ABSTRACT
Emerging LADAR and embedded sensing technologies are making inroads into the construction industry for quality control applications. Much of the research conducted and the practical usage to date have focused on a static snapshot evaluation of already constructed structures. A remaining question is how technologically feasible and applicable these technologies are for frequent inspection during construction. Researchers in the civil engineering, architecture, and robotics departments at Carnegie Mellon University are developing and evaluating a formalism for application of these technologies for supporting quality control on construction sites. This formalism consists of developing a formalism for planning inspections, collecting data, modeling as-built conditions, and reasoning with the as-built and as-designed models to detect deviations and defects on construction sites. A series of five case studies on commercial and light industrial construction sites were conducted within the context of that research to identify challenges and opportunities in using LADAR and embedded sensing technologies to support inspection and quality control processes on construction sites. Based on the experiences in these case studies, the authors present a technology and process assessment of the use of LADAR and embedded sensing frequently to support inspection and quality control on construction sites.

KEY WORDS
LADAR, embedded sensing, construction quality control, inspection.

INTRODUCTION
Defects occurring during construction result in costly rework and adversely affect the overall performance of the built environment during construction, and operations and maintenance phases (e.g. Burati et al. 1987; Assaf et al. 1996). In order to proactively identify defects on construction sites, researchers in the civil engineering, architecture, and robotics departments at Carnegie Mellon University are developing a formalism for frequent assessment of as-built conditions using emerging reality capture technologies, such as embedded sensors and LADAR (Laser Detection and Ranging, or Laser Radar used for metrology) devices (e.g. Akinci et al. 2001). These technologies permit frequent and detailed assessment of the condition of the built infrastructure during construction. LADAR technologies (also known as laser scanning technologies) can be brought to construction sites to gather detailed spatial data, while embedded sensors can be
embedded in facilities during construction in order to gather material behavior data, such as temperature, strain, and vibration. We prepare for the use of these technologies by developing detailed digital design models and inspection plans for given construction sites. These plans identify the measurement goals for inspection and the technologies to be deployed on site, and how these technologies are to be used to collect the data related to the measurement goals. An as-built model is assembled by combining the data collected from these technologies. In certain cases, the data collected from the same technology need to be registered to develop a more comprehensive as-built model. These as-built models are then compared to a given digital design model in order to detect unacceptable deviations from the properties specified in construction specifications.

Since quality has a direct impact on the performance of projects and facilities (CII 2001), use of this formalism for frequent and proactive assessment of site conditions to control quality is expected to contribute positively to project execution. While the use of rising metrology tools, such as LADAR, have been shown to improve project quality (e.g., Cheok et al. 2001), most research to date have focused on generating snapshot evaluations of the work already in place. The technological and process effects of using reality capture technologies for frequent collection of as-is data from dynamically evolving construction sites is largely untested.

In order to better understand the implications of frequently collecting as-built data using emerging reality capture technologies, we have studied five representative projects and five different technologies characterizing the range of embedded sensing and laser scanning options. This paper provides an overview of the assessment of the performance of these technologies on construction sites for frequent collection of spatial and material behavior related data and the process assessment of using these technologies for supporting quality control and inspection on construction sites.

**CASE STUDIES**

We have conducted detailed case studies in five construction projects to date (Table 1). These projects ranged in size from 1,000 - 150,000 square feet. They follow a progression of increasing spatial constraints (the space available on site was very tight in the latter projects compared to the earlier ones), increasing number of components being constructed concurrently, and increasing number of changing site and weather conditions to consider when collecting data. In most of the case studies, we studied the projects from the beginning until the end. We have collected spatial data using LADAR technologies two to four times per month, depending on the construction activity in a given month. For each site visit, we identified a focus area to concentrate our data collection and analysis efforts. Within those focus area, we collected between twenty and seventy laser scans per site visit. In certain cases, we have deployed embedded sensors, mostly temperature gauges, and collected data in time periods ranging from a hours up to a month.
Table 1: Characteristics of the case studies conducted

<table>
<thead>
<tr>
<th></th>
<th>Case Study 1</th>
<th>Case Study 2</th>
<th>Case Study 3</th>
<th>Case Study 4</th>
<th>Case Study 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Small Footbridge</td>
<td>Warehouse</td>
<td>Light Industrial</td>
<td>Office</td>
<td>Mixed-use (commercial)</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>1,000 s.f.</td>
<td>35,000 s.f.</td>
<td>50,000 s.f.</td>
<td>150,000 s.f.</td>
<td>10,000 s.f</td>
</tr>
<tr>
<td><strong>Structural materials used</strong></td>
<td>Cast in place concrete</td>
<td>Steel</td>
<td>Steel</td>
<td>Cast in place concrete</td>
<td>Steel and cast in place concrete</td>
</tr>
<tr>
<td><strong>Spatial Constraint</strong></td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Period of study</strong></td>
<td>Winter-Spring</td>
<td>Winter</td>
<td>Summer-Spring</td>
<td>Autumn-Summer</td>
<td>Summer-Winter</td>
</tr>
</tbody>
</table>

**TECHNOLOGIES STUDIED**

During these case studies, we evaluated two types of LADAR devices (Table 2) and three types of embedded temperature sensing systems (Table 3) that are commercially available. The first type of LADAR, a time-of-flight laser scanner, uses the time that a pulse of light travels from the sensor of the laser scanner to the nearest obstacle and back to estimate the distance between the scanner to the points within its line of sight. The second, a phase-based laser scanner, improves the accuracy of position estimates that can be achieved by time-of-flight estimates by considering phase differences between outbound and inbound signals. More information about LADAR options and possible future LADAR characteristics are available at (Stone and Juberts 2002).

Table 2: Characteristics of LADAR devices selected for assessment

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>File Size at Max. Range</th>
<th>Measurement frequency</th>
<th>Accuracy</th>
<th>Sensor type</th>
</tr>
</thead>
<tbody>
<tr>
<td>LADAR #1</td>
<td>80 m</td>
<td>25 MB</td>
<td>8,000 samples/sec.</td>
<td>5mm at 13m</td>
<td>Time-of-flight</td>
</tr>
<tr>
<td>LADAR #2</td>
<td>25 m</td>
<td>300 MB</td>
<td>120,000 samples/sec.</td>
<td>1mm at 13m</td>
<td>Phase-based</td>
</tr>
</tbody>
</table>

We selected three types of embedded temperature sensors for evaluation. The selected sensors varied according to how data was collected: wirelessly, wired with integrated data logger, and wired with external data logger. In the wireless configuration, a thermocouple was embedded in concrete, leading to a wireless transmitter placed on the exterior of the concrete. This transmitter communicated temperature readings to a wireless receiver and data logger located in a secured construction trailer 200 feet from the transmitter. In the integrated data logger configuration, a thermistor, integrated with a data logger in an enclosed container, was embedded in concrete with a lead extending to the exterior of the concrete for periodic data collection using a handheld reader. In the external data logger configuration, a thermistor was embedded within concrete, and connected to a data logger.
attached to the outside of the concrete. Data was collected by collecting data from the logger on site or removing the data logger and retrieving data elsewhere. These three systems were selected because they were designed for extreme conditions typically experienced on construction sites, and produced data with sufficient accuracy to be relevant to construction quality control.

Table 3: Characteristics of temperature sensors selected for assessment

<table>
<thead>
<tr>
<th>Data logging range</th>
<th>Accuracy</th>
<th>Sensor type</th>
<th>Data logger type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp.sensor 1</td>
<td>4 hrs</td>
<td>+/- 1º C</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>Temp.sensor 2</td>
<td>30 days</td>
<td>+/- 1º C</td>
<td>Thermistor</td>
</tr>
<tr>
<td>Temp.sensor 3</td>
<td>30 days</td>
<td>+/- 1º C</td>
<td>Thermistor</td>
</tr>
</tbody>
</table>

TECHNOLOGY ASSESSMENT

Results from the application of the technologies on the case study sites indicate that frequent assessment of as-built conditions on construction sites is generally technologically feasible. The laser scanners that were used in the case studies collected point cloud data in a radius of 25–80 meters in less than two minutes per scan, which correspond to collecting detailed spatial information on hundreds of components on site. Within the data collected using the laser scanners, we were able to detect items with sizes ranging from anchor bolts to columns (Gordon et al. 2003). The technologies demonstrated the powerful range and speed for data collection, and showed that they were useful for proactive quality control. In the footbridge case, for example, through frequent monitoring of concrete temperature using embedded temperature sensors, we were able to identify that a different type of concrete had been substituted in one of the footings.

While capable of supporting frequent data collection adequately, the technologies studied did not always perform as desired. Technology-related issues that we experienced include silent failures, interference among technologies, and poor applicability in weather and terrain extremes. These issues should be considered in a deployment plan when these technologies are used on construction sites or should be considered by technology providers as possible ways for improving these technologies to increase their performances on construction sites.

FAILURE MODES

We have experienced multiples types of silent failures when collecting data using laser scanners and embedded sensors. In Case Study 2, the collected data exceeded the storage capacity of the data logger of an embedded sensor system, and valuable early readings were lost. In Case Study 1, an embedded thermocouple wire was crimped as the concrete hardened, causing readings not to be collected. In preparation for Case Study 1, sensors were subjected to a high humidity wet room environment, and some failed to record data until dry. In Case Study 5, the hard drive of the computer storing the scanned data during data collection was filled without warning, and as a result the scans collected towards the end of the session were never recorded and were lost. In each of these examples, a part of a sensing system failed silently, resulting in a loss of data, and in two of the instances the
sizes of the data logger were not large enough to handle the data that needed to be collected. The limitations in data logger size are further pronounced due to the uncertain nature of construction projects, which result in more or less than expected amount of data to be collected depending on the situation observed at the site at a given point in time. These emphasize the need for devices that have larger sizes for data loggers and also suggest a need for planning for sensing deployment to minimize such surprises. The silent failure phenomenon can also be avoided with redundancy or self-diagnosing components.

INTERFERENCE

On-site testing of laser scanners was initially limited to after working hours because site personnel were hesitant about operating the laser scanners during construction operations involving, for example, laser-guided grading, or operations where crew members may inadvertently look directly at the laser. The laser scanners evaluated have eye-safe Class I lasers. However, eye contact is still not advisable. They operate at a different frequency than the typically Class II lasers used for laser leveling, so laser scanners should not interfere with laser-guided operations, and vice versa. Multiple LADAR devices may be used on site simultaneously, possibly causing interference, although interference among scanners would be momentary and would only have a small effect on the collected data.

We did not experience other issues with interference among technologies. However, frequent data collection will result in the need to frequently communicate data in similar areas of construction sites. This may result in issues with interference among several devices communicating simultaneously.

APPLICABILITY

Increasing the frequency of data collection using these technologies results in increased importance of considering the applicability of reality capture technologies to given site and weather conditions. In each case study, the technologies were applied in weather extremes, such as sub-20º F and over-90º F temperatures, and high and low humidity conditions. While the laser scanners are not expected to operate at temperature extremes, we were able to operate the time-of-flight laser scanner in sub-20º F and over 90º F weather. We were not able to use the scanners during any precipitation, for fear of damage, although these technologies can be used under protective cover. The wired external logging sensing system failed during high-humidity testing, while the remaining technologies proved capable of data collection in extreme weather conditions.

Site conditions constantly change on construction sites, including terrain, laydown area locations, hazardous area locations, and areas in use for access or by construction activities. The equipment size and its setup impact the mobility of equipment. In certain cases, a piece of equipment was not sufficiently mobile or ruggedized for possible construction site conditions, such as mud and uncompacted ground. The need for power is still a problem. We have used generators, batteries, and available power to support data collection activities, each of which affects the mobility and speed of data collection.

INTEROPERABILITY

The systems that we have utilized work stand-alone; and do not interact/interoperate with each other. There is a great value in having these technologies interoperate between each other. However, there is limited interoperability between different vendors, even within the same group of technologies.
PROCESS ASSESSMENT

Frequent collection of as-built data has several implications to quality control and construction processes. By frequently collecting as-built data on site, it is possible to monitor incremental changes in the states of components under construction, thereby highlighting emerging issues/problems as they occur, as opposed to detecting these issues after components are constructed. This requires more detailed planning of inspection and construction based on incremental as-built states. Additionally, downstream processes that may use the gathered data must be able to accommodate the varied levels of details provided by design and as-built models. Inspection plans should also consider the current site and the expected weather conditions on a project at a given point in time. Finally, frequent use of these technologies requires cooperation from upper management and field personnel in order to ensure that these technologies can be applied effectively and collected data will be useful for project quality control.

TIMING OF DATA COLLECTION ACTIVITIES

For each case study, our decisions to inspect were informed by construction milestones as well as a goal of inspecting at least biweekly. While we focused data collection on a number of inspection goals, much of the data collected at each visit was gathered opportunistically due to the large data collection range of the laser scanners used. Hence, we were able to collect data about objects at multiple points in time, while inspection requirements only warranted inspection at a single point in time. For example, for the column shown in Figure 1, we were able to gather data about conditions before installation, installed rebar, formwork prior to and after concrete placement, column after forms were stripped, and after beams were connected. This resulted in multiple opportunities to proactively reason with the data collected about the column to detect issues such as bulging or poor alignment, although it is not always possible to inspect every feature at every state. Tolerance-based scheduling strategies such as described in (Milberg and Tommelein 2003) can also help in identifying the timing of data collection.

![Figure 1a. Data collected after rebar placement](image1.png)

![Figure 1b. Data collected after formwork placement](image2.png)

![Figure 1c. Data collected after formwork stripping](image3.png)

Figure 1. Data collected at points of interest during cast-in-place column construction.

Assessing the correct location of survey points is useful for proactively ensuring that temporary and permanent structures that rely on survey locations for dimensional control are installed correctly. In Case Study 5, we were able to detect deviations in multiple survey points that could propagate to multiple other points on a site. Many of the survey
points we discovered on site were marked in ink on stationary parts of the construction site, such as completed walls. This type of marking is not visible in point cloud data (although this can be identified if the laser scanner gathers light intensity data), so we placed targets at the survey points that would be recognizable in point cloud data, and made measurements relative to the inserted target.

![Figure 2 – An impromptu geometric target was aligned to a survey marking in order to distinguish the survey point in point cloud data](image)

Proactive inspection is not always appropriate. For example, on Case Study 5, we were able to collect detailed LADAR data about a basement wall prior to two subsequent activities: installation of the elevated slab it supported to one side, and prior to backfilling to the other side. Each subsequent activity altered the plumbness of the wall until it arrived at its final position, at which point the wall was intended to be within specified tolerances. Without this knowledge, we would incorrectly identify deviations in the wall at the first two states: wall installation and elevated slab connection. However, it was possible to proactively assess other characteristics of the wall, such as strength or crack sizes, at these states since they are not affected by the subsequent construction activities.

**Frequency of Data Collection**

Due to the complexity of site topology, sensor planning is necessary to ensure that data collection operations are targeted and efficient. It is important to identify ahead of time what types of sensors should be utilized when. In addition to applicability decisions, functional characteristics, such as modality, location, time and duration of sensing, and data communication and storage, should be considered in a sensor plan. Even with a plan under expected conditions, it is often difficult to carry out inspections as desired. For example, on Case Study 4, the expected path for moving the laser scanner was blocked by a trench under excavation and an obstacle (column rebar awaiting installation), as shown in Figure 3. Later, this area served as a regular access path for concrete trucks, resulting in the need to periodically relocate the laser scanner. Given changing site and weather conditions impacting the data collection process and the need for frequent inspection using these technologies, one needs to develop not only an initial data collection plan based on the expected site conditions, but also anticipate back-up plans. In addition, on-site re-planning capability based on the observed situation would be helpful in accommodating changing site conditions.
Figure 3 – Changing site conditions motivate development of backup plans or on-site re-planning.

THE LEVEL OF DETAIL OF THE DATA COLLECTED

In some cases, the level of detail of the as-built model generated using reality capture technologies can exceed the level of detail in a design model. For example, data captured in Case Study 2 indicated the presence of corrugated metal, which was described in specifications and manufacturer drawings, but not on design drawings (Figure 4). This carries implications for both the process of developing as-designed models to have more detail, and for reasoning with inspection data, where the reasoning with the data collected should account for possible differences in the levels of detail in the data represented in as-design models and the data captured from the site using these technologies.

Figure 4: Intensity data from Case Study 2, indicating presence of corrugated metal wall

PERSONNEL SUPPORT FOR DATA COLLECTION

In many cases, the data collection activities relied on awareness of or cooperation with field personnel. Commitment to the data collection goals and training is necessary both at the upper management level and at the field level in order to ensure successful deployment. In the case studies, we have secured early commitment from owners and contractor management team to embed sensors within building components and to conduct laser scanning operations. During the installation of embedded sensors, we relied
on cooperation with field personnel to ensure that sensing system equipment was installed prior to concrete placement and not altered during data collection.

**STORAGE AND PROCESSING OF COLLECTED AS-BUILT DATA**

During the scanning process, the mobile objects and field personnel that were in the field of view of the scan complicated the processing of the data collected, such as the registration of multiple scans and reasoning with the as-built conditions. During the process of registering data, multiple scans can be combined into a single model by establishing their orientation relative to each other. The registration process can be conducted manually or automatically by establishing “ground truth” with known locations in each scan and finding corresponding points in scan data from each scan. In many cases, we were able to avoid the process of establishing ground truth in every scan due to the large number of features with which to register data, and due to overlap in collected data. This requires that the majority of objects in scans be uniform. During registration of data sets obtained during working hours, we experienced difficulty in registering multiple scans automatically, due to error introduced by the existence of some mobile objects in the scene. While avoiding the extra ground truth data collection process, the registration and deviation assessment (Figure 5) processes became more inefficient in this case, causing additional registration time, as well as extra time assessing whether identified deviations were in fact false positives.

![Figure 5: Deviations between design and as-built models, colored according to degree of deviation. Small deviations may in fact be due to registration error introduced due to mobile objects in scans.](image)

In addition to the substantial effort that can be required to register scan data into a single as-built model, collection of large volumes of as-built data, such as the 0.5 - 21.5 gigabyte of data we collected per site visit, naturally creates significant downstream challenges in data storage, processing, and visualization. The large amount of data introduces the challenge of storing the data such that the downstream users of the data can access and find relevant data. Downstream users of as-built data, such as inspectors, construction managers, and facility managers, will need assistance in searching, managing, and visualizing the volumes of data produced by substantial increases in data collection.

**CONCLUSIONS**

From a technological and process perspective, application of reality capture technologies for frequent assessment of as-built condition is feasible and has been shown to provide.
meaningful temporal and spatial range of data collection, while correctly detecting discrepancies in the built environment. The technologies studied demonstrated efficient data acquisition capabilities, although additional development is necessary for preparing for, avoiding, and reacting to technology failures. While considering frequent inspection of as-built conditions using reality capture technologies, one must consider the process implications of timing, frequency, level of detail, and personnel commitment. It is anticipated as well that frequent data collection strategies can be adopted to address bottlenecks in construction processes that rely on geometric or physical characteristics of work in place. The technologies studied motivate further research in planning, modeling, and reasoning required for frequent collection of as-built data on construction sites.

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REFERENCES