CONSTRUCTION DEFECT REPORTING USING MOBILE AND DIGITAL WORKBENCH TECHNOLOGIES

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ABSTRACT

Sending data between the construction site and an off-site design office is one of the more problematic areas in information technology for construction automation, particularly for construction defect management. The aim of this research is to investigate how mobile computing and new forms of human-computer interaction can be brought to bear on specific problems in construction management. The construction defect reporting system is one such application. Combining mobile and wireless computing technologies with a digital workbench, we have developed a system to facilitate remote telecollaboration between a construction site and an off-site engineering office. The application reported in this paper demonstrates how construction defect reporting can be streamlined by field collection of construction defect information using a mobile device and visualising the defect in a CAD model on a digital workbench in an engineering office. This paper reports on the design of the system and our tests of sending images from the construction site to the engineer's office and positional accuracy of GPS for localization of the defect.

KEY WORDS

construction defect management, mobile computing, wireless communication, digital workbench

INTRODUCTION

Building construction is an information intensive industry with timely and accurate information important for all project stakeholders as it forms the basis on which decisions are made and progress is achieved. Construction projects often experience extensive delays or rework due to information that is unavailable. Information availability problems have increased as projects have become more complex and client deliverables more challenging. The increasing availability of information technologies has not necessarily mitigated these problems.

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Construction defect reporting and management is one area in construction project management that has eluded satisfactory ICT-based solutions. During the construction process, unpredictable circumstances lead to building defects. These defects include both construction failures, such as the failure of a structural element, or deviations from the as-designed in the as-built. Akinci et al. (2006) have developed a formalism for integrating sensor and scanning technologies coupled with digital project information to assess deviations between the as-built and as-designed in order to determine if a defect exists in the first instance. Yates and Lockley (2002) recommend a 13 step process for the investigation of construction failures. The process owners consist of architects, engineers, and technicians who inspect the construction site when a defect has been identified. If a defect is found, the location of the defect, the problem, and the date and time of the inspection is recorded, usually on paper. At the same, time photos will be taken of the defect as evidence while also being used on subsequent site defect reports. These field data collection tasks follow Yates and Lockley's (2002) recommendation that documenting construction failures requires project engineers to "Maintain records of field data on failures in the form of sketches, photographs, video recordings, and eyewitness reports." Maintaining records of field data on failures is only one step of the process in documenting and managing construction failures, though. These reports are submitted to the main office for review and discussion. This involves a time-consuming and often frustrating process of searching for a particular floor plan and then finding the specific location of the defect on the plan. Additionally, before the introduction of the digital camera, film processing for photographic proof of the defect would consume extra time and effort in the review and analysis of the defect. All of the above contribute to the disconnected workflow in construction defect reporting leading to frequent errors and low efficiency (de la Garza and Howitt 1998).

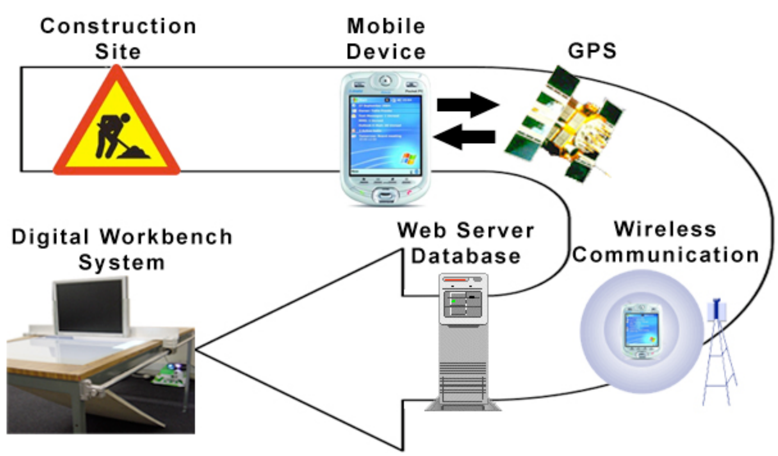


Figure 1. System architecture of how our application functions.

In this paper we focus on field collection of construction defect information and off-site visualization and review of the data. In order to enable real-time review of construction failures between people on-site and off-site, we have integrated mobile computing technologies with a horizontal tabletop interaction device. In a typical scenario envisaged for the use of our system, a site inspector will capture evidence of the construction defect on a mobile device, make textual notes about the defect, and record the relevant location of the defect using a position locating technology such as GPS. This information is transmitted to the central off-site office where the defect and its relevant meta data are stored in a computer database for retrieval and review by process stakeholders. The information about the defect is presented within a CAD model on the digital workbench for review and visualisation using augmented reality (AR) techniques. This workflow is illustrated in Figure 1.

The combination of the two technologies, mobile computing and the digital workbench, achieve the following outcomes. On-site deployment of mobile computing devices aims at improving the costly and time-consuming process of data collection and processing at the interface between physical site operations and off-site construction management activities. The digital workbench design facilitates the display, visualisation and collaborative interaction of the stakeholders around digital information depicting the defect.

SYSTEM DESIGN

Our system is a purpose-built, mobile ICT-supported construction defect reporting and management application. The two primary components are the mobile device running the defect reporting application and the digital workbench for visualizing the defect.

ON-SITE CLIENT: THE DEFECT REPORTING APPLICATION

The defect reporting application supports the capability to capture a digital image of the defect, annotate a note regarding the defect, locate the defect, and then send the information to an off-site database. The purpose of the mobile device is to provide a software platform for the construction defect reporting application and the hardware capability to take a digital image of the defect, locate the defect using GPS coordinates, and transfer the data over a wireless communication link to an off-site database.

The mobile device chosen for our system is the i-Mate PDA2k (Figure 2a). This device was selected based on requirements for our system to support a variety of wireless communication protocols such as GPRS, WiFi and Bluetooth. Additionally this mobile device is able to capture digital still images and video with its inbuilt camera. The operating system is Windows Pocket PC with the IBM “J9” J2ME runtime environment to support the construction defect reporting application. The mobile device does not have an inbuilt GPS receiver. GPS capability is achieved by attaching a GPS receiver to the secure digital input/output (SDIO) card slot as shown in Figure 2b.

Figure 2a and 2b. The i-Mate PDA2k (a) with GPS receiver (b) attached in the SDIO card slot.

The mobile computing application for sending the construction defect digital image data and meta data to the CAD application on the digital workbench system is written in J2ME (Java 2 Platform, Micro Edition) for its cross platform portability. J2ME is an open source Java development platform for small computing devices such as mobile phones and personal digital assistants (PDA). The data capture and transmission services require additional Java Specification Request (JSR) packages (Table 1). Presently there is no J2ME enabled mobile phone that supports all JSR packages. Mobile devices running the Symbian 9.1 operating system such as the Nokia N91 (to be released March 2006) will support JSR 75 and JSR 82 but only JSR 120 (Wireless Messaging API 1.1) which does not include the support for MMS. As such, our current implementation only supports data transfer via HTTP over WiFi and GPRS although it is "code-ready" for MMS and Bluetooth when those become supported in J2ME by the mobile phone vendors. The IBM "J9" runtime environment (formally known as the IBM WebSphere Everyplace Micro Environment) supports the basic set of JSR packages needed for the application including JSR75 and an operational serial port interface for Pocket PC based mobile devices. The default J2ME runtime environment on the i-mate PDA2K did not support either JSR75 or serial ports.

Table 1. J2ME Packages for Data Transmission

Feature	Optional Package	Package Description
File I/O	JSR 75	File Connection
SMS/MMS	JSR 205	Wireless Messaging API 2.0
Bluetooth	JSR 82	Bluetooth API

DEFECT LOCALIZATION USING GLOBAL POSITIONING SYSTEM

Global positioning systems (GPS) are finding their way into everyday activities such as in-car navigational systems. GPS already enjoys wide adoption in the construction industry primarily for tracking construction work materials, job safety and trafficking vehicle movements (Li et al. 2005). Direct GPS acquisition of positional data refers to a single receiver to retrieve the location data from a range of satellites (Piekarski et al. 1999).

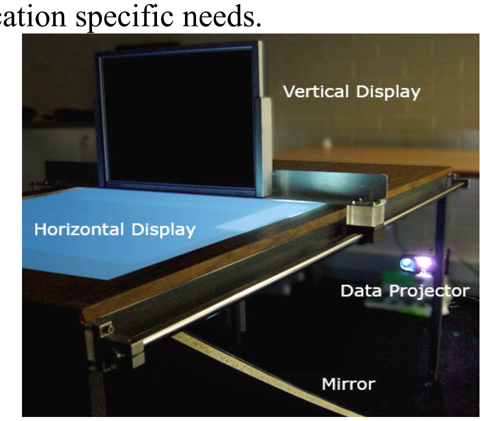
In our system, the GPS location specifies the location of the defect on the construction site. GPS data is read directly from the GPS receiver, a Pretec Whanto SD GPS receiver (Figure 2b) by the defect reporting application through a virtual serial port. All GPS devices output the satellite data (called a "sentence") formatted according to various data standards. The format that this GPS receiver supports is the NMEA format. Theoretically, the application can read the data stream continuously from the GPS receiver in its own low priority Java thread. However, practically, this diminishes the performance of the PDA and consumes power by keeping the serial port connection open between the PDA and the GPS receiver. The GPS coordinates are retrieved only when requested by the user.

WIRELESS COMMUNICATION

In order to support off-site communication, our system relies on wireless data transfer via HTTP over GPRS and WiFi protocols. The General Packet Radio Service (GPRS) is a non-voice value added service that allows data to be sent and received across a mobile telephone network. It supplements circuit switched data (CSD) and short messaging service (SMS). Theoretically, maximum speeds of up to 171.2 kilobits per second (kbps) are achievable with GPRS using all eight timeslots at the same time. This is about three times as fast as the data transmission speeds possible over fixed telecommunication networks and ten times as fast as current CSD services. However achieving the theoretical maximum GPRS data transmission speed of 171.2 kbps will require a single user taking over all eight timeslots without any error protection. Clearly it is unlikely that a network operator will allow all eight timeslots to be used by a single GPRS user and it will become important for this application to know what is actually achievable. WiFi refers to a set of wireless networking technologies more technically referred to as 802.11a, 802.11b and 802.11g. GPRS has the advantage of avoiding line-of-sight and coverage problems associated with WiFi or infrared and are thus more likely to be of use at construction sites.

OFF-SITE COMPONENT: THE DIGITAL WORKBENCH

The purpose of the digital workbench is to visualize the defect information in a CAD model. Our digital workbench, often called a horizontal tabletop interface, consists of a horizontal digital projection surface with an attached vertical screen to facilitate visualization of the defect within the context of the building model. There are a number of examples of 'digital workbench systems'; however, each one is constructed differently to accommodate application specific needs.



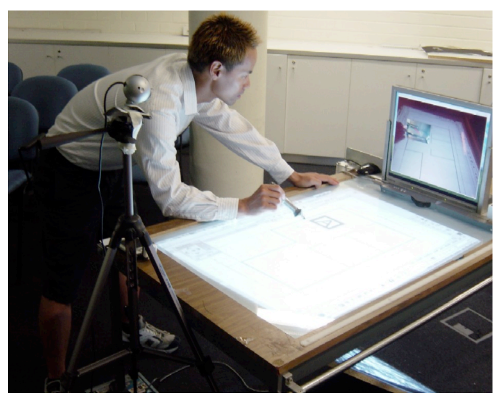


Figure 3. Digital workbench components (left) and participant using the digital workbench (right).

Our digital workbench measures 1500mm x 750mm x 700mm (L x W x H). Keeping in mind the aspect ratio of a desktop computer screen, the digital display area is 900mm x 650mm. The system consists of a projector which projects the computer image from beneath the workbench. There is a mirror hinged at approximately 45 degrees underneath the workbench; the computer projection reflects off the mirror to display on the horizontal surface. In addition to the horizontal display on the digital workbench system, there is a vertical LCD screen to display the digital images associated with the defect positioned on the horizontal display. By positioning the vertical display as close to the horizontal display of the system, we create a nearly seamless transition between the two displays as illustrated in Figure 3. The user interacts with the application on the horizontal surface of the workbench with a pen-based device using a Mimio system. The Mimio stylus is a touch screen type pointing device in the shape of a traditional pen.

In order to display the digital image of the defect in a CAD model on the digital workbench, we wrote a custom application for Microstation 8 using VBA. Visual Basic for Applications (VBA) is used to write the application to retrieve the defect image and meta data from the database and then to display the defect in a Microstation model. To take advantage of the dual screen configuration of the digital workbench, we used the horizontal projection surface to show the plan view of the CAD model and a 'beacon' to indicate the location of the defect on the plan view. The GPS coordinates of the defect are converted into the Cartesian coordinates of the CAD model. Based on the coordinates, a pattern (the beacon) from stored cells in a cell library is inserted into the CAD model at the correct location of the defect. Each beacon can be associated with a digital image file depicting a construction defect. This beacon is also an augmented reality pattern. Augmented reality is a virtual reality technology that allows digital images to be superimposed into the physical environment. On the vertical display, the beacon's pattern is replaced by a digital image of the defect as shown in Figure 3 (right) using augmented reality.

SYSTEM OPERATION

The first step is for the architect to capture a digital image of the construction defect. The digital image is additionally annotated with notes about the defect. This note can be used to describe the bearing and inclination/declination of the defect as this data is not captured due to the unreliable bearing data from the GPS receiver and lack of sensors to measure the inclination/declination viewing angle of the mobile device. For example, the inspector can annotate whether the defect appears on the ceiling or the floor. Additionally the digital image may not accurately show the defect and therefore adding a note to describe the defect in the image can help the off-site office make sense of the defect captured. Then, the defect is located using GPS coordinates. All of this information is input into the reporting form on the mobile device as shown in Figure 4.

The next step is to send this form information back to the off-site office to store in an archival database. The data sent by the mobile device is received by a computer which listens for the data from the mobile device. The service listeners include an SMS/MMS service, a Bluetooth server, and an HTTP daemon. The SMS/MMS service is supported by a Siemens MC35i GPRS modem and the NowSMS SMS/MMS gateway software. The services run continuously for the purpose of handling periodic service requests that the computer expects to receive from the mobile device. The received data is uploaded to the database server and the information can be then retrieved by the on-site personnel to view the defect in the CAD model on the digital workbench.

Display of the defect in the CAD model is handled by the custom application written for Microstation. The first step is to calibrate the coordinate system between GPS coordinates and the Cartesian coordinates of the CAD model. By establishing a reference point in the

CAD model, all subsequent locations will be calculated from this known point. In order to do this, we get the longitude and latitude coordinates that correspond to known fixed point on the CAD floor plan; the GPS coordinates of a reference point can usually be attained from surveyor's documentation about that particular location on the plan. After confirming the reference point, the GPS coordinates of the defect requested to be viewed are retrieved. These GPS coordinates, converted into the Cartesian coordinate system of the CAD model, determine where the defect is to be located on the CAD floor plan.

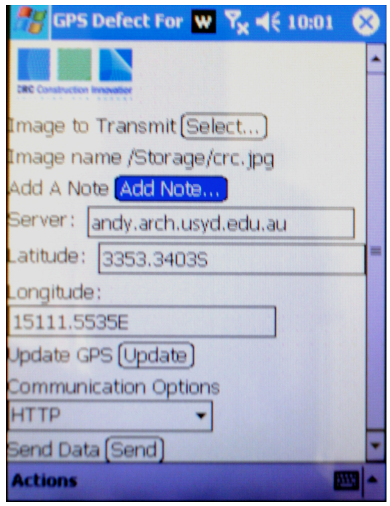
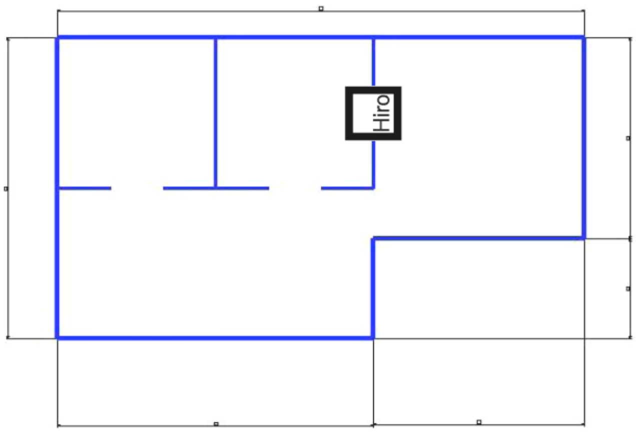


Figure 4. A screen shot of the defects form GUI displayed on the mobile device.

A digital pattern is placed directly on the floor plan (Figure 5 left) based on the GPS coordinates from the defects form. Since the approximate error of GPS is greater than ±2m, the size of the digital pattern is a three meter square with the zero error occurring at the centre of the pattern. For each digital image captured and selected for viewing, a pattern automatically displays in the floor plan. Each pattern is a cell created in Microstation using the characteristics of patterns that work with the AR toolkit[4]. After the digital pattern is displayed, a web camera positioned to aim directly at the horizontal display (Figure 5 right), recognises the AR pattern. The AR system associates the pattern with the digital file containing the image of the defect and displays it on the vertical display. By relating the vertical display with the floor plan on the horizontal display, the visualisation gives an added spatial connection to what is being seen in both displays.

[4] http://www.hitl.washington.edu/people/poup/research/ar.htm#artoolkit



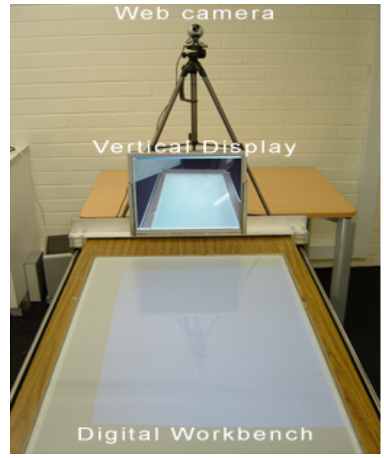
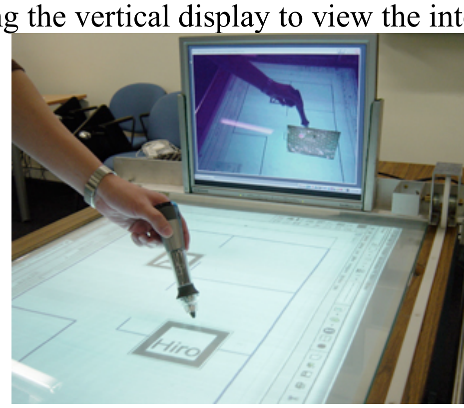


Figure 5. AR pattern positioned on the CAD floor plan (left) and the web camera focus on the horizontal display of the digital workbench (right).

The participant at the off-site office is now able to interact with the floor plan and digital AR patterns through a pen-based input directly on the horizontal display as shown in Figure 6. They can move and rotate the digital patterns to the proper orientation if it is known to them based on the metadata provided about the defect. The pen-based input provides easy manipulation and movement around the digital workbench. Using the pen-based input relies on using the vertical display to view the interaction taking place on the horizontal display.



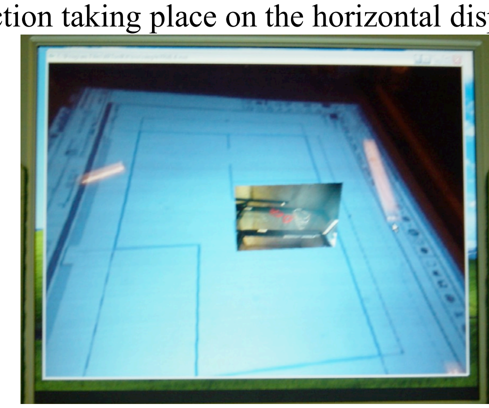


Figure 6. Interaction with the horizontal display (left) and visualising the actions of the interaction on the vertical display (right).

SYSTEM EVALUATION

The aim of the evaluation was to develop an operational understanding of the delimiting conditions of the system: 1) on the client side, the maximum size of field data about a defect a user can reasonably expect to send over these wireless communication networks; and 2) on the digital workbench side, the accuracy of GPS coordinates to locate the defect.

The first study measured the time taken to transmit data about a construction defect. Data transfer rates over GPRS through the Telstra[5] network and WiFi over a private network were

[5] Telstra is a telecommunications company in Australia.

compared. The procedure for conducting the tests is to attach and send an image of various file size ranging from 30kB to 300kB using the construction defect reporting application. Three tests were conducted for each file size; the average transmission time was then calculated. All GPRS tests were conducted indoors in an office where the signal strength ranged between tests from "very good" to "excellent." Similar conditions can be obtained outdoors. All WiFi tests were conducted indoors. The signal strength for all tests was "excellent." The tests conducted using WiFi were carried with the wireless base station located within a 2 metre radius of the mobile device. Each time a test was conducted, for both GPRS and WiFi, "time sync" was performed between the server and the mobile device. By synchronizing the time between the mobile device and server, more accurate data transmissions times were recorded. The results of the data throughput studies are reported in Figure 7.

Based on the throughput, if GPRS is the method of wireless connectivity, then the recommended maximum size of the digital image is approximately 50kB with a throughput of 9-13kbps. This is much slower than the advertised speed by Telstra. Image sizes greater than 50kB would require the site engineer to wait more than one minute to transfer the image, which we claim could have the unintended side-effect of the engineer believing that the image is not transmitting correctly. If WiFi is available, then image size is not an issue. Therefore if using GPRS, image resolution should be considered to capture only what is necessary to depict the defect.

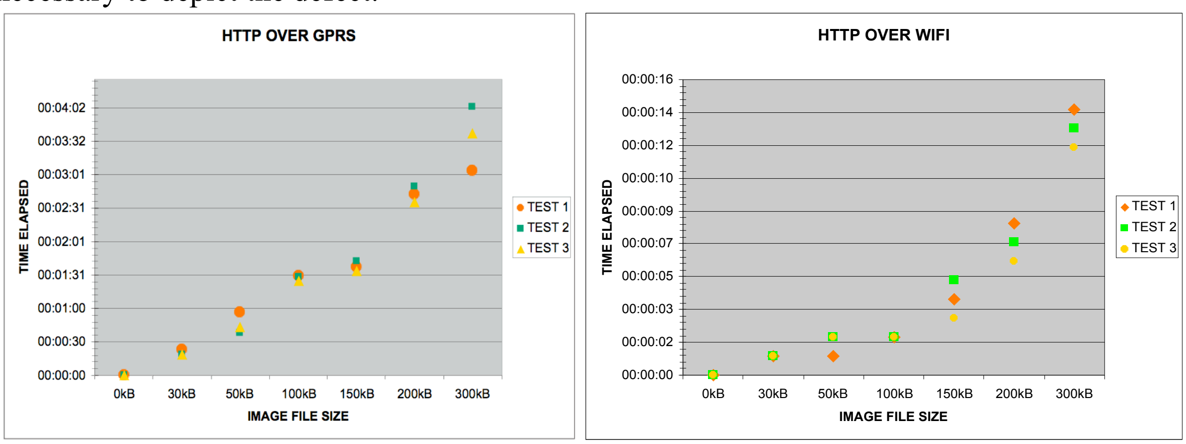


Figure 7. Data throughput graphs for sending various file sized images using HTTP over GPRS (left) and HTTP over WiFi (right).

The second study evaluated the accuracy of GPS coordinates (Wan 2005) for displaying the defect in the CAD model on the digital workbench. There are two issues related to accuracy: absolute accuracy and positional accuracy. The first issue has to do with the GPS coordinates being the "correct" reading for a given location. Because the defect is located in the CAD drawing by differencing the reading to a known location, absolute geodetic accuracy is less of an issue. The more important issue is the positional accuracy. That is, what is the potential error between where the location actually "is" and the current GPS coordinate? The positional accuracy of the GPS reading was evaluated by recording a GPS reading 10 times at 3 separate points after having recorded the position, moved to another location, and back. By calculating the average reading for each location and the difference between each reading and the average, the average sensitivity was calculated to be approximately ±0.07 seconds. Using the coordinate conversion between GPS geodetic longitude and latitude to Cartesian conversion, this is a sensitivity of ±2m. A similar finding on positional accuracy of within 2m and 5m has been reported by others (Piekarski et al. 1999). Thus, GPS can be used to locate the vicinity of a defect but not the location of objects.

CONCLUSION

This paper describes a mobile computer based construction defect reporting and visualisation system. The most significant outcome that our system demonstrates is the system's ability to provide off-site participants with real-time access to relevant information at construction sites and for on-site inspectors to send real-time information from the construction site to the appropriate decision makers off-site. This mobile computing + augmented reality digital workbench platform is intended as a working proof-of-concept to illustrate the type of computing applications that such a configuration could support.

In our future work, we plan to replace GPS with a more accurate means for locating defects, such as laser scanning or RFID tagging. We are also planning to make the vertical screen move autonomously so that vertical screen can display a perspective view of the 3D model from a cross section of the floor plan showing the location of the defect and give the viewers a near seamless "3D" visualization.

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REFERENCES

Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., and Park, K. (2006). "A formalism for utilization of sensor systems and integrated project models for active construction quality control." *Automation in Construction*, 15(2), 124-138.

de la Garza, J. M., and Howitt, I. (1998). "Wireless communication and computing at the construction jobsite." *Automation in Construction*, 7(4), 327-347.

Li, H., Chen, Z., Yong, L., and Kong, S. C. W. (2005). "Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency." *Automation in Construction*, 14(3), 323-331.

Piekarski, W., Gunther, B., and Thomas, B. "Integrating Virtual and Augmented Realities in an Outdoor Application." *IWAR '99: Proceedings of the 2nd IEEE and ACM International Workshop on Augmented Reality*, 45-54.

Wan, W. K. (2005). "A System for Construction Site Defect Reporting Using Mobile Computing and Digital Workbenches," Master of Design Science (Design Computing) Honours Dissertation, University of Sydney, Faculty of Architecture, Key Centre of Design Computing and Cognition, Sydney.

Yates, J. K., and Lockley, E. E. (2002). "Documenting and Analyzing Construction Failures." *Journal of Construction Engineering and Management*, 128(1), 8-17.