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# A Review of Automated Construction Progress Monitoring and Inspection Methods

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## Abstract

Accurate assessment of progress allows managers to make adjustments to minimise costs when deviations from the schedule occur. Current practices of predicting the performance of a construction team require inspections that are still mainly manual, time consuming and can contain errors. Improper understanding of the current status can lead to further errors and unsuitable adjustments by the managing team, leading to more delays and increased cost. The problem is amplified when inspections take place in interior environments where the tasks are more complex. Efficient progress monitoring systems can help automate progress inspections, reduce the risks of error, facilitate proper and timely corrective actions, and prevent deviations in terms of cost and schedule. This paper presents a literature synthesis and interpretation of the state-of-the-art progress monitoring methods in terms of (a) data acquisition, as in technologies that are used for capturing the as-built scenes, (b) information retrieval, as in extracting the information needed from the as-built data, (c) progress estimation, which includes the comparison between the as-built and as-planned model in order to define the progress status and (d) visualisation of the results. The methods reviewed were categorised in terms of the technology used and assessed in terms of utility, time efficiency, accuracy, level of automation, required preparation, training requirements, cost and mobility. The review concludes with a recommendation of the most appropriate technologies to use based on the type of activities, environment and the needs of the inspection.

**Keywords:** Automated Progress Monitoring, Inspection

## 1 Introduction

Monitoring and controlling a construction project according to the Project Management Body of Knowledge “*consists of those processes required to track, review, and orchestrate the progress and performance of a project; identify any areas in which changes to the plan are required; and initiate the corresponding changes*”. These processes involve the measurement of the progress through inspections and the comparison with the project plan in order to validate the predicted performance. Progress monitoring is considered as a critical success factor for projects to be delivered on time and within budget (Iyer & Jha, 2005) and as one of the most difficult tasks due to the complexity and interdependency of activities. Thus, it is one of the highest challenges that a project manager has to encounter (Saidi et al. 2003; Zhang et al., 2009).

Accurate and timely information of the progress in a regular repeated basis is needed for a well maintained and efficient project control that will ensure cost and time efficiency of the project. Hence, an efficient on site data collection, a timely data analysis and a communication of the results in a well interpreted way are major concerns for construction companies (Saidi et al., 2003). Regular repeated inspections allow managers to identify deficiencies in an early stage, prevent potential upcoming delays because tasks are linked, and make timely decisions for corrective actions (Maalek & Sadeghpour, 2012). As a result, the possibility of unpredicted costs from delays, reworks, disputes and

claims (Yates & Epstein, 2006) are mitigated (Semple et al., 1994). On the other hand, insufficient management and low quality control can cause delays, decrease in project profitability, cost increase (Zavadskas et al., 2014) and have severe impacts on productivity (Yi & Chan, 2014). The time it takes to identify the discrepancies between the as-planned and as-built model is proportional to the cost and to the difficulty to implement corrective measures. (Navon & Shpatnitsky, 2005).

Despite project control being very important, the construction industry does not have efficient monitoring systems compared to other industries (Navon & Sacks, 2007). One reason for this is that traditional methods of collecting data on the progress of construction projects still remain mainly manual (Navon, 2005) since they are usually performed by visual inspections (Zavadskas et al., 2014). Data acquisition is labour intensive as the inspector has to fill forms on site and requires extensive data extraction from drawings and databases which requires a lot of time and calculations (Navon, 2007). Many schedule delays and cost overruns in interior construction are caused by misunderstanding of complicated interior works (Koo & Flischer, 2000). A more systemised way of the reports has been recently introduced by using web-based technologies. However, the quality of the collected progress data highly depends on the inspector's experience and on the quality of measurements (Golparvar-Fard et al., 2009). Elazouni & Abdel-Wahhab (2009) noted that field inspection is subjected to uncertainty and inconsistency because the level of education and training of the inspector varies and thus, progress estimation can be subjective and can contain errors. Hollis & Bright (1999) conducted a survey regarding defect identification in a building where it was found that inspections by different people lack of consistency. In addition to this, Cox et al. (2003) noted that the estimation of the percentage of completion is highly subjective.

After the required data has been collected, data analysis is carried out to assess project performance. McCullough (1997) noted that managers spend, on average, 30–50% of their time to record and analyse site data due to the manual nature of monitoring and controlling methods and thus, they are distracted from other important tasks.

The means of representing potential discrepancies between the as-planned and as-built progress is one major factor to facilitate decision making for corrective actions. The majority of time in meetings is spent on descriptive (35%) and explanative (42%) tasks and only 12% and 11% of the time is spent on evaluative and predictive tasks respectively (Golparvar-Fard, 2006). One of the major reasons for this, is the lack of adequate means to visualise and represent the information (Lee & Pena-Mora, 2006).

Recently, there have been efforts on automating project monitoring which have shown the potential for effective construction project control. One of the automations applied to the construction industry is the adoption of Building Information Modelling (BIM). Commercial inspection software packages that use BIM model to facilitate inspection process such as LATISTA, Autodesk BIM 360 Field, Field 3D, xBIM, etc. offer to the inspector the ability to use a mobile device (Tablet PC) instead of paper documents. These software packages are very effective at issues regarding document management, but the inspection process itself has not been automated since the inspector still has to manually navigate around the BIM model while visually inspecting the building. Another survey (Gheisari et al., 2014) has shown that users prefer a mobile-based augmented reality system for inspection compared to a paper-based one as it is simpler and faster. Although the aforementioned survey was conducted for facility management purposes, it shows that mobile based augmented reality systems for inspection (e.g. BIManywhere) can be also an asset for progress monitoring. However, in that case, an installation and maintenance of QR codes is needed which is inefficient given the dynamic environment of construction projects. Such technologies do not address the subjectivity of reports and the time required for the data analysis, but only facilitate the user to have access to needed information.

Also, some companies are now shifting to automated data acquisition using Global Positioning System (GPS), barcodes, Radio-frequency identification (RFID), video and audio technologies or laser scanners (Navon & Sacks, 2007). Skansa, for example, used an RFID-based progress monitoring system to track pre-cast structural elements (Sawyer, 2008). However, not all construction elements can be tagged with RFIDs and an additional investment on equipment and human effort is required. Remote-controlled web-based cameras are also used for remote monitoring of construction sites (e.g. Oxblue) (Gomez, 2008) but their use is limited to outdoor scenes.

It can be alleged that no current practices offer an automated data analysis to estimate progress status and although there are technologies that can facilitate the visualisation of the results of the

progress estimation analysis, these technologies have not been yet implemented. However, there are technologies and methods in the literature, which will be described in the following section, that could assist the automation of progress monitoring. A map that presents the benefits and the disadvantages of each method could help inspectors to choose the best applicable case for their purposes and improve the efficiency and quality of their work.

## **2 Related Work**

An automated progress monitoring process could be divided into the following steps (a) data acquisition, which refers to sensing technologies that are used for capturing the as-built scenes, (b) information retrieval, which involves the processing for extracting the information needed from the as-built data, (c) progress estimation which includes the comparison between the as-built and as-planned model to define the progress status and (d) visualisation of the results.

### **2.1 Data acquisition**

Radio-frequency Identification (RFID) technologies have been used for inspection purposes in order to retrieve on-site data (Song et al., 2006; 2007; Ergen et al., 2007; Kim et al., 2009; Grau et al., 2012) and integrate it into a BIM model (Wang et al., 2014). Using this technology, the inspector can automatically retrieve information by scanning the tag using a smartphone or a tablet PC. Although this process facilitates data acquisition of important information and it can work with available commercial BIM-based inspection software, it still requires the installation and maintenance of RFID tags. Additional time and investment is needed and its implementation is difficult in a daily changing construction environment.

Another popular method in automated progress monitoring is to collect as-built data using laser scanning based methods. The acquired data from a laser scanner consists of a point cloud within a 3D coordinate system in which every point is described by x, y and z coordinates. Although, laser scanners offer high accuracy, their use is limited because they are still expensive, they require high cost for maintenance and they need trained users. The discontinuity of spatial data, the needed mixed-pixel restoration (Kiziltas et al. 2008), the need for regular sensor calibrations and a slow warm-up time are additional disadvantages (Golparvar-fard et al., 2012). Moreover, noisy data can be caused by moving machinery and personnel. Also, laser scanners are not easily portable and their resolution decreases as distance increases (Golparvar-fard et al., 2012). El-Omari & Moselhi (2008) presented a method that combines laser scanning and photogrammetry in an attempt to enhance the speed and accuracy of data retrieval from construction sites. However, merging of the photo images and scanned data needs is carried out by manually selecting common points.

A different way to capture as built data is to use digital images and videos. It is a common method that can provide on-site information by tracking progress, sharing information between people and documenting the different phases of construction. Unlike laser scanners, image based systems are inexpensive and easy to use. Ibrahim & Kaka (2008) present a review of imaging applications in construction and Bohn & Teizer (2010) explore the benefits and challenges of progress monitoring using cameras. Images can be collected in different ways. The camera could be either monocular (Lukins & Trucco, 2007) or stereo (Son and Kim, 2010). Ibrahim et al. (2009), Zhang et al. (2009), and Rebolj et al. (2008) used a stable camera in a known fixed position and Golparvar Fard et al. (2009), Leung et al. (2008) and Abeid et al. (2003) suggested the installation of multiple cameras on a construction site. Fixed cameras provide limited views and are prone to occlusions, obstructions and weather conditions. Thus, a comprehensive depiction of progress is not possible. In order to overcome these limitations, in Golparvar-Fard et al. (2011) a number of photos were taken in and around the construction site.

Videos are also used for capturing spatial characteristics of civil infrastructure in the form of 3D point clouds (Brilakis et al., 2011; Rashidi et al., 2011). Continuous advancements on cameras and performance processing units enhance the accuracy of the obtained data, reduce the time of processing and increase the potential of using visual data for as-built data acquisition purposes.

Interior environments require different kind of data compared to exterior scenes. Exterior scenes consist mainly of outer columns, beams and walls. However, interior scenes consist of various construction elements (e.g. electrical, plumbing, fire protection etc.) and schedules related to many subcontractors. Many tasks in an interior environment are characterised by changes in surfaces of walls (e.g. painting, tiles, wooden floor, etc.) and mounted objects (e.g. windows, doors, etc.). Some

approaches that are used for exterior environments (Bosché, 2010; Lukins & Trucco, 2007; Golparvar-fard et al., 2012) can also be used for interior environments; however they do not address the aforementioned challenges. Thus, current research activities have not reached an efficient level of treatment of indoor environment challenges.

## **2.2 Information retrieval**

Regarding laser-scanning based methods, after the required number of scans, the obtained point cloud has the 3D information that is needed for the comparison between the as-planned 3D model and thus, they do not need much further processing. However, in a point cloud it is difficult to separate objects because the points are unorderedly scattered and do not include any object related information. Point cloud processing for object detection purposes requires time and it is computationally expensive.

Regarding images and videos, in the past, data was mainly manually analysed. However, recently, a number of automated techniques have been presented for analysing and interpreting image data to retrieve information of the construction as-built scene. The first is photogrammetry. AbdMajid et al. (2004), Memon et al. (2005) and Memon et al. (2006) applied photogrammetry in construction progress monitoring. The authors used photogrammetric techniques to extract 3D models from digital images. A similar application was proposed by Bayrak & Kaka (2004; 2005). Here, the authors used a library that contains a list of elements that make up the 3D model of the building. Although these systems provide useful means of facilitating progress measurement on construction sites, they still require a great deal of human input and same as point clouds, they do not contain object related information.

Other methods for extracting information from visual data use techniques from the areas of image processing and computer vision (Brilakis & Soibelman 2005). Retrieving data from construction site images which can be incomplete and noisy, is a difficult problem (Trucco & Kaka 2004). A simple approach that uses computer vision methods, is to compare a sequence of images from a fixed camera and find the differences in the construction process to estimate the progress (Lukins & Trucco, 2007; Ibrahim et al., 2009; Zhang et al., 2009). However, these methods have limited success rate and they are not fully automated. Automated detection and identification of building elements according to shape and materials have been proposed using image processing techniques (Brilakis et al., 2005; Zhu & Brilakis, 2010a;2010b; Zhu et al., 2010). Texture, colour and shape information has been used to classify construction materials such as concrete and steel (Brilakis & Soibelman, 2008; Zhu et al., 2010; Zhu & Brilakis, 2010a, 2010b) and to detect and count the number of bricks on a façade (Hui et al., 2014). Window detection (Lee & Nevatia, 2004; Ali et al., 2007) and door detection (Stoeter et al., 2000; Noz-Salinas et al., 2004; Shi & Samarabandu, 2006; Murillo et al., 2008; Hensler et al., 2010; Yang & Tian, 2010) algorithms have also been developed. Multiple views geometry for retrieving the 3D reconstruction of building structures has also been presented (Son & Kim, 2010; Golparvar-fard et al., 2009; 2011). However, Golparvar-Fard et al. (2011) and Klein et al. (2012) have shown that the points of the 3D reconstruction are not as accurate as the points obtained by laser scanners. The process of creating a sparse point cloud from images is time-consuming as it can lead up to 7 hours of additional computational time for a single column for image processing (Golparvar-Fard et al., 2011).

Although most efforts focus on outdoor environments, several approaches regarding indoor as-built data acquisition have also been introduced. Roh et al. (2011) have proposed an interior progress monitoring system that automatically detects construction objects in indoor images. However, this method is not efficient enough since many complexities associated with the interior environment lead to errors. Klein et al. (2012) have tested photogrammetry on indoor images to obtain dimensions of a room. The disadvantages of this method is the manual extraction of dimensions of indoor environment from sparse point clouds using photogrammetry and the need to install visual markers on walls to perform image stitching. Lin & Fang (2013) developed a computer vision based automated inspection system for tile alignment assessment. Whilst the process is highly efficient, the task of tiling is a very specific sub task and as a consequence, this method cannot be generalised for other inspections. In general, object detection in indoor environment is challenging due to the following reasons (Yang et al., 2010): (a) there are many variations of appearance of objects in different interior environments, (b) there are small variations in different object models and (c) most indoor objects lack of texture.

### 2.3 Progress estimation

The as-built information that has been retrieved from the previous step, either using point clouds or images or videos, needs to be compared with the as-planned information in order to assess the current status of progress, decide if the progress is behind, ahead or on schedule and take potential corrective actions. Usually a 4D BIM model (a BIM model including the time schedule of the tasks) is used as an as-planned model and the as-built models are superimposed on the 4D BIM to proceed with the comparison between the two models. The registration process has been performed manually (Memon et al., 2005; Zhang & Arditi, 2013) or in a semi-automated way (Golparvar-Fard et al., 2011; Bosché, 2010). An additional method that requires human interaction for registering the as-built and the as-planned model was presented by Roh et al. (2011) where the user has to assign contextual data such as time, location and perspective for each image.

Following the registration, the next step in progress estimation is the recognition of objects and the matching of the as-built object with the corresponding one in the as-planned model (Golparvar-Fard et al., 2012; Bosché, 2010, 2012; Turkan et al. 2012, 2013; Rebolj et al., 2008; Zhang & Arditi, 2013). Golparvar-Fard et al. (2012) use voxels and a probabilistic model to detect the progress. On the other hand, Bosché (2010; 2012) and Turkan et al. (2012; 2013) use a surface based recognition metric. The recognized surface is calculated for every object and if that surface exceeds a minimum threshold the object is considered as recognized. Zhang & Arditi (2013) developed a method that counts the number of points in the related portions of the point clouds. Rebolj et al. (2008) have compared a segmented site image and a model using an algorithm that recognizes differences between element features. The views of the model and the site image are assumed to show the same elements in the same perspective. The aforementioned methods could not work for interior environments and tasks such as painting or tiling since they only recognize if an object exists or not in the scene and they cannot perform in real time.

### 2.4 Visualisation

As mentioned in the first section, besides efficient on site data collection and timely data analysis, efficient visualisation of the progress inspection results is also essential. An efficient way to visualise the progress of a construction project is the use of Augmented Reality (AR). The main problem of Augmented Reality systems is the accurate alignment of computer generated and real world data (Koller et al., 1997; Azuma, 1997) which depends on the accuracy of tracking the user's viewing orientation and position.

In recent years the interest for Augmented Reality and its applications has increased. Several platforms have been introduced such as AMIRE, ARVIKA, StudierStube, DWARF, DART, etc (Izkara et al., 2007). Lee & Peña-Mora (2006) and Golparvar-Fard & Peña-Mora (2007) have explored the visualisation of construction progress. For progress monitoring purposes the as-planned image from the 3D model and an image from the as-built environment are superimposed. The superimposition leads to a clear visual comparison between what was scheduled and what has been completed. The augmented image can be linked to the schedule to quantify deviations (Lee & Peña-Mora, 2006). Different colours can be used for a better visualisation of the progress deviations (Lee & Peña-Mora, 2006; Song et al., 2005). Golparvar-Fard & Peña-Mora (2007) proposed a semi-automated system for visualising progress monitoring which aligns the as-planned and as-built views by manually choosing features. However, monitoring interior environments of buildings is difficult using fixed cameras. Using many cameras is also inefficient due to the dynamic environment of the construction site. These problems render interior progress monitoring more challenging. To overcome the aforementioned challenges, Golparvar-Fard et al. (2009; 2010) and Roh et al. (2009) have developed an augmented reality model for visualising progress status where the user is able to conduct virtual walkthroughs on the construction site and assess progress.

Other AR-based approaches for inspection (Cote et al. 2013; Shin & Dunston, 2009; 2010) use large and heavy equipment mounted on tripods at fixed positions. Although these systems lead to accurate positioning, they lack of mobility. Other AR applications use fiducial markers. Wang et al. (2014) used marker-based AR to facilitate onsite information for construction site activities and Kwon et al. (2014) to develop a defect management system for reinforced concrete. These systems require additional time to install the markers in the building. In order to eliminate the use of fiducial markers, Irizarry et al. (2013) introduced Infospot which is a mobile AR system for facility management. It uses three-axis gyroscope, accelerometer, Wi-Fi and digital compass hardware. However, the user is constrained

to stand in a specific location, the system needs the use of a Wi-Fi network and information has to be assigned to InfoSpots. Additional mobile systems that use AR rely on a combination of Global Positioning System (GPS) (Meža et al., 2014) and compasses for position and orientation determination respectively (Woodward et al., 2010). However, these systems suffer from low accuracy and they are unable to be used in indoor environments (Wing et al., 2005).

Marker-less augmented reality methods have been introduced in computer vision literature that allow alignment of real and virtual objects but they have not yet employed for BIM models.

### 3 Synthesis

The objective of this paper is to present a synthesis and a evaluation of the current state of research in automated progress monitoring. We have assessed the research (Table 2) according to the following criterias:

- Utility: applicability of the system in many different visual inspection tasks (indoors, outdoors, recognising several objects, etc.). High utility means that the system must be a general case solution.
- Time efficiency: time spent to use the system (in hours).
- Accuracy: precise results in the steps of the process (data acquisition, information retrieval, progress estimation). It also includes reliability.
- Level of automation: user's level of involvement on progress monitoring process' steps (registration of as-planned and as-built, information retrieval, data analysis).
- Required preparation: time need for making the system work (in hours).
- User's training requirements: how easily and without special knowledge the user can use the system.
- Cost: equipment, installation and maintenance cost (in pounds).
- Mobility: the ability to move the system freely and easily.

The research methods are not all equivalent systems, and so best effort has been made to keep the comparisons general and fair. All the methods are compared with an ideal case in which the method can be applied in multiple occasions, is fast, accurate, fully automated, does not require any preparation or specific training, and is cheap and easy to move.

Although laser scanner based methods address the criteria of accuracy, the level of automation for the data analysis is high and they can be applied for outdoor environments quite efficiently, they cannot address the challenges of an interior environment as mentioned in the previous section. Additionally, the time required for preparation, scanning and data processing does not allow this method to be applied in real time (in one hour the user can take approximately 10 scans, 45min for registration of scans and a lot of additional time for processing the point clouds). The equipment is expensive (~30000£), the level of mobility is low (it weights at least 5kg and the battery lasts only up to 5hrs), and the user has to be trained. Vision based methods were categorised into static image (where image processing techniques are applied) and reconstruction (where 3D reconstruction is performed from images). This separation is applied because they use different methods and their utility applies to different locations and/or phases of the project. More specifically, vision based reconstruction methods are similar to the laser scanner based methods in that they can be applied for outdoor environments only, and cannot address the challenges of tasks performed in interior environments. Moreover, the 3D reconstruction requires significant time and must be performed by an experienced person. Parts of these methods are not fully automated, as noted in the previous section, and the accuracy of the results varies. However, this family of methods does not need any special preparation since it uses images that are easy to be obtained by the user, the cost is small and the mobility level is high since the user only needs a handheld camera. On the other hand, most of the static image methods are limited to specific tasks, such as detection of doors, windows, concrete or steel columns, and thus their utility is limited. Additionally, many methods from this family need manual input in several steps of their process, and although they are accurate for simple tasks, they lead to errors when the environment gets more complex. The preparation required is minimum since the user only needs a camera which is cheap and easy to be carried. RFID methods have been used in multiple project locations (both indoors and outdoors) and in different phases of construction, and they can provide instant access to information. However, the analysis of the data is not automatically performed. Although no special training is required and the equipment is easy to be carried, they require additional time and cost for installation and maintenance. Mobile AR systems can be used in

multiple locations (indoors and outdoors) and phases of construction, and no special training is required to perform the task. Although current software packages can automate data management, they do not perform any data analysis for progress tracking. Stationary AR methods include large equipment, the cost of the camera they use is high (~10000£), and the placement of the equipment requires additional time. On the other hand, mobile AR systems use handheld equipment, the cost of the mobile phone or tablet pc is low, and they do not require any special preparation.

A rating system using colour is applied where white means good performance, grey means mediocre performance and black means poor performance. The rating system for each of the criteria is illustrated in Table 1. For each of the rating a brief explanation is presented as depicted in Table 2. Numeric data is given where applicable. The rest are qualitatively assessed.

Method	Good Performance	Mediocre Performance	Poor performance
Utility	General occasion solution	General occasion solution but with some limitations	Can be used only in limited occasions
Time Efficiency	Instant information retrieval	<1h	>1h
Accuracy	Precision in all steps	Precision in some steps	Errors in all steps
Level of Automation	Every step of the process is automated	Only some steps of the process are automated	None
Required Preparation	None	<1h	>1h
Training Requirements	None	Need for training, easy to learn	Specialised personnel
Cost	<£3000	£3000-10000	>£10000
Mobility	Handheld equipment	Large equipment	Large & heavy equipment

Table 1: Rating system of the criteria

	Mobile AR	Stationary AR	RFID	Laser Scanners	Vision Static Image	Vision Based Reconstruction	Ideal Case
Utility	multiple occasions	multiple occasions	multiple occasions	only spatial data	limited applications	only spatial data	multiple occasions
Time Efficiency	time spent on manual navigation of BIM	time spent on manual registration within registered view	instant information retrieval	time needed for scans	time spent on assigning manual information	time spent on the reconstruction	automatic information retrieval and assignment
Accuracy	AR registration, errors, subjective evaluation of progress	accurate AR registration, subjective evaluation of progress	subjective evaluation of progress	accurate	accurate for simple tasks	variable results, spatial data	accurate
Level of Automation	automated document management & data acquisition, no data analysis	automated document management & data acquisition, no data analysis	automated document management & data acquisition, no data analysis	automated document management & automated data analysis	partially automated data acquisition, automated data analysis	partially automated data acquisition, automated data analysis	fully automated
Required Preparation	minimal set-up required	set the equipment (<1h)	installation and maintenance of tags (>1h)	set the equipment (<1h)	minimal set-up required	minimal set-up required	minimum
Training Requirements	none	none	none	trained personnel for using the scanner	none	trained personnel for the reconstruction	none
Cost	consumer hardware	tracking cameras (£10000)	cost of installation & maintenance	laser scanner (£30000)	consumer hardware	consumer hardware	operates on commercial hardware
Mobility	handheld equipment	large equipment on tripod	handheld equipment	large & heavy equipment	handheld equipment	handheld equipment	handheld equipment

Table 2: Performance of solutions for progress monitoring inspection

## 4 Conclusion

This paper presented a literature synthesis and interpretation of the state-of-the-art research in automated progress monitoring. As depicted in Table 2, none of the proposed systems achieve the performance of the ideal case and depending on the situation (e.g. Indoors or outdoors, building type, available budget, accuracy etc.), the choice of the best method varies.

Mobile AR systems meet more of the requirements compared to the other proposed methods. They are cheap and easy to use in every environment but the systems that have been proposed so far by researchers and presented in the literature review, use either markers which require additional time and cost for installation and maintenance; or Geospots that limit user's location, need pre-processing and need the use of a WiFi network, or they do not perform in real time. Model-based augmented reality algorithms have been developed that could be used for the registration between the as-planned and as-built model, however, their performance within the constraints required of efficient real-time operation on a construction site has not been explored. In addition to this, the presented mobile AR systems do not perform any data processing for progress estimation purposes.

Laser scanning, image processing and computer vision techniques were mostly used in research to achieve automated progress estimation and have been customised towards outdoor scenes. Laser scanning could be considered as a promising tool for 3D-built data acquisition due to its high accuracy. However, it is expensive and it needs a considerable time especially for indoor environments which require larger number of scans to obtain information for every room in a building. Even if the point cloud is reconstructed from images (Golparvar-Fard et al., 2012), point clouds do not include any object related information and the processing of defining objects in them has not been fully developed. As a result, progress measurement for interior tasks such as tiling, painting etc. cannot be performed.

Photogrammetry has similar limitations. For indoor environments, it needs a large amount of overlapping images taken from several spots in a building. Processing the images to reconstruct the 3D scene of the interior scene leads to further computational and time cost.

In computer vision and image processing field, algorithms for detecting construction objects of interest have been developed, however each of them is limited in detecting only one object (concrete or steel elements, bricks, windows, doors). Thus, there is no general approach. Several research efforts that have focused on indoor progress monitoring provide only low level of automation. The user has either to manually assign information or to manually perform the comparison between the as-planned and as-built model. Moreover, systems fail when the interior environment is complex.

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