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Review

Data acquisition technologies for construction progress tracking

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ABSTRACT

Falling behind schedule and having discrepancy between the as-built and designed baseline plans are unfavourable events that often occur in construction projects. Hence, real-time progress tracking and monitoring of construction components remains a vital part of project management and is critical to achieving project objectives. Yet manual approaches for progress tracking lack the required accuracy for integration with other construction interfaces. Conversely, automatic progress tracking can result in timely detection of potential time delays and construction discrepancies and directly supports project control decision-making. This paper examines different technologies of automated and electronic construction data collection. In particular, enhanced IT, geo-spatial, 3D imaging, and augmented reality technologies have recently achieved significant advances in this field. Each of these technologies is discussed herein in terms of its advantages and limitations. Comparisons of such technologies to identify various trends concerning their applicability in real-time data acquisition of construction projects are made, along with recommendations for their suitability in different projects. This should assist construction stakeholders in choosing appropriate tools to enhance time and cost effectiveness and achieve better control and more effective decisions during construction. It is also hoped that this review will stimulate further research on and development of these technologies.

Contents

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1. Introduction

On-time actions are necessary for a construction management system to flow forward and be operative and productive. The forward flow of actions requires a feedback signal to track the status of the system each time it is maintained and assessed [1]. Site information can provide feedback for various purposes, including progress measurement [1,2], equipment and material tracking [3,4], safety planning [5], and productivity tracking [6]. Construction site information has generally been organized into three main categories: finance, quality, and progress [7]. One example of necessary action in construction management systems is to mitigate defects and imperfections that could have time and cost consequences. Late detection of such defects is problematic and allows only minimal time to mitigate the associated detrimental cost and schedule implications [8,12]. According to Nahangi and Haas [13], about 10% of construction budgets associated with industrial projects are attributable to rework due to late detection of deficiencies in construction sites. Approximately 50% of the associated rework cost of defective components arise from human errors and 10% is attributable to material defects.

Early assessment of the as-built status during construction is also essential for effective and efficient corrective action planning. NYSOT [18] summarized the characteristics of efficient methods of progress and performance measurement as follows: measurable, reliable, consistent, understandable, verifiable, timely, and unaffected by external influences, cost-effective, useful, and suitable for effective decisions. Currently, there is a lack of systematic evaluation and monitoring in construction projects. Conventional progress tracking methods depend on extensive manual interaction, which is inaccurate, time-consuming, and labour-intensive even for small projects. Such an approach has been recognized as one of the major problems that cause project delays and cost overruns [14]. It also lack electronic data integration between different interfaces.

Progress monitoring activities are recently becoming more automated and integrated. Automated approaches have emerged as advantageous tools for quality management and as-built tracking purposes [9, 16,17] and is also important in improving productivity, which is paramount in construction management systems [10]. However, the vision for the future of the construction industry is of a highly automated project management environment integrated across all phases of the project lifecycle. This integrated environment will enable all project partners and project functions to instantly connect their operations and systems. Interconnected, automated systems, processes, and equipment will reduce the time and cost of planning, design, and construction [4].

1.1. Challenges with construction progress tracking

Most of the research efforts in the field of project control still focus on the development of cost control models where the earned value concept has proven to be the most reliable tool for tracking and control of construction projects [11]. A critical part of project control is progress tracking or as-built sensing. Construction progress tracking, however, is not a simple task and is associated with many challenges because construction projects involve large amounts of information related to a variety of functions, such as scheduling, construction methods, cost management, resources, quality control, and change order management. In addition, information is provided by a number of different sources and is presented in a wide variety of forms. Furthermore, it may be difficult to track and record changes based on conscious decisions that are made during construction. It can even be more difficult to adequately track and record deviations that are more subtle not emanating from conscious decisions (e.g., deviations due to poor workmanship) [13].

1.2. Research on automated progress tracking

A number of advanced automated data collection technologies are used today for real-time on-site progress tracking. Substantial research on automated project progress tracking has aimed at automating the measurement of physical quantities in-place using spatial sensing technologies, for example for earth moving, structural erection, and masonry work. Information technology tools have been supported by a number of research studies to improve communication on construction sites and enable daily automated progress tracking of construction activities. Three-dimensional (3D) sensing technologies are being widely investigated by several researchers for providing real-time 3D as-built information and comparing with the design information embedded in building information models (BIM) [19]. Augmented Reality can be applied to address a plethora of problems throughout a construction project's lifecycle. It has been impacting the mobile communications industry by providing a radical shift in human–computer interaction and has been receiving increasing attention of researchers and practitioners alike. Adopting such a variety of automated progress tracking technologies can provide decision makers with timely progress details to follow the project progress more effectively, facilitating schedule updates and accurate schedule forensics, delay analysis, and planning of appropriate corrective actions.

2. Research objectives

The aim of this study is to explore the automated progress and performance measurement technologies that are currently in use by the construction industry. To achieve this goal, the following sub-objectives are outlined: (1) delineate recent research efforts in this field; (2) study the characteristics of the different automated data acquisition technologies; (3) determine the challenges associated with these technologies and their potential applications with particular focus on their capabilities and limitations; (4) survey related commercial software systems; (5) provide the construction industry with guidance to make more informed decisions to select suitable technologies for their specific projects; and (6) outline the technology gaps for future research.

3. Research methodology

The methodology adopted for the achievement of the above objectives is as follows: (1) collect a wide range of recent research on automated progress tracking; (2) examine the different automated progress tracking methods; (3) cluster the methods into different technologies based on predefined perspectives; (3) explore the benefits of applying each technology and its limitations; (4) evaluate the significant research progress on the different methods; (5) compare the technologies to identify key application areas; (6) examine the developed integrations between different technologies; (7) explore the commercial software for data acquisition technologies; (8) recommend guidelines to the construction community for the selection of appropriate technologies; and (9) address challenges in the technology gaps that need further research and development.

4. Review of automated technologies for data collection

4.1. Data sources and procedures to extract articles

This review is based on carefully selected articles retrieved from eight diverse academic journals within the domain of project construction and management in an attempt to capture recent and relevant developments. Leading research conferences were also considered in a similar manner. The articles were searched using some key phrases such as "data acquisition" and "progress tracking". This process initially identified 176 papers. The articles were examined to extract their main findings and emphasis. Articles which primarily did focus on automation of data acquisition were discarded. Accordingly, the final survey qualitatively aggregates the results of a selected set consisting of 134 research studies, among which 70% were published over the recent five years. The selected articles were evaluated to be defined and classified in relevant categories. Table 1 lists the searched journals and conferences along with the numbers of associated papers identified.

4.2. Categorizing data acquisition technologies

As a means of comprehensively determining the knowledge gaps, the relevant literature is investigated from three perspectives, namely: (i) collecting as-built data; (ii) organizing as-built data: and (iii) analyzing as-built data. On the project process continuum of collecting, organizing and analyzing as-built data, we have found these technologies to predominantly fit in the roles illustrated in Fig. 1. Based on the different applications of these technologies as defined by their original authors, it was decided to classify the relevant technologies into four categories as shown in Fig. 2. For clarity, we present these groups separately. Yet, there is substantial overlap in their applications. For example, global positioning systems (GPS) and photo/video-grammetry could be categorized under Geo-spatial techniques and 3D Sensing technologies. However, each category is investigated in the present study to frame its knowledge gaps.

Table 1
List of searched journals and conferences and associated numbers of articles.

Journal/conference	Number of papers
Automation in Construction	39
Advanced Engineering Informatics	13
Computing in Civil Engineering	12
Construction Engineering and Management	10
Information Technology in Construction	6
Computer-Aided Civil and Infrastructure Engineering	4
International Journal of Project Management	3
Construction and Architectural Management	3
Construction Management and Economics	2
Miscellaneous Journals	15
Construction Research Congress	8
ISARC/CSCE/IEEE…	7
Thesis	4
Online Web Page	8
Total	134

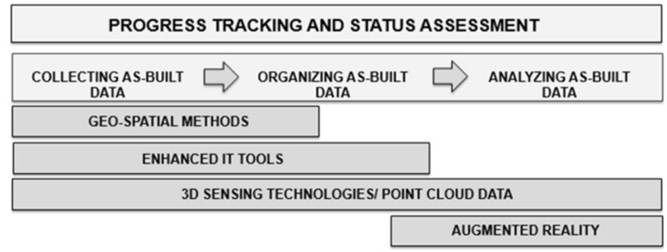

Fig. 1. Categorization methodology for data acquisition technologies.

5. Enhanced IT technologies

In view of the challenges related to site information tracking, several researchers have examined the use of various IT-based communication tools [20–22]. This includes multimedia tools (e.g. digital camera and video), email services, voice-based tools, short message services (SMS), and handheld computing tools. Such low-cost tools have great potential to control project delays and cost overruns through improvement of communication [22]. A summary of the advantages and limitations of common tools in this category is shown in Table 2 and is discussed below.

5.1. Multimedia tools

Using multimedia such as digital photographs, videos, and audio recordings as attachments to schedule activities has been proposed since 1990 to improve data collection for delay analysis purposes [23]. Multimedia tools are important because they enable information to be visualized and problem areas to be highlighted [24]. Moreover, they could be employed for quality control. For instance, Abudayyeh [25] developed an information management model where a video camera and a microphone are attached for recording events related to activity progress. The proposed model linked the project schedule with the recorded timely multimedia field data. Abeid and Arditi [26] developed *PHOTO-NET II*, a real-time monitoring system that links time-lapse images of construction activities with the critical path method (CPM) and progress control techniques. The proposed system can acquire, store, and display digital images in sequence to create a movie recording of construction activities. Leung et al. [27] introduced a web-based

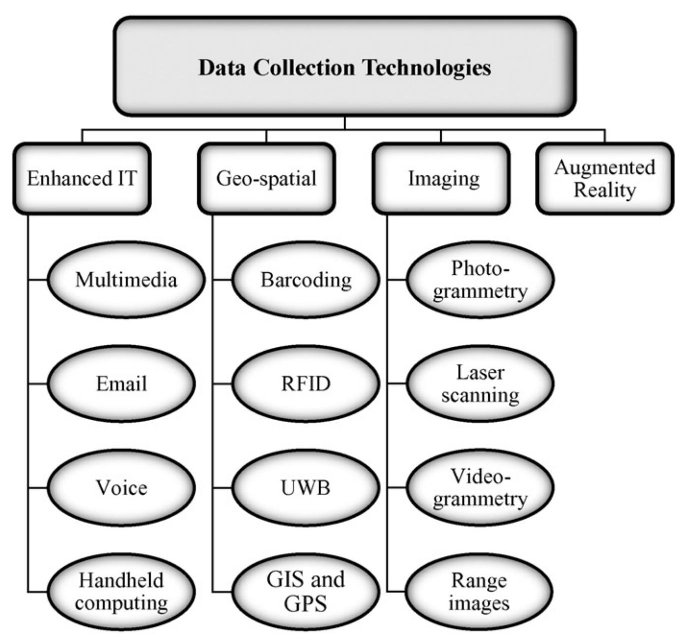

Fig. 2. Technologies for construction site data acquisition.

Table 2
Advantages and limitations of IT tools for data acquisition.

Technology	Multimedia	Email	IVR	Handheld Computing
Advantages	1)- Visual data recording 2)- Beneficial for quality control purpose	1)- Users able to review questions and answers 2)- Enough time for users to review answers before responding 3)- Users able to attach photos, videos, and other documents	1)- Quick responses 2)- Immediate forwarding of urgent information 3)- Time-saving, efficiency, and convenience 4)- Recorded messages that can document site events	1)- Small size 2)- Superior mobility 3)- Can be integrated with other technologies such as RFID readers 4)- Can have all features
Disadvantages	1)- Requires much time and effort from users 2)- Probably using manual process	1)- Possibility some users not having access to the internet 2)- Difficulty in replying from cellular phones	1)- User confusion about long surveys and multiple choices 2)- Not enough time to think and respond 3)- Difficulty backing up to correct previous answers 4)- User error in the selection of responses	1)- High cost 2)- Requires special apps to be developed 3)- Limited portability

collaboration platform that utilized network cameras to monitor the progress and quality of construction works in real-time and share the information with authenticated parties. Schexnayder et al. [28] used a fixed webcam on a five-story building construction site to assist the construction management team in acting proactively, improving communication between site management and workers, and improving safety. Jaselskis et al. [29] utilized live video and audio from mobile cameras for remotely monitoring a variety of construction projects without a physical site presence. The approach is promising as an effective management tool and needs further dedicated research.

5.2. Email-services

E-mail has become a common form of data collection, reciprocity, and participation. Ahsan et al. [30] studied the storage of communications produced during a project life and concluded that the importance of email usage increased in communicating and storing major information. Another study by Elamin et al. [31] used different criteria in evaluating project communication tools and categorized email as an effective technique to track, store, and extract progress data. Hegazy and Abdel-Monem [32] proposed a low-cost framework that utilizes email to develop a project-wide system for progress tracking. The proposed framework integrates three main components: (i) email forms to collect as-built information; (ii) customized scheduling application to allow activities to be aware of their planned progress and automatically initiate communications to request updates on actual progress; and (iii) customized email tool that stores the activities' communication parties. Based on the email responses of site personnel, the system automatically updates the schedule and generates an as-built full schedule report with all communications stored at the activity dates on a bar chart. Hegazy et al. [33] later extended the system to apply it to projects that involve linear and/or repetitive activities and where a construction sequence or delivery approach is changed.

5.3. Voice-based tools

Voice-based IT tools have improved substantially over the past few years. Telephone systems can currently operate using a Voice over Internet Protocol (VoIP), or internet telephony. For example, Sunkpho and Garrett [34] used voice commands to facilitate the documentation of bridge inspection through the use of handheld devices. Voice recognition was also utilized in construction by Tsai et al. [35] as a means of recording and updating site material logs. Interactive voice response (IVR) has been used extensively by several companies for technical support purposes. It is an efficient tool that enables interaction with the user to automatically input site information into the system by voice and provide the ability to efficiently access information from computer systems [28]. Speech recognition and (IVR) systems can reduce the time and cost of collecting site information and record work progress [36]. Abdelrehim and Hegazy [37] developed a voice-visual framework that integrates activity-specific tracking forms with different categories of site information and a cloud-based IVR service to communicate with multiple parties simultaneously with the calls dynamically controlled based on the user's answer. Automated IVR and email can replace the lengthy manual process of progress tracking and minimize the time and cost associated with the collection of construction site information.

5.4. Handheld computing

With modern communication technologies progressing rapidly, handheld computers and tablets are gaining popularity in the construction field and have been identified as important IT support for construction sites. They can enhance project control by providing site personnel with a variety of information such as resource data, project delivery information, and progress information [38]. Several researchers have investigated the use of handheld devices on construction sites for collecting, storing, and exchanging site information [39,40]. Smart phones and personal digital assistants (PDAs) can handle spreadsheet and industry-specific applications, and can have camera, GPS, voice, email, and internet access [41]. They could also be integrated with other technologies, such as barcodes and radio frequency identification readers. Tserng et al. [42] attached PDA to barcode readers in order to support the management of supply and storage of materials on a construction site. Tablet PCs have been used for site information management to improve the productivity by filling forms directly on site, while ensuring that construction quality standards are achieved [39,41]. Rugged tablets and notebook PCs have the advantage to suit the site's harsh environments.

6. Geospatial technologies

Geospatial tools help site managers visualize on-site construction objects. These include: barcoding, radio frequency identification (RFID), ultra-wide band (UWB) tags, geographic information systems (GIS), and global positioning systems (GPS). Researchers have put broad efforts into adapting these new techniques for use in construction planning and automated data acquisition. An overview of recent attempts for automating construction documentation using such tools is presented below and a concise comparison thereof is illustrated in Table 3.

6.1. Barcoding

Barcoding is one of the oldest information data collection technologies employed in construction and is still being used foremost due to its low cost. A series of parallel and adjacent bars are scanned with a barcode reader, or scanner, which is a handheld or stationary input device used to capture and read the information contained in a barcode about the item in question. This method allows real-time data to be collected. Barcode technology has been proposed primarily for materials tracking, inventory, construction progress tracking and labour tracking [43], as well as for controlling engineering deliverables such as drawings, reports, and specifications [44], and for the management of documents [45]. The advantages of using barcoding are: (i) high capacity of data content and type; (ii) high reliability; (iii) ease of production; and (iv) can be easily identified by mobile devices such as phones and is readable in any direction [46].

6.2. Radio frequency identification (RFID)

RFID system is an automatic identification technology in which radio frequencies are used to capture and transmit field data. They are able to store and retrieve significant data from identified items by means of small tags in which this information can be easily read and written and hence, can be utilized for progress measurement [47]. There are three types of tags: active, passive and hybrid. Active tags incorporate the power supply for their circuits and propagate the signal to the reader. Passive tags obtain the required energy by induction from the readers. Passive tags can be used for distances of up to approximately 15 m, whereas active tags have a much bigger range of action (up to 500 m) and can store a larger quantity of information. Hybrid tags can transmit, but they need to be turned on by a signal, which could be a satellite. The system's range of action is also influenced by whether a low frequency or a high frequency antenna is installed in the reader. RFID readers are either fixed readers, hand-held readers or vehicle mounted readers [48].

The rapid development of this technology and the tags' adaptability for use on a great variety of surfaces have led to the expansion of RFID technology over the last few years. Numerous researchers have applied RFID for the automated collection of data. For example, Ghanem and AbdelRazig [49] applied an RFID wireless system for tracking construction progress. Song et al. [50] used RFID technology for the automatic identification and tracking of individual pipe spools. They reported that the benefits of using RFID technology in automated pipe spool tracking include: (i) reduced time for identifying and locating pipe spools; (ii) more accurate and timely information about shipping, receiving and inventory; (iii) a reduction in the number of misplaced pipes and associated search time; and (iv) an increase in the reliability of the pipe-fitting schedule. RFID tags have also been widely used for tracking materials on construction sites. Montaser and Moselhi [51] utilized RFID technology for tracking earthmoving operations in a near real time capturing system. The proposed RFID system consists of passive RFID tags attached to hauling units (trucks) and fixed RFID readers attached to designated gates of projects' dump areas. Chien [52] developed a 3D-Web-GIS RFID location sensing system for construction objects. Turkan et al. [53] have revealed that the proposed system can provide faster, more accurate, and more stable 3D positioning results than other location sensing algorithms. The overall advantages of the RFID technology include its wide reading range, ability to operate without line-of-sight, and its durability in construction environments under different weather conditions [50]. The major limitations of RFID systems are its relatively high initial and maintenance costs [54] along with a decrease in signal strength levels, and limited lifetime and periodic battery replacement associated with the active RFID type [55]. When used in enclosed or partially covered building sites, RFID tags suffer from a sharp decrease in communication range with the existence of metals in their vicinity (e.g., reinforcement mesh, steel scaffold, shoring, or shutter, metal doors and hoardings) [56].

6.3. Ultra-wide band (UWB)

UWB is another type of radio technology that can be applied to short-range communications. An UWB system is a network of receivers and tags communicating with each other over a large bandwidth (>500 MHz). The tag transmits UWB radio pulses that enable the system to find its 3D position coordinates, even in the presence of severe multipath effects [57]. Some potential applications of UWB technology on construction sites include material tracking and activity-based progress tracking as well as various safety-related applications [58]. UWB has emerged as an effective real-time location sensing and resource-tracking technology in harsh construction environments [59]. For example, Cheng et al. [60] applied the UWB technology in construction projects where it was successfully used for a 3D material location tracking in real-time. Another application is by Shahi et al. [61] who utilized the UWB positioning system to track the progress of pipelines construction activities (e.g. welding and inspection). They reported that UWB could be effectively used for a wide range of construction related applications.

Some of the UWB technology advantages compared to other tracking and positioning technologies are: (i) has longer read ranges than laser scanning or vision-based detection and tracking systems (up to 1000 m); (ii) has ability to work both indoors and outdoors; (iii) low average power requirement that results from the low pulse rate; and (iv) compared with RFID systems, UWB does not need to be integrated with other technologies to provide an accurate 3D location estimate [58].

6.4. Geographic information system (GIS) and global positioning system (GPS)

GIS appears to have the potential of integrating project specific spatial and non-spatial information and has been widely utilized to analyze and manage large amounts of data involved in the procurement, preconstruction management, and construction monitoring [62]. The emergence of 3D CAD technologies in the architecture, engineering and construction industry have allowed researchers to combine it with CPM schedules, which has led to the development of 4D CAD. Currently, several commercial tools allow planners to build such 4D models. Liang et al. [47] integrated 4D-PosCon software and robotic total station to track and visualize the position and orientation of

Table 3
Comparison of geospatial methods of data acquisition, adapted from [21].

Evaluation	Barcodes	RFID	UWB	GIS and GPS
Storing information	Barcode labels	RFID tags	UWB tags	Geo-notes
Receiving stored information	Barcode reader	RFID reader	UWB reader	Signals
Communication relationship between activity workers and operation devices	One-way	One-way	One-way	One-way
Modifying errors	Manual	Manual	Manual	Automatic
Transfer information within WLANs?	Yes	Yes	Yes	Yes
Require additional costs	Yes	Yes	Yes	Yes

building components during the erection process. Bansal and Pal [63] presented a Geographic Information System (GIS) based navigable 3D animation of project activities to visualize and review a construction project schedule as an alternative to existing 4D CAD tools. The animation of project activities utilizes dynamic linkage between schedule activities and the corresponding 3D components, thus, allowing detection of missing activities and logical errors in the project schedule. The database management capabilities of GIS are also utilized to maintain and update the construction resource database to facilitate project planning [64].

Another spatial technology, the Global Positioning System (GPS), is satellite-based and widely used where the position and navigation of construction activities are considered [23]. The functional ability of the system is dependent on the reception of signals from satellites in order to locate the position of a specific object attached to a tag [65]. GPS has been used for example to track steel structural materials throughout the construction process, from manufacturing to the construction site, from inventory until installation, and even for long-term maintenance [65]. Similar to GPS positioning, Shen et al. [66] utilized a robotic total station and sensors to automate the process of data collection and positioning for a tunnel boring machine used in constructing sewer and storm water municipal pipelines. Real-time survey data for the tunneling progress are acquired with precise coordinates in the 3D underground space. The main limitations of using GPS are the multipath errors in congested environments where positioning can be severely degraded due to blockage, deflection and distortion of satellite signals. The system becomes uneconomical when there is need to attach a GPS receiver to each site object [56].

7. Imaging technologies

Research on progress tracking using imaging technologies has been rapidly growing in recent years [20,67,68]. Most recent research has been focusing on using digital images to generate 3D information about various objects on site for use in progress analysis. Table 4 shows a concise comparison of techniques used in 3D data acquisition. The different methods differ in terms of capturing speed, cost, and processing time as discussed below.

7.1. Photogrammetry

This technique is an accurate method to generate 3D (or point cloud) models of a construction site from digital photos. Such an as-built 3D model is then compared to 3D CAD models to automatically calculate the percentage completion of each component and measure the progress of construction projects [69]. While it is a robust method, given the nature of time-lapsed images and having the most automation reported so far, its application in construction projects was limited due to: (i) the considerable time of computation process; (ii) the sensitivity of the region of interest and detectors to different lighting conditions, particularly in the presence of severe shadow lines, affecting image processing; and (iii) progress can be monitored only on the closest structural frame of the component to the camera [70]. Numerous researchers have applied photogrammetry for the automated collection of data. For example, Dai and Lu [71] used photogrammetry to collect geometric measurements and orientations of building elements in order to record as-built information. El-Omari and Moselhi [20] developed a tracking system that produces 3D images of scanned objects, which are then used to estimate quantities of work performed over the time interval between two scans. Ahmed et al. [72] presented an efficient low-cost 3D automatic surveying method for pothole detection in pavements. Other examples of point cloud generation and reconstruction using photogrammetry in construction projects can be found in [73].

Table 4
Comparison of 3D imaging methods of data acquisition.

Method	Affordability	Portability	Processing time	Point cloud accuracy	Range distance
Photogrammetry	✓✓✓	✓✓✓	✓	✓✓	✓✓
Laser scanning	✓	✓✓	✓✓✓	✓✓✓	✓✓✓
Videogrammetry	✓✓	✓✓	✓	✓✓	✓
Range images	✓✓	✓✓	✓✓	✓	✓

✓: Low; ✓✓: Medium; ✓✓✓: High.

Moreover, the availability of inexpensive point-and-shoot and time-lapse cameras as well as smartphones has significantly increased the number of photos that are being captured on construction sites on a daily basis. Thus, many photography documentation services such as *EarthCam*, *MulitVista*, and *JobSiteVisitor* have emerged in recent years to deliver “visual as-built” records of the construction phase to the project participants [72]. Although data processing has become easier and faster using these existing software packages, it is still limited since it requires an extensive amount of human intervention, which makes such an application time-consuming and less attractive for repetitive progress-monitoring tasks [74].

7.2. 3D laser scanning

Three dimensional laser scanning, also known as LADAR (Laser Detection and Ranging), has become a common technology to acquire 3D point clouds in many engineering fields. It operates by emitting a pulse of laser light to a target and calculating the distance to the target by timing the round trip time of the pulse of light. Therefore, one laser scan may collect millions of 3D points in minutes [75]. It was first introduced as an accurate method to capture construction sites and items and subsequently used to capture the current status of construction projects [67,76]. The technique was used by Akinci et al. [8] to develop a framework for quality control purposes on construction sites. They have shown that using 3D sensing and laser scanning technologies can avoid potential errors that cause rework. LADAR was then used as a method of structural health monitoring [15].

El-Omari and Moselhi [20] compared some of the currently available 3D scanners in terms of speed, accuracy, range and cost. In studies by [1, 77–80], LADAR was used to track the progress of construction sites by recognizing built components from 3D point clouds and comparing it with 3D BIMs. For instance, Bosché et al. [80] used 3D laser scanning point cloud models and BIM for monitoring Mechanical/Electrical/Plumbing (MEP) installments. Gao et al. [81] and Liu et al. [82] utilized LADAR to capture actual construction progress and used the extracted information to develop a complete as-built BIM. In a recent study, Turkan et al. [75] developed an automated 4D object-oriented progress-tracking system to update the construction schedule through the use of a project 3D CAD model and 3D point clouds acquired via laser-scanning. The 3D point clouds are registered with a 4D as-planned model in the same coordinate system in order to extract useful information on the project progress. Subsequently, progress measurement and schedule updating is automatically performed by recognition of as-built objects. However, more research is required to study the effects of materials reflectivity and texture on the efficient application of laser scanners for automated progress tracking [83].

Laser scanning is still not widely employed due to its high cost, need for a clear line of sight, and the difficulty of using it in congested interior work. In addition to the need for regular sensor calibrations, it typically has a slow warm-up time. For example, moving machinery and personnel regularly in the construction site can create noise in a point cloud model and consequently cause the expenditure of additional effort on the part of the user to manually improve the point cloud in a post-processing stage [84]. Like other sensing devices that depend on the line of sight, as the distance between the laser scanner and the building components increases, the level of detail that can be captured is reduced. Since scanners are not easily portable, they cannot efficiently be used for scanning indoor environments. For these technical reasons, the value of applying laser scanners has not yet been significantly observed in construction projects [85].

7.3. Videogrammetry

This technique extracts features from video recordings. Since video frames are sequential, pixels existing in each frame are progressively reconstructed based on the previous frame. This characteristic of videogrammetry enhances the reconstruction of civil infrastructure more quickly. The level of accuracy for progressive reconstruction using videogrammetry has become reasonable using high resolution cameras. Several studies have recently investigated the effectiveness and robustness of using videogrammetry in construction projects [e.g. 80]. Examples of using videogrammetry for damage detection and safety evaluation in infrastructure projects can be found in [86–89] where the technique provided desirable accuracy in different sectors. In a similar study, an algorithm was developed to identify objects from video frames in order to detect moving equipment on construction sites [90]. Dia et al. [83] investigated two bridges and a building under different camera setting and reported that videogrammetry produced 3D point clouds without suffering from the site temperature changes or edge biases of the objects, but is significantly impacted by a large number of factors such as the presence of robust features on the surface of the object, camera model, focal length, data capturing range, and the camera's resolution. They also presented an analytical and quantitative comparison of photogrammetric, videogrammetric, and laser scanning methods with respect to accuracy, quality, time efficiency, and cost. The study indicated that video/photogrammetry can produce results of moderate accuracy and quality but at a much lower cost compared to laser scanning. Similar to photogrammetry, videogrammetry can produce promising results, and thus needs concerted research efforts.

7.4. Range images

Range images are a special class of digital images, also referred as depth images. They are acquired with range sensors (range cameras) and offer an inexpensive and accurate means for digitizing the shape of 3D objects. 3D range cameras are useful for tracking moving objects and construction equipment and materials [91–93]. For instance, Teizer et al. [91] developed a 3D model using a high-frame range sensor to detect the characteristics of construction objects. Teizer and Allread [94] developed a method to rapidly determine blind spots using range images. In a similar study by Bosche et al. [78], range images were used for obstacle avoidance on construction sites in order to reduce the likelihood of accidents. Recently, a 3D range camera called *Kinect™*, developed by *Microsoft*, has been used for safety purposes [95], performing real-time monitoring of construction workers to avoid hazardous postures and gestures. The development of RGB-D (Red, Green, Blue plus Depth) cameras, have also great potential for spatial sensing and modeling applications at construction sites. The RGB-D cameras are novel sensing systems, which can capture pairs of mid-resolution color and depth images almost in real time [96]. Range cameras are independent of the backlight and can cover a wide field of view [95]. They are less costly than laser scanners, but more expensive than digital cameras used in photogrammetry. They are more suitable for short range applications.

8. Augmented reality

Augmented reality (AR) is defined as "a live, direct or indirect view of a physical, real-world environment whose elements are augmented by virtual, computer-generated imagery" [97]. AR is the culmination of a diverse group of technologies. The hardware typically involves head mounted displays, GPS, data gloves and smart boards. Examples of software utilized in AR include *3D Studio Max* and *BIMs* [98]. AR application areas can be classified as visualization or simulation, communication or collaboration, information modeling, information access or evaluation, and safety or inspection [99]. AR has been used for instance in municipal infrastructure [100], residential and commercial [101,102], highway [103,104], and industrial projects [105]. One of many specific applications of AR is the comparison of different project status. Reality versus model comparisons first involve the collection of site data through various means such as photogrammetry, videogrammetry [106,107] and laser scanning [1]. Then the collected data are compared with data provided within software models such as *4D BIM* [108]. In order to make the comparison between as-built and model data intuitive, the two sets are usually overlaid. With the *4D BIM* model directly displayed with the as-built, decision-making personnel can identify construction progress statuses, any potential defects, and apply remedial actions if necessary.

The current AR trend is the use of portable web-based mobile augmented systems for field construction monitoring [109]. Examples of AR application that were successfully used for construction are *BIManywhere* and *SMART REALITY* where users focus on a given 2D printed paper design or plan file with the camera on their iPad or iPhone. The apps then recognize the design. The screen overlays a virtual 3D model of what the structure will look like [110]. *MAPTEK* is another AR application used recently in the mining industry. It allows operators to use handheld devices to compare laser scanned surface data during excavation against 3D plan designs for conformance in the field [110]. Although the application of augmented reality technologies in construction projects has enormously increased in recent years, these technologies are still in the research stage and their full potential has not yet been fully achieved [111]. Researchers are currently addressing practical challenges related to mobile field implementation of AR such as user comfort, power limitations, ability to function in harsh environments, robust image registration for outdoor uncontrolled conditions, filtering ambient noise and data interferences, and adding more interactivity features to the AR interface [112]. The features of AR apps are evaluated in Table 5 and data acquisition using *BIManywhere* is illustrated in Fig. 3.

9. Commercial software systems for monitoring progress

Primavera Project Planner (*Primavera 2014*) and Microsoft Project (*MS Project 2014*) are the most common software applications for scheduling and controlling construction projects. They provide relatively accurate scheduling and tracking of project progress with commercial web-enabled applications for accessing and updating the project for basic progress information such as actual start time and percentage completion to-date. Moreover, several commercial software systems

Table 5
Evaluation summary of augmented reality apps.

Evaluation criteria	Augmented reality
Cost effectiveness	Assuming the projects already have BIM and laser scanning capabilities, the apps are extremely affordable.
Time and level of training required	Simple and easy for the end users in the field. It enables all users to instantly access the information they need, saving precious time and avoiding frustrations with traditional systems.
Level of automation	In order to deal with the intimidation posed by orienting in the BIM and laser scanner point clouds, AR automatically orients the user in the digital space and thus, covers the problem of navigation with 3D modeling.
Level of readiness of required data	Data input is twofold; capturing the *as*-built environment at several stages during construction using 3D laser scanning and the creation of a 3D BIM.
Capability to support the decision makers	The decision makers are able to walk into a room with a tablet and see exactly where everything is and access information on a piece of equipment without having to refer back to their computer.

Fig. 3. Data acquisition and as-built status capturing using BIManywhere.

are available for project management. For example, *Construction Superintendent* has been designed for small tablets and offers generic construction forms so that site information can be easily collected and sent back to head office. *Autodesk BIM 360 Field* is a BIM-based software that can help construction personnel document construction details on their tablets and then synchronize the saved data with head office. Other systems such as *Onsite, AEC, Newforma's Punch List*, and *Latista Punch List*, can also be used to record daily site reports electronically, attach photos, and synchronize reports with head office, navigate drawings and attach notes [23].

Most providers of laser-scanning systems have developed software that enables the 3D as-built from 3D point clouds. Examples include *Trimble RealWorks* by Trimble, *Leica Cyclone* and *Leica CloudWorx* by Leica Geosystems. The leading 3D CAD vendors have also developed software that enables the 3D layout of as-built from 3D point clouds. For example, *AutoCAD Plant 3D* by Autodesk, and *SmartPlant 3D* by Intergraph [113]. There are also many other promising software applications recently used in the construction industry for data collection such as *Bridgit* as an IT enhanced tool, *iBeacon* as a geospatial tool, *Creaform Handyscan* as a handheld scanner, and *BIManywhere* as an augmented reality-based mobile app. Table 6 summarizes the pros and cons of some software available for recording construction site information.

10. Integration of data acquisition technologies

Many researchers presented control models that integrate different automated data acquisition technologies to collect data from construction sites [114–119]. Integrating these technologies alleviates limitations associated with each of them when employed individually. For example, a point cloud from digital photos can be produced significantly faster and more accurately when integrated with laser scanning to automatically measure the progress of construction projects [70]. Accordingly, the so-called hybrid approach, combines data acquired from photo/video-grammetry and laser scanning surveys, was used by Guarnieri et al. [114] for acquisition of as-built data on civil infrastructure. The data acquired by photogrammetry and laser scanning can also be combined with data obtained by other identification and localization

Table 6
Characteristics of commercial software systems for monitoring/collecting progress data.

Technology	Software	Description	Pros & Cons	
			Pros.	Cons.
Enhanced IT	Construction Superintendent (Journeyman) [128]	The system provides a comprehensive set of site management forms and reports that can be collected and sent back to the head office. The application deals with three concepts: Manage concurrent projects, manage resources, and record site information data	Record and track daily reports, RFIs, and inspection forms. Can attach photos and notes to the reports	Cost record forms are not included. Progress not linked to the planned schedule automatically
Enhanced IT	Autodesk BIM 360 Field [129]	Is a building information model (BIM)-based software with cloud based collaboration and reporting. It permits the navigation of drawings, record modification, and showing the markup. The application deals with site work quality, safety, and progress	Use an intelligent 3D model to inform and communicate project decisions. Record and track daily reports and RFIs. Can attach notes and photos	Progress not linked to the planned schedule automatically. The markups are linked to the drawings, not to specific activities
Enhanced IT	Asta Powerproject [130]	The software allows supervisors for recording the daily progress percentage on spreadsheets. It has its own scheduling engine that operates in a manner similar to that of the MS Project and Primavera systems	Tracking actual cost and resources. Able to exchange data from Primavera and MS Project. Applicable for wide range of project construction sectors	Does not include critical path segments to represent mid-activity details. Progress not linked to the planned schedule automatically
Enhanced IT	Bridgit [131]	It is a cloud-based apps recently introduced in the industry and allows for real-time notifications through trackable and tagged multimedia messages. It marks up the photos to clearly identify any issue on site and all data is securely stored and backed up	Provides measures on the amount and types of deficiencies on site. External users are integrated via email; receive real-time notifications	Progress and actual cost are not linked to the planned schedule automatically. The markups are linked to the drawings, not to specific activities
Geospatial	iBeacon [132]	It allows mobile apps to listen for signals from beacons in the physical world and react accordingly. It deliver hyper-contextual content to users based on location. The iBeacon devices could be attached to the moving vehicles to retrieve data around the site	High accuracy and range awareness. One beacon ID can cover multiple locations. Fast in communication and transferring the data. Inexpensive	Required more sensors to be added to provide better context. Progress are not linked to the planned schedule automatically
Imaging	Creaform Handyscan [133]	It is a scanning equipment designed in particularly to track progress and inspection for pipeline projects. It provides automated and progressive generation of 3D point clouds. The built status can be compared with the designed models automatically	Portable as it weighs only 1 kg. Can capture occluded areas. The color map enables the localization of discrepancies in the scanned point clouds	The scanner should be held at about 25 cm from the objects which could be inaccessible. Data should be verified for reliability
Augmented reality	BIManywhere [134]	Provides access to BIM model information anywhere on the construction. Quick response stickers could be located in different locations so, could be scanned using iPad to provide access to the 3D model and update project status automatically	One of the current fastest model viewer. Combination of laser scans and BIManywhere makes it more efficient with laser scan point clouds	Expensive compared with other systems. Not yet applied on projects in different sectors to evaluate its efficiency.

technologies, including RFID [115], UWB [116], and information and communication technologies such as BIM and mobile technologies [117].

El-Omari and Moselhi [65] developed a control model that integrates barcoding, RFID, 3D laser scanning, photogrammetry, multimedia, and pen-based computers to collect actual data from construction sites. In their model, the scanned and digital images are modeled to determine quantities of work performed while bar coding and RFID are utilized for material and labour tracking. Razavi and Haas [118] furnished tag readers with GPS antennas to obtain precise position of construction elements. Currently, GPS RFID tags are commercially available to identify the location of tags. For instance, Liu et al. [119] proposed a real-time dam material monitoring system with integrated technology of RFID, GPS, GIS, and PAD. Costin et al. [120] utilized passive RFID in a BIM model for real-time visualization and location tracking of workers, materials, and equipment.

In addition, several studies have investigated the benefits of the effective integration of BIM and GIS [62–64]. In a recent study, Kang and Hong [64] proposed an integration model utilizing both technologies for the management of municipal facilities. Their model validation indicated several benefits such as its reusability and extensibility. GIS and BIM are similar in modeling spatial information and as a result, *buildingSMART* has been developed and standardized the Industry Foundation Class (IFC) data model, which is an integrated GIS/BIM model scheme capable to describe construction information [85]. In addition, the integration of multiple projects within an organization, and integration of multiple organizations within the industry, have recently emerged as an important area of research using the AR technology [121].

11. Discussion of present data collection solutions

11.1. BIMs application of data collection

BIMs incorporate the relevant project's information such as 3D design drawings, schedule, materials, costs, and safety specifications. The four most commonly used BIM viewers are *DDS CAD*, *Tekla BIMsight*, *Autodesk Navisworks* and *Solibri* [122]. Nowadays, the use of BIM goes beyond the planning and design phase of a project and extends throughout the life cycle of the modeled facility or infrastructure. The concept of BIMs fosters the use of real-time visualizations as a tool to communicate ideas and share construction information and all data among and between different stakeholders in a project. For example, contractors can input critical information into the model before starting construction, such as pre-fabricate or pre-assemble some systems off-site, minimize waste on-site, and deliver products on a just-in-time basis rather than being stock-piled on-site [123]. When linked with project CPM schedules, BIMs form detailed chronological models that allow visual 4D [(3D) + time] clash detection and schedule update simulation to be conducted. The automated recognition and visualization of construction progress monitoring with 4D simulation models have received the attention of many researchers [123–127].

Applications of BIMs during the construction phase increased with the potential added values from integrating BIMs with as-built models. Generating as-built BIMs is a challenging, yet necessary process for facilities not equipped with an as-planned BIM and for facilities where the as built conditions differ from the as-planned BIM [124]. The two types of non-contact spatial survey technology (photo/video-grammetry and laser scanning) have made it possible to efficiently acquire as-built data [125]. With either of these types of survey technology, as-built data can be acquired by capturing the shape and structure of an object in point-cloud format. Generally, the as-built modeling process comprises the point cloud generation, point cloud pre-processing, and as-built modeling. For instance, Golparvar-Fard et al. [85] integrated unordered daily construction photos and as-planned BIMs to automate progress tracking and explore the expected and reconstructed elements with an interactive, image-based, 3D viewer where deviations are automatically color-coded over the BIM. The system quantifies progress automatically and accounts for occlusions and recognizes whether reconstructed elements are missing because of occlusions or because of changes. In a similar study by Han and Golparvar-Fard [126], Point cloud models were generated from construction site images and superimposed with 4D BIMs to monitoring of construction progress. Patraucean et al. [127] presented various up-to-date research works performed on the as-built modeling process for the task of automatic as-built BIM generation for infrastructure. Producing such accurate automated as-built BIMs have a high potential impact in the construction industry.

11.2. Comparison of data collection technologies

Accurate and efficient tracking, analysis and visualization of actual status for construction progress are critical components of a successful project monitoring. The present investigation of data collection technologies revealed that each technology has some advantages and can be employed in different applications during construction phases. To identify key application areas which could be used to guide the construction industry and help the contractors to track and control their projects in a timely manner, the investigated technologies were compared from different viewpoints in Table 7 and are discussed below.

While enhanced IT techniques are powerful low-cost tools having great potential to control delays and cost overruns through improvements of project communication, the present survey indicates that they have several limitations. These include lack of collaboration, insufficient technological support, requirement for extensive user training, and lack of metrics for assessing value and quantifying the benefits of such technologies. In addition, numerous factors must be considered when IT approaches are applied in construction, such as the expenses of purchasing equipment and software, maintenance costs and upgrading of the hardware, the upgrading and licensing required for the software, the fees of required wireless services, need for in-house technical support personnel, and the training of users.

Geospatial tools help construction site managers collect, track and visualize geographic and geospatial aspects of on-site construction objects. They provide real-time data with a wide reading range and are considered as high-durability tools in the construction environment. They also have the ability of tracking a material's progress through their supply chain, from manufacturing to the construction site gate. However, the high initial and maintenance costs of these methods limit their use in construction sites. The data from geospatial technologies are becoming more effective and useful through their integration with other technologies such as 3D imaging, BIM and IT tools.

3D laser scanning is the most common technology to acquire 3D point clouds in engineering practice because of its accuracy and range. It enhances the speed and accuracy of data collection from construction sites. It can be used to track the progress of a construction site by recognizing existing built components and comparing them with the corresponding 3D CAD model. The benefits of using 3D as-built BIM have been well acknowledged in the AEC industry. The process starts with the collection of as-built building conditions using remote sensing devices, such as laser scanners or digital cameras. Then, the sensing data collected from multiple locations are registered, and building elements in the sensing data are recognized. One case study in which this technology has been successfully employed, is the construction of an engineering building at the University of Waterloo where a high degree of accuracy for automated progress tracking was achieved. However, the full potential of this technology has not yet been achieved. The reason may be that related commercial software packages are still too complicated for processing scanned data and the high equipment cost making it infeasible for small projects. In comparison, image technologies (photo/videogrammetry) are inexpensive, easy to use, and time efficient in acquiring data on site. The reduced level of accuracy compared

Table 7
Comparison of available technologies for site data acquisition.

Criteria	Enhanced IT	Geospatial	3D Imaging	Augmented reality
Setup and cost	Moderate	Moderate	Very high	High
Automation level	Semi-manual	Semi-automated	Automated	Automated
Automated analysis	Semi-automated	Automated	Automated	Automated
Applicability	All projects	All projects	All projects	All projects
Training required	Low	Low	High	Moderate
Pre-processing level	Low	Low	Moderate	Low
Integrated readiness	Moderate	Moderate	High	High
Meaningful support for decision makers	Moderate	Low	High	High
Computational cost	Low	Low	High	Low
Project size	Small/moderate	Small/moderate	Moderate/large	Moderate/large
Comments	Widely used but with manually tracking process	Time consuming and relatively unstructured	Not affordable and reasonable in all projects	Promising-still does not provide detailed information

to time-of-flight laser scanning constrains the applicability of image-based technology.

Augmented Reality in which 3D virtual objects are integrated in real time into a 3D real environment, is a promising technology which culminates numerous groups of technologies. The new AR software applications provide automated real-time notification systems and can record data that appear directly on the project schedule, and thus can provide timely schedule updates to help decision makers take better corrective actions. The AR models have been applied to address many project challenges. One case study in which this technology has been successfully employed, is the Oakland medical center replacement project where the contractor implemented *BIManywhere*. Quick response (QR) location stickers were placed in doorframes of the building. When construction personnel entered a space and needed to access information pertaining to that space, they would scan the QR code using an iPad. This would trigger a wireless communication with a *BIManywhere* server. The service would provide access to the 3D-model display of the space identified by the QR sticker, as well as related equipment documentation, graphics and other project information such as change orders, warranties, 2D plans, submittals, equipment manuals and markups.

11.3. Future research directions

Automated data acquisition technologies are rapidly evolving. More research is required to resolve knowledge gaps and better benefit the industry from adopting these technologies. Recommendations for future research based on the analysis conducted in this study include: (1) resolving how to obtain complete sets of data as construction projects become larger and more complex. The problem of incomplete data will continue to significantly affect the automated measurement of construction progress; (2) solving how to automatically quantify the discrepancies between as-designed and as-built status; (3) providing the construction industry with cost analysis to help in the decision making process regarding the application of automated data acquisition technologies; (4) developing quantitative performance measures for tracking the progress of construction projects; (5) enhancing the integrated systems for automatically acquiring data for different construction areas; (6) integrating photogrammetry and laser-scan surveys with data acquired by other identification and localization technologies; (7) using 3D location sensing technology to develop mechanisms for tracking the movement of construction objects within construction sites; (8) enhancing methods which are based on scan-versus-BIM frameworks as they have not yet achieved a high level of effectiveness; (9) determining how BIM coupled with AR-based visualization can effectively interact with the information database provided on site to facilitate the physical context of each construction activity or task; and (10) improving the methods used for processing the huge amounts of 3D as-built data acquired from civil infrastructure projects that often has vast, noisy, and unstructured data.

12. Concluding remarks

There is an abundance of technologies available to help a project team streamline and automate its information flow. This process is critical since project stakeholders confront the ever increasing amount of information circulating on construction sites. When given a particular application that demands a certain level of data accuracy and quality, engineers usually face a question of which data collection method should be chosen to achieve the desired levels while minimizing the cost. An extensive survey of the literature indicates that there is clear need for research studies that can provide guidance toward informed decision making regarding data collection methods. This study presents an in-depth literature review of data acquisition technologies in the construction industry. The primary finding of this survey is that the decision as to which technologies to employ and invest in is a multi-faceted issue, which becomes possible knowing the specific characteristics of the project in terms of the required degree of accuracy, project size, level of automation, and the ultimate purpose of progress tracking. The following recommendations were drawn from the comparative analysis in the present study:

1) Enhanced IT tools require the least level of training and are less costly compared to other technologies. Their use is relatively limited to tracking and documenting a project's status manually and hence are applicable mainly in small projects. Automating the process of data collection for such low-cost tools will enhance its features and extend their application over a wide range of residential, commercial and infrastructure projects.
2) 3D sensing technologies are the most accurate and speedy data acquisition tools that can be used for high precision purposes, they are costly and as a result may not be affordable for a variety of projects. However, they are recommended for use in large, non-congested and accessible projects such as landmark development projects (e.g. water, gas, sewer and storm water pipelines). "Scan-vs-BIM" object recognition systems, which integrate 3D point clouds from laser scanning or digital photogrammetry with 4D BIM, provide valuable information for tracking such construction works.
3) Geospatial Technologies are mainly suitable for 3D material location tracking in real-time. Compared with some other locating technologies, RFID has its advantages in aspects of durability, rich data capacity, repetitive read/write, noncontact features, and low cost. It is also recommended for procurement management, preconstruction management, and resource management.
4) AR applications are the most promising technologies, being suitable for all projects' types and sizes. They are growing rapidly as web-based and wireless network technologies are becoming more accessible. Lightweight mobiles and immersive AR systems are therefore recommended for field personnel due to the dynamic environment of construction fields. They offer significant support to decision makers through providing high accuracy and timely

schedule updates. With ongoing technological development of such applications, they are increasingly becoming more cost-effective with enhanced ability to provide more detailed information on various project tasks. This will make them preferable solutions for stockholders and main components of future infrastructure development initiatives.

5) Data collection technologies are evolving at an extraordinary speed, it is recommended to the construction participants to monitor this developing area closely in order to get the latest update.

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References

[1] Y. Turkan, F. Bosche, C.T. Haas, R. Haas, Automated progress tracking using 4D schedule and 3D sensing technologies, Autom. Constr. 22 (2012) 414–421.
[2] C. Kim, H. Son, C. Kim, Automated construction progress measurement using a 4D building information model and 3D data, Autom. Constr. 31 (2013) 75–82.
[3] J. Yang, O. Arif, P.A. Vela, J. Teizer, Z. Shi, Tracking multiple workers on construction sites using video cameras, Adv. Eng. Inform. 24 (4) (2010) 428–434.
[4] M. Memarzadeh, M. Golparvar-Fard, J.C. Niebles, Automated 2D detection of construction equipment and workers from site video streams using histograms of oriented gradients and colors, Autom. Constr. 32 (2013) 24–37.
[5] S. Chi, C.H. Caldas, Image-based safety assessment: automated spatial safety risk identification of earthmoving and surface mining activities, J. Constr. Eng. Manag. 138 (3) (2012) 341–351.
[6] J. Gong, C.H. Caldas, An object recognition, tracking, and contextual reasoning-based video interpretation method for rapid productivity analysis of construction operations, Autom. Constr. 20 (8) (2011) 1211–1226.
[7] S. Scott, S. Assadi, A survey of the site records kept by construction supervisors, Constr. Manag. Econ. 17 (3) (1999) 375–382.
[8] B. Akinci, F. Boukamp, C. Gordon, D. Huber, C. Lyons, K. Park, A formalism for utilization of sensor systems and integrated project models for active construction quality control, Autom. Constr. 15 (2) (2006) 124–138.
[9] B. Akinci, S. Kiziltas, E. Ergen, I.Z. Karaesmen, F. Keceli, Modeling and analyzing the impact of technology on data capture and transfer processes at construction sites: a case study, J. Constr. Eng. Manag. 132 (11) (2006) 1148–1157.
[10] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: a review of related techniques, Autom. Constr. 19 (7) (2010) 829–843.
[11] X. Xiong, A. Adan, B. Akinci, D. Huber, Automatic creation of semantically rich 3D building models from laser scanner data, Autom. Constr. 31 (2013) 325–337.
[12] D. Arditi, H.M. Gunaydin, Total quality management in the construction process, Int. J. Proj. Manag. 15 (4) (1997) 235–243.
[13] M. Nahangi, C.T. Haas, Automated 3D compliance checking in pipe spool fabrication, Adv. Eng. Inform. 28 (2014) 360–369.
[14] G.K. Gajamani, K. Varghese, Automated project schedule and inventory monitoring using RFID. 24th International Symposium on Automation and Robotics in Construction, (ISARC), Kochi, India, September 19-21 2007, pp. 47–53.
[15] H.S. Park, H.M. Lee, H. Adeli, I. Lee, A new approach for health monitoring of structures: terrestrial laser scanning computer-aided civil and infrastructure, Engineering 22 (1) (2007) 19–30.
[16] H. Fathi, I. Brilakis, A videogrammetric as-built data collection method for digital fabrication of sheet metal roof panels, Adv. Eng. Inform. 27 (4) (2013) 466–476.
[17] A. Bhatla, S.Y. Choe, O. Fierro, F. Leite, Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras, Autom. Constr. 28 (2012) 116–127.
[18] The New York State Office for Technology (NYSOT), New York State Project Management Guidebook, Release 2, Section II (Chapter 4), Performance Measures. 2003 (Accessed online July 18, 2014, at http://www.oft.state.ny.us/pmmp/guidebook2/).
[19] H. Son, F. Bosche, C. Kim, As-built data acquisition and its use in production monitoring and automated layout of civil infrastructure: a survey, Adv. Eng. Inform. 29 (2015) 172–183.
[20] S. El-Omari, O. Moselhi, Data acquisition from construction sites for tracking purposes, Eng. Constr. Archit. Manag. 16 (5) (2009) 490–503.
[21] M.K. Tsai, Improving communication barriers for on-site information flow: an exploratory study, Adv. Eng. Inform. 23 (3) (2009) 323–331.
[22] C.H. Liao, P.H. Tseng, Influential factors of VoIP adoption of top 500 export-import enterprises in Taiwan, Contemp. Manag. Res. 6 (1) (2010) 11–28.
[23] M. Abdelrehim, Interactive Voice-Visual Tracking of Construction As-Built InformationPh.D. Thesis University of Waterloo, 2013 (168 pp).
[24] T. Hegazy, M. Attalla, L. Hayter, S. Penny, Ultra mobile computer system for accurate and speedy inspection of buildings, The 1st International Construction Specialty Conference, CSCE, Quebec City, Quebec, Canada, June 10–13, 2008.
[25] O.Y. Abudayyeh, A multimedia construction delay management system, Microcomput. Civil Eng. 12 (1997) 183–192.
[26] J. Abeid, D. Arditi, Time-lapse digital photography applied to project management, J. Constr. Eng. Manag. 128 (6) (2002) 530–535.
[27] S. Leung, S. Mak, B.L. Lee, Using a real-time integrated communication system to monitor the progress and quality of construction works, Autom. Constr. 17 (6) (2008) 749–757.
[28] C. Schexnayder, E.J. Jaselskis, C. Fiori, G.C. Recavarren, M. Celaya, Tele-Engineering from the Inka Road." 9th LACCEI Latin American and Caribbean Conference, Engineering for a Smart Planet, Innovation, Information Technology and Computational Tools for Sustainable Development, Medellin, Colombia, August 3–5, pp: WE1-1 – WE1-10, 2011.
[29] E. Jaselskis, A. Sankar, A. Yousif, B. Clark, and V. Chinta. (2015)." Using telepresence for real-time monitoring of construction operations." J. Manag. Eng., Vol. 31 (1), pp: A4014011-1 - A4014011-11.
[30] S. Ahsan, A. El-Hamalawi, D. Bouchlaghem, S. Ahmad, Applications of converged networks in construction, Int. J. Product Dev. 7 (3/4) (2009) 281–300.
[31] M. Elamin, D. Flynn, D. Bassler, M. Briel, P. Alsono, P. Karanicolas, G. Guyatt, G. Malaga, Choice of data extraction tools for systematic reviews depends on resources and review complexity, J. Clin. Epidemiol. 62 (5) (2009) 506–510.
[32] T. Hegazy, M. Abdel-Monem, Email-based system for documenting construction as-built details, Autom. Constr. 24 (2012) 130–137.
[33] T. Hegazy, M. Abdel-Monem, D.A. Saad, Framework for enhanced progress tracking and control of linear projects, Eng. Constr. Archit. Manag. 21 (1) (2014) 94–110.
[34] J. Sunkpho, J.H. Garrett, A. Smailagic, Opportunities to use speech recognition for bridge inspection, in: Kenneth Walsh (Ed.), Construction Congress VI: Building Together for a Better Tomorrow in an Increasingly Complex World, Orlando, Florida, American Society of Civil Engineers, United States 2000, pp. 184–193, http://dx.doi.org/10.1061/40475(278)21.
[35] M.K. Tsai, J.B. Yang, C.Y. Lin, Integrating wireless and speech technologies for synchronous on-site data collection, Autom. Constr. 16 (3) (2007) 378–391.
[36] E. Jaselskis, J. Ruwanpura, T. Becker, L. Silva, P. Jewell, E. Floyd, Innovation in construction engineering education using two applications of internet-based information technology to provide real-time project observations, J. Constr. Eng. Manag. 137 (10) (2011) 829–835.
[37] M. Abdel-Monem, T. Hegazy, Enhancing construction as-built documentation using interactive voice response, J. Constr. Eng. Manag. 139 (7) (2013) 895–898.
[38] M. Ward, T. Thorpe, A. Price, C. Wren, Implementation and control of wireless data collection on construction sites, J. Inf. Technol. Constr. 9 (2004) 297–311 (Special Issue: Mobile Computing in Construction).
[39] S. Bowden, A. Dorr, A. Thorpe, C.J. Anumba, Mapping site processes for the introduction of mobile IT, Proceedings of the 5th European Conference on Product and Process Modeling in the Building and Construction Industry (ECPPM), eWork and eBusiness in Architecture, Engineering, and Construction, Istanbul, Turkey, September 8–10 2004, pp. 817–830.
[40] A. Löfgren, Mobility in-site: implementing mobile computing in a construction Enterprise, Commun. Assoc. Inf. Syst. 20 (2007) 594–604.
[41] A.A. Ghanem, Real-time Construction Project Progress Tacking: A Hybrid Model for Wireless Technologies Selection, Assessment, and ImplementationPh.D. Thesis The Florida State University, 2007 (217 pp).
[42] H.P. Tserng, R.J. Dzeng, Y.C. Lin, S.T. Lin, Mobile construction supply chain management using PDA and bar codes, Comput.-Aided Civ. Infrastruct. Eng. 20 (4) (2005) 242–264.
[43] R. Navon, and R. Sacks. (2007). "Assessing research issues in automated project performance control (APPC)." Autom. Constr., Vo1. 16 (4), pp: 474-484.
[44] T. Shehab, O. Moselhi, An automated barcode system for tracking and control of engineering deliverables, Construction Research Congress: Broadening Perspectives, San Diego, California, United States, April 5-7 2005, pp. 1–9, http://dx.doi.org/10.1061/40754(183)28.
[45] T. Shehab, O. Moselhi, E. Nasr, Barcode-assisted system for document management of construction projects, Int. J. Constr. Educ. Res. 5 (2009) 45–60.
[46] Y. C. Lin, W. F. Cheung, and F. C. Siao. (2014). "Developing mobile 2D barcode/RFID-based maintenance management system." Autom. Constr., Vo1. 37, pp: 110–121.
[47] A.R. Jiménez, F. Seco, F. Zampella, J.C. Prieto, J. Guevara, Indoor localization of persons in AAL scenarios using an inertial measurement unit (IMU) and the signal strength (SS) from RFID tags, Series Commun. Comput. Inf. Sci. 362 (2013) 32–51, http://dx.doi.org/10.1007/978-3-642-37419-7_4.
[48] N. Li, G. Calis, B.B. Gerber, Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations, Autom. Constr. 24 (2012) 89–99.
[49] A. G. Ghanem, and Y. A. AbdelRazig. (2006). "A framework for real-time construction project progress tracking." Proceeding of 10th Biennial International Conference on Engineering, Construction, and Operations in Challenging Environments, League City, Houston, Texas, United States, March 5–8, pp: 1–8. DOI: http://dx.doi.org/10.1061/40830(188)112.
[50] J. Song, C.T. Haas, C. Caldas, E. Ergen, B. Akinci, Automating the task of tracking the delivery and receipt of fabricated pipe spools in industrial projects, Autom. Constr. 15 (2) (2006) 166–177.
[51] A. Montaser, O. Moselhi, RFID+ for tracking earthmoving operations, Construction Research Congress: Construction Challenges in a Flat World, West Lafayette, Indiana, United States, May 21–23 2012, pp. 1011–1020, http://dx.doi.org/10.1061/9780784412329.102.
[52] H.K. Chien, 3D-web-GIS RFID location sensing system for construction objects, Sci. World J. 2013 (2013) 1–8, http://dx.doi.org/10.1155/2013/217972.
[53] Y. Turkan, F. Bosché, C.T. Haas, R. Haas, Tracking of secondary and temporary objects in structural concrete work, Constr. Innov. 14 (2) (2014) 145–167.
[54] M. Ahmed, C.T. Haas, R. Haas, Using digital photogrammetry for pipe-works progress tracking, Can. J. Civ. Eng. 39 (2012) 1062–1071, http://dx.doi.org/10.1139/L2012-055.

[55] S. Kiziltas, B. Akinci, E. Ergen, P. Tang, C. Gordon, Technological assessment and process implications of field data capture technologies for construction and facility/infrastructure management, J. Inf. Technol. Constr. 13 (2008) 134–154 (Special Issue: Sensors in Construction and Infrastructure Management).

[56] H. Khoury, D. Chdid, R. Oueis, I. Elhajj, D. Asmar, Infrastructureless approach for ubiquitous user location tracking in construction environments, Autom. Constr. 56 (2015) 47–66.

[57] Y.K. Cho, J.H. Youn, D. Martinez, Error modeling for an untethered ultra-wideband system for construction indoor asset tracking, Autom. Constr. 19 (1) (2010) 43–54.

[58] A. Shahi, A. Aryan, J.S. West, C.T. Haas, R.C. Haas, Deterioration of UWB positioning during construction, Autom. Constr. 24 (2012) 72–80.

[59] D. Chdid, R. Oueis, H. Khoury, D. Asmar, I. Elhajj, Inertial–vision sensor fusion for pedestrian localization, Robotics and Biomimetics (ROBIO), IEEE International Conference, Karon Beach, Phuket, Thaïlande, December 7–11 2011, pp. 1695–1701, http://dx.doi.org/10.1109/ROBIO.2011.6181533.

[60] T. Cheng, U. Mantripragada, J. Teizer, P.A. Vela, Automated trajectory and path planning analysis based on ultra wideband data, J. Comput. Civ. Eng. 26 (2) (2012) 151–160.

[61] A. Shahi, J.S. West, C.T. Haas, Onsite 3D marking for construction activity tracking, Autom. Constr. 30 (2013) 136–143.

[62] V.A. Petrov, A.V. Veselovskii, D.A. Kuz'mina, A.N. Plate, T.V. Gal'berg, Spatial-temporal three-dimensional GIS modeling, Autom. Doc. Math. Ling. 49 (1) (2015) 21–26, http://dx.doi.org/10.1080/17549175.2013.879452.

[63] V.K. Bansal, M. Pal, Construction schedule review in GIS with a navigable 3D animation of project activities, Int. J. Proj. Manag. 27 (5) (2009) 532–542.

[64] T.W. Kang, C.H. Hong, A study on software architecture for effective BIM/GIS-based facility management data integration, Autom. Constr. 54 (2015) 25–38.

[65] S. El-Omari, O. Moselhi, Integrating automated data acquisition technologies for progress reporting of construction projects, Autom. Constr. 20 (6) (2011) 699–705.

[66] X. Shen, M. Lu, S. Fernando, Automation system design and lab testing to facilitate tunnel boring machine guidance in construction of large-diameter drainage tunnels, Construction Research Congress: Construction Challenges in a Flat World, West Lafayette, Indiana, United States, May 21-23 2012, pp. 110–120, http://dx.doi.org/10.1061/9780784412329.012.

[67] D. Rebolj, N.Č. Babič, A. Magdič, P. Podbreznik, M. Pšunder, Automated construction activity monitoring system, Adv. Eng. Inform. 22 (4) (2008) 493–503.

[68] X. Liang, M. Lu, J.P. Zhang, On-site visualization of building component erection enabled by integration of four-dimensional modeling and automated surveying, Autom. Constr. 20 (3) (2011) 236–246.

[69] Z.A. Memon, M.Z. Abd.Majid, M. Mustaffar, An automatic project progress monitoring model by integrating auto cad and digital photos, International Conference on Computing in Civil Engineering, Cancun, Mexico, July 12–15 2005, pp. 1–13, http://dx.doi.org/10.1061/40794(179)151.

[70] M. Golparvar-Fard, F.P. Mora, C.A. Arboleda, S.H. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, J. Comput. Civ. Eng. 23 (6) (2009) 391–404.

[71] F. Dai, M. Lu, Assessing the accuracy of applying photogrammetry to take geometric measurements on building products, J. Constr. Eng. Manag. 136 (2) (2010) 242–250.

[72] M. Ahmed, C. Haas, A. Shahi, A. Aryan, J. West, R. Haas, Rapid tracking of pipeworks progress using digital photogrammetry, Proceedings of the 9th Construction Specialty Conference, CSCE, Ottawa, Ontario, Canada 2011, pp. 14–17.

[73] S. El-Omari, O. Moselhi, Integrating 3D laser scanning and photogrammetry for progress measurement of construction work, Autom. Constr. 18 (1) (2008) 1–9.

[74] Y.M. Ibrahim, T.C. Lukins, X. Zhang, E. Trucco, A.P. Kaka, Towards automated progress assessment of work package components in construction projects using computer vision, Adv. Eng. Inform. 23 (1) (2009) 93–103.

[75] Y. Turkan, F. Bosché, C.T. Haas, R. Haas, Towards automated earned value tracking using 3D imaging tools, J. Constr. Eng. Manag. 139 (4) (2013) 423–433.

[76] T. Rabbani, S. Dijkman, F. van den Heuvel, G. Vosselman, An integrated approach for modelling and global registration of point clouds, ISPRS J. Photogramm. Remote Sens. 61 (6) (2007) 355–370.

[77] F. Bosche, C.T. Haas, Automated retrieval of 3D CAD model objects in construction range images, Autom. Constr. 17 (4) (2008) 499–512.

[78] F. Bosche, C.T. Haas, B. Akinci, Automated recognition of 3D CAD objects in site laser scans for project 3D status visualization and performance control, J. Comput. Civ. Eng. 23 (6) (2009) 311–318.

[79] F. Bosche, Automated Recognition of 3D CAD Model Objects in Dense Laser Range Point CloudsPh.D. Thesis University of Waterloo, 2008 (170 pp).

[80] F. Bosche, A. Guillemet, Y. Turkan, C. Haas, R. Haas, Tracking the built status of MEP works: assessing the value of a scan-vs.-BIM system, J. Comput. Civ. Eng. 28 (4) (2014) (5014004–1 - 5014004-13).

[81] T. Gao, B. Akinci, S. Ergan, J. Garrett, Constructing of as-is BIMs from progressive scan data, International Symposium of Automation and Robotics in Construction, ISARC, Eindhoven, The Netherlands 2012, pp. 1–7, http://dx.doi.org/10.4017/gt.2012.11.02.500.00.

[82] X. Liu, M. Eybpoosh, B. Akinci, Developing as-built building information model using construction process history captured by a laser scanner and a camera, Construction Research Congress, Construction Challenges in a Flat World, West Lafayette, Indiana, United States, May 21-23 2012, pp. 1232–1241, http://dx.doi.org/10.1061/9780784412329.124.

[83] F. Dai, A. Rashidi, L. Brilakis, P. Vela, Comparison of image-based and time-of-flight-based technologies for three-dimensional reconstruction of infrastructure, J. Construct. Eng. Manag. 139 (1) (2013) 69–79.

[84] F. Bosché, Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction, Adv. Eng. Inform. 24 (1) (2010) 107–118.

[85] M. Golparvar-Fard, F.P. Mora, S. Savarese, Automated progress monitoring using unordered daily construction photographs and IFC-based building information models, J. Comput. Civ. Eng. 29 (1) (2015) (04014025–1 - 04014025-19).

[86] C. Koch, G. Jog, I. Brilakis, Automated pothole distress assessment using asphalt pavement video data, J. Comput. Civ. Eng. 27 (4) (2013) 370–378.

[87] Z. Zhu, I. Brilakis, Machine vision-based concrete surface quality assessment, J. Construct. Eng. Manag. 136 (2) (2010) 210–218.

[88] I. Brilakis, M. Lourakis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, A. Makhmalbaf, Toward automated generation of parametric BIMs based on hybrid video and laser scanning data, Adv. Eng. Inform. 24 (4) (2010) 456–465.

[89] C. Koch, I. Brilakis, Pothole detection in asphalt pavement images, Adv. Eng. Inform. 25 (3) (2011) 507–515.

[90] S. Chi, C.H. Caldas, Automated object identification using optical video cameras on construction sites, Comput. Aided Civ. Infrastruct. Eng. 26 (5) (2011) 368–380.

[91] J. Teizer, F. Bosche, C.H. Caldas, C.T. Haas, K.A. Liapi, Real-time, three-dimensional object detection and modeling in construction, 22nd International Symposium on Automation and Robotics in Construction, ISARC, Ferrara, Italy, September 11-14 2005, pp. 1–5.

[92] J. Teizer, 3D range imaging camera sensing for active safety in construction, J. Inf. Technol. Constr. 13 (2008) 103–117.

[93] Z. Zhu, I. Brilakis, Comparison of optical sensor-based spatial data collection techniques for civil infrastructure modeling, J. Comput. Civ. Eng. 23 (3) (2009) 170–177.

[94] J. Teizer, B.S. Allread, U. Mantripragada, Automating the blind spot measurement of construction equipment, Autom. Constr. 19 (4) (2010) 491–501.

[95] S.J. Ray, J. Teizer, Real-time construction worker posture analysis for ergonomics training, Adv. Eng. Inform. 26 (2) (2012) 439–455.

[96] Z. Zhu and S. Donia (2013)."Spatial and visual data fusion for capturing, retrieval, and modeling of as-built building geometry and features." Vis. Eng., Vol. 1 (1), pp: 1–10.

[97] X. Wang, M. Truijens, L. Hou, Y. Wang, Y. Zhou, Integrating augmented reality with building information modeling: onsite construction process controlling for liquefied natural gas industry, Autom. Constr. 40 (2014) 96–105.

[98] S. Rankohi, L. Waugh, Review and analysis of augmented reality literature for construction industry, Vis. Eng. 1 (1) (2013) 1–18.

[99] A. Shirazi, A.H. Behzadan, Design and assessment of a mobile augmented reality-based information delivery tool for construction and civil engineering curriculum, J. Prof. Issues Eng. Educ. Pract. 141 (3) (2015) (4014012–1–4014012-10).

[100] G.D. Aschwanden, T. Wullschleger, H. Müller, G. Schmitt, Agent based evaluation of dynamic city models: a combination of human decision processes and an emission model for transportation based on acceleration and instantaneous speed, Autom. Constr. 22 (2012) 81–89.

[101] A. Russell, S.S. French, N. Tran, W. Wong, Visualizing high-rise building construction strategies using linear scheduling and 4D CAD, Autom. Constr. 18 (2) (2009) 219–236.

[102] A.Z. Sampaio, A.R. Gomes, J.P. Santos, Management of building supported on virtual interactive models: construction planning and preventive maintenance, J. Inf. Technol. Constr. 17 (2012) 121–133.

[103] L.S. Kang, H.S. Moon, N. Dawood, M. Kang, Development of methodology and virtual system for optimised simulation of road design data, Autom. Constr. 19 (8) (2010) 1000–1015.

[104] M. Golparvar-Fard, V. Balali, J.M. Garza, Segmentation and recognition of highway assets using image-based 3D point clouds and semantic Texton forests, J. Comput. Civ. Eng. 29 (1) (2015) 1–14.

[105] D.H. Shin, P.S. Dunston, Identification of application areas for augmented reality in industrial construction based on technology suitability, Autom. Constr. 17 (7) (2008) 882–894.

[106] I. Brilakis, H. Fathi, A. Rashidi, Progressive 3D reconstruction of infrastructure with videogrammetry, Autom. Constr. 20 (7) (2011) 884–895.

[107] Y.M. Ibrahim, A.P. Kaka, G. Aouad, M. Kagioglou, As-built documentation of construction sequence by integrating virtual reality with time-lapse movies, Archit. Eng. Design Manag. 4 (2) (2008) 73–84.

[108] M. Golparvar-Fard, F. Pena-Mora, S. Savarese, D^{4}AR – a 4-dimensional augmented reality model for automating construction progress monitoring data collection-processing and communication, J. Inf. Technol. Constr. 14 (2009) 129–153.

[109] X. Wang, M.J. Kim, P. Love, S.C. Kang, Augmented reality in built environment: classification and implications for future research, Autom. Constr. 32 (2013) 1–13.

[110] F. Pena-Mora, G. Dwivedi, Multiple device collaborative and real time analysis system for project management in civil engineering, J. Comput. Civ. Eng. 16 (1) (2002) 23–38.

[111] X. Wang, P. Love, M.J. Kim, W. Wang, Mutual awareness in collaborative design: an augmented reality integrated telepresence system, Comput. Ind. 65 (2) (2014) 314–324.

[112] M. Arashpour, R. Wakefield, N. Blismas, T. Maqsood, Autonomous production tracking for augmenting output in off-site construction, Autom. Constr. 53 (2015) 13–21.

[113] M.F. Ahmed, C.T. Haas, R. Haas, Automatic detection of cylindrical objects in built facilities, J. Comput. Civ. Eng. 28 (3) (2014) (4014009–1 - 4014009-11).

[114] A. Guarnieri, N. Milan, A. Vettore, Monitoring of complex structure for structural control using terrestrial laser scanning (TLS) and photogrammetry, Int. J. Archit. Herit. 7 (1) (2013) 54–67.

[115] S. Moon, B. Yang, Effective monitoring of the concrete pouring operation in an RFID-based environment, J. Comput. Civ. Eng. 24 (1) (2010) 108–116.

[116] R. Maalek, F. Sadeghpour, Accuracy assessment of ultra-wide band technology in tracking static resources in indoor construction scenarios, Autom. Constr. 30 (2013) 170–183.

[117] E. Valero, A. Adan, C. Cerrada, Automatic construction of 3D basic-semantic models of inhabited interiors using laser scanners and RFID sensors, Sensors 12 (5) (2012) 5705–5724, http://dx.doi.org/10.3390/s120505705.
[118] S.N. Razavi, C.T. Haas, Using reference RFID tags for calibrating the estimated locations of construction materials, Autom. Constr. 20 (6) (2011) 677–685.
[119] D. Liu, B. Cui, Y. Liu, D. Zhong, Automatic control and real-time monitoring system for earth-rock dam material truck watering, Autom. Constr. 30 (2013) 70–80.
[120] A. Costin, N. Pradhananga, J. Teizer, Passive RFID and BIM for real-time Visualization and Location Tracking, Construction Research Congress: Construction in a Global Network, Atlanta, Georgia, May 19-21 2014, pp. 169–178, http://dx.doi.org/10.1061/9780784413517.018.
[121] A.H. Behzadan, S. Dong, V.R. Kamat, Augmented reality visualization: a review of civil infrastructure system applications, Adv. Eng. Inform. 29 (2) (2015) 252–267.
[122] C. Eastman, P. Teicholz, R. Sacks, and K. Liston. (2011). "BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors." 2nd ed. Publisher: John Wiley and Sons, Inc., Hoboken, New Jersey, 626 p.
[123] M. Johansson, M. Roupé, P.B. Sijtsema, Real-time visualization of building information models (BIM), Autom. Constr. 54 (2015) 69–82.
[124] M. Golparvar-Fard, F. Pena-Mora, S. Savarese, Integrated sequential as-built and as-planned representation with D^{4}AR tools in support of decision-making tasks in the AEC/FM industry, J. Constr. Eng. Manag. 137 (12) (2011) 1099–1116.
[125] F. Bosche, M. Ahmed, Y. Turkan, C.T. Haas, R. Haas, The value of integrating scan-to-BIM and scan-vs-BIM techniques for construction monitoring using laser scanning and BIM: the case of cylindrical MEP components, Autom. Constr. 49 (2015) 201–213.
[126] K.K. Han, M. Golparvar-Fard, Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs, Autom. Constr. 53 (2015) 44–57.
[127] V. Patraucean, I. Armeni, M. Nahangi, J. Yeung, I. Brilakis, C.T. Haas, State of research in automatic as-built modelling, Adv. Eng. Inform. 29 (2) (2015) 162–171.
[128] Construction Superintendent [Computer software]. (2014). Accessed online on Aug. 10, 2014 at www.constructioncentric.com.
[129] Autodesk BIM 360 Field [Computer software]. (2014). Accessed online on Aug. 12, 2014 at www.bim360field.com.
[130] Asta Powerproject [Computer software]. (2014). Accessed online Aug. 11, 2014 at www.astadev.com
[131] Bridgit [Computer software]. (2014). Accessed online on Aug. 13, 2014 at www.gobridgit.com.
[132] iBeacon [Computer software]. (2014). Accessed online on Aug. 14, 2014 at www.ibeacon.com.
[133] Creaform [Computer software]. (2014). Accessed online on Aug. 15, 2014 at www.creaform3d.com.
[134] BIManywhere [Computer software]. (2014). Accessed online on Aug. 16, 2014 at www.bimanywhere.com.