine the location of the sensors using discretized signature pulse. On the other hand, remaining channels can be used in general data communication that includes monitoring capacity. Different sensor monitoring scheme can be categorized, identified, and applied to the construction materials according to the characteristics of material property and measurement type within the geometry of construction site. For example, humidity sensor can be attached to the bulk of a cement bag or a steel beam to sense the level of humidity in order to avoid the hardening or corrosion caused by water in the humid environment. Other examples can be demonstrated in the PVC pipes where a temperature sensor is placed to detect the temperature variance to avoid melting or any defect caused by high

temperatures in the hot summer, allowing a field manager with the next step of preparedness to mitigate the observed phenomenon by associating with procurement and supply chain management.

OPTIMIZATION OF ROUTER PLACEMENT

In this section, we employed placement optimization for fixed router position required for complete coverage in construction site. Problem statement illustrates that the minimum numbers of routers should be placed optimally to determine the location of sensor nodes deployed for tracking construction materials. The coverage of routers should be within their RF communication range for ad hoc while each sensor node should be reachable within ultrasound wave range by at least three routers to determine the coordination of sensor nodes. Also, the maximum coverage is defined by the result of numerical simulation based on specification of each device, such as RF module, transmission power, antenna and ultrasound transducer. Once coverage ranges of RF and ultrasound are defined, ILP is applied to solve optimal number of routers according to the different size of construction sites ranged from small, medium and large. Brief procedure for solving the optimization is described in Figure 4.

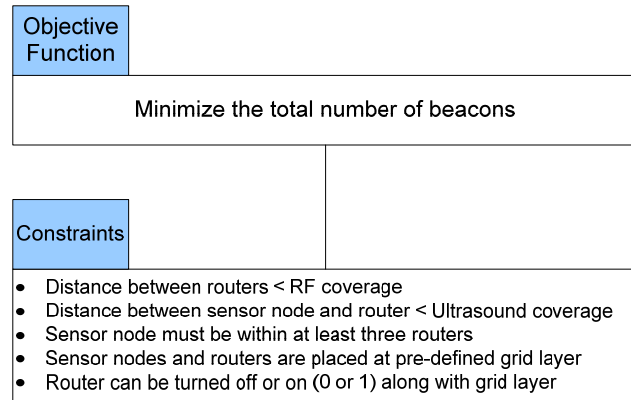


Figure 4: Router Placement Optimization

COST BENEFIT COMPARISON

This section introduces the cost benefit analysis for deploying future AMTRACK system in construction site, and compares the expected implementation cost of AMTRACK with manual and RFID-based tracking system. Investigation on identifying economic, operational and logistical perspective is important to assess the potential impact of automated tracking and monitoring capacities in construction. For quantitative measuring, this research will investigate scenario-based application simulation in real construction site to gather the field information about tracking practices in typical job activities. After performing the cost benefit analysis, it is expected that decision makers should be able to identify the main factors of cost savings and positive return on investment when these new technologies are deployed. In addition, it is possible to maximize the potential advantages, while minimizing the risk, of future implementation and integration of those technologies.

To obtain the expected cost of a manual tracking system, it is necessary to identify and observe all the resources that will be used in materials tracking practices in construction sites. For example, a number of labor crews and their working hours should be correctly identified for controlling and reporting the materials delivery, storage information, handling of shortage/surplus, distribution and installation. After a certain amount of duration of observation, usage of the labor resources is capitalized as an implementation cost of manual tracking.

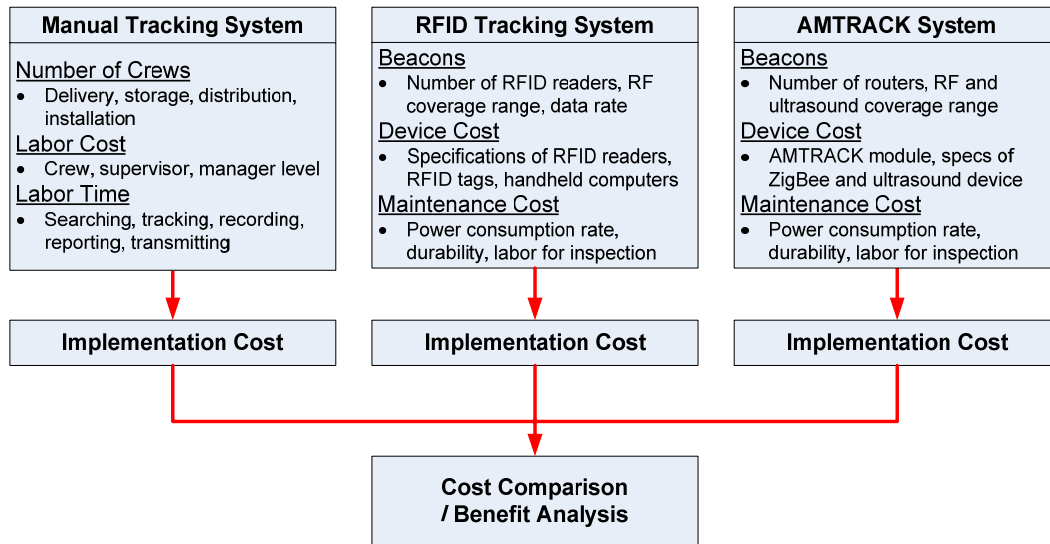


Figure 5: Component diagram of cost comparison and benefit analysis

On the other hand, expected cost of technology-based systems, such as RFID and AMTRACK, can be obtained directly from the specifications of particular devices deployed. For example, information about coverage range, power consumption, transmission rate and device cost of the wireless platform deployed can be easily found in the market. Based on the result of router placement optimization explained in previous section, routers are placed in real construction site to track either RFID tags or ZigBee sensors embedded in construction materials. Total optimal number of fixed routers and mobile devices are then capitalized into the implementation cost together with the maintenance cost. Schematic description of the procedure is illustrated in Figure 5.

CONCLUSION

This paper introduced one of few research efforts for automated materials tracking in construction process. To overcome the limitations of previous RFID- and GPS-based technologies observed in current construction practices, a new ZigBee-based localization technique with two different types of query and response pulses has been presented for more accurate positioning performance. AMTRACK system architecture with respect to coordinating and operation of query and response pulse has been described. An initial feasibility study showed that combination of radio frequency and ultrasound will provide a better performance in measurement accuracy than the one that uses only RF.

Based on the associated components of the AMTRACK prototype for real-time field data acquisition with performance- and cost-effective way, we plan to continue our investigation related to the development of the localization algorithm, such as frequency modulation, scheduling and mobility models. In addition, we will implement network topology formulation and the device design for practical application to construction sites for cost- and performance effectiveness.

REFERENCES

- ABI Research, The market for RFID readers. Technical Report from ABI Research 2005, Document code RR-RFR available online at: http://www.abiresearch.com/products/market_research/RFID_Readers, (Sep.5, 2006).
- Bell, Lansford C. and McCullouch, Bob G. (1988). "Bar Code Applications in Construction", *Journal of Construction Engineering and Management*, ASCE, 114 (2), 263-278.
- Bell, Lansford C. and Stukhart, George (1986). "Attributes of Materials Management Systems", *Journal of Construction Engineering and Management*, ASCE, 112 (1), 14-21.
- Bell, Lansford, C. and Stukhart, George (1987). "Costs and Benefits of Materials Management Systems", *Journal of Construction Engineering and Management*, ASCE, 113 (3), 222-234.
- Goodrum, P. M., McLaren, M. A. and Durfee, A. (2006). "The Application of Active Radio Frequency Identification Technology for Tool Tracking on Construction Job Sites", *Automation in Construction*, Elsevier, 15 (3), 292-302.
- Lu, M., Chen, W. and Chan, W. H. (2004). "Discussion of 'Building Project Model Support for Automated Labor Monitoring'", *Journal of Computing in Civil Engineering*, ASCE, 18 (4), 381-383.
- Saidi, Kamel S., Lytle, Alan M. and Stone, William C. (2003). "Report of the NIST Workshop on Data Exchange Standards at the Construction Job Site", *Proceedings of 20th International Symposium on Automation and Robotics in Construction (ISARC2003)*, The Future Site, September 21-25, Eindhoven, The Netherlands, 617-622.
- Song, J., Ergen, E., Haas, C. T., Akinici, B. and Caldas, C. (2006). "Automating the Task of Tracking the Delivery and Receipt of Fabricated Pipe Spools in Industrial Projects", *Automation in Construction*, Elsevier, 15 (2), 166-177.