Cost-Benefit Analysis of Embedded Sensor System for Construction Materials Tracking

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Abstract: Tracking and monitoring the location of materials on a construction job site is an important, yet commonly overlooked aspect of field data acquisition because timely information about the status of materials, equipment, tools, and labor resources are directly related to the successful completion of a project. With the advanced technologies and innovations in the construction industry, it has become technically viable to implement automated tracking for construction materials. Through the development of an embedded sensor system, this paper illustrates the implementation of pilot experiments examining the accuracy of a system's performance. A cost-benefit analysis is conducted to illustrate labor savings associated with construction materials handling by comparison between manual and sensor-based materials tracking. The presented embedded sensor system can be extended into diverse application areas in tracking and monitoring framework by providing improved method of field data acquisition and information management.

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Introduction

A report published by the Business Roundtable in 1982 defines materials management as the management systems that leverage the efficient utilization of materials and equipment with all necessary efforts to ensure that the right quality and quantity of materials and equipment are appropriately controlled in a timely manner with reasonable cost and availability (Business Roundtable 1982). This report claimed that materials management is a distinct system that can contribute to increase the cost effectiveness of a construction project. 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 afford clear establishment to justify the impact of materials management practice on productivity (Bell and Stukhart 1986).

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 labor are directly related to the successful completion of a project. Inefficiencies related to the manual operations of reporting, recording, and transferring field data in current tracking systems are becoming an evermore important issue as the size and scale of construction projects increase. While advancements in low power microelectronic devices and sensing technologies provide us with a capability to automate and integrate individual tasks for tracking and monitoring in the construction industry, a proven architecture or framework has not emerged to integrate them into practice. This can be attributed to the lack of cooperation among different participants, lack of information sharing, and inefficient use of communication technologies.

The presented research works introduce a new prototype framework of an automated tracking system that will address the needed shift into sensor- and network-based collaboration and communication systems for construction processes. By embedding the external ultrasound (US) device with a MICAZ platform, enhancements to networking flexibility and accuracy performance will be examined over the previous technologies used in the construction material tracking systems. Finally, cost-benefit analysis based on a quantitative approach will be discussed to illustrate the cost efficiency by comparing three tracking approaches. In addition to cost benefits, intangible and comprehensive benefits from the use of a sensor-based tracking system will be discussed for the expected efficiencies in communication, labor utilization, document management, and resource management.

Background

In 1994, the Construction Industry Institute (CII) established the materials management task force to examine the critical issues outlined in the 1982 Construction Industry Cost Effectiveness (CICE) Report. The task force attempted to develop information and concepts that prove the value and cost effectiveness of integrated and proactive materials management systems. The key findings from the materials management task force include the following:

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- When properly planned and executed, clearly defined materials management provides an invaluable tool to improve labor productivity;
- More than 6% of all construction labor costs could be saved if materials and equipment had been available at the work site when needed; and
- Few published case studies have measured the impact to specific instances of good and poor materials management practices.

In the meantime, their findings triggered several research efforts to examine the cost benefit of the materials management system. Bell and Stukhart examined benefits related to craft labor productivity with 20 different case study projects (Bell and Stukhart 1987). This research found that good materials management would reduce overall craft labor costs by 6% and increase direct labor savings by 8%. They also pointed out that, on projects lacking a materials management system, craft foremen spent 20% of their time hunting materials and another 10% tracking purchase orders and expediting. They also found that the ineffective or fragmented materials management system could incur bulk materials surplus as high as 10%. Finally, this research concluded that integrated computer-aided systems that track bulk materials would produce an additional 4–6% savings in craft labor costs.

Another recent survey (Futcher 2001) indicated that the site managers wasted a lot of time manually entering data and creating reports. In fact, field supervisory personnel spend 30–50% of work time on recording and analyzing field data (McCullouch 1997) and 2% of construction field work is categorized as manual tracking and controlling of materials handling (Cheok et al. 2000). In those manual processes, the accuracy and process time often rely on the judgments and writing skills of the personnel collecting the data. Furthermore, the time-consuming process of manually inserting and typing the field data to the computer terminals often obstruct the anticipation of prompt decision or job activities.

Currently available computer and sensor network technologies provide potential for data acquisition and communication. It has become viable on construction sites to collect the field information about tracking of construction materials, equipment, tools, and labors with the advanced location and identification sensing technologies. Bernold (1990) asserted that bar code technology is one alternative receiving more attention from the construction industry. Cheng and Chen (2002) proposed an automated schedule monitoring system using bar code-based radio frequency (RF) technology and geographic information system (GIS) in major critical-path activities. By developing the ArcSched system, they demonstrated that the efficiency of lifting operations for precast building construction has been improved in monitoring and controlling the erection progress.

During several years, significant beneficial applications of radio frequency identification (RFID) technology had been already found in retailing, manufacturing, transport, and logistics industries, and security and access control due to its robust functionalities with inexpensive and nonlabor intensive means of identifying and tracking products. Jaselskis and El-Misalami (2003) conducted a pilot test using RFID in the construction process. In their research, they developed a list of potential applications that include engineering design, material management, maintenance, and field operations. Song et al. (2006) conducted field tests of current RFID technology to examine its technical feasibility for automatically identifying and tracking individual pipe spools in laydown yards and under shipping portals. The field test indicated that RFID technology could function effectively even in the construction field environment of large metal objects, and the authors expected the potential benefits in automated pipe spool tracking, which include (1) reduced time in identifying and locating pipe spools and more accurate information gathered in a timely manner; and (2) reduced searching effort of misplaced pipes and increased reliability of pipe fitting schedule. Yagi et al. (2005) and Umetani et al. (2006) presented RFID applications in parts and packets unification for construction automation, where RFID devices were attached to construction components to investigate the relationship between the components and their information.

While RFIDs provide an advanced materials tracking method when compared with previous technology, e.g., bar code, the proximity method adopted by the RFID tracking system becomes a limitation when the exact position of mobile sensor nodes is required. Thus, multiple reference nodes, e.g., RFID readers, are often adopted to improve the position accuracy by using an intersection area among multiple references, in which it is still difficult to determine the coordination of the unknown location. Some researchers introduced the combination of RFID and global positioning system (GPS) for the accuracy improvement (Ergen et al. 2007), but the positioning errors superpositioned by GPS may entail the additional errors of the unknown location. In addition, the combination of RFID and GPS may have a challenge in network scalability and flexibility when large scale application domain is in consideration.

Wireless Sensor Networks

Emerging technology of wireless sensor networks has been gradually replacing the traditional paradigm of wired sensor networks during the past several years. Wireless sensor networks are characterized as the combination of processing, sensing, computing, and communication throughout distributed mesh networks. Tiny embedded devices with CPU, memories, radio components, and supply power form a flexible network by peer-to-peer communication protocols, such that the individual devices are interconnected throughout the network where data is seamlessly routed among all the nodes. While the capability of any single device for networking is not surprising at all, the composition of hundreds of single nodes offers new technological possibilities.

Most current deployments of sensor networks include small size generic sensor devices, e.g., square-in. size. Their network capability consists of an interconnected mesh tied to the internet through multiple gateway-class devices. The recent developments in first-generation wireless sensor networks are now evolving into a new generation of hardware capable of dealing with complex data streams and robust communication. Platforms for sensor network hardware available today are listed in Fig. 1.

Testbed Experiment

MICAZ, produced by Crossbow Technology Inc., has been selected as a *ZigBee* compliant low-power and low-cost wireless module capable of providing a flexible and expandable networking scheme, such as a mesh network that can configure up to 65,000 nodes (Egan 2005). As an industrial network protocol, the *ZigBee* compliant device has the potential for various applications in construction automation, structural health monitoring, and automated control and operation. In order to perform the distance estimation, three MICAZs were connected to the US receiver, US

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Mote Type	WeC	Rene	Rene 2	Dot	Mica	Mica2Dot	Mica2	Micaz	Telos
Year	1998	1999	2000	2000	2001	2002	2002	2004	2004
									
Microcontroller									
Type	AT90LS8535		ATMEGA163		ATMEGA128				MSP430
Program Memory (KB)	8		16		128				60
RAM (KB)	0.5		1		4				2
Active Power (mW)	15		15		8		33		3
Sleep Power (μW)	45		45		75				6
Wakeup Time (μs)	1000		36		180				6
Storage									
Chip	24LC256				AT45DB041B				ST M24M01S
Connection Type	I^2C				SPI				I^2C
Size (KB)	32				512				128
Communication									
Radio	TR1000					CC1000		CC2420	
Data rate (kbps)	10				40	38.4		250	
Modulation Type	OOK				ASK	FSK		O-QPSK	
Received Power (mW)	9				12	29		38	
Transmit Power at 0dBm (mW)	36				36	42		35	
Power									
Minimum Operation (V)	2.7								1.8
Total Active Power (mW)	24				27	44	89		41
Programming and Sensor I/O									
Expansion	none	51-pin		none	51-pin	19-pin	51-pin		10-pin
Communication	IEEE 1284 with RS232								USB
Integrated Sensors	no			yes	no				yes

Fig. 1. Mote family of TinyOS for wireless sensor network (Levis and Culler 2002)

transmitter, and MIB510 interface (as a base station), as shown in Fig. 2.

The embedded sensor system includes four major components: ultrasound transducer, beacon node, remote node, and base station. First, ultrasound devices were connected throughout the external connectors provided in MICAZ, and 9V external power was supplied to the ultrasound devices. An ultrasound transducer, Jameco 40TR16F used in this experiment, has a dominant frequency of 40 kHz with 4 kHz bandwidth, and has a sound pressure level (SPL) of 119 dB at 40 ± 1 kHz for a transmitter and a minimum SPL of 65 dB at 40 ± 1 kHz for a receiver. Second, a set of MICAZs and an ultrasound device was assigned as a beacon node. The beacon node, consisting of RF module and ultrasound receiver, will be placed at the fixed location as a reference point, and periodically sends RF trigger signals to generate ultrasound response signals at remote nodes. Third, another set of MICAZs and an ultrasound device was assigned as a remote node. The remote node, consisting of a RF module and ultrasound transmitter, will be attached at the mobile construction materials of interest, and sends ultrasound response signals to measure the distance between a remote node and beacon node by the time-of-flight method. Finally, one MICAZ attached to the interface board acts as a base station node, and collects and forwards the wirelessly communicated message to the PC interface. The base station server will perform the trilateration with three measured distances to determine the coordinates of the remote node.

Fig. 3 illustrates the test configuration setup for distance estimation at the outdoor environment. A set of beacons is then placed at a fixed location and a set of remote nodes is placed at variable positions starting from 1 to 15 m. A base station node collects and transfers the wireless message to the connected laptop. Fig. 4 describes the percentile errors measured in each location, and an almost 80th percentile of measurements at each location show the error at less than 20 cm. In addition, average standard deviation shows 9.7 cm, which is fairly accurate in distance ranging from 1 to 15 m.

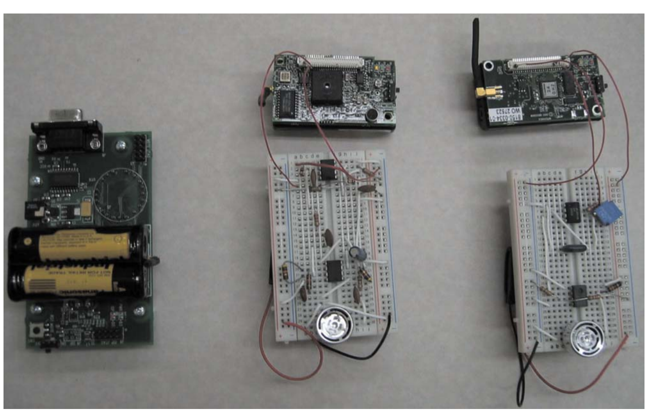

Fig. 2. Device configuration for a MIB510 interface (left), a beacon (center), and a remote node (right)

Fig. 3. Configuration of setup for distance estimation test

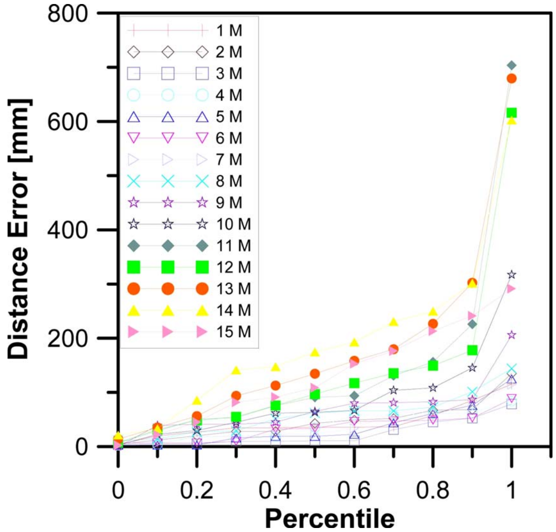

Fig. 4. Plot of percentile errors

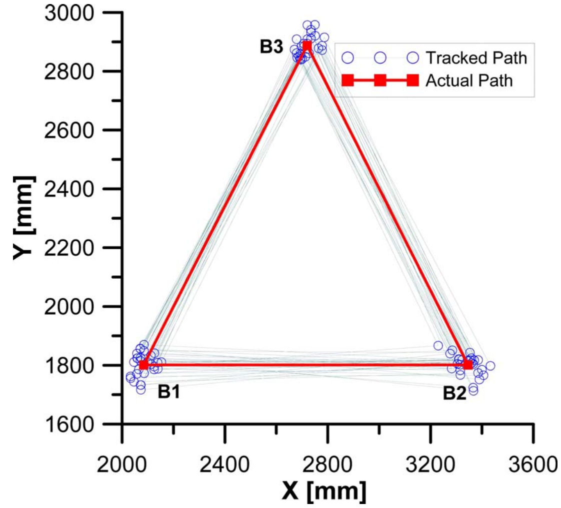

Fig. 5. Measuring the position of a remote node that turns around a triangular path

A line of sight is required between the beacon and remote node because the ultrasound wave cannot penetrate a blocking object unless the power of the transmitted signal is sufficiently strong. This requirement may incur a limitation when this system is deployed in the practical construction site because the nature of the construction field consists of many blocking objects such as vehicles, materials, building structures, etc. However, we can increase the line of sight between them by placing the beacons at higher locations, such as attachment to a light pole in the field or a ceiling inside a building, which is similar to a satellite placement that allows an increased line of sight with GPS applications. As a consequence, this challenge might be well resolved if a practical deployment strategy on a real construction site is examined when applied.

For position estimation, three beacons are positioned along with the triangular shape, with 5 m distance from each other, and a triangular path with a 1.3 m length is set for measuring the position of the remote node that is circling the triangular path. The position of the remote node is measured and tracked at each vertex point of the triangular path every 5 sec until it circles the path 30 times, as shown in Fig. 5. This setup model is advantageous to identify whether or not the proposed tracking system can sufficiently detect and measure an object's movement in such a small triangular path. Thus, the result would justify the real application scenario in a construction site by the expanded mesh networks with high measurement resolution and accuracy. Fig. 6 describes the error estimation where average deviation of position is measured ranging from 43 to 47 mm in radius, and standard deviation also shows accurate measurements ranging from 18 to 29 mm in radius.

In sum, the experimental results showed notable improvement of measurement accuracy and networking flexibility, indicating that the individual distance estimation indicated that the 90th percentile of measurements among more than 1,000 samplings ranges from 3 to 25 cm up to a ranging distance of 15 m. The positioning accuracy also ranges from a mean of 4.3 to 4.7 cm among 30 samplings. Unlike the proximity approach, a trilateration method generates the geographic coordinates of mobile objects with increased accuracy. Comparison with GPS also illustrates the improved accuracy in that an average 10 cm error variation has been observed in even differential GPS (DGPS) (Kechine et al. 2003).

Cost-Benefit Analysis

Quantitative Approach

Quantitative approaches to cost-benefit analysis involve the use of explicit monetary values and processing times associated with field material management. However, many material management systems in construction fields cannot represent definite values because actual lengths of processing time in material management differ between sites, types of projects, construction project time, and physical locations. The difficulties with determining required labor associated with material tracking also pose a challenge in defining the actual process time. Accordingly, the method of expert interviews with various construction and engineering companies was selected as a source to determine the monetary values and process time of material tracking implementation because expert experiences would provide a critical reference for the process information. By summarizing these interviews, field material tracking could then be represented by cyclic processes consisting of check-in cycle, daily checkup cycle, and installation cycle. Although actual material management includes complicated activities, such as requests for quotation (RFQ), bid documents, purchase orders (POs), material delivery, materials receiving report (MRR), accounting documents, payments (Lee et al. 2004), the quantitative approach in this section defines the processes

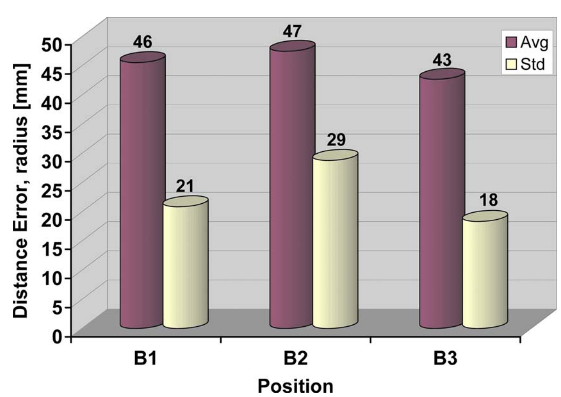

Fig. 6. Distance errors in radius (unit: mm)

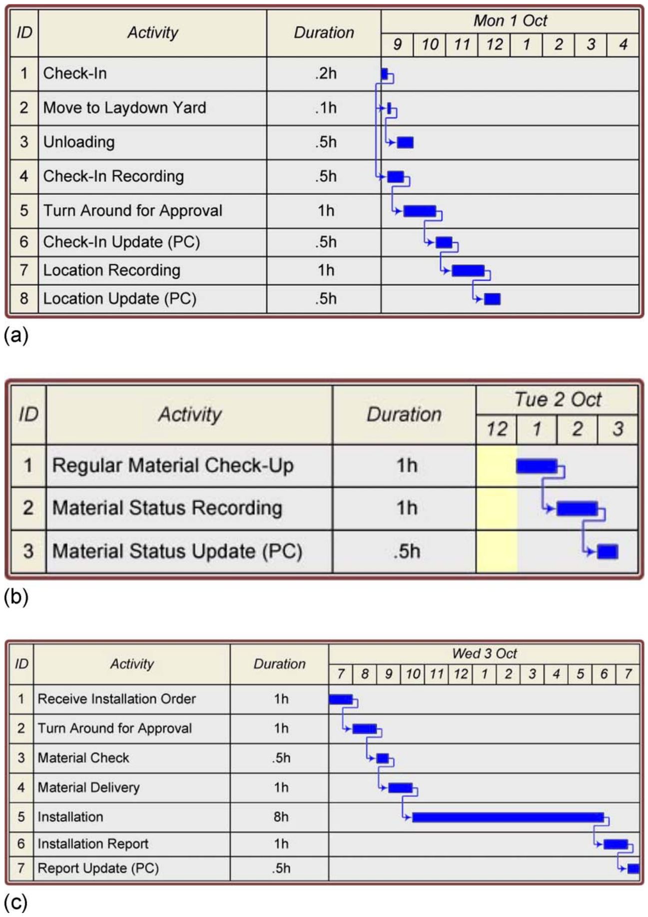

Fig. 7. Three cyclic procedures associated with the material tracking and handling: (a) check-in cycle related to the materials reception and unloading; (b) daily checkup cycle related to the daily checkup status of materials; and (c) installation cycle related to delivery and installation process

involved from material receiving to installation where the wireless sensor framework for construction material tracking functions as a tool for data collection and updates that can replace the manual processes.

Scenario-Based Tracking Simulation

The three cyclic processes, shown in Fig. 7, represent the materials management processes at a simulated construction site. It is assumed that the listed processes include only in-site activities, while preprocesses such as RFQ, manufacturer's handling, shipping, etc., are not considered. Installation activities are performed during the designated timeframe after the material PO and delivery, and daily checkup cycles are repeated during the installation process. After the information about total material quantities and their installation processes are determined, the material delivery cycles can be estimated for partial or entire project duration.

From the interviews of more than 20 experts, we identified the detailed activity procedures, activity durations, resources, and crew's responsibility associated with the materials management in a typical construction project. Fig. 7 illustrates the three process cycles with break-down activities from check in to installation cycle. The unit labor hours were obtained by comparing the manual-based process and sensor-based process (including both RFID and embedded systems). It is reasonable to divide the cycle into three parts because the timeframe required in each cycle is different. For example, the check-in cycle corresponds to the delivery cycle, the time by which available trucks take to carry the materials from a manufacturer's site to a construction site. Thus, the delivery schedule is followed by the installation schedule and material PO, in which the required amount of materials can be determined. On the other hand, the daily checkup cycle represents the cycle required for a material crew to daily check the material storage about the material status, items, quantity, and locations. This daily checkup is typical material management conducted in almost every construction site because information about the material status is important when prompt actions for hunting or installation of materials are needed in a specific situation. The daily checkup cycle is determined by the time required for the materials to be stored between delivery and installation, so enough but not too long a period of time should be allocated to avoid any process delays in a limited laydown yard. Finally, the installation cycle represents the activities that are incurred when the installation order is placed, and is determined by the installation schedule per each day.

The unit labor hours required to conduct each cycle and the comparison between manual and sensor-based methods are shown in Table 1. It is important to note that activities such as reporting, paperwork, data updates, and daily checkups are considered labor-intensive tasks that could be removed when a sensor-based method is applied. The rationale behind this is that an RFID or embedded-sensor system could automate material check in, recording the material status, paperwork for approvals, and data updates without labor activities. As a consequence, the deducted amount of working hours from a sensor-based method represents the savings of unit labor hour in each cycle associated with the material and information handling. By estimating the required activity durations in each cycle, labor hour in check in, daily checkup, and installation cycle could be improved by savings of 2.7 hr/cycle, 3 hr/cycle, and 3 hr/cycle, respectively.

With the findings from the savings of the unit labor hour, the quantitative approach for the cost-benefit analysis was conducted on an example construction project. After structural evaluation, a State of Massachusetts investigation determined that a highway bridge in Boston, MA built in 1970 required superstructure replacement. Current steel girder and concrete decks are replaced by a steel girder and fiber-reinforced polymer (FRP) deck after preliminary design of the superstructure. The overview of the bridge is described in Table 2.

Quantity take off for the superstructure replacement was conducted based on the bridge drawings. It should be noted that only four bulk materials, e.g., girder, decks, drainage pipes, and bracing structure are considered for the materials tracking scenario, even though the entire materials may include tiny entities, e.g., bolts, expansion joints materials, cements, connection rings, etc. Since the installation of those bulk materials represents between 70–90% of the total project activities, specifically in bridge superstructure replacement, such small and less critical materials were excluded from this calculation. Table 3 describes a summary of quantity take off for the major bulk materials in the superstructure replacement project.

The cycle estimation was performed by considering each individual cycle of check in, daily checkup, and installation. The check-in cycle may be calculated based on the delivery schedule for specific activities, and the numbers of cycles were obtained based on data in Table 4. Because installation activities were implemented by individual span construction, a 1-day duration was assumed for them. Accordingly, eight girders with 49-lateral

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Table 1. Estimation of Unit Labor Hours in Three Different Process Cycles

Category	Manual Activity	Manual Duration	Manual Resources	Manual Function	Wireless sensor Activity	Wireless sensor Duration	Wireless sensor Resources	Wireless sensor Function
Check in cycle	Check in	0.2	Crew	Reception	Check in		Sensors	Reception
	Move to laydown	0.1	Truck		Move to laydown	0.1	Truck	
	Unloading	0.5	Crane		Unloading	0.5	Crane	
	Check in recording	0.5	Crew	Counting and item check	Check in recording		Sensors	Automatic record
	Turn around for approval	1	Crew, manager	Approval signature	Turn around for approval	1	Manager, PC	Approval signature
	Material reception update	0.5	Crew	Typing to PC	Material reception update		Sensors	Automatic record
	Paperwork for location information	1	Crew	Update location log	Paperwork for location information		Sensors	Automatic record
	Material location update	0.5	Crew	Typing to PC	Material location update		Sensors	Automatic record
	Subtotal	4.3			Subtotal	1.6		
					Working-hour-saving per cycle	2.7		
Daily checkup cycle	Regular material checkup	1.5	Crew	Counting and item check	Regular material checkup		Sensors	Automatic record
	Paperwork for material status	1	Crew	Update status log	Paperwork for material status		Sensors	Automatic record
	Status update	0.5	Crew	Typing to PC	Status update		Sensors	Automatic record
	Subtotal	3			Subtotal	0		
					Working hour saving per cycle	3		
Installation cycle	Installation order received	0.5	Crew	Order reception	Installation order received		Sensors	Automatic record
	Turn around for approval	1	Crew, manager	Approval signature	Turn around for approval	1	Manager, PC	Approval signature
	Material check for items and quantity	1	Crew	Counting and item check	Material check for items and quantity		Sensors	Automatic record
	Material delivery	1	Truck, crane		Material delivery	1	Truck, crane	
	Installation	8	Crane		Installation	8	Crane	
	Installation report	1	Crew	Update installation log	Installation report		Sensors	Automatic record
	Data update	0.5	Crew	Typing to PC	Data update		Sensors	Automatic record
	Subtotal	13			Subtotal	10		
					Working hour saving per cycle	3		

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Table 2. Overview of State of Massachusetts Bridge Requiring Superstructure Replacement

Bridge Overview	
Structural type	Stringer/multibeam steel girder bridge
Service on bridge	Highway
Service under bridge	Highway-waterway
Traffic lanes	Six
Daily traffic	70,770
Total span length (m)	310.3
Span width (m)	24.4
Operating rate	53.5 tons
Number of spans	Nine
Girder material	Steel
Deck material	Concrete

beams (seven beams at 5-m length), five FRP bridge decks, and 12 PVC pipes were installed into individual span construction.

Cost Analysis

Three project durations of 3, 12, and 24 months were considered to compare the labor hour savings associated with the material and information handling among three different tracking methods, e.g., manual, RFID based, and embedded system. It should be mentioned that device purchases were considered in implementation cost, because the infrastructure for a sensor-based network system must be configured before actual implementation. As a tracking domain, a 50-by-50 m laydown yard was selected to store the bulk materials. It is assumed that the RFID and the embedded system have the same capacities of tracking functionality and coverage range in order to provide a consistent comparison between them. A 10-m coverage range was applied to both sensor-based methods, and a total of 16 beacons were placed to configure the network for tracking of the remote nodes attached to the bulk materials. Since the entire bulk materials cannot be stored in the limited laydown yard at a time, the actual materials are delivered according to the installation cycles that require 57 remote sensors for tracking. These remote nodes may be detached and reattached whenever new bulk materials are checked in.

Total implementation costs of the three different tracking schemes are presented in Fig. 8. In current market places, device purchases require RFID tags costing 10 cents each, and a ultra-

Table 3. Quantity Take off of Major Bulk Materials for Superstructure Replacement

Item	Dimension (m)	Quantity[a]	Unit
I-shape steel girder	35 L × 1.3 H to 1.8 H	79	EA
Cross steel beam	3 L × 0.5 H	485	EA
FRP deck	24 W × 7 L	50	EA
Drainage pipe	D30 × 6	683	EA

[a]Quantity includes 10% contingency.

Table 4. Cycle Estimation for Typical Bulk Materials

Item	Check-in cycle (days)	Installation cycle (days)
I-shape steel girder	79/(2 EA × 1 day) = 40	9 spans/1 SPD[a] = 9
Cross steel beam	485/(10 EA × 1 day) = 49	9 spans/0.28 SPD = 32
FRP deck	50/(1 EA × 1 day) = 50	9 spans/1 SPD = 9
Drainage pipe	683/(50 EA × 1 day) = 14	9 spans/1 SPD = 9
Total cycle	153	57

[a]SPD = span per day.

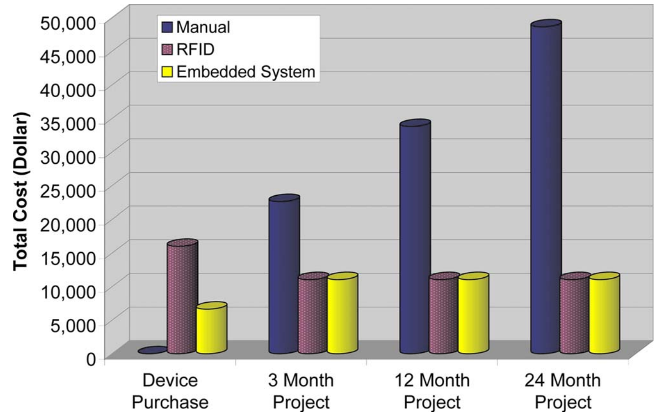

Fig. 8. Total implementation cost for field materials tracking compared with three tracking alternatives; based on the median hourly wages for bridge construction labor: $13.55 (*Occupational Outlook Handbook* 2007)

high frequency (UHF) (900 MHz) or high frequency (HF) (13.56 MHz) RFID reader with 10-m measuring distance costs from $1,000 to $2,500 depending on the capacity of the devices (Mohamadi 2004). On the other hand, it is hard to estimate the cost of the embedded systems because the proposed system with an ultrasound device is still in the research stage. It is assumed that a MICAZ wireless sensor module costs $91 including the cost of an external ultrasound device. Based on this information, it can be found that RFID readers have a high cost associated with device purchases, approximately $16,000 (a total of 16 beacons at approximately $1,000 each), and an embedded system costs approximately $6,600 (16 beacons and 57 remote nodes at $91 each).

Unlike the sensor-based tracking system, the manual process does not require the device purchase. However, unit labor cost increases at the manual-based material tracking stage. The implementation cost for a manual process is $22,000 for a 3-month project, $34,000 for a 12-month project, and $48,000 for a 24-month project. On the other hand, the implementation costs for sensor-based material tracking remain the same at the level of $11,000, even if the project duration increases. This is because sensor-based implementation automates the labor tasks required in the daily checkup cycle, and there is no increase in labor hour under the sensor-based method. For example, recording, paperwork, checkup, order reception, and data updates are automated by the sensor-based systems, and the related labors are removed from the information handling tasks.

Even if the initial device purchase requires a large budget for sensor-based systems, gradual increase in labor costs associated with material handling is getting ahead of the implementation cost of a sensor-based tracking system. The labor cost increase in a manual tracking system is proportional to the entire project duration, and the labor intensive tasks, such as information handling, impact the project budget. Furthermore, the high cost of an RFID reader influences an adverse effect on deciding the adoption of a RFID-based tracking system even though the implementation cost equals that of the embedded tracking system.

Sometimes, direct comparison of implementation costs cannot represent the actual project situation because the conditions of construction tasks vary according to many different situations. This fact often causes a challenge to quantify the cost savings and expected cost benefit, but the approach presented in this section

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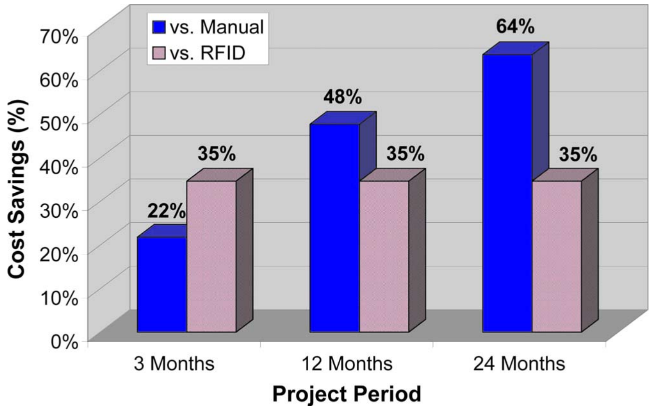

Fig. 9. Labor cost savings in percentage due to the deployment of embedded sensor-based tracking methods

may help review the unit labor cost savings in a typical construction project. For a more general expression, the comparison between manual or RFID versus an embedded system was obtained by the fractional rate of percentage, which is shown in Fig. 9. This result shows that up to 64% of labor cost associated with the material tracking and information handling can be saved if the current manual process is replaced by an embedded system framework. When RFID is compared with the embedded system framework, less savings up to 35% are expected due to the high cost of device purchase. If a large construction domain is considered, the difference between a RFID and an embedded system will increase, assuming that both devices have the same capacities in tracking the construction materials.

Qualitative Approach

The benefits from the use of a sensor-based framework may be discovered in many aspects of project practices. First of all, the most important, intuitive benefit may be the efficiency of communication. A wireless sensor-based framework provides an automated means of information transfer for data acquisition. Prompt updates of field information regarding material status, locations, quantity, etc., along with the wireless networks make it easy to manage and control the construction process with many types of management software. More importantly, material tracking at critical path activities can benefit from the automated updates of installation orders/confirmations and of status checkups while minimizing the delays. Recent advancements in communication technologies give better opportunity to a wireless sensor framework that can reside in different communication platforms such as handheld devices, portable internet devices, and GPS platforms. The communication platforms can increase their functionalities when combined with a wireless sensor network, thus, the current practices of field information acquisition can be improved.

Ease of use, less effort associated with documentation, cycle time reduction in approvals, and efficient utilization of labor force will also provide tangible benefits. The aforementioned survey shows that significant time and effort in location hunting, recording, updating, and paperwork would be saved if the field materials management is improved, which has been shown in the proposed quantitative analysis as well. Increased efficiency in data acquisition can also improve the associated tasks, such as data retrieval, data representation, and data manipulation, if the system dynamically interacts with the management systems. This fact may increase the level of comfort and convenience to many end users

Table 5. Qualitative Benefits by Adopting a Sensor-Based Tracking System

Category	Qualitative benefits
Communication	• Improved data acquisition
	• Interoperability to management systems
	• Prompt updates of field information
Operation	• Ease of use
	• Less effort for documentation
	• Process time reduction
	• Efficient utilization of labor force
Paperwork	• Reduced volume of historical archives
	• Cost savings on document handling and storage space
	• Reduced use of papers
Resource management	• Improvement of procurement and accounting systems
	• Enhanced information sharing
	• Increased ownership and responsibility

through the use of wireless sensor systems, while it is hard to estimate it in a qualitative manner. For example, one can easily think of the expected benefit of internet technology, and everyone can agree that the internet provides comfortable, convenient, fast, and an easy way of communication, information sharing, and work processing. On the other hand, it is not easy to quantify the benefits from the use of the internet because diverse factors, such as user's age, gender, location, purpose of use, organization, etc., need to be factored into calculating the amount of benefits.

If a sensor-based framework is connected with a database system, benefits can be expected through reduction of the volume of historical archives. As the number of projects that a construction company has accumulated increases, extensive efforts are required for document management. Therefore, the costs associated with the document handling and the storage space could be saved by automating the traditional paperwork involved in the construction projects. Additional expenses for the use of printers and copy machines may be saved by an automated data management framework as well.

Finally, a resource management system can benefit from the sensor-based framework. Most materials management systems are intertwined with other project management modules. For example, material procurement modules can be shared with the material tracking system, enabling prompt decisions on the material RFQ and PO. Another example shows that an accounting system could be associated with the field information acquisition module in the management system, and prompt updates of cash flow information can increase the efficiency through the improved method of field information handling.

In the world of fast changing information technology, the framework for consistent management in work processes may be realized by an "everywhere" sensor network. Hence, the potential of the sensor network promises to reorganize standards and coordination toward the new paradigm and trends of project management. At the same time, new construction industry developments endowed with the emerging technology will provide the new understanding of the implications that may deliver the efficiency and effectiveness of construction projects. The summary of the quantitative benefits by adopting a sensor-based tracking system are listed in Table 5.

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Conclusions

This paper explored the cost benefits of the embedded sensor system for an automated materials tracking system in construction sites. The benefits to this pilot implementation are: (1) high accuracy; (2) low cost; and (3) robustness using the combination of ultrasound and RF. With flexible, efficient network capabilities provided by RF communication, ultrasound technology fits well with the extended application scenarios on construction sites. Based on the hardware and software architecture of the embedded system, a pilot experiment was implemented, resulting in average standard deviation error of 9.7 cm in single distance estimation, and less than 5 cm error in position estimation.

Three alternative materials tracking practices were compared: manual, RFID, and an embedded sensor system. Based on the bridge construction project described, it was possible to examine expected savings of labor cost associated with construction material tracking practices. By deploying the embedded sensor technology, up to 64% of the labor cost associated with the material tracking and information handling could be saved in a 2-year-long bridge construction project. In addition, proposed sensor-based construction material tracking could provide an efficient way of data communication, resource management, document management, and labor utilization.

With the benefits described in this paper, it is expected that the presented tracking framework can be extended into diverse application areas, such as construction asset tracking, safety monitoring for workers, and further interoperability among different technologies in project management systems, such as enterprise resource planning (ERP) systems, Web-based project management systems, and multidimensional visualization tools.

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