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Image-Based Modeling Approaches for Projects Status Comparison

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Abstract: Project professionals frequently compare as-planned models with the as-built status to re-plan and coordinate site work, control project quality, monitor progress, detect defects, and inspect building health. During the last few years significant research has been undertaken on image-based modeling (IBM) techniques for construction projects. This paper investigates current IBM tools and techniques for project status comparison to identify gaps and overlaps in this area. To provide a state-of-the-art study on this topic, this research reviews 93 articles published in 16 civil engineering journals and conference databases between 2005 and the summer 2013. Based on reviewing these 93 articles, authors developed a process framework for image-based project monitoring systems. Moreover, among those 93 articles, ten articles have been selected based on their comparison technique and purposes. These ten articles are further investigated from the following perspectives: (a) image-based modeling approaches (collection, analysis, and representation); (b) process followed, product produced, and resource used in each image-based modeling phase (as-planned modeling, as-built modeling, and status comparison). In summary, literature shows that the majority of articles have focused on using off-the-shelf image-based modeling hardware (digital camera, 3D range camera, and laser scanner) and software (BIM, AutoCAD and AutoDesk products) available for as-built and as-planned data modeling to automatically monitor project progress or detect defections. Moreover, literature shows lack of research in some areas including image-based modeling of interior construction; as-built verification and plan updating procedures; and validation of success for the developed image-based monitoring systems.

1 Introduction

The use of image modeling techniques in the construction engineering practices has tremendously increased in recent years. Photography which is referred as “writing with light,” is considered an efficient visualization technique to capture real-time construction information. Recent advances in electro-optical technologies have enabled off-the-shelf digital cameras to capture high quality images while preserving the portability and convenience of taking pictures (Dai 2011). Construction participants take daily photographs on construction sites for documentary purposes, while these photographs could also have other essential applications such as monitoring progress, resolving disputes and training for similar projects (Rankohi 2013).

This paper discusses how digital photographs have been and could be applied in the construction engineering industry for comparison between the as-planned and as-built status, to monitor the project progress and to control discrepancies. The work presented in this paper provides a state-of-the-art review of research efforts undertaken in this area of knowledge, and outlines the research voids and opportunities for future applications of construction photographs to monitor and control projects.

2 Background

Research efforts in using photographs for construction progress monitoring goes back before the year 1989, when photography enabled analysts to conduct studies on time-lapse site photographs for productivity enhancement (Oglesby 1989). Visualization of project progress through comparison of site images and building model information has been recognized by many researchers as an effective way to monitor progress and control performance (Abeid 2003, Kerzner 2005, Song 2005, Lee 2006, Poku 2006, Waugh 2006, Golparvar-Fard 2009, Dai 2011, Zhu 2012, Yang 2013).

In this industry sector, researchers have developed various image-based applications for documenting and monitoring construction projects in recent years. Waugh (VR Doc. 2013) developed a web-based panoramic project monitoring system, which enables project managers to remotely monitor and compare construction site status on specific dates and at specific locations. Bae (2013) developed an image-based mobile augmented reality system for context-aware construction applications, which allows site personnel to access a large volume of information in real-time. The ENMAX Corporation (2013) developed an image-based construction monitoring system at Alberta's largest natural gas-fired generation facility project which allows viewers to follow the construction progress on a regular basis.

3 Research Method

The research methodology used in this paper consists of: (a) selecting the leading journals and conferences in the area of IT and construction engineering, (b) identifying the articles in the field of image-based modeling techniques, (c) reviewing the identified articles and selecting ten articles with a focus on comparing as-planned and as-built status, (d) reviewing the ten selected articles and defining their dimensions and categories (e) classifying the articles in the defined dimensions and categories.

Each paper was reviewed to determine its level of relevance to our research domain. To focus on recent work, only articles published from the spring 2005 to the summer 2013 were considered. The criteria for identifying papers was image-based modeling work in the areas of construction engineering and management. Those articles that concentrated solely on image-based modeling rather than their applications in construction management were excluded. Considering that image-based modeling for the construction industry is an emerging area and there are not a significant number of journal articles, we also searched the leading construction engineering research conferences. Unfortunately, we were limited to databases that were electronically accessible and as a result we were unable to search ConVR conference proceedings. Table 1 shows the number of articles from each journal and conference.

Table 1: The number of selected articles from each journal and conference

Sources	Number of articles
Journals	
ASCE: Computing in Civil Engineering (CCE)	26
Automation in construction (AIC)	19
ASCE: Construction Engineering and Management (CEM)	15
Advanced Engineering Informatics (AEI)	8
Computer-Aided Civil and Infrastructure Engineering (CACIE)	4
Information Technology in Construction (ITCON)	3
Infrastructure Systems (IS)	1
Management in Engineering (MIE)	1
Canadian Journal of Civil Engineering (CJCE)	1
Conferences	
International Association for Automation and Robotics in Construction (IAARC)	5
International Conference on Computing in Civil and Building Engineering (ICCCBE)	3
Construction Research Congress (CRC)	3
Cold Region Engineering (CRE)	1
International Conference of Chinese Transportation Professionals (ICCTP)	1
Analysis and Computation Specialty Conference (ACSC)	1
European Conference on Product and Process Modeling (ECPPM)	1
Total	**93**

4 Literature Analysis

The distribution of articles by year of publication and first author's country of residence is shown in Figure 1. The maximum number of articles in a calendar year were published in 2011 (19 articles or 20%), while 16 articles (17%) are published in 2013 (by the end of summer). With 53 articles (57%), first authors residing in the USA has the highest number of the articles.

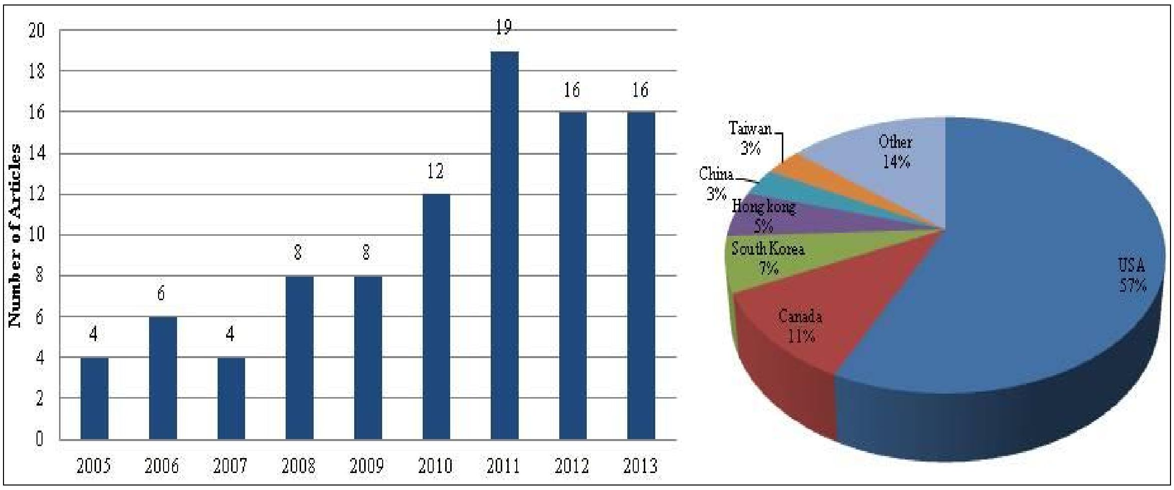

Figure 1: Number of articles by year of publication and first author's country of residence

Figure 2 shows 64 articles (69%) and 25 articles (27%) respectively focus on image-based modeling techniques in the construction and maintenance phases of the projects. From a comparison-purpose perspective, 28%, 20% and 17% of articles use image-based modeling techniques for progress monitoring, defect detection and spatial data collection respectively.

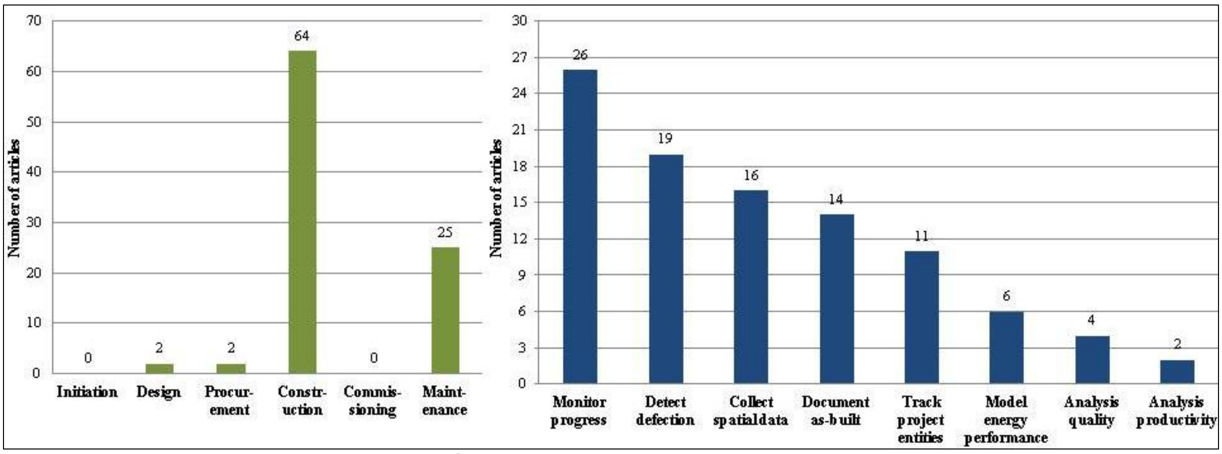

Figure 2: Number of article by project phase and comparison purpose

Figure 3 shows a process overview of image-based project monitoring systems. This flowchart was initially generated based on review of a limited number of articles and the authors' personal experience. It was refined as the authors reviewed all 93 articles and then further refined based on the ten selected articles.

The flowchart indicates image-based modeling techniques for the construction industry consist of three major phases: (a) as-planned modeling, (b) as-built modeling, and (c) status comparison. Each of these phases has steps, and the process will loop if the model is revised or the schedule is updated.

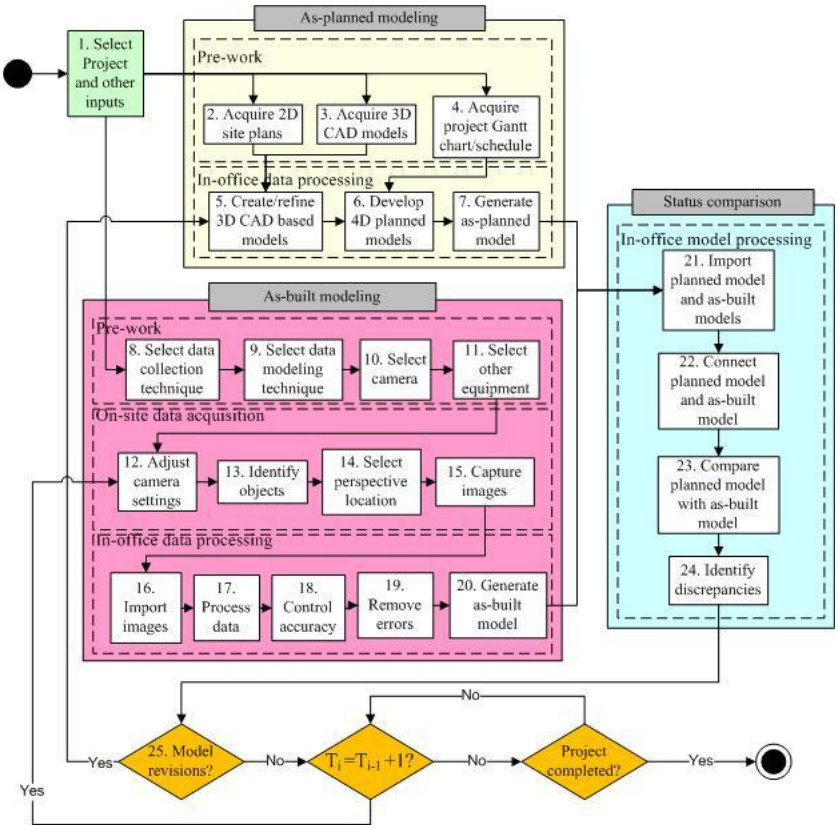

Figure 3: Generate image-based construction monitoring process

5 The Ten Selected Articles

5.1 Selection Methodology

From the 93 identified articles, ten articles were selected that focus on comparing as-planned and as-built models. The following criteria were used to select these ten articles: comparison of as-planned and as-built models, diversity of research method, diversity of the first author's country of residence, and year of publication (since 2008). It worth mentioning that we selected these ten articles based on our interpretation, however, we acknowledge that other people might interpret them differently.

Table 2 lists the ten selected papers with their comparison approach and purpose. As shown, seven of the ten selected articles focus on automatic comparison for project monitoring while two articles develop manual comparison approach.

Table 2: Comparison approach and purpose of the ten selected articles

Paper	Comparison technique	Comparison purpose
1. Kim et al. 2008	Manual	To develop a system for performing comparison between construction images and the corresponding VR images and to validate the proposed system
2. Rebolj et al. 2008	Automatic	To develop a system for automating data collection, automating construction activity monitoring, and updating the activity plan.
3. Son et al. 2010	Automatic	To develop an automated 3D structural steel component recognition and modeling method which employs color and 3D data from a stereo vision system for monitoring project progress.
4. Roh et al. 2011	Automatic	To develop a walk-through model to visualize and compare 3D BIMs and as-built photographs for monitoring detailed interior construction progress.
5. Dai et al. 2011	NA	To propose an analytical approach to incorporate virtual photos of invisible underground infrastructure into site photos.
6. Bhatla et al.	Manual	To generate photo-based models from photos taken with handheld digital cameras,

2012		compare them to the actual as-built model (developed using 2D drawings), and check the accuracy of the modeling process.
7. Golparvar-Fard et al. 2012	Automatic	To develop an automated approach for recognition of project progress based on daily construction photo collection, and IFC-based BIMs.
8. Kim et al. 2013 a	Automatic	To develop an automated method for construction progress measurement using a 4D BIM in concert with 3D data obtained by remote-sensing technology.
9. Kim et al. 2013 b	Automatic	To develop an image processing-based methodology for the automatic updating of a 4D CAD model.
10. Turkan et al. 2013	Automatic	To propose a 4D automated progress tracking system for construction monitoring that transforms from objects to their earned values.

Within the selected articles the automatic image-based modeling *techniques* (through batch processing techniques) are the most frequent. Moreover, image-based modeling techniques have been used for various *purposes* e.g., progress monitoring, defect detection, spatial data collection, as-built documentation, tracking project entities, energy performance modeling, quality analysis, productivity analysis. Among these, progress monitoring and defect detection have received the highest attention.

5.2 Image-based Modeling Approaches

In this section, image-based modeling approaches are divided in three categories: collection, analysis, and representation. Table 3 indicates the collection, analysis, and representation processes for the ten selected articles that are listed in Table 2. From a collection perspective, most of the articles focus on digital imagery for collecting as-built information. Five of the ten selected articles focus on a combination of as-built images and 3D CAD models, while an overlapping five articles refer to the application of BIM in project monitoring. From an analysis perspective, the articles mainly focus on photo registration, object detection, 3D coordinate generation, and photo augmentation. From a representation perspective, the 3D models are mostly overlaid on 3D as-built point clouds and the discrepancies between as-planned and as-built status is automatically detected.

Table 3: Image-based modeling approaches for the ten selected articles

	Collection	**Analysis**	**Representation**
1.	As-built photographs using fixed-point camera (continuum and momentary), and 3D CAD model	VR model registration and photo augmentation by determination of camera 3D viewpoint	3D model overlaid on as-built photographs for progress monitoring
2.	As-built 2D photographs, 3D CAD model, BIM, Gantt chart	Photo segmentation and object detection, registration of 4D model and site photos	4D BIM compare with site photos in split screen for material tracking, re-scheduling activity plan
3.	As-built 2D rectified images, 3D data using stereo vision system, 3D CAD models, project activities	Object recognition using color and 3D data, recognizing 2D and 3D structural components	3D CAD models register with the extracted 3D as-built data for progress monitoring
4.	As-built photographs, schedule and BIM (process and product model)	Object detection and matching, color coding index	3D model and as-built photograph in split screen for visual progress representation
5.	As-built photographs using ultrasonic camera and subsurface imaging technologies, and 3D CAD model	VR model registration and photo-augmentation	3D as-built model overlaid on as-built photographs for progress monitoring
6.	As-built photographs, laser scanner 3D point cloud (a university external wall)	Image 3D coordinates generation, comparing it with laser scanner 3D point cloud	3D as-built model, overlaid with 3D CAD model for dimension accuracy control
7.	As-built unordered daily photographs, schedule and 3D IFC-based BIM	Feature detection and matching, color coding, image as-built model generation	Colored and labeled detected 3D as-built elements and labeled as-planned models fed into the D^4AR viewer, overlaid to visualize progress deviations.
8.	As-built 3D date (remote sensing methods), laser scanner 3D point cloud, as-planned data extracted from BIM	3D as-built data registration with 3D model	3D as-built model, overlaid with as-planned model for progress monitoring
9.	As-built photographs (under construction bridge), project schedule, project 3D CAD models	3D CAD-based image filters generation from as-built photographs, color coding	Updated 4D CAD model by integrating schedule information and 3D models
10.	As-built 3D point cloud data acquired by laser scanner, Gantt chart, Earned value, WBS, and BIM	4D object detection and matching, color coding, Co-registering 4D model and 3D point clouds	Updated schedule by co-registering 3D as-built point clouds and 4D model for progress monitoring

The selected articles show that among other data collection techniques in the construction industry, digital photography stands in the first place in terms of accessibility, affordability, and accuracy. From an analysis perspective, researchers apply digital photogrammetry techniques e.g., 3D point cloud generation; model/image registration; photo-augmentation; object, feature, pattern, activity recognition; and as-built reconstruction to address project monitoring demands. From a representation perspective, 3D models/digital information are usually overlaid on as-built images in a common screen, and construction images are augmented which enables the user to track discrepancies and to control the project.

5.3 Image-based Modeling Phases

In this section the selected articles are reviewed from resource used, process followed, and product produced in each image-based modeling phases (as-planned modeling, as-built modeling, and status comparison) perspectives.

5.3.1 Resource used

Table 6 shows resources used during the image-based modeling process for the ten selected articles. In this table we only focus on technology resources (i.e., software, hardware, and equipment). Other resources are not considered, i.e., human resources (site staff/workers, project managers, etc.), natural resources (location, weather, etc.), service and material resources.

AutoCAD and BIM models are used in at least seven of the ten articles during as-planned modeling. Gantt charts, and WBS are being used for developing 4D plans (3D + time) project schedule. In one of the articles EV analysis is connected to as-built and as-planned models to control project cost and budget. From an as-built modeling perspective, most researchers use off-the-shelf portable digital cameras, and the literature analysis show only two of the ten articles use fixed-point cameras. In three of the ten selected articles laser scanners are also used to generate site 3D point clouds. From a status comparison perspective, most of the articles use off-the-shelf modeling software, while some of them use or develop custom comparison algorithms. Four of the ten selected articles use various Autodesk productions (i.e., Autodesk 3DS Max, Autodesk Photofly, Autodesk Revit, and Autodesk JetStream).

Table 4: As-planned, as-built, and comparison resource

Resource	As-planned modeling	As-built modeling	Status comparison
1.	AutoCAD, MicroStation, Autodesk 3DS Max, Visual Basic, WorldUp	Fixed-point camera (continuum and momentary), as-built photographs, tripod	VCS system, Autodesk 3DS Max
2.	3D CAD model, BIM, Gantt chart, Internet, 4D browser, BIM, MS Project	Camera, Single interface (4D browser) for activity, material and communication tracking	UMTS/GPRS internet network connection, Automated construction activity tracking system (4D-ACT)
3.	Bumblebee XB3 stereo vision system, Triclops software, Matlab for analysis and viewing	Stereo vision camera to provide a 2D rectified color image, Matlab software, HSI Model for color-based image processing object detection	Matlab software, 3D as-planned Data, As-built model
4.	3D CAD, BIM, Gantt Chart, WBS	Carry-on camera, site digital photographs, OpenCV (Open Source Computer Vision), Gentle Ada Boost	OpenGL (Open Graphics Library), BIM, Ray casting technique
5.	3D CAD, Autodesk 3DS Max	Koden Ultrasonic Drilling Monitor Model DM-602/604, Ultrasonic waves and ground penetrating radars, Koden test, subsurface imaging technologies	Autodesk 3DS Max 2009, 3D CAD planned model, 3D as-built model
6.	2D CAD drawing, 3D CAD model, Autodesk Revit, Autodesk Photofly	DSLR camera, and Leica GeoSystems ScanStation C10 laser scanner, 3D as-built point cloud	Autodesk Photofly, ANOVA analysis using Palisades StatTools
7.	IFC based BIM model, WBS, Project schedule	Digital image database, Digital camera, Structure from Motion (SfM) algorithm	Multi-View Stereo (MVS), Voxel coloring algorithm, Bayesian probabilistic model, Support vector machine (SVM) classifier, 3 control points for registeration
8.	4D BIM model, Autodesk Revit Architecture	Remote sensing, laser scanner, digital camera, color-model-based machine	Synchro, 4D BIM model

		learning algorithm proposed by Son et al. (2012)	
9.	AutoCAD 3D, Autodesk Revit Architecture, Autodesk JetStream v5	Closed-circuit television (CCTV) camera, Server and wireless data transfer system, Microsoft Excel spreadsheet, MATLAB image processing toolbox, Microsoft Project	Autodesk JetStream v5 TimeLiner module
10.	Gantt chart, WBS, BIM, EV, Auto CAD 3D	Trimble GX 3D laser scanner, 3D Range Camera	Object detection algorithm (Bosché and Haas (2008) and Bosché (2010))

The majority of articles follow a common process to generate as-planned and as-built models (Table 4). From a product perspective, the following are generated to monitor activities and control construction project at different stages: 3D and 4D (3D + time) as-planned models; 2D as-built photo-logs and 3D as-built models; and virtual image-based project monitoring systems e.g., VCS, 4D-ACT, HD4AR. From a resource perspective, the following have been used for states comparison depends on the type of product: AutoCAD, BIM, Gantt chart, WBS for as-planned modeling; 2D digital camera, 3D range camera, stereo vision camera, 3D laser scanners, and various image-processing software and algorithm (i.e., Matlab, Image modeler, SfM algorithm) for as-built modeling; and VR visualization software e.g., Autodesk Photofly, 3DS Max, and Synchro.

5.3.2 Process followed

Table 4 shows which image-based modeling process steps (based on the step numbers given in Figure 1) each of the ten selected articles (listed in Table 2) followed. All the articles follow at least 19 of the 25 defined steps. Moreover, five of the 25 process steps for as-built modeling are fully covered by all the ten selected articles. It is also shown that only three articles follow step 25 (revise model/update schedule).

Table 5: As-planned, as-built, and comparison process

Process	**As-planned modeling**							**As-built modeling**													**Status comparison**				
	Pre-work				**In-office modeling**			**Pre-work**				**On-site data acquisition**			**In-office modeling**						**In-office model processing**				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
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5.3.3 Product produced

Table 5 shows the products (interim results) for the three phases during the image-based modeling process for the ten selected articles. As-planned modeling usually results in 4D planned models (half of the ten selected articles). During the as-built modeling phase, seven of the ten selected articles produced 3D as-built models. Finally during status comparison process most of researchers developed a system which automatically compares the as-planned and as-built status and reports the discrepancies.

Table 6: As-planned, as-built, and comparison product

Product	**As-planned modeling**	**As-built modeling**	**Status comparison**
1.	3D CAD system, VR system and a CG system	Construction site 2D as-built digital images, and videos captured on the project foundation	Virtual construction site (VCS) system to control project progress, a walk-through system
2.	4D as-planned model with virtual camera view, 4D as-planned model connect to BIM to track activity	2D site as-built photos, Mobile computing system for communication, image-based activity and material tracking system	An automated activity tracking system (4D-ACT), an automated material tracking system, and a mobile communication system
3.	3D and 4D CAD as-planned models	2D site as-built images, RGB images, 3D data, Steel frame 2D and 3D	3D As-built model overlaid by 3D as-planned model for progress

		extracted objects, and as-built model	monitoring
4.	3D as-planned models integrated with project schedule and BIM	3D As-built model, and as-built visualization of interior building in a walk-through environment	3D Walk-through model to compare as-planned and as-built for progress monitoring
5.	3D as-built virtual model of underground structure	A 3D as-built model of the bored pile which is built based on the Koden test	As-built construction 2D images overlaid by 3D as-built model of underground structure for visualization/progress monitoring
6.	3D CAD model generated by CAD and Autodesk Revit	Accurate 3D as-built image-based model, 3D point cloud from laser scanner, and site photographs	3D as-built model of under-construction bridge, overlaid by 3D CAD model to control dimensions
7.	4D as-planned model generated by BIM model and construction schedule, as-planned voxel coloring and labeling algorithm	Dense 3D as-built model, as-built voxels, of RH (Residence Hall) and SD (Student Dining) projects, as-built voxel coloring and labeling algorithm	D^4AR model to automatically measure progress deviations
8.	4D BIM model generated by Autodesk Revit	3D point cloud of a new four-floor concrete building under construction in South Korea, 3D as-built data integrated with project schedule	An automatic construction progress measurement system using 4D BIM and 3D as-built data
9.	3D model converted into the files with the JetStream format, Planned schedule in MS Project format	HSV images, Gray scale images, Binary images, 3D CAD-based image masks	An updated 4D CAD model by combining the as-built schedule with a 3D CAD model
10.	4D model include design and schedule data for the Portland's Energy Centre in Toronto and the Engineering V Building at University of Waterloo	3D point cloud of the Portland's Energy Centre in Toronto and the Engineering V Building at University of Waterloo	An automated object-based construction progress tracking system

6 Discussion and Recommendations

6.1 Our assumptions about the researchers' goals

The literature shows that researchers mainly seek to develop an automatic image-based monitoring system to connect the BIM and the project schedule to daily construction images. This would enable users to compare as-planned with as-built status and detect deviations and thereby monitor project progress. In addition to progress monitoring and defect detection, a few researchers pursued other image-based modeling applications on construction projects i.e., activity monitoring, as-built documentation, tracking project entities, energy performance modeling, productivity analysis, QC/QA analysis, and safety monitoring. These applications are also interesting areas of focus for future research. Moreover, the literature shows that many researchers aim to connect project as-built data bases to the BIMs and project schedule in order to improve construction process analysis, design coordination, team collaboration, information visualization, and project schedule organization.

6.2 Gaps in the research

The literature shows that image-based modeling techniques for project monitoring are still under development, and that there remain research gaps to be addressed for image-based modeling techniques to become standard practices. The following gaps have been identified in this study:

- Construction project: there is a gap in the application of image-based modeling techniques in the maintenance and initiation/design phases of the construction projects. Moreover, most of current research applies these techniques on outdoor construction sites, and there is a gap in the application of IBM techniques on interior and indoor construction sites.
- As-built verification and updating procedures: there is a gap in using image-based modeling techniques for updating the project plan or rescheduling/updating the project schedule to reflect project changes.
- Validation of success: only a few studies show that the success of the developed systems has been tested and validated in practice. Therefore, there is a gap in evaluating and validating the success of image-based modeling approach for monitoring construction projects.

6.3 What practitioners actually want

Our perception is that project participants prefer automated approaches to fast-track project activities and rapidly detect defections. From a content perspective we assume construction industry practitioner would seek automated access to project real-time as-built information integrated with as-model information (e.g., BIM, EV, WBS, etc.). From a representation perspective, they would seek a portable (mobile) remotely accessible user friendly interface that can be integrated into their content workflow process and that facilitate the comparison of project statuses over time. From a value perspective, we further assume that they would seek an affordable cost (initial and ongoing) for which the payback period is short; a system which enables early detection of project failures to prevent schedule delay and cost overruns.

6.4 Recommendations for researchers

Based on this review, our recommendation for researchers in the area of image-based visualization techniques for the construction industry is that analyzing construction models requires more comprehensive systems to overcome limitations of existing stand-alone approaches. There is an opportunity for more research on the combination of different types of data acquisition sensors (e.g., 2D digital cameras, 3D range cameras, laser scanners) with high levels of accuracy and measurement range that will increase the reliability and accuracy of image-based modeling methods. From a monitoring perspective, we recommend development of current systems to enable more detailed interior project monitoring with fusion of different project management resource e.g., 3D/4D BIM, project schedule, WBS, and EV. BIM technology has to be used to its full extent in combination with the project schedule and budget to generate a comprehensive project as-planned model. Moreover, a method of consistent activity definition for BIM elements has to be developed. From an image-processing perspective, we recommend expansion of current systems to allow advanced object detection, pattern detection, material recognition (e.g., concrete, steel, masonry, and timber), and activity recognition. In addition, the assessment of success of developed systems should be validated by researcher and practitioner from academy and industry. From an application perspective, besides progress monitoring and defect detection, other comparison purposes which are mentioned in section 6.1 should be further investigated.

6.5 Recommendations for practitioners

The literature shows that the current image-based approaches are not yet extended to their full potential; however with future technological advancements, the construction industry will be able to reap full benefits of these emerging technologies. We believe that the construction industry greatly benefits from image-based monitoring systems from various perspectives mentioned in section 6.1. Current trial systems are in their development stage, and they have limitations due to expensive and fragile equipment, lack of accessibility, portability and trained operators. However, as the technology is swiftly evolving, recently developed systems offer valuable features and may provide competitive advantages to industry participants. Therefore, we recommend that practitioners interested in using these technologies as a competitive advantage, monitor new application developments and build up a partnership with a research team in order to get the latest updates on the newly developed systems. Moreover, the application of image-based modeling systems requires a good understanding of its concepts and components by all participants, therefore additional education and training for all project participants is essential.

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