Construction Progress Monitoring and Reporting using Computer Vision Techniques – A Review

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Abstract –

In complex and dynamic construction sites, efficient progress monitoring and reporting play an important role in preventing schedule delays and cost overruns. Such reporting requires detailed and accurate records from job sites to help project managers in comparing project's current state to its as-planned state for enabling timely corrective actions. Currently used manual traditional progress reporting is time-consuming, costly, labor-intensive and can be inaccurate. Recently, there has been a shift toward utilization of digital images and computer vision techniques to overcome the above stated limitations and automate the tasks of progress reporting.

This paper investigates current practices and research works to provide an overview of the main computer vision techniques, tools and applications for progress monitoring and reporting using digital images. The paper also provides current achievements, challenges, and future research direction in this domain. According to the findings it can be concluded that computer vision is a promising path for improving the performance of automated progress monitoring systems in construction.

Keywords –

Progress Monitoring; Computer Vision; Object Detection; 3D Scene Reconstruction

1 Introduction

Monitoring and progress reporting are key management functions in delivering construction projects with least delays and cost overruns. In progress reporting, the current state of the project is compared to its as-planned state in order to identify unfavourable performance early and apply corrective actions in a timely manner [1], [2]. Construction progress monitoring and reporting encompass data collecting, storing, reviewing, reporting, and representing the findings in an efficient manner [1].

It is also crucial to do progress monitoring in a repeated manner in complex and dynamic construction sites to address potential problems such as unpredicted costs derived from improperly performed work, reworking, lack of coordination, inaccurately allocating resources, etc. [3], [4]. However, current progress monitoring and reporting in construction is a challenging task for project managers due to inefficient manual systems which are time consuming, erorr-prone and labor-intensive. In addition to manual reporting and updating schedules based on drawings, schedules, and paper surveys, these systems are dependent on experts and their visual inspections for data collection [5].

To address the above stated issues, it is crucial to have an automated system to collect and analyse data accurately, visualize and report the findings in an interpretable format for different responsible parties [5]. Recently, new technologies and methods have been introduced and applied in the construction industry to automate the processes of monitoring and progress reporting. These processes are: (a) data collection of captured as-built/as-is scenes, (b) data analysis of collected data, (c) progress estimation by comparing as-built and as-planned information, (d) visualization of the results [4] as shown in Figure 1.

In recent years, low-priced and high-resolution digital cameras with high-capacity memories enabled construction companies to make use of these cameras in data capturing of construction operations on sites. Digital cameras can produce a large number of images and videos on a daily basis from as-built scenes containing lots of useful and detailed information [5], [6]. However, due to different challenges in image analysis tools such

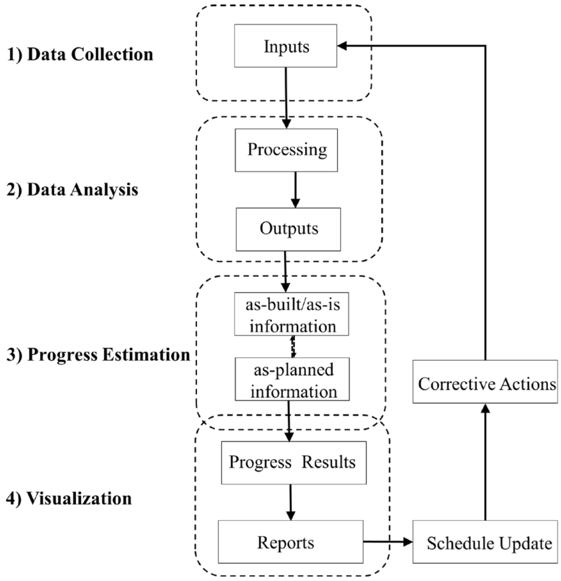

Figure 1 Construction Progress Monitoring and Reporting Process

as computation time, accuracy and cost, the images are analysed manually only for documentation and data recording purposes. As a result, only a small portion of this information were utilized and the rest became useless [6]–[8]. With developments in hardware platforms and algorithms, computer vision (CV) technology improved significantly [9]. Computer vision is a branch of artificial intelligence that uses computers to obtain high-level understanding from visual data, like human visual systems. During the last decade, computer vision has attracted many researchers due to its wide range applications in enhancing automation in construction. It can be applied for different project management purposes such as safety monitoring, quality control, productivity analysis and progress monitoring [10].

In progress monitoring systems which use computer vision techniques, the collected data are analyzed through different algorithms to have an understanding of the project's current state, then the results are compared with as-planned state to find progress deviations. Computer vision techniques can be categorized into 3D scene reconstruction, object tracking, object detection and image segmentation [8].

In recent years, the number of research studies related to automated progress monitoring and computer vision techniques in the construction industry has increased. Kopsida et al. [4] provided an in-depth review of automated progress monitoring steps and their related state-of-the-art technologies and methods. Patel et al. [11] explored recent developments, existing challenges, and future works for progress monitoring in the construction industry. Ekanayake et al. [12] reviewed different research studies regarding computer vision techniques for indoor progress monitoring.

The objective of this research is to provide a systematic review regarding recent developments in automated progress monitoring using digital images and computer vision techniques. Also, their applications in construction sites, related challenges and future works in this domain were discussed.

2 Research Methodology

This research adopted a systematic literature review to obtain findings and developments related to image-based progress monitoring using computer vision techniques. The literature was collected through search engine Google Scholar and academic databases such as ScienceDirect, ASCE, Springer, and IEEE Xplore. The keywords used in this study include: "construction progress monitoring", "digital images", "image processing", "computer vision", "object detection", "instance segmentation", "3D scene reconstruction", "as-built 3D reconstruction", "deep learning", "building information modeling". Then the related articles from peer-reviewed journals and conference proceedings were selected through analysing abstracts and titles. A total of 58 papers including 42 journal articles and 16 conference proceedings all written in the English language were selected and reviewed. The selected papers were stored by publication years, publication sources and the first author's country. As shown in Figure 2. these papers were published over a period from 2007 to 2021 and are categorized into "object detection and segmentation techniques", "3D reconstruction" and "review papers". The year 2021 has the highest number of published articles related to the topic.

Figure 3. shows country-based distribution of the selected articles, the United States has the highest number of publications, then the United Kingdom is the second. Figure 4. shows the number of publication sources. From 58 selected papers, the Automation in Construction journal has the highest number of published articles related to progress monitoring and computer vision techniques and after that is the Journal of Computing in Civil Engineering.

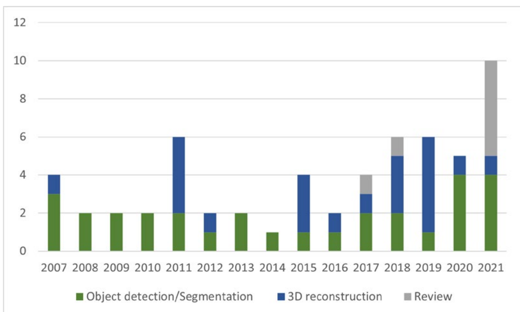

Figure 2. Chronological distribution of the selected articles

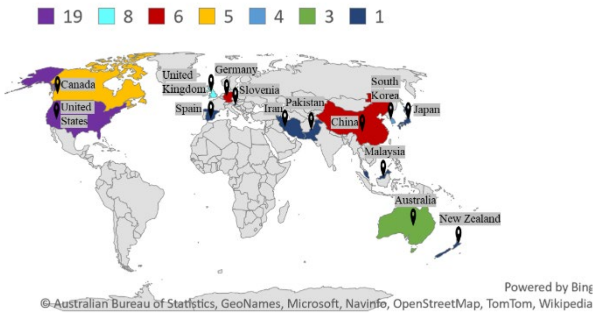

Figure 3. Country-based distribution of the selected articles.

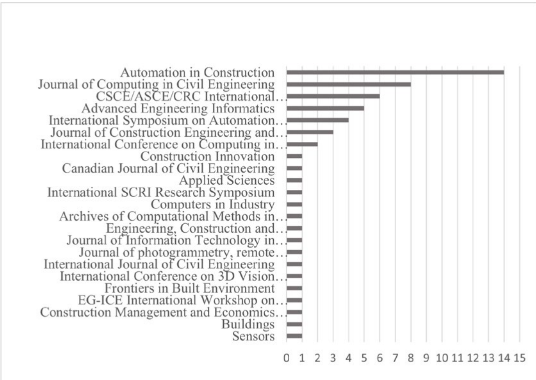

Figure 4. Number of publication and their sources.

3 Results and Discussion

An in-depth literature review reveals that three major computer vision techniques are used for construction progress monitoring and reporting using digital images, namely (i) 3D scene reconstruction, (ii) object detection, (iii) image segmentation. In this section, recent algorithms and technologies in these areas are discussed and the challenges are highlighted. In addition, the integration of building information modeling (BIM) with computer vision techniques are described subsequently in part 3.3.

3.1 3D Scene Reconstruction

In this technique, 3D representations (mesh models, point clouds and geometric models) are generated from one or multiple images taken from construction sites [13], [14] as shown in Figure 5. These 3D representations contain critical information pertinent to the current state of the project, which can then be compared to the as-planned state to track and report the project progress. For this purpose, collected data from cameras (monocular, stereo, video, panoramic, and RGB-Depth) is required to generate the point cloud models [13], [15].

Computer vision techniques and algorithms for generating 3D scene reconstruction are different due to the characteristics of the input images. The input images are categorized into single and multiple images [16]. Single images can be taken using regular cameras or RGB-Depth cameras such as Azure Kinect. The Azure Kinect camera can easily create as-built 3D scenes using streams of depth and color images. However, for creating 3D reconstruction scenes using regular cameras, there is a need to calculate the depth of pixels in the images using computer vision techniques [17]. Eder et al. [18] developed and trained convolutional neural networks with a dataset containing RGB-D images to predict depth estimation of a single 360° image of an indoor scene that provides all information for creating the 3D as-is model.

The multiple images are divided into (i) multi-perspective 2D images and (ii) video sequences. In general, 3D scene reconstruction using multiple images have fewer challenges and is studied more frequently in the literature since they are more accurate with a higher level of detail compared to approaches using single images. In multi-perspective 2D images, several images with different perspectives of the objects are taken and create 3D scene representations based on parameters and poses of cameras [16], [17]. Fathi et al. [19] proposed a framework to create 3D point clouds using two calibrated cameras. The feature points captured from two video frames were detected using the Speeded Up Robust Features (SURF) algorithm. Automatic point matching between two video frames using Euclidean distance was applied and the outliers were removed using the RANdom SAmple Consensus (RANSAC) algorithm. Then triangulation was used to estimate spatial coordinates of the points in the frames and create point clouds of the construction objects on site.

Figure 5. 3D reconstruction from captured images by Omar et al. [54].

Video sequences can be utilized as an input for computer vision techniques to reconstruct 3D scenes. One of these techniques is the structure from motion (SFM) method that uses the shared information between consecutive frames by repeatedly extracting and matching features between two images, filtering outliers, and estimating poses of images and point clouds through image registration and triangulation [16], [17], [20]. In the study done by Golparvar-Fard [1] unordered daily photographs were used to reconstruct the as-built environment by using the SFM technique. Creating 3D point cloud models and as-built data, enabled project management team to visualize the project's current state through different viewpoints.

3.2 Object Detection

Due to numerous construction activities which use a wide variety of resources including materials, equipment, and workers, it is important to identify which resources are in the scene and which ones are involved in performing the task of interest [21]. Object detection is used to identify tracked building components automatically on site from the captured images and videos. This technique facilitates analysis of tracked activities and material allocation to support progress monitoring and reporting [22]. Object detection is a computer vision task that performs both classification and localization. Meaning that it classifies the objects in the captured image into pre-defined categories and predicts the location of each object in the image as shown in Figure 6.b [21], [23], [24].

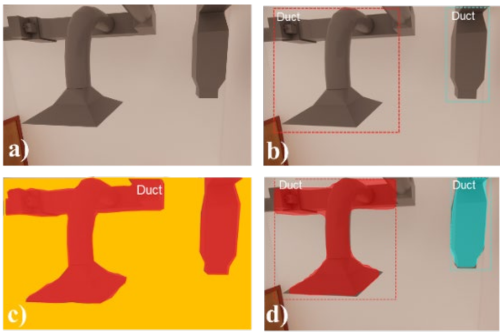

Figure 6. a) Original image b) Object detection result c) Semantic segmentation result d) Instance segmentation result

In the early stages of object detection, many researchers used traditional (feature-based) algorithms which are essentially performed in a step-by-step process, requiring a specific model for each task. In these algorithms, the image features are extracted using feature descriptors such as Scale Invariant Feature Transform (SIFT), Local Binary Pattern (LBP), Binary Robust Independent Elementary Features (BRIEF) and Histogram of Gradients (HOG). Next, these feature descriptors are combined with machine learning classifiers such as Support Vector Machine (SVM), K-Nearest Neighbors (KNN), naive Bayes classifiers and neural networks for classification tasks [21], [23], [25].

Hamledari et al. [26] utilized different feature extraction and classification techniques such as color space selection, thresholding, edge extraction, and support vector machine to detect partitioned elements such as drywall, insulation, studs, and electrical outlets to report their actual state. Hui et al. [27] proposed a framework to detect and localize bricks in video frames using image processing techniques such as color thresholding and edge detection, then estimated the number of the bricks on the building façade automatically to improve performance of progress monitoring. These traditional methods have limitations in model generalization for detection purposes since they are based on hand-crafted features and require significant expertise effort for feature selection and extraction [28], [29].

In recent years, deep learning algorithms consisting of neural networks with many hidden layers, have provided solutions with better performance and reduced human involvement. This is achieved by introducing end to end learning process, which means that for completing feature learning, classification and regression tasks only a dataset of annotated images or video frames is required [28], [30], [31].

Many research studies have been developed using deep learning algorithms to monitor construction operations on site to support progress monitoring and reporting. For example, Hou et al. [6] trained Deeply Supervised Object Detector (DSOD) deep learning algorithm and detected building components including columns and beams automatically. Martinez et al. [32] proposed a framework to track progress of construction tasks automatically in offsite jobsites. In this research, Faster Region-based Convolutional Neural Network (Faster R-CNN) is applied to detect and classify the construction resources that are utilized in each task. Also Pour Rahimian et al. [33] developed a framework using computer vision techniques for building elements identification, integrating BIM and virtual reality to provide as-built information.

3.3 Image Segmentation

In image segmentation, which is also named as pixel-level classification, a digital image is separated into different meaningful regions to find how the interest objects are displayed in the image [9]. Image segmentation can be divided into semantic segmentation and instance segmentation [8]. Semantic segmentation refers to assigning a class label to each pixel in the image as shown in Figure 6.c [34]. In instance segmentation, detection and segmentation are joined in one model, making detected objects distinguishable by pixel-wise masks. Compared to semantic segmentation, objects here from the same class, can be distinguished as separate instances as shown in Figure 6.d [9], [23], [35]. Through segmenting objects of interest by predicted masks, shape and size of objects in the image can be identified. In addition, the object boundaries can be extracted, providing spatial information for further geometry analysis, localization, and tracking which can assist progress monitoring systems [36]–[38]. Wang et al [38] developed an integrated framework using different computer vision tasks including instance segmentation and object tracking to monitor the progress of precast walls. Mask Region-based Convolutional Neural Network (Mask R-CNN) were utilized for detecting and segmenting the walls and DeepSORT for tracking walls through consecutive frames. Shamsollahi et al. [39] trained Mask-RCNN using transfer learning and data augmentation techniques to detect and segment HVAC ducts automatically for progress reporting the status of completed work on site. Table 1. Shows related research papers using computer vision techniques for progress monitoring and reporting.

3.4 BIM and Computer Vision Techniques

Through using BIM, construction entities can create and visualize 3D models, record, manage and analyze construction information. It also facilitates communication and collaboration among users [40]–[43]. 4D simulation is one of the most commonly used BIM methods for progress monitoring, which allows project managers to visualize and compare as-planned and as-built information through semantically enriched 3D models that are linked with project schedules [44]–[46]. As a result, the number of studies utilizing computer vision techniques and 4D BIM for automated progress monitoring in construction sites has increased in recent decades [47]–[49]. For example, Kropp et al. [50] utilized 4D BIM to find information related to the objects associated with specified activities as well as motion information to do a simple 2D classification. To evaluate the model, computer vision tasks including HOG features and SVM classifiers were applied to recognize heating devices in indoor construction site from image frames.

Also, other integrated systems using BIM and computer vision techniques have the potential to support progress monitoring systems. Ying and Lee [36] Developed an automated framework that creates as-is BIM elements using images taken from construction sites. Mask R-CNN, a deep learning-based object recognition algorithm were applied to detect and segment Walls, Doors, and Lifts from images. After the segmentation task, the masks boundaries of detected objects were extracted to generate surface geometries and construct IFC building objects.

Cloud-based BIM technology is another BIM development that provides opportunities for users to have access to project progress information in real-time. It is also a cost-effective collaboration tool that enables project entities to share and exchange necessary information through devices such as tablets and smartphones in different locations. This allows decision-makers to track the progress, organize construction schedules and apply early corrective actions [51]–[53]. Deng et al. [43] developed a method using computer vision and BIM to automatically measure and visualize the progress status of tiles. Computer vision techniques including local binary patterns (LBPs) and SVM classifier were used to identify tiles and the improved edge detection algorithm was applied to extract boundaries of the installed tiles from digital images. By using camera calibration and BIM model information the real tile area was calculated and the results were transferred to the BIM cloud platform for progress visualization.

Table 1. Applied computer vision techniques for progress monitoring and reporting.

Technique	Objectives	Ref.
3D scene reconstruction,	Creating as-built 3D model to visualize the project's current state.	[5,18] [49] [54]–[59]
Object detection,	Detecting construction components to acquire progress information.	[6,27,32] [33,36] [38,39] [60,61]
Image segmentation	Recognizing regions of objects in the image for spatial analysis and track the progress.	[26,33] [36], [38], [39]

4 Research Challenges

Despite many advances in implementation of computer vision tasks for progress monitoring, still some limitations are existed that need to be discussed. Some 3D scene reconstruction related issues are (1) lack of automation level in all the required steps for creating as-built models such as data collection and removing outliers. This increases, the operation time, and errors in the models [14], [15]; (2) Lighting conditions, occlusions, and cluttered backgrounds are unavoidable in construction sites which make 3D representations incomplete and noisy [13], [62]; (3) limited operating spaces in indoor environments [13]; (4) incapability of existed techniques in reconstructing of building elements with complicated geometric shapes (cylindrical, spherical, L-shaped, etc.) which mostly are in indoor environments [17]. The main challenges currently encountered in object detection and segmentation in the construction industry are (1) lack of available open-source datasets of building elements for training models in a timely manner; (2) existed models are not generalized yet to detect different building elements through one model; (3) Lighting conditions, occlusions experienced on jobsites, camera movements, and limited view range have a negative effect on detection and segmentation performance [6], [26], [38], [61], [63].

5 Conclusion and Future Work

This research study described the importance of automated progress monitoring and introduced research on computer vision techniques. Next, a systematic review of articles published in journals and conference proceedings was carried out focusing on recent applications of digital images and computer vision techniques for construction progress monitoring and reporting. Also, integrated frameworks using computer vision tasks and BIM were discussed. The challenges of these techniques including 3D scene reconstruction, object detection and image segmentation in construction industry were identified and summarized. In future, more research study is required to improve algorithms in terms of accuracy and speed for generating the point clouds and object recognition purposes. Computer vision tasks can be linked with BIM automatically to create as-built models. Also, integration of computer vision techniques with tracking technologies such as radio frequency identification (RFID) and ultra-wide band (UWB) need to be investigated to provide more information about the current state of the project and generalize their applications on complex construction sites [12], [13], [15].

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