

# TECHNOLOGICAL ASSESSMENT AND PROCESS IMPLICATIONS OF FIELD DATA CAPTURE TECHNOLOGIES FOR CONSTRUCTION AND FACILITY/INFRASTRUCTURE MANAGEMENT

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**SUMMARY:** *Collection of accurate, complete and reliable field data is not only essential for active management of construction projects involving many tasks, such as material tracking, progress monitoring and quality assurance tasks; but also for facility/infrastructure management during the service life of facilities and infrastructure systems. Limitations of current manual data collection approaches in terms of speed, completeness and accuracy, and implications of these limitations for construction management practice are discussed by many researchers. Advancements in field data capture technologies (such as smart tags, laser scanners, and embedded sensors) enable collecting, storing and reusing field data accurately, completely and reliably. We show that while these technologies are capable of streamlining the associated processes, their performances differ from the manufacturers' specifications when utilized on construction sites due to issues, such as interference, data reading range, data accuracy, interoperability of hardware and software, and memory limitations. In addition, while these technologies eliminate some non-value adding tasks associated with corresponding project management processes, they can also add new tasks that need to be performed prior to, during, or after the utilization of a technology at the field. Hence, a thorough understanding of both the technological capabilities and process implications of these technologies is needed to be able to utilize them effectively during construction and service life of facilities.*

**KEYWORDS:** *field technologies, laser scanner, RFID, embedded sensors, construction, facility/infrastructure management, data collection.*

## 1. INTRODUCTION

Around 50-80% of the problems on construction sites are attributed to missing and delayed information access (Howell and Ballard 1997, Thomas et al. 1997). Collection of accurate, complete and timely field data is not only essential for active management of construction projects, but also for facility/infrastructure management during the service life of facilities and infrastructure systems. For example, during construction, a project team needs to quickly

and accurately identify the locations and identifications of available resources, and to determine whether the components in place have satisfied quality specifications. Similarly, during facility usage, facility management personnel need to access data about components and systems within facilities in a timely manner. However, in current practice, it is still a challenge for construction and facility personnel to access information in a timely, accurate and complete manner. Limitations of current manual data collection approaches in terms of speed, completeness and accuracy are discussed by many researchers (e.g., Davidson and Skibniewski 1995; Navon 2005, Reinhardt et al. 2004, Sacks et al. 2005, McCullouch 1997, Cheok et al. 2000a).

Advancements in field data capture technologies, such as smart tags, laser scanners and embedded sensors enable collecting, storing and reusing field data accurately (i.e., without inaccurate recording of manual process), completely (i.e., without missing data), and timely (i.e., whenever needed). A large number of research studies have developed approaches for application of a set of technologies to construction and facility/infrastructure management. Examples of these studies include barcode and RFID applications for improving construction supply chains (e.g., Rasdorf and Herbert 1990, McCullouch and Lueprasert 1994, Finch et al.1996, Jaselskis and El-Misalami 2003); laser scanner applications for quality control (e.g., Akinci et al 2006a, Jaselskis et al. 2006), condition assessment (e.g., Fuchs et al. 2004, Gordon et al. 2004), component tracking (e.g., Gilsinn et al. 2005, Bosche et al. 2006), and productivity monitoring (e.g., Su et al. 2006), and embedded sensors for quality control (e.g., Akinci et al. 2006a). In general, these studies compare current manual approach with the approach developed by leveraging automated data capture technologies in terms of timeliness, accuracy and completeness of collected data. The study provided within the context of this paper builds on and complements the previous studies by combining individual findings of these studies and by providing a more comprehensive assessment of technical performance and process implications of using a set of technologies at the field.

This paper first provides an overview and technological assessments of field technologies under changing environments that they face during construction and facility/infrastructure management. Second, it details process implications of utilization of these technologies on construction and infrastructure management processes. Both of these discussions are based on the observations and findings of a set of case studies conducted on construction sites and in operating facilities. We will specifically focus our discussions on utilization of laser scanners, radio frequency identification (RFID) technology, and embedded sensors, to support material tracking and defect detection during construction and condition assessment during operations and management. Various automated identification technologies can be utilized for identifying and tracking goods in construction and facility/infrastructure management, such as barcode, two dimensional barcode, optical character recognition (OCR), contact memory technology, and radio frequency identification (RFID) (Rasdorf and Herbert 1990, McCullouch and Lueprasert 1994, Finch et al.1996, Jaselskis and El-Misalami 2003). In the field tests explained in this paper, RFID technology was selected due to its longer reading range and on-board data storage capacity. Among possible 3D imaging technologies (flash lidar, 3D photogrammetry and laser scanners), we used laser scanners due to their ability to rapidly capture high-resolution 3D data about a construction scene in a short amount of time and with a better resolution as compared to other 3D imaging systems.

While these technologies are capable of streamlining the associated processes, their performances can differ from the manufacturers' specifications at the field (Ergen et al. 2007a, Ergen et al. 2007b). Specifications often times provide ranges for accuracies of a technology, but do not provide specifics about how this technology will perform given a field condition. Hence, these technologies need to be tested under varying conditions, so that field engineers confidently rely on the data coming from these technologies. In addition, while these technologies eliminate some of the non-value adding activities associated with corresponding management processes, such as communication loops to complete missing data; they also add new tasks that need to be performed (Akinci et al. 2006b). Hence, a thorough understanding of both the technological capabilities and process implications of these technologies is needed to be able to utilize them effectively at the field.

## **2. OVERVIEW OF FIELD TECHNOLOGIES UTILIZED IN THE STUDY**

Within construction and facility supply chains, the tasks that are representative for field engineers include assessing whether quality requirements of constructed entities are met, assessing material qualities and tracking them within a

field. We conducted experiments with RFID, laser scanners and embedded sensors, since these technologies are capable providing required data to support such variety of tasks during construction and facility/infrastructure management. Below are the details about the characteristics of technologies we used in the experiments.

## 2.1 Radio Frequency Identification (RFID) Technology

RFID is a type of automated identification technology, which utilizes radio waves to transmit data. Besides identification, RFID is also used to store data in a distributed fashion. Unlike similar identification technologies (e.g., barcode), RFID does not require line-of-sight, close proximity, individual readings, or direct contact. It can be read at longer distances and durable to harsh construction environment (Jaselskis and El-Misalami 2003, Song et al. 2005, Ergen 2007b). RFID has two main components; a reader and a tag (Figure 1). A tag, which consists of an electronic chip coupled with an antenna, is attached to an object, and stores data about the object. The reader reads/writes data from/to a tag via radio frequency and transfers data to a host computer. Reading/writing ranges depend on the operation frequency (low, high, ultra high, and microwave), and whether the tag needs a battery to operate (active) or not (passive). Active tags have typically higher reading ranges; however, they have limited life-time, requiring periodic battery replacement.

One of the advantages of RFID technology is its ability to enable data entry and access at any time throughout the lifecycle of a tag. Another advantage is the data storage capacity; which is currently up to 64 KB for active tags, allowing for storage of additional information beyond identification information on the tag. RFID does not require line-of-sight and allows for multiple readings at once at longer distances; thus, it is suitable for automating the identification of multiple items.

In the field tests, active UHF technology was selected due to longer reading ranges and large data storage capacity. The components of the RFID system used in the tests are given in Figure 1 and characteristics are summarized in Table 1. In three of the related field tests, a fixed circularly polarized antenna (*Type 1* in Figure1) was used since it was insensitive to orientation of the tags, which is a requirement for dynamic test environments such as construction sites. In one of the tests, where a user collects data carrying the reader and antenna, a dipole antenna (*Type 2* in Figure1) was used, since its small size was suitable for a mobile application.

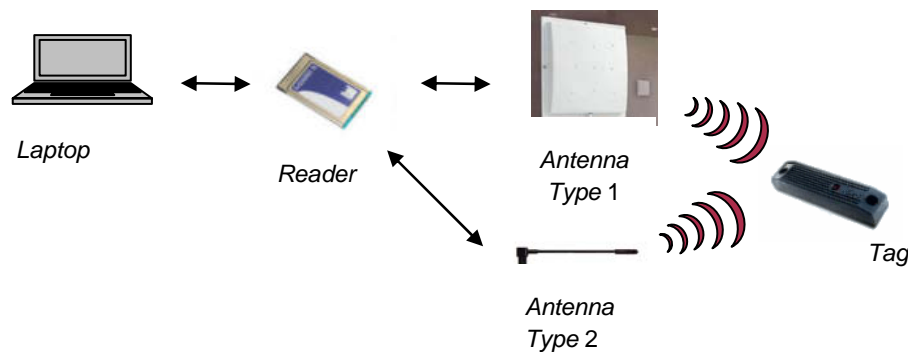


FIG. 1: RFID hardware used during the field tests.

A limitation of active RFID technology is that the internal battery of a tag is needed to be replaced approximately at every 5-10 years. In addition, the cost of active tags and readers is relatively high in comparison to barcode technology. However, since RFID is an evolving technology, new active and passive RFID systems consistently have decreasing costs and new active RFID systems continue to feature larger data storage capacities. Another limitation of RFID is the performance reduction that is observed around metals and liquids at higher frequencies (UHF and microwave). Encapsulation of tags helps in decreasing the performance reduction. Since radio waves are absorbed or reflected by objects in the environment, technology providers strongly suggest testing the performance of RFID technology in real-life environments.

Table 1: Characteristics of RFID technology utilized during field tests.

Criteria	Values
Data collected	ID and/or maintenance info
Technology used in data collection	Radio signals
Data collection method	Automated or manual
Typical range (m) (min-max)	3-27
Main components	Active tags Reader
Data storage capacity (kb) (max)	32

## 2.2 Laser Scanning Technology

A laser scanner is a 3D imaging technology designed for capturing vast amounts of measurements of points in its vicinity in a short time. These measurements of points, collectively “point clouds” are used to create 3D models. We used a commercially available laser scanner in our case studies about application of laser scanning technology for construction and infrastructure management. Table 2 shows technical data about this scanner, as specified by the manufacturer. Two common types of laser scanners are time-of-flight scanners and phase-based scanners. Time-of-flight scanners directly record the round-trip time for a laser signal to reach the nearest object in its line of sight and reflect back to the scanner. By contrast, the utilized scanner is a phase-based scanner, which uses the phase difference between the signal sent out and the received signal to calculate the round trip traveling time of the laser for the range determination. This approach theoretically achieves measurements with higher accuracy as compared to time-of-flight scanners. The data collection rate of this scanner can be up to 625,000 points per second, which means that a typical scanning process can take as low as 100 seconds for a low resolution scan. The accuracy of the measurement of position of a single point by using this scanner is about 13 millimeters at 25 meters, and about 3.5 millimeters at 10 meters. The collected range images are of high resolution, with the vertical angular resolution of the scanner as low as 0.018° and the horizontal angular resolution as low as 0.01°. Assuming that the distance between a planar surface facing the scanner and the scanner is 10 meters, the described angular resolution values means that the vertical surface sampling step is about 3.1 millimeters, and the horizontal surface sampling step can be about 1.7 millimeters.

Table 2: Characteristics of the laser scanner used in field tests.

Criteria	Values
Scanning range (meter)	5 10 25
Field of view (degree)	360° (horizontal) x 310° (vertical)
Typical range	Min(meter) 1 Max(meter) 53.5
Range resolution (millimeter)	0.38
Range accuracy (millimeter)	Linearity error 3 3 3 Random noise 1.6 1.6 4.5
Angular resolution (°)	Vertical 0.018 Horizontal 0.010
Angular accuracy(rad)	Vertical 0.020 Horizontal 0.020
Data collection rate (typical/up to)	125,000 / 625,000 points/sec
Typical full scan files size (MB)	150
Num of points in a typical full scan (points)	50,000,000

We chose this scanner also partly due to its fast data collection rate compared with other types of scanners. Many commercially-available time-of-flight scanners collect at a rate of several thousands of points per second, which requires a significantly longer time spent at the field for data collection. In such longer data collection durations, it is

likely that measurements of objects that move in the scene during scanning will result in noisy data. In highly dynamic environments, such as a construction site, it is not practical to keep the scene static for such a long time. The scanner used in this research is almost 100 times faster than a typical data collection rate for a time-of-flight scanner (up to 5,000 points per second), and is able to finish a 360° scan with an object surface sampling step less than 1 cm within a few minutes. Hence, this high speed scanner is promising for fast and detailed 3D scene capture and deserves further exploration in our case studies.

To reconstruct 3D models from laser scanned data and extract geometric features from those models, we chose two commercially available reverse engineering environments for data processing and geometric information extraction according to specific functionality requirements identified in our case studies. Raw laser scanned data contains various sources of noise, each requiring a filter for removal. At a single position, a laser scanner can only capture objects visible to it in its line of sight. As a result, occluded parts of the objects need to be captured by scans from other positions. This requires a process of aligning several scans into a more comprehensive data set, which is known as data registration. The filtered and aligned data set supports construction of 3D models, and extraction of geometric features of the models to retrieve required geometric information items such as distance between a point and a plane. A tool provided by the manufacturer of the scanner can remove mixed pixels (details in the following section), align scans, and measure basic distance measurements. We also used another commercially available reverse engineering package, which is a collection of tools for data importing, cleaning and registration, 3D model reconstruction, geometric feature extraction and measurement within the 3D environment.

### 2.3. Embedded Sensing Technology

Embedded sensors and supporting devices (e.g., data loggers, transceivers, and power sources) form embedded sensor systems, which can be placed within or near building elements to sense, store, communicate, and process data about such properties as temperature and strain. These systems are limited both by operating constraints of the sensors (such as minimum and maximum sensing range and sensor accuracy), but also by the ability of supporting devices to provide power to the sensor system, and store, process, and communicate streams of data. Table 3 outlines the differentiating characteristics of three sensor systems studied. The sensor systems vary in terms of the data logging capability, the type of sensor used, and the placement of components of the sensor systems with respect to building components being inspected. The data logging capabilities varied due to the amount of data that could be stored on the data logger before its memory gets filled. Temperature was measured in this comparison of systems to determine the strength of a concrete using maturity method, and two sensor types were chosen: thermistor, and thermocouple. The quoted and measured accuracy of each sensor was within +/- 1 degree Celsius in the experiments. The data loggers associated with each system varied in terms of their placement relative to a building element, and the type of communication used to transmit sensor data. During experiments with each system, the sensor was placed within the component. The data logger in System 1 was placed adjacent to the building element until all the needed data was collected, at which point the logger was removed and data was downloaded to a computer. The data logger in System 2 was placed within a construction trailer, and data was sent directly from the sensor location using a dedicated transceiver. The data logger in System 3 was placed with the building element, along with the sensor, and data was collected using a mobile data collector. The software for each system reads the data from each respective data logger and provides a visual display of the temperature readings over time. Each system provides a file output, showing temperature readings over time, which can be read into a spreadsheet application. The software for Systems 1 and 3 also calculate the estimated concrete strength based upon the temperature readings over time in comparison to actual strength readings and provide outputs of these estimates as well.

Table 3: Sensor systems utilized in experiments.

Sensor System	Sensor type	Accuracy	Data logging range	Data logger type
System 1	Thermistor	+/- 1 degree C	30 days	Wired/external
System 2	Thermocouple	+/- 1 degree C	4 hours	Wireless/external
System 3	Thermistor	+/- 1 degree C	30 days	Wired/internal

### **3. RELATED BACKGROUND RESEARCH**

This research builds on, complements, and extends the research in utilization of RFID technology for resource tracking and identification, laser scanners for quality control and embedded sensors for construction inspection within construction and facility/infrastructure.

#### **3.1 Utilization of RFID for resource tracking and identification within construction and facility/infrastructure**

Previous research on RFID in the construction industry mostly focused on three areas: (1) identification of conceptual applications of RFID technology for construction (Jaselskis et al. 1995, Yagi et al. 2005) (2) performance of a set of RFID technologies for automated identification during delivery and receipt of components (Jaselskis and El-Misalami 2003, Aksoy et al. 2004) and (3) utilization of RFID technology for tool tracking (Goodrum et al. 2006) at construction sites. In the field tests performed in these studies, both active and passive tags were used and tags on the components were manually read with handheld readers either at a close proximity or at a distance up to 9 m. Another research effort combined active UHF RFID and GPS technologies to automatically identify the location of materials on a construction site by utilizing proximity techniques (Song et al. 2005). All the previous studies tested the performance of RFID at a portion of construction supply chain for one party's use. The field tests described in this paper build on these previous studies and focus on determining the performance of RFID in multiple phases of a construction and facility/infrastructure management processes.

#### **3.2 Utilization of laser scanners for quality control within construction and facility/infrastructure**

Many researches have shown the technical feasibility of using laser scanning technology for various construction management tasks such as progress monitoring (e.g., Su et al. 2006 for excavation activity), quality control (e.g., Jaselskis et al. 2006 to measure the thickness of concrete pavements, Akinci et al. 2006a for defect detection) and object, such as equipment and components, tracking at job sites (e.g., Bosche et al. 2006, Cho et al. 2002, Kim et al. 2005, Kwon et al. 2004, Teizer et al. 2005). In addition to these, research studies are performed for understanding the technical feasibility and performance evaluation of laser scanning technology for automation in construction (e.g., Cheok et al. 2000b, 2001, 2003, Cheok and Stone 2004, Stone and Juberts 2002, Stone et al. 2004). In addition to its application within construction, laser scanning technology has been adopted within facility/infrastructure management as well, such as bridge geometry documentation within departments of transportation (e.g., PennDOT), federal projects (e.g., FHWA) (Fuchs et al. 2004), condition assessment on bridges (e.g., Gordon et al. 2004), and surveying (Jaselskis et al. 2005).

As discussed above, most of the previous studies related to laser scanning technology within construction and facility/infrastructure management focus on evaluating technical feasibility and performance of the technology and streamlining some data delivery processes utilizing laser scanned data, and only a few of them systematically assess the process implications of laser scanning technology on construction and facility/infrastructure management processes. In addition, existing technical assessments of laser scanning technology for construction and infrastructure management tasks are focusing on a few specific task-oriented issues, and a systematic framework for comprehensive technical feasibility evaluation is still a topic for further investigation. Akinci et al. (2006b) used discrete event simulation technique to analyze the process implications of laser scanning technology on construction sites. Gordon and Akinci (2005) have come up with a preliminary framework for technology and process assessment of the use of sensing technology for construction quality control. We will build our work on these preliminary results and develop a more in-depth and systematic analysis of the technical assessment and process implications of laser scanning technology for construction and infrastructure management.

#### **3.3 Utilization of embedded sensors for construction inspection**

Numerous embedded sensors, such as temperature sensors, accelerometers, and strain gauges, may be utilized for data collection to support decisions about construction management and facility/infrastructure monitoring. Research on applications of embedded sensors within construction and facility/infrastructure management contexts has

typically focused on design of sensor systems (such as the power, communication, time synchronization, and placement of sensor systems) and interpretation of data (such as statistical methods). Previous studies also provided some assessment of whether a specific sensor-based approach worked or not, and some analysis of the financial impacts of utilizing a specific technology. Studies, such as (Nassif et al. 2003) and (Lynch et al. 2004), describe field tests of one or more types of sensing technologies for evaluation of existing facilities, the technological considerations necessary to gather required data using these technologies, and the methods used to interpret the collected data. Studies, such as (Goodrum et al. 2004), describe field tests of individual technologies, the tasks associated with implementing these technologies, and suggested implications to schedule, cost, and quality. These examples of research in embedded sensing focus on limited applications, and hence do not investigate process implications associated with applying embedded sensors on hundreds of components that comprise buildings or infrastructure and interpreting the corresponding data during construction and operation.

#### **4. OVERVIEW OF CASE STUDIES**

The authors conducted four case studies related to technical assessment of RFID, four cases related to laser scanning and two cases related to embedded sensors. Each case had different characteristics in terms of types of materials (e.g., pipe spools, precast elements), and components (e.g., bridge girders, walls, railway runway) focused, was performed on projects having different types (e.g., heavy/civil, commercial), and at different phases of construction and facility/infrastructure management processes (Table 4). In addition, testing environments were either static or dynamic and components were either mobile or immobile. Such varieties in the cases were selected proactively to demonstrate performance variances of technologies as compared to specifications provided by their vendors. While performing experiments with these technologies to understand their technical capabilities under changing site conditions, we have also documented changes to current data collection, dissemination and storage processes to understand in detail some process implications of utilization of these field technologies.

As shown in Table 4, to identify if RFID technology performs well throughout a construction supply chain, the authors have conducted four case studies where different kinds of components and/or related information need to be tracked at different phases in a construction supply chain. Case 1 was conducted to track the locations of precast components at a precast storage yard of a precast manufacturing plant (Ergen et al. 2007b). The second and third cases (i.e., Case 2 and 3) were performed to track components as they were being shipped from the manufacturing plant to construction sites, and the fourth case (Case 4) was conducted to track fire valves and related maintenance history information at an existing building. The components that were tracked in RFID cases were structural precast concrete components, pipe spools and fire valves and their size varied greatly (i.e., from  $0.2 \times 0.2 \times 0.2\text{m}^3$  to  $0.6 \times 5 \times 15 \text{m}^3$ ). In the first three cases, components to be tracked were mobile and in the fire valves case (Case 4), components to be tracked were stationary, since fire valves were installed at fixed locations in a facility (Ergen et al. 2007a). In Case 4, other building components that were in the environment (e.g., ceiling panels, walls) blocked some of the fire valves and some fire valves were located close to one other. In this environment, the objective was to store maintenance information with the component and make it available for the inspectors, who inspected the facility repetitively and over a longer period of time.

For tracking precast components in a storage yard, a prototype application was developed in Visual Basic .NET. This application (1) communicates with the GPS receiver and the RFID reader to acquire coordinates and tag ID data, (2) identifies the tag ID that belongs to the piece that is picked, (3) determines the location of the pieces that are moved, and (4) stores the new location with the ID of the piece that is moved in a database. For tracking precast and pipe spools during shipping and receiving and for tracking historical information of fire valves, a demonstration software that is provided by the technology supplier was used to detect multiple tags in an environment and to read data from or write data to the tags selected.

Table 4: Characteristics of case studies.

	Case#	Purpose of the study	Project type	Project phase	Collected data type	Component studied	Experiment environment
RFID	Case1	Material tracking in a storage yard	Building	Manufacturing	ID and location	Precast	Dynamic Uncontrolled Outdoors
	Case2	Material tracking during shipping & receiving	Building	Manufacturing /Construction	ID	Precast	Dynamic Controlled Outdoors
	Case3	Material tracking during shipping & receiving	Power plant	Manufacturing /Construction	ID	Pipe spool	Dynamic Controlled Outdoors
	Case4	Tacking building components and relevant info	Building	Operations & Maintenance	ID and historical info	Fire valve	Static Controlled Indoors
Laser Scanner	Case5	Condition assessment	Heavy /Civil	Operations & Maintenance	Geometric data	Bridge girder and piers	Dynamic Uncontrolled Outdoors
	Case6	Quality control defect detection	Heavy /Civil	Construction	Geometric data	Light rail tracking system	Dynamic Uncontrolled Outdoors
	Case7	Quality control defect detection	Commercial	Construction Operations & Maintenance	Geometric data	CIP concrete columns walls	Dynamic Uncontrolled Indoors
	Case8	History capture Heritage	Building	Operations & Maintenance	3D data	Entire building	Dynamic Uncontrolled Outdoors
E. Sensors	Case9	Bridge footing inspection	Bridge	Construction	Temperature	Concrete footing	Dynamic Uncontrolled Outdoors
	Case10	Building inspection	Building	Construction	Temperature	Concrete Slab	Dynamic Uncontrolled Outdoors

In the case of the laser scanning experiments, Case 5 was conducted for condition assessment of a bridge, Cases 6 and 7 were conducted for quality control during construction of a transportation system and operations and maintenance (O&M) of a facility, respectively. Case 8 was performed for recording historically important information (in case rehabilitation is needed) in a building. Cases 9 and 10 involved the use of embedded sensors to monitor the temperature of concrete components and reason with this data to assess the strength of the components.

Environments in which the tests were performed showed variances as they were performed in static/dynamic, controlled/uncontrolled environments either indoors/outdoors. Components were also either mobile or immobile. In Case 1 (Table 4), large size components were mobile as they were relocated by gantry cranes in a large open-air storage yard, where up to 5,000 precast elements were stored at any given time. The environment was uncontrolled since the paths of the cranes, and the position of the component on the crane, were not fixed. In this environment, the objective was to automatically identify the ID of a component that is relocated (i.e., selective identification) and to determine the new location of the relocated component in an automated way. Cases 2 and 3 had similar environments, where components were mobile and being transferred from one location to another. In contrast to Case 1, components have relatively controlled mobility, where precast components and pipe spools loaded onto trailers passing through an open-air portal when leaving manufacturing plants and entering construction sites. For Case 3, the trailer was very congested with many pipe spools as compared to the precast case, where only one or two components were loaded on a trailer. In both of these environments, the objective was to identify all the components that were loaded on a trailer in an automated way as the trailer passes through the portal. The laser scanner cases were performed in uncontrolled environments since everything was dynamic, both outdoor and indoor environments (Table 4). During the process of the scanning, moving objects in the scene will cause data noises, so the authors tried to coordinate with other activities concurrently happens on the job site to minimize the scene changes during the scanning process. The embedded sensor cases were performed in dynamic, uncontrolled environments, in concert with placement of concrete and reinforcement.



## 5. TECHNOLOGICAL ASSESSMENTS OF FIELD TECHNOLOGIES

### 5.1 Overview

Considering the entire test results, the field technologies we tested performed well and met the requirements identified for each test case. For instance considering RFID cases, test results showed that active UHF RFID technology meets the requirements identified for tracking components and their history for the selected cases (Song et al. 2006, Ergen et al. 2007a, Ergen et al. 2007b). For the precast storage yard case (Case 1), the actual reading range of the RFID tags was reduced to 1/4 -1/5<sup>th</sup> of the nominal reading range for open air environments; however, this reading range was still sufficient for tracking precast components (Ergen et al. 2007b). All the precast pieces were successfully identified for all the relocation actions, in which the crane moves from one location to another.

For shipping of precast components (Case 2), the components were successfully identified in all nine truck passes, where different antennae (i.e., long range and mid-range) were tested for different truck speeds (i.e., 2, 5, 10 mph) (Ergen et al. 2007c). For shipping of pipe spools (Case 3), the average reading rate was 98.1% for 12 passes at different truck speeds, and the statistical analysis of the results of the larger sets of tests done in pipe spool tracking showed that driving at 1-2 mph, and using four antennae, will allow for automatic identification of all the components on a trailer (Song et al. 2006).

For the fire valves case (Case 4), reading distance ranged from 3.2 meter to 27.4 meter, which met the 3 meter requirement (Ergen et al. 2007a). The maximum 1 meter reading range requirement for the maintenance activities can also be met by reducing the reader's power and consequently the reading distance. The observed reading distances changed greatly within a facility environment due to reflection and attenuation possibly caused by various objects and obstructions. Thus, it is hard to claim a single reading distance that is valid for all tags and readings. General indications show that the observed reading distance is approximately 50% of the reading distance expected in open air if there are no massive obstructions between the reader and the tag (e.g., a wall) to block the signals. Successful reading/writing rates in the first attempt were observed to be high (97% on average) and all data stored on the tags were retrieved successfully and consistently in all readings.

Considering the laser scanning cases, the results of the experiments show that capturing detailed and accurate geometric information of structures using laser scanning technology is technically feasible and a geometric data collection process employing a laser scanning has significant time advantages over current manual geometric data collection and processing tasks. We were able to collect dense point clouds and capture detailed geometric information of a structure in a relatively short time, which generally met the requirements of the users in a dynamic environment, such as construction sites. We established a framework for comparing a proposed laser scanning-based process and current manual process, in terms of data accuracy, data comprehensiveness and the potential of data for information retrieval and interpretation. Our assessments showed that in all these aspects, a laser scanning based process has essential advantages over current manual approaches (Tang et al. 2007a).

We compared the data accuracy of the scanner used in this research and a commercially available total station system, which is one of the commonly used tools for geometric data collection on construction sites. In terms of single point accuracy, the angular accuracy of the total station is 5 seconds, which is better than the single point angular accuracy of the scanner, which is 72 seconds; the distance accuracy of the total station is about 3 millimeters within a range of 170 meters, which is better than the single point distance accuracy of the scanner, which is 3 to 9 millimeters depending on object surface reflectivity within a range of 26 meters. However, the scanner can capture thousands of 3D points in a few minutes, and 3D models of objects can be generated from dense point clouds of laser scanner using least square surface fitting and triangulation algorithms, while total station can only capture one 3D point in a couple of seconds, and the collected sparse accurate points can hardly be used for surface assessment and mesh generation. The 3D model based on dense point clouds can achieve much higher accuracy than single-point accuracy of a total station, because according to least squares adjustment theory, the model error is only one over square root of n of the single point error of the scanner, where n is the number of points used for surface model generation. This means that if a point cloud contains 1,000,000 points with noise level around 3 millimeters, the error of the model would be 0.003 millimeters.

Each temperature sensor studied in Cases 9 and 10 measured temperature within the specified +/- 1 degree Celsius. While we did encounter faults in some deployments of sensor systems, due to data logger size, wire crimping, and water intrusion, the sensor systems that did gather complete data were able to generate data that correctly evaluated the strength of the building elements within which they were embedded. For example, using the embedded sensors in Case 9, we were able to correctly determine that a different (albeit stronger) concrete was substituted in place of the specified concrete without our knowledge. Figure 2 shows the performance of several samples of the specified concrete, cured under laboratory conditions, in comparison with the concrete that was delivered. The set of overlapping curves, ranging in strength from 0 to 3,700 psi all represent the expected strength gain, based on the samples tested in controlled conditions. The top curve, ranging in strength from 0 to over 5,000 psi, represents the actual strength gain predicted for the footing by measuring the temperature over time and applying the concrete maturity method to predict the strength of concrete. Only after noticing this deviation from the expected values did we learn that an undocumented field change resulted in placement of a different concrete than specified. A stronger concrete was placed in the footing; this was correctly identified using data gathered using sensors embedded in the footing.

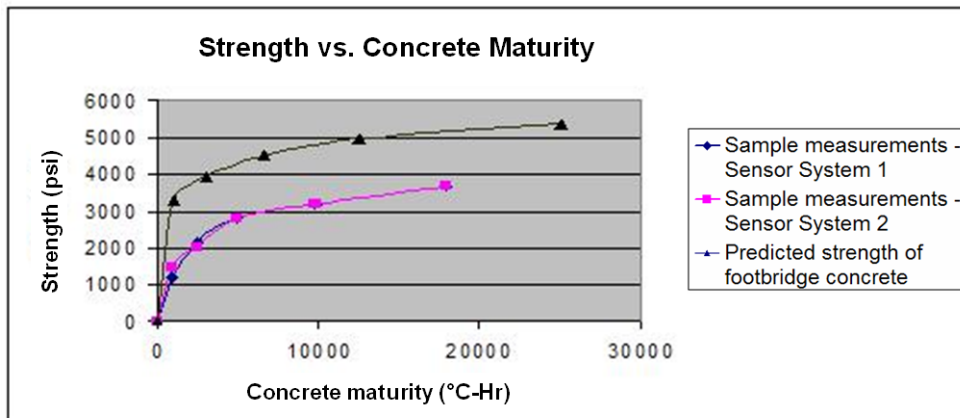


FIG 2: Strength predictions derived using the concrete maturity method with two different sensor systems (shown in the lower two curves) indicate that the predicted strength of the concrete mix (shown in the upper curve) was stronger than specified.

While conducting the experiments, we realized that though the performance of these field technologies is compatible with the technical specifications in ideal cases, there were conditions/cases where the performance of the technologies might show differences as compared to their technical specifications. We have grouped these issues under the following categories as *interference*, *data reading range*, *data accuracy*, *interoperability of hardware and software* and *memory problem*.

## 5.2 Interference

Interference has been defined, in this context, as any visible and invisible impediments that might influence the performance of the technology adversely. Interference might include obstructions, such as moving cars on a highway bridge for a laser scanner, any object that stands between the laser scanner and the object of interest, metal objects in the range of the reader for RFID experiments.

For UHF RFID technology, metal and liquid in the environment are known to cause interference. In the experiments that were conducted by the authors, massive objects that block tags and the existence of metal are two important factors that reduced the reading distance. The performance reduction is caused via reflection or absorption of the UHF radio signals by the objects in the environment. To minimize this effect, encapsulated tags or an insulator between the tag and the attached surface need to be used. In addition, in highly metallic and congested environments, as in the pipe spool case, multiple antennae can be used to increase the performance.

In case of laser scanning, interfering objects were any object in the line of sight of the scanner that would hinder capturing the point clouds of an object of interest. Also, performance of laser scanning technology will be affected by moving objects, resulting in additional artifacts in the point cloud data and making the data region influenced by those artifacts less reliable. Currently, users must remove the interfering objects while only keeping those data from static part of the 3D scene; another option is to keep the scanned scene static while the laser scanner is in action, which is typically very hard to do in active construction sites.

To directly measure phenomena within building elements, embedded sensors typically must be in contact with the material or building element being measured. For example, if an embedded temperature gauge comes into contact with rebar that has been exposed to the sun prior to concrete placement, the concrete temperature readings will be off.

### **5.3 Data reading range**

Data reading range can be defined as the maximum distance that data can consistently be retrieved from RFID tags and embedded sensors remotely, or the maximum distance that point cloud data in required density can be obtained with laser scanners. It is important to consider the data reading range while using field technologies since their performances vary based on the selected reading range.

While evaluating the performance of the field technologies, we realized that testing environment (whether indoor or outdoor) and the interfering elements (as discussed above) were among the factors affecting performance of the field technologies. Depending on the environment (e.g., existence of metal and congestion), the reading distance of RFID ranges from 1/5<sup>th</sup> to 1/2<sup>nd</sup> of the reading distance expected in open air. For tags that are underneath a ceiling panel and moderately surrounded by metal, average reading distance was half of the original reading distance, while for a tag that is highly surrounded by metal and partially blocked by a wall, average reading distance decreases to 20-25% of the original distance. Therefore, field tests need to be conducted to identify the actual reading distance within a given environment

Considering laser scanning technology, as the distance between the laser scanner and the object of interest increases, the data density will decrease if the angular resolution is kept constant. That means in one scan, the surface sampling step of objects further away from the scanner is larger, and hence, fewer details of the object surfaces will be captured. Maximum scanning ranges are provided by technology vendors; however, our experiments showed that even though the single point accuracy of the data agrees with the technical data provided by the manufacturer, the data density acquired at maximum ranges can not capture detailed surface features even at the highest resolution option provided by a scanner. The scanner used in the experiments has only three resolution options: medium, high, and super high. In Case 6, experiments were conducted with varying resolutions. Experiment results showed that laser scanner utilized in the experiments could not provide the data density that is required to detect surface features having sizes 20 centimeters in diameter and 3 millimeters in thickness, with a scanning distance of 10 meters. However, the same laser scanner used in the super-high resolution option could provide the required data density. Visual inspection of the data collected at 10 meter scanning distance shows that there were fewer than 700 points on a given surface feature with the super-high resolution option. Given this, we could deduce that when the scanning distance is 50 meters, the points associated with a given surface feature of same size would be no more than 30 points, which will be too sparse to generate an accurate surface model of the feature. Hence, data reading range is critical to get a required density point clouds.

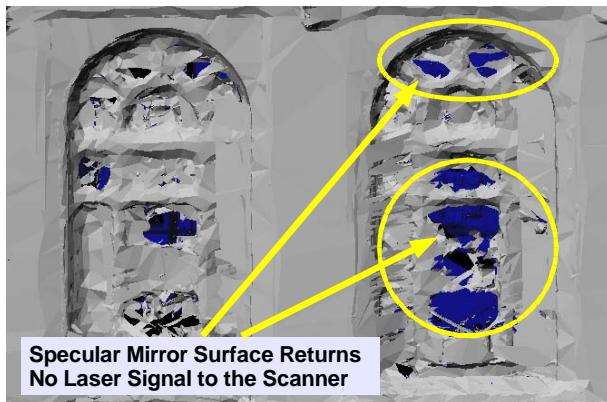
In case of embedded sensors, the reading range of embedded sensors depends on the communication technology used. The wired data loggers that were utilized in Cases 9 and 10 (Table 4) were read only by visiting the component; however, the wireless data logger was capable of gathering data wirelessly at a distance of 70 meters, which is within the manufacturer's specification.

### **5.4 Data accuracy**

Data accuracy, in this context, is defined as correctness of the readings/writings to/from RFID and embedded sensing technologies and quality of measurements obtained from the laser scanning technology. Accuracy of data retrieved

or collected using the field technologies are tested and provided by technology vendors in specifications. However, accuracy of the field technologies might show variance as compared to their technical specifications based on a combination of factors. This phenomenon is especially important and relevant for laser scanning cases. During the experiments we have realized that for better performance from laser scanning technology, users should consider technical details that might influence the performance, such as the reflectivity of the object of interest, in case of spatial discontinuities, the 'mixed pixel' phenomenon, scanning range and sensor calibration. These issues should be kept in mind while scanning.

The reflectivity problem (Figure 3), which is defined as the measurement error in scanners when the scanned surfaces are reflective and affect the laser scanner performance, was tested in Case 7 and 8. In all the experiments, where the reflectivity of surfaces were high, such as for glasses and metals, the obtained laser scanner range information was wrong for the majority of points, as compared to data from diffused surfaces. In addition, some parts of the reflective surface did not reflect any signal back to the scanner and the range information for those parts were missing in the point cloud data.



*FIG 3: Range image of windows scanned in Case 8 demonstrating the reflectivity problem associated with laser scanned data.*

Another issue that reduces the accuracy of the data collected by laser scanners is the mixed pixel phenomenon, which is defined as noisy pixels spanning over spatial discontinuities. Mixed pixels in a given scene can hinder accurate assessment of edges, or in extreme cases can result in losing the whole edge in the generated 3D model. The amount of lost edge is influenced by the incident angle of the laser beam on the object surface, the scanning distance, the laser beam spot size and the resolution of the data. Part of this research team is developing a model to estimate lost edge width due to mixed pixel effects, and preliminary results show that at scanning distances smaller than 10 meters, the width of the lost edge vary from 4 to 80 millimeters. Specifically, if we scan a board at 10 meters with the optimal configuration, at each edge of the board there will be a 1.5 centimeter-wide edge loss. Hence, the 3D model of the board created from laser scanned data will be at least 3 centimeters shorter than its actual size.

In addition, the accuracy of 3D models will decrease with the increasing scanning distance as discussed in the reading range subheading. In our experiments, the standard deviation of the data increases from 5 to 8 millimeters while the scanning distance increase from 10 to 23 meters. Reading range should also be considered for achieving accurate 3D models from scanned data.

Calibration of sensors is also among the factors affecting accuracy of point clouds from laser scanners. Sensors need to be calibrated before any data acquisition. For instance, while we were performing experiments in Case 6 (light rail tracking system), we were unaware of the fact that the scanner drifted out of calibration, and hence, we observed abnormal data patterns, as shown in Figure 4. We have integrated a calibration checking step into our data collection procedures to prevent future accuracy problems associated with calibration. Calibration can be performed by a system check functionality integrated within a scanner



FIG 4: Geometric distortion patterns caused by a scanner that is not calibrated observed in Case 6.

Finally, a laser scanner needs to be warmed up before actual data collection to get accurate data, and the data transmission between the scanner and the computer need to be checked. The transmission can be interrupted, if the cable connecting the scanner and the computer is not tightly plugged into the data transmission slots. In our experiments, we observed missing blocks due to this interruption problem. At missing blocks, the range values of the pixels are usually wrong. In the extreme case, if missing blocks are observed on targets used for data registration, the targets can not be correctly positioned as shown in Figure 5.

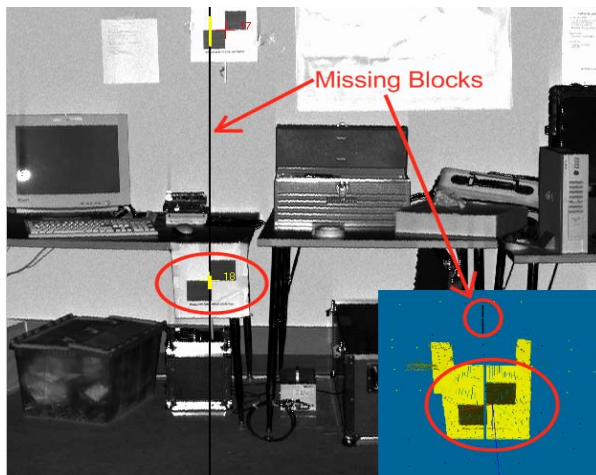


FIG.5: Blocks of missing data due to intermittent interruptions in the data transmission from a scanner to a laptop.

For RFID, inaccuracy might be caused by not detecting a tag in the environment due to interference problems which was explained in the Interference section. For embedded sensor data, the data is only as accurate as its perceived context. For example, a temperature sensor placed prior to concrete placement will measure ambient air temperature until concrete is placed. Once the concrete is placed, the temperature sensor will measure concrete temperature.

## 5.5 Interoperability of hardware and software

Interoperability of hardware, in this context, has been defined as enabling components of a technology (e.g., RFID readers and tags) to work together, whereas interoperability of software has been defined as enabling communication of different software applications working with field technologies, that might be produced by different vendors. It is important to consider interoperability between different hardware and software systems in order to have fully functioning set of technologies.

To support the interoperability between the passive RFID tags and readers, industry-driven standards are being developed for the Electronic Product Code (EPC), which is being used by some of the passive RFID technology providers. However, interoperability for active tags has not yet been accomplished. In addition to this, for RFID technology, middleware, (software between the reader and the enterprise applications) will be needed. Since the same tag can be read multiple times by the same reader in a short time-span (e.g., at entrance or exit gates), data flow can be large for RFID applications and data cleaning might be needed. Thus, middleware is needed to process and filter the data received from RFID and to transfer the necessary information to the related databases and applications such as ERP systems.

A similar interoperability problem can also be experienced with laser scanners. In the case of laser scanners, output files have proprietary formats, which are usually specific to the vendor companies' software. There are even problems between the output files of new sensor models and previous versions of a software system provided by the same vendor. Currently, this problem is solved by exporting the sensor data in more widely used file formats (e.g., ASCII or VRML). However, these geometric file formats provide very limited support for transferring semantic information. Hence, if laser scanners are potentially considered as a field technology, interoperability of files generated should be addressed.

Embedded sensors, like RFID technologies, are produced by several vendors, and hence face challenges of interoperability among sensor system components, such as data loggers, and among data derived from different sensors' readings. Efforts, such as IEEE 1451, have been initiated to develop standards for interoperability among sensor system components. Similarly, efforts, such as IEEE 1278, have been initiated to support data exchange from multiple sensors. A continuing challenge for interpreting sensor data is time-synchronization, where sensor data refers to the same frame of reference with respect to time. An additional problem noted in Case 9, is that the properties derived from a sensor's data using one manufacturer's on-board computation may differ substantially from another's. In Figure 6, for example, two sensor manufacturers clearly used different assumptions about how to calculate concrete maturity based on the same temperature readings. If these two sensors were to be used on the same jobsite, the concept of 'concrete maturity' would be confusing, without standardization of the method used to calculate this derived quantity (e.g. the Arrhenius method or the Nurse-Sauls method).

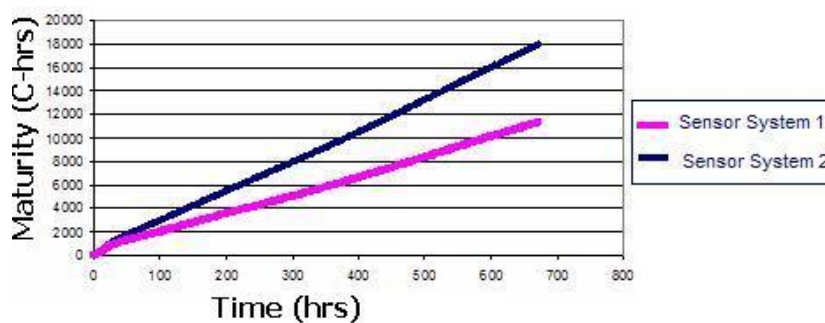


FIG 6: Concrete maturity values calculated using similar temperature data obtained by sensors from different manufacturers.

## 5.6 Memory problem

Memory problem, in this context, has been defined as the problems that might be faced due to having limited memory space for storing/retrieving data to/from field technologies. It is important to consider the memory limitations, since they may result in missing opportunities to collect real-time data (e.g., concrete temperature data) or losing them as overwrites on collected data might occur.

In Case 9, the memory of the sensor systems performed as specified within the 30-day testing period. The data logger in System 1 had limited access to the memory until after logging was complete to ensure that data was not tampered with during data collection. Hence, access to the memory is an additional issue for embedded sensors. In Case 10, we encountered memory limitations due to the variability of the concrete placement timing with respect to sensor placement. In this case, due to later-than-expected concrete placement, the data logger gathered ambient air temperature for much of its logging capacity, and did not gather significant concrete temperature data when the concrete placement did start. This highlights not only the limited memory associated with this particular sensor system, but also the variability of the processes that are conducted in concert with embedment of the sensor system components.

Given the issues provided above as factors that might affect the technical capability of field technologies, users should be aware of these issues while relying on the technical specifications of the vendors and keep them as control variables when results are interpreted. Knowing the possible effects of these factors enables better assessment of the performances of the technologies. The next section describes how utilization of field technologies is observed to affect construction and facility/infrastructure management processes.

## 6. PROCESS IMPLICATIONS OF FIELD TECHNOLOGIES

### 6.1 Overview

We identified implications of utilizing field technologies on construction and facility/infrastructure management processes by recording the changes to these processes when the field technology is introduced. This helped us understand the current data collection, storage and retrieval tasks and process implications when field technologies are introduced.

Process implications of utilization of field technologies were grouped in three phases, as *before*, *during* and *after* the technology is utilized. The next three subsections detail process implications observed for each technology during each phase (Figure 7).

### 6.2 Prerequisite tasks to be performed before field technologies are utilized

This section describes process implications related to the preparations that need to be performed before actual utilization of a technology at the site. It is important to understand such preparation work to fully assess the process implications of a technology.

In the case of RFID technology, tags need to be attached to each component manually. The tag IDs and component IDs need to be associated and stored in a database. To identify the location of components in a storage yard, a geo-referenced map needs to be created once at the beginning of a project using GPS. Finally, the reader locations need to be identified based on reading ranges of the specific RFID technology being utilized.

In the case of laser scanning, prerequisite tasks include site preparation (i.e., site investigation, surface cleaning, removal of interfering objects), equipment setup (i.e., assembling the laser scanner, leveling of equipment, preview scanning and several trial scans to confirm correctness of data collection plan) and target placement (i.e., setting up fiducial markers) to be utilized for registration of scanned data. In Case 5, a group of engineers used a time-of-flight scanner to scan the same bridge parallel with our scanning session. For a 15 meter highway bridge, they spent about four hours to finish their setup and data collection tasks. For the same case, we used a phase-based scanner and completed the setup and data collection tasks in less than two hours.

Prerequisite tasks for embedded sensing include coordinating and conducting placement of sensor system components within or near components (this may involve affixing sensor system components to rebar or formwork in the case of concrete monitoring), documentation of the component and sensor IDs and sensor location, and start-up of data collection (Figure 7). These steps may be completed in one or more visits to the sensor location.

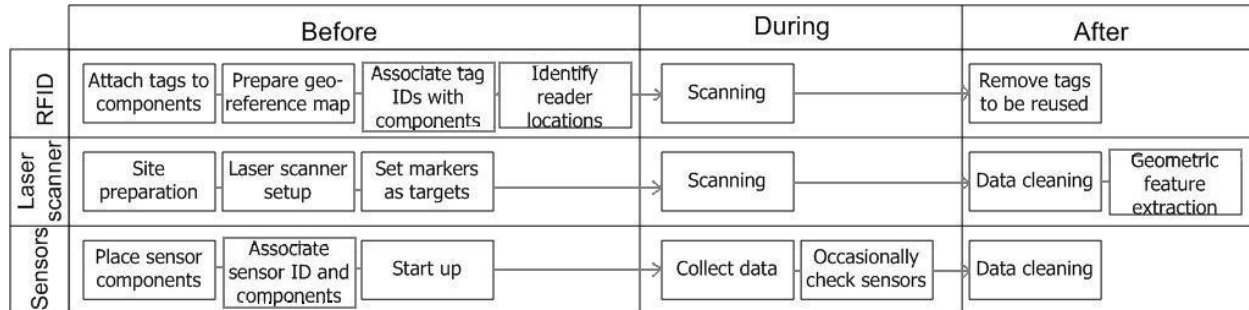


FIG 7: Tasks introduced to current process of data collection, storage and processing by technology utilization.

### 6.3 During utilization of field technologies

Several supporting processes need to be conducted during data collection using field technologies. The tasks that need to be performed when technologies are in use for data collection/interaction take considerably less time as compared to the current manual approaches.

In RFID utilization, for semi-automated solutions (e.g., fire valve case- Case 4), manual recording of ID information is replaced by scanning activity (Figure 7). In such cases, scanning takes less time and needs less attention from a worker. In cases where the shipped pieces are automatically identified or the relocated piece and its location are identified in an automated way, there is no need for manual identification of each component or tracking the location of a piece when relocated.

In Case 6, while using a laser scanner, a single scan took only about ten minutes including equipment and site preparation time and scanning time. Compared to manual data collection of location identification or manually tacking components, laser scanner enables engineers to acquire 3D scene in a much faster manner.

Collection of embedded sensor data is largely an automated process during the data collection time period. However, due to system failures related to problems, such as crimped wires or water intrusion, it is helpful to check the incoming data occasionally to ensure that data is still being collected. In Case 9, for example, two sensor systems failed for these reasons, silently interrupting data collection mid-way into the data collection time period.

### 6.4 Post-processing tasks after technology utilization

Once the field technologies are utilized, there are still tasks to be performed for data cleaning and processing for analyses, and for getting ready for the next cycle of data collection (e.g., for RFID case, if the tags are going to be recycled, the tags need to be removed before the components are being shipped or being installed). These tasks especially require more time in the case of laser scanners (Figure 7).

Currently, laser scanner users need to spend a large amount of time to process the collected data to ensure certain level of accuracy of data. A process model described in another publication describes an envisioned process of utilizing laser scanning technology for improving the effectiveness and efficiency of bridge geometric data collection and interpretation (Tang et al. 2007a). This process model introduces a post-processing procedure of raw laser



scanned data in detail. The data processing activities include removal of noisy data, data registration, geometric feature extraction and geometric information deduction based on extracted geometric features.

Data collected using laser scanners result in large files containing various types of noisy data. Removal of noise from the data and manipulation of those large 3D data sets are still time-consuming and are manual processes. Operators need to manually configure algorithm parameters based on their knowledge about various factors influencing data accuracy such as scanning distance and registration error. Each algorithm for removing noises from raw data has a different impact on the processed data. That adds complexity to the data processing process. Based on previous studies, we are experimenting with ways for automatic noise removal and identifying accuracy implications of those data cleaning approaches. The mixed-pixel phenomenon mentioned above is one type of noise in laser scanned data. Many previous studies have investigated ways to automatically remove mixed-pixels from point clouds (Liu et al. 2005; Tuley et al. 2005). One previous comparative analysis about the performances of several mixed-pixel processing algorithms showed that a surface-normal-based algorithm has the best overall performance on a collection of data sets of various representative contexts generating mixed pixels. However, this research also pointed out that there is no unique solution for all contexts. In some cases, other mixed-pixel processing algorithms perform better than the normal-based algorithm (Tang et al. 2007b). At Carnegie Mellon, authors are also investigating the impacts of removal of those noisy data on the accuracy of the extracted features based on cleaned data. Understanding those impacts will lead to ways to remove noisy data without sacrificing any valid geometric information contained in the data and ways to accurately recover lost geometric information due to data cleaning operations, such as the lost of edges of objects in the data. We are also experimenting with several filtering algorithms for removing range noise from the raw data so that following geometric feature extraction can extract more accurate geometric features. The overall goal of this research is to understand the implications of various data cleaning methods on feature-level accuracy, such as the accuracy with which we can extract the width of a board from a point cloud, rather than being aware of positioning accuracy of each single point in the point cloud.

With the cleaned data, many geometric feature extraction algorithms can extract various geometric features from cleaned point clouds, such as planes, cylinders, and cones (Gruen and Akca 2005; James and Charles 1996; Kwon et al. 2004; Vosselman et al. 2004). Currently, a typical geometric feature extraction process involves large amount of manual effort. Because most geometric feature algorithms fit a predefined feature against a patch of data containing only the feature to be extracted, operators have to manually select a patch of point clouds and execute geometric feature extraction algorithm on that data patch according to the feature characteristics. For example, operators have to select a data patch on a flat surface, and execute “plane fitting” algorithm to extract a plane from that data patch. These manual works are repeated many times when operators need to extract many geometric features to calculate some required geometric information item such as extract two planes for calculating the distance between them. This repeated work is non-value added and consumes large amounts of time. Some researchers tried to segment the point cloud into data patches corresponding to geometric primitives before geometric feature extractions. However, effectively and efficiently segmenting scans of cluttered scenes, which are typical in civil engineering applications, is still challenging and requires further research (Yu et al. 1994).

In addition, laser scanner data typically contain only Cartesian coordinate information of scanned points (some scanners also provide color and surface reflectivity information) and carry no semantic information, such as which point belongs to which structural component. Working with this type of featureless data makes the geometric reasoning based on laser scanned data tedious and error prone.

Interpretation of embedded sensor data requires assessment of which portions of the data set are truly applicable and whether the data collected is sufficient to support decisions about the component or components being evaluated. This means that the data must be evaluated to determine whether to ignore data that does not describe the conditions that are being evaluated. For example, if a sensor is supposed to measure concrete temperature and starts sensing data before concrete is placed, data need to be ignored belonging to the time period during which the sensor measures air temperature. Secondly, this requires assessment of each data stream associated with each component to ensure that sufficient data has been collected (in light of possible technology failures) or if additional data is required to evaluate the component.

## 7. CONCLUSION

Field technologies have been identified to remedy current problems of limited access to timely, complete and accurate field data. However, a thorough understanding of how these technologies behave under changing conditions, and what issues should be considered for technological assessment need to be performed. In addition, process implications of the field technologies on the current data collection and processing tasks need to be assessed.

Detailed experiments with field technologies (in this case RFID, laser scanner and embedded sensors) showed that these technologies work well in streamlining data collection during construction and condition assessment in operation and maintenance phases. We have provided overview of findings from four cases, where detailed experiments with RFID were performed. In a precast storage yard, all precast pieces were successfully automatically identified as components being relocated from one area of the storage yard to another (Case 1) and during shipment (Case 2). Between 96.0 to 98.1 % of pipe spools were identified on average for different test beds during shipment of pipe spools on a trailer (Case 3). Successful reading/writing rates in the first attempt were 97% on average, and all the data was retrieved successfully in all readings for the monitoring of fire valves during the service life of a facility (Case 4). Similarly, we studied four cases in which we conducted detailed experiments with laser scanners. Experiments showed that capturing detailed and accurate geometric information of structures using laser scanning technology is in general technically feasible. In case studies, a phase-based scanner was used and could identify surface features less than 1 centimeter, which is a reasonable accuracy level for construction site applications. In the case of embedded sensors, two case studies (Cases 9 and 10) were related to experiments with temperature sensors. Accuracy of temperature data obtained from the sensors were within the specified +/- one degree Celsius.

However, the behavior of these technologies may show variance than their technical specifications provided by the vendors. A set of issues were identified during the detailed experiments. These issues related to technical assessment of these technologies were listed as (1) *interference*, which is defined as any visible and invisible impediments that might influence the performance of the technology adversely between the technology and the object of interest; (2) *data reading range*, which is defined as the maximum distance that data can consistently be retrieved from RFID tags and embedded sensors remotely, or the maximum distance that point cloud data in required density can be obtained; (3) *data accuracy*, which is defined as correctness of the readings/writings to/from RFID and embedded sensing technologies and quality of measurements obtained from the laser scanning technology; (4) *interoperability of hardware and software*, which is defined as enabling components of a technology (e.g., RFID readers and tags) or software applications developed by different vendors to work together; and (5) *memory problem*, which is defined as the problems that might be faced due to having limited memory space for storing/retrieving data to/from field technologies. One needs to keep in mind these issues that might influence performance of the field technologies and take precautions to get the most performance from these field technologies.

In addition to understanding technological capabilities of these technologies, technology implementers at the field level should know how these technologies change the current processes of data collection, processing and storage. There are time savings as compared to manual data collection processes as some tasks are eliminated when a technology is introduced. However, there are also tasks that need to be considered with technology implementation at job sites. We have shown in this study that, these tasks are observed in three phases as before, during and after the technologies are used and vary with the technology selected. Again, for understanding and quantifying the burden and benefit of these technologies on management of construction and facility/infrastructure activities, the tasks coming with technology implementation should be considered by the field personnel.

## 8. ACKNOWLEDGEMENTS

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