Benefits and Barriers of Construction Project Monitoring Using High-Resolution Automated Cameras

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Abstract: A more rapid and widespread use and implementation of technology in construction often fails since its benefits and limitations remain somewhat unclear. Project control is one of the most variable and time consuming task of construction project managers and superintendents and yet continues to be mostly a manual task. Controlling tasks such as tracking and updating project schedules can be assisted through remotely operating technology such as high-resolution cameras that can provide construction management and other users with imaging feeds of job site activities. Although construction cameras have been around for many years, the costs, benefits, and barriers of their use have not been investigated nor quantified in detail. Subsequently, definitions and understanding vary widely, making it difficult for decision makers at the organizational level to decide on the investment in camera technology. This paper reviews the status of high-resolution cameras and their present use in construction. Results of a multiphased survey to industry professionals were collected in order to identify benefits and barriers and develop a cost-benefit model that can be used for implementation technology in construction.

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Introduction

The often complex nature of processes related to construction project delivery creates a significant potential for ever more streamlined processes to reliably deliver high quality and more economical projects. Monitoring and tracking the performance of construction projects plays a major role in achieving this goal, but is often a difficult and complicated task due to the constantly changing job site environment. Although construction-site control in the majority of the construction industry is still mostly a manual task using visual inspection and paper based checklists, project participants such as owners, architects, contractors, and subcontractors increasingly rely on using technologies to update data when collecting site performance information.

Examples of job site technologies that require tagging construction resources, but otherwise operate based on wireless signals, are: global position systems for machine site utilization and position control (Navon 2006), radio frequency identification (RFID) for material locating and tracking on and off-site (Jaselskis and Gao 2003; Song et al. 2006), and ultrawideband for real-time resource tracking and work zone safety (Teizer et al. 2005). Examples of field technologies that do not require placing physical devices on the object, but otherwise depend on optical measurements that require line-of-sight, are: laser rangefinders for machine guidance and position and laser scanners for three-dimensional point cloud measurement (Akinci and Ergin 2008; Bosche and Haas 2007; Lytle and Saidi 2006).

While most of above technologies have proven to require less rework than traditional methods due to automated and increased measurement accuracy and at the same time provide large amount of savings through increased productivity (Hannon 2007), tracking the location and performance of tagged jobsite resources (workforce, equipment, and material) may not be feasible because of several reasons; workforce, for example, may not want to be tracked due to ethical reasons and tracking eventually thousands of items may not offer an economical (implementation cost of technology) or practical (size or type of material to place tag) approach.

Research that uses data from still and video cameras with applications in construction management concentrated mainly on controlling the measurement environment that cameras operate in and processing its visual contents provided. Abeid and Arditi (2002) developed software packages to aid in the efficient storage of images and production of time-lapse movies. Brilakis and Soibelman (2005) focused on searching algorithms for image databases and techniques to convert digital stereo images into readable three-dimensional environments that allow tracking equipment movements (Brilakis et al. 2008). Katz and Saidi (2008) focused on calibrating multiple stereo camera systems. Navon (2006) conducted research in automated measurements of project performance by studying time-lapse photography for productivity purposes. Research that focused on techniques applying augmented reality for positioning and occlusions (Kamat and Martinez 2005) and progress monitoring (Lee et al. 2006) was also performed.

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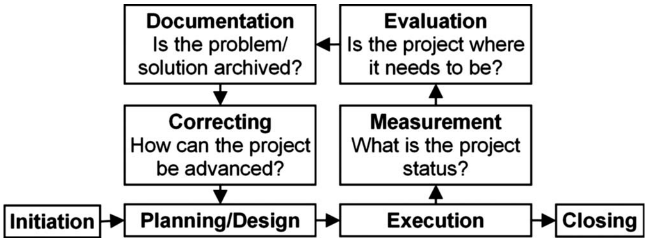

Fig. 1. Typical development phases to control a project or work task

The reader will become familiar with the features and capabilities of camera types used and their application areas in construction. To determine the benefits and barriers of camera technology in each of the identified application areas, a survey instrument and its target group will be introduced, followed by a discussion of the survey results. This paper then identifies construction tasks where automated camera technology is likely to have a high impact to make complex project management tasks more effective and efficient and ultimately justifies its use by yielding a high ROI.

Background on Camera Technology in Construction Management

Construction project management can be defined as the planning, monitoring, and control of all aspects in a construction project and the motivation to achieve the project objectives to the specified cost, schedule, quality, and safety. Monitoring and controlling includes measuring the variables of ongoing project activities against the project plan and project performance baseline defined at the project or work task initiation. Identifying and addressing the risks and issues requires project oversight and the approval of changes to take corrective actions. In any construction project, measurable changes during execution require adjustment in planning or design of execution. The flow diagram in Fig. 1 illustrates where monitoring and controlling technology in a construction project can assist project participants in making better decisions faster during the execution phase of a construction project.

The following sections review how camera technology in the construction industry is used to measure, evaluate, document, and correct projects or work tasks. The reader will learn about hardware and software that ranges from still image to video cameras, from small handheld cameras to commercially used remotely operated cameras for construction purposes only. An introduction to the application areas of automated high-resolution cameras and their cost is given in more detail since they are relevant for the remainder of this paper.

Digital Handheld Camera Photography

For decades it is common practice within the construction industry to use cameras to provide project documentation. Only recently have they become a tool integral to construction management. Over the past 10 years, their use for project organization has become widespread (Hannon 2007). Older methods of using standard film cameras are being replaced by more innovative ways, for example, from print to digital format. Digital images offer a unique capacity to construction by documenting and monitoring project progress and maintaining site condition controls. Thus, cameras that take digital images or videos are part of important tools for managing construction projects (Brilakis 2007). Automated construction cameras, which are remotely controlled and take standardized digital pictures at set intervals, can be a critical tool for real-time data analysis and project documentation.

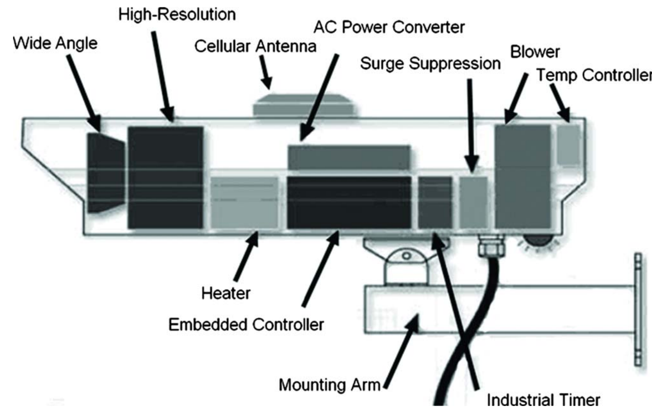

Fig. 2. Typical components of a construction camera

In summary, cameras are largely used in construction since they provide an acceptable return on investment (ROI). Users are any project participant, for example, owners, general contractors and construction managers, and suppliers that are in need for a tool that provides documentation from a subjective perspective at any given moment and means for project evaluation.

High Resolution Digital Cameras in Construction

The growths of information technologies and data storage opportunities in recent years have made image and video data collection and processing available and affordable for many construction companies. This has been manifested in the form of high-resolution automated cameras provided by third party suppliers, as shown in Fig. 2. These types of cameras are used to take static images at set intervals and record moving video of a site and its operations (Hannon 2007). High-resolution cameras were chosen for the scope of this research due to the increasing adoption of the technology and large amount of benefits they produce. Additionally, static cameras rather than video cameras were analyzed due to the low use of video cameras across the construction industry and the significant drawbacks they create, for example, setting high data storage requirements. Cameras are reusable from project to project but require cellular data transmission to transmit images. Once power is supplied to the cameras, they begin taking high-resolution digital pictures ranging from 3–10 Mpixels on set intervals, for example, every 10 min. Yet, the transmission of single images requires a much lower bandwidth connection and thus is preferred over video data transmission. Permanent structures that are placed in line-of-sight of one or more camera(s) call for foresight in camera placement on construction sites.

A summary of the features and capabilities of both the hardware and software of construction cameras is provided in Table 1. A standard screenshot of a typical user interface is shown in Fig. 3. It includes archived calendar, weather, and recorded images that are useful for construction management purposes, such as scheduling and documentation.

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Table 1. Hardware and Software Features and Capabilities of Construction Cameras

Hard/software features	Capabilities
Mounting hardware	Fixed wall or pole mount
High-definition cameras	3–10 Mpixels (between $2,048 \times 1,536$ and $3,600 \times 2,700$ pixels)
Wide angel lens	6.3–63 mm (38–380 mm equivalent in 35-mm photography)
Optical zoom	Up to 50 times
Electric protection	Integrated surge protection, 120 V, and 83 W (solar option)
Data storage	Central server, transmitting automatically 30 min after installation
Weather proofing case	Operates in most weather types
Frame rate	25/30 frames/second (video) or one image/10–15 min (still)
Heat/cold resistance	Operates from $-40°C$ to $56°F$
External recording	DVR, DVD, or film
Image transmission	Dial-up (56 kbs), LAN, WAN, and cellular
Hosted project website	Interactive user interface: Retrieve and categorize project photos
Time-lapse photography	Automatic production and image comparison to detect changes
Weather data and features	Real-time, historically recorded, and autoresponse lens wipers
Camera movement	Digital pan, tilt, zoom (78° of view when static)
User interface	Internet browser (restricted password protected access possible)

Application Areas of Automated High-Resolution Cameras

The following paragraphs detail the application areas that were the focus of this survey.

Project Controls/Management

Having well maintained project controls and management is vital to minimize unnecessary cost on construction projects. Data collected at random time periods and in a nonstandardized fashion is not as helpful for project management as data collected regularly. Standardization will make identifying problems and deviations more obvious. Cameras are useful in monitoring the progress of construction activities, especially from a distance and at a standardized viewpoint. Camera users can log into a web user interface and see if building sections or components have been completed or if rework is needed, allowing for early detection of issues or problems while still performing the same construction tasks. The ability to follow the progress of activities allows users to predict upcoming roadblocks and better plan for the immediate next or following work task(s). Digital images may also reduce time needed for inspection by allowing this task to be done remotely (Brilakis 2007). Seeing real-time weather can help project managers to plan and schedule accordingly.

Fig. 3. Typical camera user interface

Communication and Documentation

One of the most significant problems in managing construction projects arises in delays resulting from poor communication or documentation. Cameras can help reduce problems ahead of time. A large cost is often encountered with regard to travel time to and from a construction site by company executives or project managers. The tangible impacts of travel are discussed later but intangible benefits exist as well. When meetings are held, meeting participants can instantly learn about the project status thus eliminating waiting periods to retrieve information. The need for short answer e-mails or telephone calls is reduced as well for questions involving project progress or site conditions. Site visits can thus be optimized and condensed.

Another important documentation advantage stems from the standardization of site pictures. Since a camera is mounted in a single spot, all pictures are taken from the same vantage point, thus reducing confusion that may arise from multiple perspectives. A standard time between each photograph taken allows users to know what time scale they are looking at and can accurately gauge progress. This reduces time needed for field employees to venture into the site to take pictures. The standardization of pictures allows for time-lapse photography presentations to be made which can be used for postproject analysis or marketing purposes. Unlimited off-site data storage allows the project to be documented from start to finish. The ease of many website features allow these pictures to be instantly categorized and viewed in an organized fashion by date and time. Having these unlimited photos makes documentation easier, by provided easy-to-access photos for as-builts and progress reports. Additionally, some written documentation may become unnecessary because all data are stored in pictures, for example, daily weather conditions. Pictures can be used for legal purposes such as dispute avoidance and litigation, possibly saving millions of dollars in expenses, time, and relationships.

Resource Management

Cameras are considered "semiautomated" in the sense that the physical task of tracking resources in a sequence of images is performed by the user or image processing algorithms. Using cameras for tracking workforce, materials and inventory, and equipment across a site can reveal a number of important imbalances for a project. Time wasting, task completion time, and inefficiencies can be recognized and adjusted for better optimization of project resources (Senior and Swanberg-Mee 1997). Inventory and control of large equipment and bulk materials can be quickly located if they are in the view of the camera. Presence and location of project workforce personnel can effortlessly be identified as well.

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Travel and Safety

Travel can become a large cost for project managers, executives, and owners if they work directly on project sites which can be located hundreds of miles away from their main office. Instant access to a website that hosts an image library of the project can reduce the frequency of trips, saves gas expenses, and wear-and-tear on company vehicles. Should travel be required, the traveler can be already informed of the site condition before departing. Cameras can become a useful tool in scheduling site visits, since managers can judge when certain stages may be completed or needing input, and plan their trips accordingly.

Safety is an important issue that cameras help with. Jobsite hazards can be recognized remotely and the safety staff on duty can be informed to remove the hazard. Improper methods being used on-site can be identified and stopped if captured by the cameras. Theft and vandalism to site equipment and materials may also be reduced by the presence of protective camera housing alone. Cameras may catch thieves in the act, but due to the intervals between pictures, it is less likely to occur. Their presence alone provides a deterrent from for thieves to enter a site.

Costs of Automated High-Resolution Cameras

Costs for cameras include initial purchase, service fees, installation, maintenance, training for employees, and any expenses for troubleshooting during the operational time. A baseline cost in 2008 for purchasing construction cameras is around $2,000–$12,000 annually depending on the model and capabilities needed. There is typically a one time hardware cost and then either recurring service fee or running cost. Due to the harsh environment construction cameras operate in, warranties are given for a specified amount of time in case of damage. Monthly service fees for access, operation, and technical support usually are between $200 and $600.

Research Objective and Methodology

A main issue regarding the widespread implementation of construction cameras is that benefits and barriers are not fully understood and costs are not sufficiently quantified. A study conducted by the National Highway Cooperative Research Program states that the largest barrier for successful implementation of camera technology is “lack of understanding/knowledge of the potential applications of jobsite images and video” (Hannon 2007). The main objective of the study was to identify the potential applications, and furthermore to determine the benefits and barriers that exist when using high-resolution cameras.

Based on the performed literature review, preliminary discussions with several camera providers, and phone interviews with a handful of experienced camera users, a survey instrument was developed and distributed to a large number of existing camera users of construction camera suppliers. 142 individuals answered. Although the exact number of contacted survey participants is kept confidential (to researchers and camera suppliers), the performed data analysis is not significant. The data analysis performed in this study, however, includes a total number of responses that is up to eight times larger than any of the previously conducted research studies, for example, Hannon (2007), and involves a variety of construction project types that go beyond infrastructure construction only. This survey was based on many different project types, sizes, budgets, and lengths and thus was not skewed in any one direction.

Survey and Results

The following sections present results obtained from questions of the survey. The results will be presented in the order that they were asked.

Personal Background

“Section 1” asked for personal and company background information of the survey respondent. 142 survey participants belonged to 114 different organizations. For this question multiple answers were allowed, resulting in 166 returned answers. The majority of respondents were project managers (51 responses, 31% of all 166 answers), owners (32, 19%), contractors (23, 14%), and developers (16, 10%), making up 74% of all respondents. Each of these positions usually has higher project responsibility and thus control and monitors the progress of projects more frequently than other groups. The remaining 26% were spread among superintendents (12, 7%), information technology specialists (12, 7%), consultants (6, 4%), and others (14, 8%). Suppliers were not among the respondents, since they more or less rely on decisions made by project management or contractor before doing any of their tasks. These numbers indicate, however, almost all personnel involved in the surveyed construction project use cameras to some extent.

Project Background

“Section 2” of the survey asked for project background information (physical size of project, number of stories/floors, and project budget) that the respondent is using camera(s) on. An equal percentage of projects (34%) were found for sites of 1–5 acres and 5–25 acres. As previously mentioned, the use of cameras seems to be less useful in projects that cover very large (above 50 acres) or very small areas (less than one acre).

The largest percentage of projects was commercial (45% of all responses), followed by industrial (13%), heavy civil (8%), government (5%), residential (8%), other (8%), healthcare (5%), hotel (4%), mixed use (3%), and demolition (1%) jobs. Commercial projects often have strict delivery timeframes as owners rely heavily on the income generated from stores that open on time. Early or on time openings of stores are important business factors. Cameras that allow tracking the progress or delays visually can deliver early warning indicators of potential delays. The savings that cameras generate for commercial builders are likely to be higher than in other types of construction projects. A later review of the use in heavy civil projects indicated that infrastructure monitoring using camera mostly concentrates on large vertical structures such as bridges or dams. The current uses for cameras in heavy civil projects are thus on isolated project spots and not on segments that stretch over multiple miles, for example, road construction.

About half of the projects were 2–10 stories in height, with about 40% being a 1-story facility. Again, height is a limiting factor as larger buildings are more difficult to monitor than smaller buildings. 13% were greater than 10 stories in height.

The majority of projects had high budgets (greater than $25 million, 56% of all responses). Project with higher budgets eventually allow easier allocation of money to purchasing and operation of construction cameras. Projects with budgets less than $1 million had few respondents.

Overall, the respondents prioritize the usefulness of a single camera to be significantly higher on small to medium-sized con-

J. Constr. Eng. Manage., 2010, 136(6): 632-640

struction sites. Large construction sites may require multiple cameras. Smaller projects, however, that cost not more than $400,000 and last less than 1 year could have up to 1% of the total project budget allocated to camera technology. This was calculated using the lower end of the camera price range of a $2,000 camera cost and a $200 monthly fee. Provided additional feedback by respondents stated that other monitoring solutions than camera technology comes generally at even larger cost.

Respondents were then asked to estimate the duration of their project. Projects ranging from 6 to 24 months were the majority, with 88 of all respondents. This is a typical duration range for commercial or residential projects. With the majority of respondents in this range, it was difficult for the respondents to asses long-term benefits associated with the use of cameras. Only 23 of the projects were longer than 24 months and thus were underrepresented compared to jobs with shorter time frames.

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Task Impact

"Sections 3–6" of the survey obtained ordinal data. All answers were provided on a 1–5 scale, with 1 being the least important and 5 being the most. Ranked in the order of the highest average score, the top 5 work tasks that respondents consider having the highest:

(1) Impact on a project level (general, not camera specific): External communication (3.9), jobsite issues/roadblocks (3.9), task completion (3.8), inside company communication (3.8), and scheduling (3.8). All of these top tasks are categorized under the sections "communication/documentation" and "project management and controls." All tasks under the section "resource management" had the lowest impact rating, showing that tracking construction resources (workforce, equipment, and materials) is less important for the survey participants;

(2) Potential for improvement (general, not camera specific): A correlation analysis was done between these tasks with high impact and high potential for improvement, as many of these tasks already appeared on the list of highest impact. Results considered to be well correlated have a value of 0.5 or greater. External communication (3.6 average rating/0.69 correlation score), scheduling site visits (3.5/0.72), and internal communication (3.4/0.52) all correlated well while jobsite issues/roadblocks was low (3.5/.48). "resource management" tasks were again ranked the lowest rated tasks for potential improvement;

(3) Expectation to reduce work tasks using cameras (when considering cameras, but before having them applied): four of the top 5 were categorized under section "security and travel" since tangible aspects are associated with travel and the savings that can be generated in gas, vehicle wear-and-tear, or flight fairs. The average rating was: project status before site visits, task completion, avoidance and theft/vandalism, scheduling site visit(s) (each 3.3) and safety enforcement (3.1). Respondents most likely were able to directly associate numbers with these tasks and then associate values for how they can be reduced. Task completion had high potential for reduction by cameras and was also in the top 5 for highest impact in (1), though the correlation value between the two was low (0.42). Again, tasks in section "Resource management" were ranked lowest; and

(4) Measured impact on work tasks (when cameras were applied): Respondents gave average rating to project status before site visit(s) (3.4), scheduling site visit(s) (3.4), external communication (3.3), inside company communication (3.2), and task completion (3.2). Both internal and external communications as well as task completion were also found among tasks with high impact in (1), but each had low correlation when considering (4). Knowing project status before site visits had high correlation (0.68).

Project-Type Breakdowns

An important research task was to identify which work tasks cameras impact the most and least when considering project specific types, such as duration, budget, stories/floors, and acreage. This analysis may help camera users identify in which areas they can expect considerable benefits and in which they might not yield sufficient ROI when using cameras.

Duration

Respondents believed that cameras benefit projects at any given project duration the most when the tasks are: external and internal communication, scheduling site visits, and knowing the project status. Cameras become beneficial to some users when used as safety enforcement tool for longer termed projects. Using cameras for resource management tasks offered the least ROI. Survey respondents might see little impact of using cameras in manually tracking resources in longer termed projects. A potential solution could be automating the tracking of resources using camera images.

Budget

In smaller sized project budgets, cameras provided the most benefits when providing documentation and communication of deliverables. Cameras were most beneficial in use in projects ranging from $26–$50 million when supporting internal communication and knowing the project status before visiting the site. Projects with higher budgets (>$26 million) found higher value for using cameras in lawsuit and dispute avoidance.

Stories/Floors

Based on the height of the project, cameras show a high return when being used in smaller sized projects (1–10 floors) and see large impact for scheduling site trips. It is likely that project managers are in charge of few to many smaller projects at the same time, thus benefiting the most of using cameras to oversee several construction sites at the same time with less effort. Taller projects use cameras mostly for external communication and marketing. Cameras impact resource management the least, especially with regard to tracking materials and inventory.

Acreage

Cameras have the biggest impact on smaller projects (1–5 acres) and mostly used for internal communication and scheduling purposes, while cameras on larger projects (>5 acres) have impact on external communication. Larger projects are often more complex and thus have more people outside of an organization involved who need to share information. The lowest impacted task was for resource tracking.

Observed Benefits

An important objective of this survey was to measure if the envisioned benefits before applying camera technology in construc-

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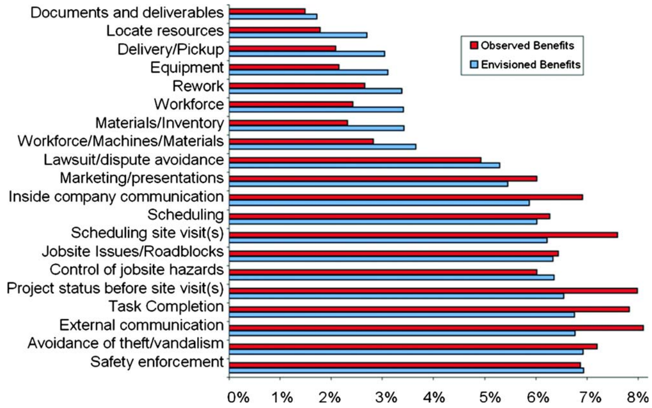

Fig. 4. Observed versus envisioned benefits

tion later meet the observed benefits once camera technology has been applied. If a difference between expectations and reality exists, corrective actions may be taken.

The first step is to determine the *envisioned benefits*. The average ordinal values of survey questions for questions (A), (B), and (C) are multiplied, weighted, and then ranked. Each weighted rating takes into account task impact, potential for improvement, and potential improvement from camera use. The formula is

$$\text{Envisioned Benefits} = [(A)(B)(C)]/[\text{Total Sum of values of all responses}]$$

where A=general task impact on project; B=general potential for improvement; C=envisioned potential on improvement on task using cameras; and D=impact of cameras on task observed.

The second step includes the calculation of the *observed benefits* by multiplying the envisioned benefits with the score of survey question (D). The large number of responses (144) from different positions in 114 companies ensured objective and reliable data from actual camera users. Similar to the envisioned benefits, the observed benefits are weighted and ranked

$$\text{Observed Benefits} = [(A)(B)(C)(D)]/[\text{Total sum of values of all responses}]$$

A chart displaying the weighted ratings of each task for both envisioned and observed benefits is illustrated in Fig. 4. These weights can further be used to develop a toolkit for further cost-benefit analysis for construction cameras as explained later in this section.

Including the observed benefits into the calculation changes the result of the rankings. Based on the comparison of observed versus envisioned benefits, a number of work tasks exceed the envisioned potential of the respondents [these are: scheduling site visit(s); project status before site visit(s); external communication; internal communication; and task completion]. Each exceeded their expected value by at least one full point.

As a result, survey respondents overestimated the performance of camera technology for work tasks that relate to documentation and communication of deliverables, identifying rework, and tracking construction resources such as workforce, equipment, and materials, as well as logistical efforts for delivery and pickup.

Tasks where expectations are not being met fall predominantly under the resource management category. Respondents believe that cameras should aid more in tracking resources than actually happens in reality. The task of tracking of inventory/materials had the largest disparity. There are a number of reasons why monitoring these tasks with cameras may not be a successful task for high-resolution automated cameras. Resource management based on single or multiple cameras that are not working in real-time (at least 1 Hz) and are eventually blocked by line-of-sight requirements may under perform to existing approaches. The same reasoning can be applied to safety enforcement and hazard control, and lawsuit/dispute avoidance. While it is possible to identify areas of dispute, the cause of the dispute may not always be recorded.

Benefits and Barriers in Current and Future Uses

In "Section 7" respondents were asked to identify specific areas in construction where cameras are believed to have the most impact. By picking the top five work tasks from a given list that cameras can help with, the five most frequently picked work tasks were (in order): foundations (16%), grading/earthwork (15%), steel (13%), concrete (13%), site preparation (12%), demolition, roofing, and finishing (each 6%), facilities management/landscaping (5%), front-end planning (4%), procurement (3%), and interior (1%). The analysis of this question demonstrates that construction cameras are primarily applied successfully earlier rather than later in most projects. This is mostly due to the fact that once walls are erected or any other obstructions exist on job sites, a camera may lose somewhat its effectiveness since the line-of-sight no longer exists. In such a case, many camera users remount the camera to other locations, for example, for interior work and finishing of buildings. Additionally, proper planning of camera location is required to avoid relocation efforts.

Respondents were then asked to pick the top barriers for further implementation of construction cameras. This section was designed to identify areas where problems exist and reasons why cameras are not being (more frequently) used by their organization. Presented with a list of 11 choices and asked to pick three choices, 46% of all survey respondents identified price as major barrier for more widespread use of camera technology in construction. Either camera technology has not been considered "in the budget" or the "owner won't pay for it." It is believed that a rigorous cost-benefit analysis that quantifies cost and benefits can help solve this problem. The next highest ranked obstacles in using cameras were camera(s) not being a top priority (12%), concerns about liability (8%), or lacking support from executive management (5%), client (4%), or project manager (3%), and other reasons (8%). 10% had misunderstanding of what camera technology does.

Respondents were also asked what pains cameras can help with. On a list of eight choices and asked to choose the top 3, the top choices were "knowing what is going on at the jobsite" at 29% (of all respondents) and "long-term project documentation" at 21%. These answers are consistent with the higher ranked tasks when asked about impact in Sections 3–6. Supporting marketing efforts was listed third at 16%. The ability to automatically create time-lapse movies (using a sequence of project images) is considered a very helpful tool attracting and promoting business. Other votes where communication with external team members (13% of all respondents), documentation to help resolve dispute resolution and claims (9%), general accountability (6%), coordination with internal members (3%), and others (2%).

Return for Projects

Respondents in "Section 8—Return for Project Area" were asked to quantify the percent of budget, dollar amount of budget, and

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days of the schedule that camera technology helped to save in each of the four survey categories (Sections 3–6). For these questions, 14 respondents were able to quantify values.

Although many survey respondents were able to qualitatively describe the benefits of using camera technology, they were unable to quantify an absolute ROI. Several reasons can cause this lack of sufficient data. First, data are not collected or available in the detail needed to accurately describe monetary or schedule benefits. Decision makers have not recorded detailed data since their job priorities lay in different areas (managing day to day operations, etc.). Second, the data that needs to be collected is unknown or difficult to obtain or quantify. Additionally, the relatively low cost of camera technology (a few thousand dollars) may prohibit a serious research effort. Most construction companies have not attempted this kind of analysis of time and money in regards to how cameras are helping them. Tracking this information would be a useful but significant and time consuming undertaking. Future research should use a toolkit to analyze a case study of camera use on construction projects in a detailed and long-term fashion.

Camera savings over a longer time frame can be analyzed for several projects using the weighted values found in this research (see Fig. 4). Comparisons need to be made for each task in year X and subsequent years $X+1$. Year X would be the control project (not using automated cameras) while year $X+1$ would be the same or a similar project that uses cameras. Data would need to be recorded both on a cost basis (dollars) and a schedule basis (time) involved in each task. Project managers, for example, would need to document their schedule throughout the observation period and eventually record detailed schedule data on deviations. Values could then be compared, showing possible savings in time and money. This method can then be applied for all tasks and multiplied by their given weight factors in order to normalize the task appropriately. The formula is as follows for a typical project

$$\begin{aligned}
\text{Savings due to cameras} \\
&= (\$\Delta \text{ in Task 1 from } X \text{ to } X+1) \\
&\quad \times (\text{Task 1 Weight factor}) \\
&\quad + (\$\Delta \text{ in Task 2 from } X \text{ to } X+1) \\
&\quad \times (\text{Task 2 Weight factor} + \ldots + (\$\Delta \text{ in Task } N) \\
&\quad \times (\text{Task } N \text{ Weight factor})
\end{aligned}$$

If this analysis was implemented across a number of projects, one could begin to see value savings, for example, documenting savings on external communication due to cameras. In Year 1, values could be tracked for number of hours spent on calls with outside stakeholders and cost of shipping/producing paper materials. A direct comparison could then be made with data from Years 1 and 2, revealing direct savings when done across multiple projects. Using the weighted values of the observed benefits, the difference in dollar savings from Year 1 and Year 2 would be multiplied by this factor. If the savings were found to be $5,000 between the two years for these tasks, this value would need to be properly weighted in order to quantify the savings achieved from camera use. As shown in Fig. 4, for external communication, the weight factor found in the survey was 8.11%. Multiplying ($5.000)(0.0811) yields $405.5 yearly savings for external communication due to construction cameras

$$\text{Savings due to cameras} = (\$5{,}000)(0.0811) = \$405.50$$

Fig. 5. Bridge demolition by daily progress (left) and pavement process by the minute (right)

Looking at an individual project as an example can help illustrate quantitative savings, created by cameras. For this research, a construction camera was placed overlooking the demolition and construction of the 14 Street Bridge in Atlanta, Georgia. Site personnel, company executives, and others involved in the project had access to the camera's web interface and accessed the photos regularly. A daily work log was created of site activity purely from the images created by the cameras. From interviews with the users, benefits were determined and analyzed. While this project did not record detailed information on their camera use, benefits were still observed, both qualitatively and quantitatively.

It is not uncommon for project managers to be based out of locations far from a project site. The distance requires frequent site visits by a manager in order to assess conditions of the site and make decisions to move the project along. For the 14 Street Bridge Project, the headquarters of the general contractor was in a suburb of Atlanta. Assuming a manager is billed at $80/h and completes a weekly site visit in three hours, traveling 20 km for a round trip, the cost for this task can be calculated using the IRS 2009 standard of 35 cents/vehicle kilometer traveled. The 12 h/month equal to $960. Travel alone would cost $75.75. In summary a cost of $1,035.75/month occurs. A significant part of this cost may be avoided if the project manager is able to view the bridge using the cameras instead of a site visit that was planned. If three trips are avoided by a project manager that is equal to roughly the cost of a camera unit (approximately $3,000). In these cases, the initial invested cost of the camera is paid back to the purchasing company.

With more detailed studies, savings due to material tracking can be quantified also. Fig. 5 shows selected images from camera images of the placement and compaction of an asphalt layer for Interstate 75/85 over a 2-day period. This task lasted 15 h. Project managers can use cameras to quantify costs for this timeframe by visualizing productivity of the operation throughout the days. Wasted or unnecessary downtime can be identified and the processes adjusted to be scheduled properly, reducing the number of hours worked and saving money. Six workers can be seen completing the paving task in the first image when viewing the task in the interface. Using the Engineering News Record labor cost of $32.74/h (The McGraw-Hill Companies, Inc. 2008), the total

J. Constr. Eng. Manage., 2010, 136(6): 632-640

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labor cost is estimated at $2,946.60. Any reduction of time or process (i.e., unnecessary worker identified and obstructions) would create savings for the project. Identifying one unnecessary worker would save $491 in labor cost for this task alone. This labor cost could then be applied to another aspect of the project for tasks that are behind schedule or require more manpower. Project management can see how much asphalt has been placed and estimate time to competition. The number of asphalt trucks hauled for the job was recorded as well and can be useful for quantity tracking and verification.

Qualitative impact of the cameras was generated through increased public awareness of the project. Contractor and Georgia Department of Transportation (GDOT) received positive publicity in an article published in the Atlanta-Journal Constitution (Hart 2008) that informed readers about the camera accessibility and linked them to the website interface. Because of this, the public could be just as up to date as project staff. Prior to this article, the average users per day were approximately 20 people. The following week had an average of 1,337 users per day, far greater than the initial average. For the remaining weeks of the project, the number of users averaged out to approximately 225 users per day and remained in this range for many weeks.

Demolition of the bridge was one of the most involved and most dangerous tasks for this project. Fig. 5 shows the sequences in the progress of the bridge demolition recorded by the camera. These images allow for future planning and training of bridge removal techniques. Officials at GDOT stated they would use these images in the future as a teaching device for new engineers, demonstrating the proper procedure for bridge construction. By creating a log of the events in the camera, off-site user can compare the planned schedule to as-builts. For many large tasks such as bridge demolition, detailed schedules are not created, rather a generalized process is listed and many of the more detailed tasks are left to the discretion of superintendents and managers. The original demolition schedule showed five unique tasks, whereas 15 tasks were identified and recorded in the daily camera logs. This allows for better planning on future projects by having a much more detailed idea of what equipment is involved, how many hours workers are present, and the tasks that need to be completed.

There are a number of prospects for continued development and integration of cameras with emerging technologies in order to establish a data-rich construction site. Research on extracting data from images produced by automated construction cameras for object recognition is currently being conducted. Using two-dimensional images, algorithms being developed recognize objects on perceived three-dimensional (3D) distance (Brilakis et al. 2008). Further optimization for data transfer and site communication and object tracking is being developed as well (Brilakis and Soibelman 2005). Research into augmented realities to facilitate in decision-making processes is being conducted (Lee et al. 2006). This research is also focusing on automated object recognition and camera matching to compare with as-planned models. All of these developing technologies will aid in resource tracking and allow a more quantitative value to be applied to construction savings. Currently, there is research into automatic identification of inventory and progress tracking in relation to scheduling (Navon 2006). Development of automated identification algorithms will be greatly aided with the help of the standardized and detailed images created by construction cameras. Automating the organization of files created by imaging technologies into a readable database is important to manage the large volume of files created (Caldas and Soibelman 2003). Further integration with Building Information Modeling (BIM) software and RFID tracking technology will need to be investigated as well, possibly linking an as-built BIM model with actual as-built images and virtual reality (VR) displays (Woodward et al. 2007). All of these developing technologies will aid in resource tracking and allow a more quantitative value to be applied to construction savings. Future research into construction progress monitoring is currently underway using 3D range point clouds produce by laser scanners light detection and ranging (LIDAR) to record site activities.

Conclusions

This paper presented the benefits and barriers associated with the use of high-resolution construction cameras for construction management. It recognized tasks where cameras have the greatest impact and areas for improvement. The benefits of construction cameras have been consistently found to exceed their expected impacts and a large potential exists for improving their use, for example, in resource management. Benefits for tasks were found to differ for certain project types (e.g., high budget and large area) and knowing project limitations are essential to achieve the maximum potential offered by cameras. Determining quantitative savings was a difficult task, as companies do not record needed data and requires a more in-depth analysis of individual projects. While researchers were unable to determine quantitative savings, qualitative results show that cameras are having a significant impact on projects. From interviews with users and data collected from surveys, the majority of respondents supported use of cameras and express desire to continue their use on future projects. The rapid adoption of this technology by construction companies tends to support this claim. Further long-term research will need to address quantitative savings. Developing metrics and collecting data in long-term studies can be the next step in research rapid adoption of technology in construction.

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