Emerging Tools to Enable Construction Engineering

A. B. Cleveland Jr.[1]

Abstract: Those working within the domain of construction engineering—the planning and management of the construction of infrastructure assets—today employ a wide range of information technology tools. The vast majority of these tools are used on desktop computers processing tabular information associated with scheduling, tracking, updating statuses, reporting, and similar tasks. In spite of the significant penetration of information technology into construction engineering, there is little direct reuse of the engineering information created during the design phase. Likewise, access to rich engineering information and applications to exploit this information have yet to be extended to mobile workers on the construction jobsite in any significant way. This paper explores a sampling of some of the emerging information technology tools that may be effectively applied to support construction engineering in the field. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000278. © *2011 American Society of Civil Engineers.*

CE Database subject headings: Construction management; Information technology (IT).

Author keywords: Construction engineering; Information technology.

Introduction

The task of construction engineering is potentially on the cusp of significant breakthroughs in productivity, quality, and safety, enabled by existing and emerging information technology capabilities. Glimpses of these breakthroughs can be seen through the features of software applications both within and outside the construction industry. The purpose of this paper is twofold. The first objective is to provide a glimpse of some of this potential by describing some illustrative examples—some within commercial products, but primarily within the realm of research prototypes—of applying new information technologies to construction tasks. The collection of examples cited is not intended to be complete or exhaustive. Rather, it is more anecdotal and intended to motivate thinking about how the construction process might be transformed through innovative applications of information technology.

The second objective is to abstract from these examples the major underlying information technology issues that must be addressed if the industry is to realize these potential breakthroughs in a significant and, importantly, scalable way. These broad issues are abstractions based on considering the prerequisites for implementing some of the examples cited and the author's general experience in the area of applying information technology to construction. Each issue will be discussed in some detail, including a summary of its importance to construction and potential approaches to addressing the issue.

Background

When considered broadly, the state of information technology aligns very well with the needs of the infrastructure industries:

- Server-based computing cycles, memory, and mass storage are very plentiful and infinitely scalable. This is the promise of cloud computing, for example.
- High-bandwidth wireless communications are affordable, readily available everywhere, and allow for communications not only between computers, but also between individuals virtually anywhere in the world.
- Portable smart devices—e.g., smartphones, ultramobile computers, tablets, global positioning systems (GPS)—are readily available, affordable, and well accepted for certain types of applications.
- Likewise, the raw computing power, mass storage, and memory of these portable devices, although somewhat limited today, is continually improving.

Compared with just a few years ago, new technologies and deployment strategies that are increasingly aligned with the requirements of the construction industry continue to emerge in the information technology landscape. The following section explores a few examples of how construction engineering might benefit from these emerging capabilities.

Promising Technologies for Construction Engineering

This section explores a few features of the information technology landscape that are relevant to construction engineering. This includes a few examples of how these and other technologies might be applied—individually and in combination—to construction engineering tasks.

New Computing Form Factors

From an information technology point of view, one of the primary characteristics marking the past decade is the explosion of handheld computing devices. The convergence of the simple cellular phone with the downsizing of desktop computing has resulted in a wealth of high-powered portable devices. Coupled with this is the growth and nearly global coverage of high-bandwidth wireless communication. Additionally, new form factors with novel approaches to the user interface continue to emerge. This includes such technologies as touchscreens, inertial devices, compasses, voice recognition, and

[1]Senior Vice President, Bentley Systems Inc., 685 Stockton Dr., Exton, PA 19341. E-mail: buddy.cleveland@bentley.com

Note. This manuscript was submitted on July 14, 2010; approved on August 25, 2010; published online on August 1, 2010. Discussion period open until March 1, 2012; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 137, No. 10, October 1, 2011. ©ASCE, ISSN 0733-9364/2011/10-836–842/$25.00.

J. Constr. Eng. Manage., 2011, 137(10): 836-842

global positioning capabilities. In addition, today's devices can create, display, and capture information in multiple media including text, audio, image, photos, and video. Finally, complex computing functions are not limited to the raw computing power of the handheld device. High-bandwidth communication coupled with concepts such as cloud computing and software as a service (SaaS) enable mobile workers to participate in an information rich, high-performance computing environment. All of this bodes extremely well for the construction industry given the characteristics of construction jobsites, which are often located in remote areas, populated by workers who must be mobile and function "untethered."

Virtual and Augmented Reality

Virtual reality is, in one form or another, nearly 50 years old (Burdea and Coiffet 2003). There are many definitions of virtual reality, but the simplest—and broadest—is the simulation of a three-dimensional (3D) environment on a computer. Although many technologies, such as immersive viewing and head and body tracking, may be employed to increase the reality of the virtual experience, virtual reality may be experienced with nothing more than a computer screen and a mouse. The use of virtual reality and associated technologies to support construction is itself nearly 25 years old (Cleveland 1987, 1989). Many of these applications of virtual reality fall under the umbrella term "4D planning" (Skolnick 1993; Fischer and McKinney 1998). These applications have been used to support construction to date almost exclusively in conjunction with desktop computers or in fixed environments. There have really been virtually no practical applications to date for the mobile, untethered construction worker.

Augmented reality might be considered the child of virtual reality. Again from the multiple definitions, the simplest is augmenting the real world with information from the virtual world. For example, the real world might be viewed through a video image on a handheld device. The 3D virtual world, such as a proposed new building, would be superimposed on the video image. As the user moves in the real world, their motion would be tracked in real time with sufficient accuracy and frequency to continuously update the image of the virtual world such that it is always displayed in the correct location in the context of the view of the real world. As such, augmented reality is by definition intended for mobile users. Many applications of augmented reality have been proposed for the construction industry (Webster et al. 1996; Behzadan and Kamat 2005). However, broad-based, practical applications for construction requires (1) addressing the issue of easily and accurately tracking position in real time across the jobsite and (2) user interfaces that are compatible with the functionality and safety requirements of the mobile construction worker. These will be discussed in more detail subsequently in this paper.

Digital Paper

Digital paper technology makes it possible to digitally capture handwritten notes and drawings that are drawn on paper. The most common digital paper technology, patented by Anoto, consists of two basic elements. The first is the paper itself. What makes this paper special is a patented dot pattern printed on the paper either prior to or along with the other printed text and images. The dot pattern consists of very small dots spaced approximately 0.3 mm apart across the paper. The dots are not arranged in a precise grid. Rather, each dot is located slightly off of the grid point. Any group of 6×6 dots is unique over a population of approximately 2^{72} dots, which results in an area of roughly 4.6 million km^2.

The second element of the technology is a digital pen, which is basically a ballpoint pen equipped with integrated digital camera, microprocessor, and digital storage. The pen captures 50 photo images per second, processes the dots in each image to determine exactly where it is at that point, and stores the resulting coordinate. These coordinates are then be transmitted to a host computer through either a wireless connection or a USB docking device.

To date, many of the applications of this technology have been applied to forms documents, for which manual entries on paper form documents are captured digitally. A few companies, notably Bentley Systems, Inc. and Adapx, have applied this technology to construction drawings. The Bentley Systems implementation is known as "Dynamic Plots." This implementation of digital paper has demonstrated significant benefits to the process of commenting on drawings—often referred to as "redlining"—by greatly reducing cycle times, reducing costs, and increasing accuracy.

Technology Application Examples

The following sections describe a number of examples in which the technologies described previously were applied singly or in combination to validate their feasibility and potential applicability for supporting the tasks of mobile construction workers.

Portable Virtual Reality

As noted previously, most applications of virtual reality in construction rely on desktop computing to achieve the performance required to realize a truly interactive experience. With the increasing performance and improving graphic displays of handheld devices, there is a significant opportunity for virtual reality to become portable. However, portable virtual reality applications for mobile construction workers cannot simply be downsized versions of desktop applications, which rely heavily on one or more input devices, e.g., mouse, keyboard, joystick, or head tracker. There a number of characteristics of construction workers that would make simply downsizing the desktop for the sake of portability problematic:

- They are mobile and cannot be encumbered with devices that restrict their mobility;
- They work in a hazardous environment and cannot afford distractions that jeopardize their safety;
- The jobsite is temporary and must mobilize and demobilize quickly; and
- They often work outdoors and other extreme environments wearing gloves and protective gear.

However, the new computing form factors not only enable portability, but capabilities such as GPS, touchscreens, and inertial sensors also enable new paradigms for interaction with digital content that may be more compatible with the realities and needs of the mobile construction worker.

In one prototype, the sensors available on an iPad and similar handheld devices are used for the user's interaction with a 3D digital model downloaded to the handheld device (Cote 2010; Smith 2010). In this mode, the user is positioned within the model and the computer serves as a virtual "spyglass" to examine the 3D model by simply moving the device up and down, left and right, turning their body left and right, and so forth. These are completely intuitive and natural actions requiring no additional input devices. To query additional information about a specific component, the user simply touches the component on the screen with their finger to display the business properties associated with the component. In a production environment, these models would be published from the design models with the scope and associated business properties appropriate for the specific construction usage and then delivered wirelessly to the handheld device. These types of models might be delivered as part of a broader multimedia work package that might include drawings, procedures, and instructional videos.

From the point of view of the handheld device, the most significant issue is performance. Although the computing and graphics

J. Constr. Eng. Manage., 2011, 137(10): 836-842

Fig. 1. Viewing 3D model on an iPad (image by the author)

performance of these devices continues to improve, they will never match the graphics performance and visual reality of desktop systems. As a result, they may not meet the user expectations set by desktop system performance. Current research at Bentley is focused on using 3D panorama views generated from the 3D model. These panoramas perform extremely well on handheld devices using the user interaction paradigm described previously. These panoramas can be generated “in the cloud” ahead of time and accessed by the user by indicating their position on a plan-view drawing. For outdoor applications, the user’s position can be determined using the handheld device’s onboard GPS system. By prepublishing the panoramas on high-performance computers, they can incorporate whatever level of detail and visual reality the user requires without impacting performance. Using the touchscreen, the user will be able to add comments and notes. Likewise, they will be able to attach audio, photograph, and video files to their comments. Employing patent-pending technology, the user will be able to interact with individual components within the panorama through the touchscreen interface. This component interaction can include query, highlight, update status, and so forth. An example of viewing a 3D model on an iPad is shown in Fig. 1.

Seeing the Invisible with Augmented Reality

Much like virtual reality, an important technology component is computing the viewer’s position and orientation. Many of the augmented reality applications are “marker based” in that the position computations are based a marker placed in the real world. These markers are similar to a two-dimensional (2D) barcode, as shown in Fig. 2. Using a video camera, such as the camera on a cell phone or handheld device, the image is captured and, employing computer vision technology, the position of the camera relative to the marker is computed. The virtual image is then positioned relative to the marker and superimposed on the video image captured by the camera. This happens many times per second, such that as the viewer moves in the real world, it appears as if they are also moving relative to the virtual model that is fixed to the marker. Thus it is possible, for example, for a user to view a 3D model as if the model is sitting on top of a 2D drawing. The user examines the 3D model by simply moving the device around, again similar to a spyglass, or by rotating the drawing. An example is shown in Fig. 3 (Smith 2010). In this example, the image shown in the upper left is the image seen by the user in the view screen of the handheld device. In this implementation, the drawing itself serves as the marker.

Fig. 2. Sample augmented reality marker

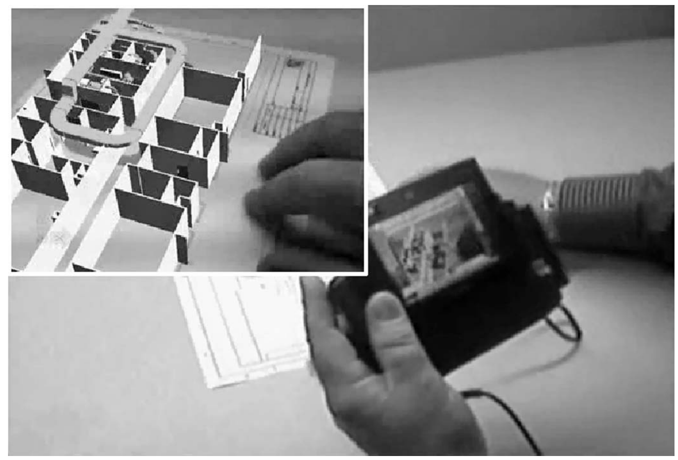

Fig. 3. 3D model superimposed on 2D drawing (reprinted with permission from Smith 2010)

The example in Fig. 3 shows the virtual model in relation to the marker and is therefore useful for interacting with virtual models whose exact location in the real world is not critical. However, if the marker’s position is accurately known in relation to the real world, then the virtual world can be superimposed in relation to the real world itself. From a construction point of view, this creates a number of opportunities related to layout and inspection, including visualizing hidden components, such as those underground and behind walls. For example, Fig. 4 illustrates the view a user might see examining the underground piping beneath an urban intersection.

In any augmented reality application that associates virtual images with real-world images, its effectiveness will depend largely on the accuracy, and secondarily the latency, of the viewer calculations. The degree of accuracy required will depend on the nature of the task to which it is applied. For example, an application that simply associates names or properties of an object, for which just being close to the real object is good enough, can be a lot more forgiving in accuracy as compared to using the virtual image to stake out new construction. The issues and challenges associated with position calculation will be discussed in greater detail subsequently in this paper.

Virtual Reality CAVE in the Construction Trailer

The concept of a virtual reality CAVE (computer automatic virtual environment) providing a completely immersive virtual reality environment has been around for nearly 20 years (Cruz-Neira et al. 1992). There have also been a number of studies on its applicability

J. Constr. Eng. Manage., 2011, 137(10): 836-842

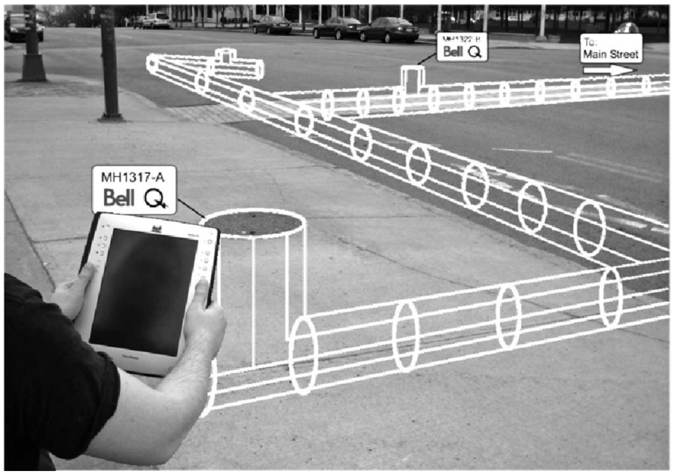

Fig. 4. Augmented reality view of underground piping (reprinted with permission from Côté 2010)

to construction (Thabet et al. 2002). However, fully immersive CAVE implementations can be quite costly, often into the millions of dollars. At this level of capital investment, the CAVE likely exists in a fixed location, and the users come to the CAVE, not the other way around. Given the potential benefits of a CAVE or similar technology to construction (Thabet et al. 2002), the ability to establish a CAVE at a construction jobsite quickly and inexpensively could be a useful tool for the comprehension, planning, and training of construction activities.

A current research project aims to enable an inexpensive and portable CAVE capability (Cote 2010). This project leverages the marker-based positioning methodology from augmented reality, as described previously, and the advent of low-cost headsets that support immersive viewing and are equipped with small video cameras to support the real-time position computations.

In this project, which is referred to as Navideck (shamelessly borrowing from the *Star Trek* Holodeck), a standard room or office, such as might be found in a construction trailer, is used to create the CAVE. A collection of markers appropriate for augmented reality applications are printed on sheets of paper, which are then attached to wall. The precise location of each mark is arbitrary. The only requirement is that one or more complete markers are visible from whatever location and orientation the user is looking while standing in the room. Then the user's starting point, i.e., location and head orientation, is aligned with a location and orientation in the 3D model, which calibrates the location of the markers visible in the starting location and orientation. Then, by simply panning across the room, the remaining markers can be automatically calibrated. Once completed, all of the markers are then calibrated with the 3D virtual model and with one another. The user can then explore the model by turning their head, walking, and so on, within this low-cost CAVE environment, as shown in Fig. 5.

This approach has two distinct advantages over the portable virtual reality applications described previously. First, with this approach, the user can move through the model by walking. In the earlier examples, the user was limited to changing their view orientation. To move through the model would require a gesture or some other user input to "walk" within the 3D model. Second, this approach can support multiple users. The marker calibration can be saved and shared with other users without requiring them to go through the calibration process. The position of each person is known at all times, making it possible to display the avatars of other participants as they walk through the model in the CAVE. In addition to simply examining and querying the 3D model, animations

Fig. 5. A user walking within the Navideck (reprinted with permission from Côté 2010)

of construction activities can be played for the purposes of familiarization and training as the users are moving through the model.

The objective of this project is to make it possible to create a CAVE such as described here for a cost on the order of \$1,000 to \$2,000 per participant. Based on early results, it appears that this goal should be achievable.

Paper: New User Interface

For many years, paper has been positioned as anathema to information technology with the stated goal of a "paperless" process. However, in an era of "digital paper," the status of paper can be elevated from a necessary by-product to a full partner in digital workflows. This trend begins with the digital paper technology described previously. However, integrating digital paper with some of the technologies underlying augmented reality opens up new opportunities for paper within digital workflows.

A research project was initiated to explore the possibilities of the digital paper concept beyond markup workflows (Smith 2010). The primary objective was to extend the richness of the information that can be delivered through a paper document, beyond what is actually seen on the paper document or drawing. The focus of the project was the application of digital paper to the activities of mobile workers, such as those in construction. In formulating the project, it was decided to limit the technology to what a mobile worker might normally carry. Therefore, the technology was limited to paper and a handheld device with the form factor of a smartphone or an ultramobile personal computer. Secondarily, the paper was limited to standard paper documents created with commonplace printers.

The approach employs the same technology used in marker-based augmented reality application. In this case, the drawing itself is the marker. Thus, when a drawing is viewed through a digital camera, once again employing the spyglass paradigm, it is possible to determine the point on the drawing at the center of the view and therefore what component on the drawing is being pointed to. Finally, knowing the component, the business properties associated with component can be retrieved. To enable this, the prototype implemented by this project creates a digital package of information when a paper plot is created. The content of this package enables the process described previously through a patent-pending process. This digital package is then downloaded to the handheld device. In operation, the user identifies the drawing by pointing the camera at a 2D bar code printed on the drawing. Then, as the user

J. Constr. Eng. Manage., 2011, 137(10): 836-842

Fig. 6. Querying component on paper drawing (reprinted with permission from Smith 2010)

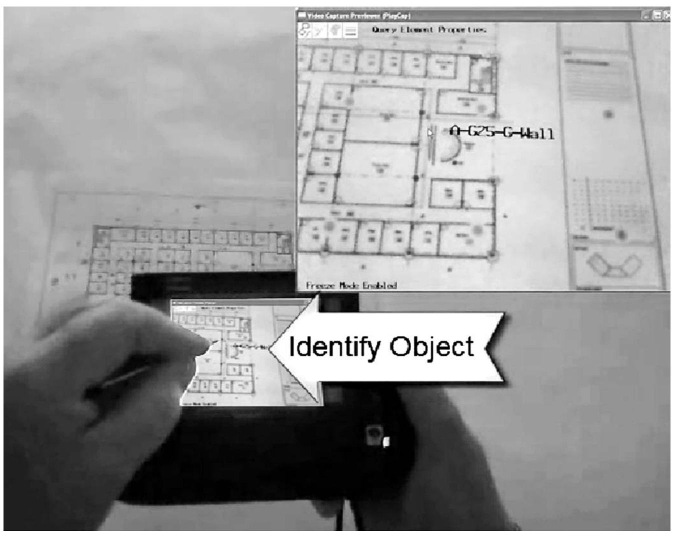

Fig. 7. Querying drawing with touchscreen (reprinted with permission from Smith 2010)

passes the device over the drawing, the business properties of components are displayed as they pass through the center of the view. This is illustrated in Fig. 6.

In alternate mode, the image can be frozen in the view and then, if the handheld device is equipped with a touchscreen, the user can query any of the components within the scope of the view simply by touching the screen, as shown in Fig. 7. This prototype has been extended to also include adding redline comments and attaching audio, photo, and video notes to the components on the drawing, all through the handheld device and the paper drawing (Smith 2010).

Major Technology Issues

Clearly, information technology trends present tremendous opportunities for the construction industry. The examples cited in this paper a largely related to the distribution and effective use of rich and complex information by mobile construction workers.

Transforming Digital Information for Construction Use

Perhaps the most significant use impediment to the expanded use of information technology in support of construction engineering, particularly as it relates to the reuse of digital content created in the engineering phase of a project, is the very nature of infrastructure projects themselves. Executing an infrastructure project—regardless of the life-cycle phase—always presents significant challenges. The project enterprise is always temporary. The multiple project participants and the project supply chain are brought together quickly, exist for a short time relative to the length of the asset life cycle, and then disbanded. Further, it is extremely unlikely that the exact project enterprise configuration of a past project will appear again in a future project. New technology, new suppliers, and new requirements can have a significant impact on what the project delivers in terms of new or modified infrastructure, which inevitably changes the configuration of the project enterprise. This dynamic is reinforced because every infrastructure project is bound by place, a specific location on the earth. As such, it is subject to local regulations, the local political and economic environment, local practices and methods, local suppliers, and the local workforce. In the end, every project is unique.

From the inherent geographic distribution, organizational fragmentation, and uniqueness of every infrastructure project, a number of specific issues arise that relate to the application of information technology within construction engineering.

Misalignment in the Information Requirements

Inevitably, the organization of the digital information and the deliverables created by engineering will be organized to optimize the performance of the engineering tasks. This extends to the structure of the information, regardless of whether it is digital or paper; the level of detail created or captured; and the scope of the information. In all these dimensions, construction has different requirements than engineering largely because construction information requirements are, in the end, related to the information required to perform a specific construction task, which takes place in a specific location on the construction site.

In the case of organizational structure of project information, "system" or "discipline" may be a first-order element of the information structure, where "location" is likely to be a second-order element. For example, an engineer may be responsible for a piping system that spans the entire facility. On the other hand, the information structure requirement may be just the opposite because it is likely more useful from a construction engineering point of process information for all disciplines and systems in a single location.

Level of detail is also an issue. For example, during the design phase, a wall may be represented in a digital model as a single element. However, as it relates to construction engineering, that wall must be decomposed into its constituent parts to align with the planning and execution of specific construction tasks. Conversely, certain types of preassembled modules and assemblies may have been designed at the level of individual components, which must be aggregated into a single component to support construction engineering tasks.

The scope of the information created within the design phase may be incompatible with the scope that is required for construction engineering. There are many examples in which the detailed design is relegated to the construction team, such as small piping, conduit, block walls, supports, and so on. Often the design elements must be modified to support construction engineering, such as subdividing a concrete slab to correspond to multiple concrete pour tasks. Finally, construction engineering may require construction specific components, such as scaffolding, form work,

J. Constr. Eng. Manage., 2011, 137(10): 836-842

construction equipment, or temporary services that are not created as part of the engineering tasks.

Level of Effort Required to Transform Information

Given this misalignment of information requirements, there is a significant effort required to transform the digital content into a structure, level of detail, and scope that is directly usable by construction engineering applications. This is not a simple translation of data from one format to another. Overcoming the misalignment described previously, this transformation may require

- Normalization of information into a usable information model;
- Aggregation of information from multiple sources;
- Decomposition of high-level information to the necessary level of detail;
- Filtering information for a specific purpose or task;
- Reorganizing information for consistency with a specific task or application; and
- Delivering the information in the appropriate digital format for a given application.

Today, these operations—if carried out at all—are still largely manual or semiautomated at best and as such are costly, error prone, difficult to manage, and not timely. A strong case can be made that significant portion of the \$15.8 billion wasted each year due to the lack of interoperability, which NIST identified in its 2004 report (Gallaher et al. 2004), is due in large part to the efforts focused on this transformation of information between life-cycle phases. These wasted dollars only account for the cost related to the lack of interoperability and do not begin to quantify the lost opportunities.

Accurate Real-Time Positioning

Considered broadly, the importance of location to the construction process is well understood, and the significant benefits as location information becomes more accurate, timely, and personal have been well articulated (Beliveau 1996; Beliveau et al. 1995). As noted several times in this paper, effective application of virtual reality and augmented reality depends heavily on accurate, real-time location information. The algorithms for performing the required calculations, the hardware and software technologies for displaying graphics, and the computing power required are well understood and continually improving, but transparent access (i.e., requiring little or no setup time) to highly accurate, real-time location information remains elusive.

The required accuracy and timeliness of the location information depends heavily on the specific application area. The potential accuracy and timeliness of the location information depends on where the work is being conducted and the positioning technology employed. For example, a recent study (Cote 2010) included calculations to define the required accuracy of location information for augmented reality applications where the virtual world was to be projected on the visible real world. The objective was to determine the accuracy of the viewer 2 km from the viewer, and then the viewer's position needed to be accurate within 3.6 m. This would indicate for outdoor applications where the objects of interest are relatively far from the viewer, global positioning technology would likely be accurate enough. However, if the object of interest was 2 m away, then the accuracy of the of the viewer's location must be within 3.6 mm for no more than a 1 pixel error. These levels of accuracy can potentially be approached for outdoor applications, where available global positioning technology is used in combination with other technologies, such as real-time kinematic and laser technologies. However, achieving this accuracy indoors requires significant setup, which can be difficult if not impossible to achieve in an environment as dynamic as a construction site.

The solution to highly accurate positioning on the construction jobsite will likely require the seamless integration of multiple technologies. For example, in a current research project, the integration of inertial dead reckoning and ultrasound technologies with real-time error correction using the 3D model as a filtering mechanism is being explored for indoor position tracking (Cote 2010; Girard et al. 2011). Continued research and new solutions to the location problem are critical to the successful implementation of new applications for construction. In an ideal world, this would mean something along the lines of "position tone"—ubiquitous access to location information anywhere on the jobsite, indoors or outdoors, at the level of accuracy required for the application.

User Interfaces Appropriate for Construction

Construction personnel operate in a hazardous environment, often under extreme weather conditions. They are encumbered with hard hats and other protective gear. Enabling more effective use of digital information and information technology tools will require user interfaces that can be used effectively and, more importantly, safely in a construction environment. This is not simply user interfaces enabled by software as it is traditionally considered in application development. It will require new computing form factors and software applications designed to exploit them. Exploiting new hardware and software technology on behalf of mobile construction personnel need not be limited to mobile computing and handheld devices. Other broad information technology trends, such as cloud computing, SaaS, and wireless broadband communications are directly supportive of the needs of the mobile construction worker. These technologies enable the seamless integration of the construction worker with a wealth of rich digital content and the computing power to deliver this content directly to them in the form most appropriate for their task at hand.

Conclusion

The construction industry is on the verge of a potentially dramatic improvement in productivity, quality, and safety enabled by construction engineering and information technology. In the context of the broader information technology trends, the industry is in a position where server-based computing cycles, memory, and mass storage are very plentiful and infinitely scalable. This is the promise of cloud computing. High-bandwidth communication is readily available everywhere and affordable, not only between computers, but also wirelessly to individuals virtually everywhere in the world. Likewise, mass storage and memory is increasingly available and affordable on portable devices such as smartphones, handheld computers, GPS, equipment controllers, and so on.

However, to fully realize this potential, there are significant issues to address and hurdles to overcome. Addressing these major issues and hurdles goes beyond adding new features of one software application or another, beyond a new "killer app." In summary, there are three obstacles that must be tackled to enable major breakthroughs in construction engineering: information delivery from engineering to construction; ubiquitous access to accurate, real-time position information; and user interfaces appropriate to the demands of the mobile construction worker.

References

Behzadan, A., and Kamat, V. (2005). "Visualization of construction graphics in outdoor augmented reality." *Proc., Winter Simulation Conf.*, IEEE Computer Society, Washington, DC, 1914–1920.

Beliveau, Y. J. (1996). "What can real-time positioning do for construction?" *Automation in construction 5*, Elsevier Science, Netherlands.

J. Constr. Eng. Manage., 2011, 137(10): 836-842

Beliveau, Y. J., Williams, J. M., King, M. G., and Niles, A. R. (1995). "Real-time position measurement integrated with CAD: Technologies and their protocols." *J. Constr. Eng. Manage.*, 121(4), 346–354.

Burdea, G., and Coiffet, P. (2003). *Virtual reality technology*, 2nd Ed., Wiley, Hoboken, NJ.

Cleveland, A. B. (1987). "CAD, 3-D modeling and construction management." *Constr. Specifier*, 40(4), 78–89.

Cleveland, A. B. (1989). "Real-time animation of construction activities." *Proc., Construction Congress I—Excellence in the constructed project*, ASCE, New York.

Côté, S. (2010). "Virtual and augmented reality in infrastructure engineering." *Applied Research Seminar—Bentley Be Together Conf.*, Bentley Systems, Inc., Exton, PA.

Cruz-Neira, C., Sandin, D. J., Defanti, T. A., Kentyon, R. V., and Hart, J. C. (1992). "The CAVE: Audio visual experience automatic virtual environment." *Commun. ACM*, 35(6), 64–72.

Fischer, M., and McKinney, K. (1998). "Generating, evaluating and visualizing construction schedules with CAD tools." *Autom. Constr.*, 7(6), 433–447.

Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L., and Gilday, L. T. (2004). "Cost analysis of inadequate interoperability in the U.S. capital facilities industry." *Prepared for NIST*, RTI International and Logistics Management Institute, McLean, VA, and Research Triangle Park, NC.

Girard, G., Côté, S., Zlatanova, S., Van Oosterom, P., Barrette, Y., and St-Pierre, J. (2011). "Indoor pedestrian navigation using foot-mounted IMU and portable ultrasound range sensors." *Sensors*, 11(8), 7606–7624.

Skolnick, J. F. (1993). "A CAD-based construction simulation tool kit for construction planning." *Proc., 5th Int. Conf. on Computing in Civil and Building Engineering*, ASCE, New York.

Smith, M. (2010). "Dynamic plot research update." *Applied Research Seminar—Bentley Be Together Conference*, Bentley Systems, Inc., Exton, PA.

Thabet, W., Shiratuddin, M., and Bowman, D. (2002). "Virtual reality in construction: A review." *Engineering computational technology*, B. Topping and Z. Bittner, eds., Saxe-Coburg Publications, Edinburgh, UK, 25–52.

Webster, A., Feiner, S., Macintyre, B., Massie, W., and Krueger, T. (1996). "Augmented reality in architectural construction, inspection and renovation." *Proc., 3rd Congress on Computing in Civil Engineering*, ASCE, New York, 913–919.

J. Constr. Eng. Manage., 2011, 137(10): 836-842