A Systematic Classification and Evaluation of Automated Progress Monitoring Technologies in Construction

V.K. Reja [a, b], M.S. Pradeep [a], K. Varghese [a]

[a] Department of Civil Engineering, IIT Madras, India
[b] Faculty of Engineering & Information Technology, UTS, Australia
E-mail: varunreja7@gmail.com, meghaspradeep64@gmail.com, koshy@iitm.ac.in

Abstract-

Progress monitoring is one of the essential tasks while executing a construction project. Effective monitoring will lead to an accurate and timely analysis of the project's progress which is required to make vital decisions for project control. On the other hand, inefficient and delayed updates regarding the project's progress, which is estimated by comparing the as-built status with the as-planned status, will lead to time and cost overruns. Automated progress monitoring techniques are preferred over the conventional manual data entry method as the latter is time-consuming and complex, especially if the project scope is vast. Numerous tools and technologies are being used for progress monitoring of construction projects. Therefore, it is necessary to systematically classify and evaluate them based on their advantages and limitations for successful and appropriate implementation. Hence, this article identifies several progress monitoring methods and classifies them based on the technology they use to support progress monitoring. Then they are evaluated by highlighting their advantages and limitations. Several qualitative and quantitative factors affecting the selection of these technologies for implementation have also been identified. In future, a framework for objectively identifying the project-specific technology will be developed.

Keywords –

Progress monitoring technologies; Data acquisition; BIM; Internet of Things (IoT); Sensors; Computer vision; Extended reality; Literature review; Challenges; Limitations

1 Introduction

A project life cycle in a construction industry involves several stages, like designing, planning, scheduling, execution, monitoring, controlling, and demolition. Monitoring and control to minimize time and cost overruns are crucial for a construction project. Accurate progress monitoring is an essential step for achieving quality and safety parameters.

Progress monitoring also plays a vital role in avoiding unexpected circumstances and eliminating disputes and legal challenges among the stakeholders. Automating various tasks in monitoring and controlling will reduce the complexity involved in manual documentation and calculations in a project to a considerable extent. Hence, selecting a prompt and feasible automated progress monitoring technology is essential in the present-day construction sector [1][2].

Automation in progress monitoring has evolved over the past two decades, with several technologies with varying levels of automation used in projects. With several technologies available, there is not enough clarity on the type of technology that will be appropriate to be used for a specific case or project.

Existing papers have focused on the specific technology of progress monitoring, for example, specifically, vision-based [3] or IoT (sensor) based [4]. For a robust implementation, firstly, there is a critical need to identify and classify these technologies and, secondly, evaluate them based on their advantages and limitations. Hence this paper aims to:

1. Identify, classify, and evaluate technologies available for progress monitoring of construction projects.
2. To list and categorize factors that enable appropriate technology selection for the project-specific use case.

The paper is structured as follows. The review methodology has been discussed in Section 2. This is followed by a detailed review of the technologies in Section 3. The factors affecting progress monitoring technology selection are presented in Section 4. Section 5 is a discussion followed by conclusions in Section 6.

2 Review methodology

The reference literature for the review was collected from Scopus and Web of Science databases using a keyword search-based method, followed by snowballing technique. A total of 61 papers with 49 journal articles and 12 conference papers were identified from the databases, and an exhaustive review with analysis was performed. The chronological distribution of the selected papers is shown in Figure 1.

The search attributes used in the review with the keywords used and search scope is as shown in Table 1. The relevant articles for the construction domain were filtered after reading the abstracts. The filtered articles were considered for meta-analysis.

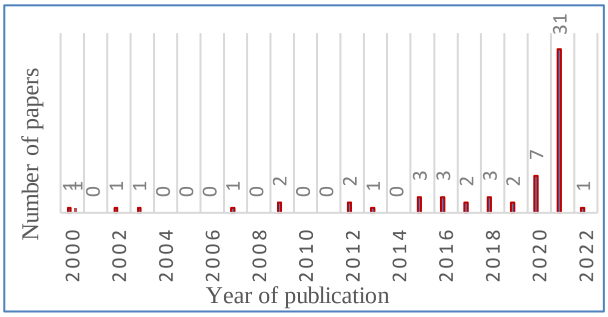

Figure 1 Chronological distribution of the selected papers

Table 1 Search attributes

Search attributes	Values used in the search
Databases	Web of Science, Scopus
Language	English
Duration	2000-2022
Type	Journal & conference articles
Keywords	Progress monitoring technologies, Automated progress monitoring.

3 Automated progress monitoring technologies

The selected papers contained case studies, challenges, and benefits of various automated techniques. Based on the meta-analysis, seventeen state-of-the-art progress monitoring techniques were identified. As shown in Table 2, these techniques were classified into six major categories based on the technology they use to support progress monitoring. These are conventional Information & Communication Technologies (ICT), tag-based methods, geospatial technologies, building information modelling and associated commercial software, computer vision-based approaches, and extended reality and are discussed below:

3.1. Conventional ICT: These include handheld computing devices (Personal Digital Assistants or PDAs, handheld personal computers), Interactive Voice Response or IVR, multimedia tools, and e-mails. These are the most basic techniques, which are information technology-based communication tools. These technologies are primarily of lower cost with a limited level of automation but can increase the chances of communication between stakeholders, thereby helping in information tracking [2].

3.2. Tag-based techniques: These involve using tags and codes that can be attached to various resources on-site and are primarily used for material tracking and inventory, employee badge scanning, and equipment tracking. These include barcodes, quick-response or QR codes, radio-frequency identification or RFID tags, and ultra-wideband or UWB tags. Each tag has its working principle based on Automatic Identification and Data Capture (AIDC). It must be noted that a tag-based technology cannot directly extract spatial element information, visually represent the site changes, and collaborate with other vision-based techniques [5][6][7].

3.3 Geospatial techniques: These include fundamental technologies based on location-based sensors like Geographic Information System (GIS) and Global Positioning System (GPS). These techniques are used for geo-referenced data capture, analysis, and modelling. GIS can be used in large infrastructure projects where there is a need to store and handle huge amounts of data. It can be a useful geospatial tool, which uses location as the primary focus in database management, whereas GPS aids in the spatial analysis and navigation of different activities on the site [8].

3.4. Building Information Modelling (BIM) Based: BIM is a process involving different tools, technologies, and contracts, which aids in better visualization of construction sites for accurate project management. BIM also aids in stakeholder management practices of the construction industry for different aspects of communication, collaboration, engagement, and satisfaction. This can be used along with commercial scheduling software like MS Project so that progress monitoring can be done efficiently [9].

3.5. Computer Vision-Based Construction Progress Monitoring (CV-CPM): It is an emerging field that focuses on information retrieval through visual inputs [3]. These inputs can be digital images, videos, thermal images, as-built point clouds, panoramas, and photo-spheres. These techniques involve fixed surveillance, photogrammetry, videogrammetry, range imaging, and 3D laser scanning. Computer vision sub-domains include learning, 3D scene modelling, video tracking, 3D pose estimation, object recognition, scene reconstruction, object detection, and event detection, which can be used for progress monitoring [3][10][11]. For this, digital twin technology are also being explored for effective real time monitoring of projects [12].

Table 2 Detailed review of the progress monitoring technologies

No		Technology	Advantages	Limitations	Ref
1.	Conventional ICT	**Hand-held computing**	• Small-sized, portable, handy, flexible devices with several features, that can be integrated with other technologies.	• Some devices are costly, and suitable applications need to be developed so that integration can be made more efficient.	[2]
		Interactive Voice Response or IVR	• Efficient and quick means of sending information from sites.	• Manual errors might occur while responding to multiple choices. • Difficulty in retracing the already answered correct messages.	
		Multimedia	• Flexible tool to aid remote progress monitoring by safe documentation and visualization of project information.	• Manual site data capture results in errors.	
		Electronic Mails or E-Mails	• E-procurement tool for quality supply chain management. • Attached with images, documents, videos, forms, etc, where the site personnel respond with the easy retracing of answered questions.	• Improper internet connection, and difficulty in responding from small devices might cause a delay in information exchange.	
2.	Tag based	**Bar-codes**	• Cost-effective, accurate, easy to use, portable, and flexible. • No need for an external device to read the codes.	• Direct line of sight required for data capture, time taking in item tracking. • Labels can get destroyed or lost due to adverse weather conditions.	[2][15]
		Quick Response or QR codes	• Portable and flexible technology with a better storage capacity. • QR code reading applications can be installed on devices easily. • Lightweight wireless QR code pocket printers can be used in sites.	• Might get affected by harsh environmental conditions. • More effective in indoor tracking compared to outdoors. • Monitoring of reinforcement, concreting, and those which are not easily accessible are difficult to be monitored using QR codes.	[16]
		Radio Frequency Identification or RFID tags	• Use radio waves that can be read accurately outside the line of sight as well, without direct contact compared to light waves. • Reliable, portable, flexible, reusable, technique that can withstand harsh environmental site conditions. • Supports indoor tracking of materials, facility and building component management, and information flow in large projects. • Capable of identifying individual items and can read multiple items in an instant simultaneously. • Storage capacity is higher than that of a barcode and is unaffected by differences in illumination.	• Costlier than barcodes. • If there are metals or liquids or moisture in the nearby area, the results can be erroneous. • Using RFID can be time-consuming, and costly if a single tag is used to track each one among several materials and equipment. • Limitation of the battery operation time, and there is insufficient accuracy in location identification if it is not depending on a fixed network. • There are insufficient international standards, multi-protocol tags and readers, and also a concern on the return of investment.	[1][6][7] [17]
		Ultra-wide band or UWB tags	• More accurate than RFID with strong signals even in obstructions. • Provide real-time resource tracking, 3-D coordinates for position sensing and consume low energy.	• UWB tags are not cost-effective compared to RFID. • No daily necessity embedded tool or mini-device.	[7]

No	Technology		Advantages	Limitations	Ref
3.	**Geospatial**	**Geographic Information System or GIS**	• Optimal location for construction equipment can be found, with efficient capture, storage, and analysis of geo-referenced information with minimum redundancy. • Creation of geographical maps of high quality, by visually representing the construction schedule to monitor the plant and equipment, that can be provided to the clients. • Can be used as a forecasting tool for early identification of time and space conflicts, and better safety regarding worksite considerations.	• Difficult to use in indoors. However there have been studies on the use of radio based (Wi-Fi, IoT, Bluetooth, UWB) and vision based signals like (markers/QR codes) to assist with obtaining the geospatial data.	[4][5][8]
		Global Positioning System or GPS	• Accurate location of positions while material tracking in construction supply chain management can be facilitated by using the Global Positioning System or GPS.	• Difficult to use in indoors. • Tagging several construction elements using GPS tags is very expensive.	[18]
4.	**BIM and commercial software**		• Visualization- clash detection & information management. • Schedule updates- automatic quantity take off & cost-estimation. • Enhanced collaboration & information exchange among stakeholders. • Integrated with supply chain for product design & material delivery. • Integration with LPS or Last Planner System for lean construction. • Knowledge based systems that are active, along with various simulations in BIM contribute to data analysis. • Choosing inputs using a hybrid video and laser scans, as-built BIM can be generated automatically.	• Limited in monitoring, scheduling, and decommissioning phases. • Errors resulting from the manual navigation of BIM model and need for constant automated updates, especially for fast-tracked projects. • Limited interoperability, even with other data acquisition techniques. • Commercial software like MS Project, Primavera, etc cannot provide digital drawings and visualisation for construction.	[1][4][17][19][20]
5.	**Computer Vision (CV-CPM)**	**Fixed surveillance (crane cameras, closed circuit television cameras, etc)**	• Safe, cost-effective, fully automated techniques, with low labour requirements that can be deployed in multi-building as-built point cloud extraction in conjunction with BIM. • Inefficient site coverage should be resolved by the deployment of more crane cameras. • Can be used for documenting daily or weekly progress in the construction site. • The data acquired from the CCTV images can be directly transferred to the head office from the site through the internet.	• Crane camera images may result in noisy as-built point clouds and may get affected by heavy winds. Mounting the camera may require extra effort, and there is limited flexibility due to the motion range of the cranes. • 3-D point clouds may be fragmented if there is incomplete site coverage. • As the position of cameras is fixed, there is a limitation in the application of CCTV cameras in huge projects. There is a need to arrange several cameras, and the data clashes between different cameras have to be fixed.	[1][6][7][3][12][17][18][19]

No	Technology		Advantages	Limitations	Ref
	Computer Vision (CV-CPM)	**Photogrammetry**	• Automatic identification of objects using cameras and image processing algorithms by integration with n-D BIM. • Lesser equipment cost and technical requirement, along with portability for the image capturing devices and improved flexibility. • High resolution compared to satellite imaging, for representing the geometric attributes and high texture representation. • The recorded images can be analyzed using software packages with computer vision techniques and machine learning algorithms for automatic updates with as-built -3D models by reconstruction.	• There is a limitation due to difference in lighting conditions, which may affect the resolution. Thermal images along with wireless sensors and BIM can be used to overcome this problem. • Object edge detection might not be proper, occlusions, noisy images and presence of shadows will affect the accuracy of progress estimation. • The location from which the photos are taken has to be matched with the check-points in the drawings, which can be a difficult problem.	[3][18]
		Videogrammetry	• Can be used for both indoor and outdoor progress tracking. • Moving equipment can be tracked.	• Less accurate than laser scanning and photogrammetry, may get affected due to occlusions.	[7] [3][20]
		Range or depth cameras	• Easier as-built point cloud generation directly, as it contains depth information. • Higher resolution compared to normal digital cameras, and higher portability with lower technical pre-requisite.	• Cost is lower than that for laser scanners but will be generally higher than that of normal digital cameras. • Range of shooting is limited and is mostly used in automated indoor construction progress monitoring.	[3][18]
		3D Laser scanners	• High-resolution, precise, and accurate progress monitoring technology unaffected by illumination, and is used for quality control, structural health monitoring, condition assessment of structures, and tracking of components, along with active collaboration between the stakeholder teams. • Automatic comparison being done between as-built and as-planned point clouds so that progress deviation detection becomes easier, and the schedule is updated accordingly.	• Highly expensive equipment with low portability, limited texture information, time-consuming data acquisition, mixed pixel restoration, need for sensor calibrations regularly, greater warm-up time. • Operation requires larger technical knowledge, and might not be suitable for progress monitoring continuously. • Accuracy of the data acquisition using laser scanning might be affected due to occlusions and in the site.	[6] [3][7][17][18][19][21][22]
6.	**Extended reality (XR)**		• Enables accurate visualization of the construction site from various angles. • Worksite planning in construction, visualization of equipment operation for inspection, comparison between as-planned and as-built images can be done. • They can be used easily in both interior and exterior locations, under different construction phases, and is cheap with the requirement of minimal training and set-up time.	• Automation quality depends on the technology in the device used. • Stationary methods are limited in portability, have less cost-effectiveness, and need additional time for setting up the equipment when compared to mobile methods. • Installation of fiducial markers requires additional investment in time and cost.	[1] [3][13] [18][23]

3.6. Extended Reality (XR) Based: The relatively newer technology allows a combined real and virtual environment, supporting human-machine interactions. These techniques can be further classified into augmented reality (AR), virtual reality (VR), and mixed reality (MR), based on the difference in visualization. These techniques can be employed for the collection of digital data and can handle computing and network technologies in progress monitoring [13].

Each of these technologies has its unique advantages and limitations in construction site monitoring. Hence, there is a need for a detailed analysis to identify these to be used effectively. It is also to be noted that efficient integration of suitable technologies in sites has been done in various case studies, and it was found that time and cost overruns have been reduced to a great extent. A detailed and systematic review of each of the above-mentioned technologies is presented in Table 2, along with the relevant references.

4 Factors affecting progress monitoring technology selection

As shown in Table 2, each technology is characterized by its advantages and limitations. Apart from these, some key factors should be considered before choosing the appropriate technology for progress monitoring in a construction project. Some of these parameters have been identified by several authors through their research [1][14].

In our recent study [3], we conducted a systematic literature survey using PRISMA methodology and identified factors which affect progress monitoring technologies in construction.

Figure 2 shows the key factors to be considered while selecting the appropriate technology for progress monitoring. These factors are categorized into quantitative and qualitative factors based on how they will be evaluated for consideration. The context of these factors for selection is described as follows:

A - Quantitative Factors

1. **Time efficiency:** The speed of data acquisitions as well as data processing.
2. **Operating range:** The distance up to which the employed technology works.
3. **Accuracy:** The reliability of the collected data along with precision.
4. **Cost:** The amount of financial cost as well as the computational cost incurred to adopt and implement the technology.

B - Qualitative Factors

1. **Utility:** Adaptability of the technology to be used both in interior and exterior construction progress monitoring. In other words, whether the technology is a general case solution.
2. **Level of Automation:** The extent of manual effort required while using the technique.
3. **Preparation required:** The level of preparation required while setting up the equipment or process at the deployment stage.
4. **Training required:** The amount of training or knowledge a user requires prior to using a particular technique.
5. **Susceptibility in adverse weather:** The extent of use of the technology in harsh environmental conditions like low visibility.
6. **Compatibility for use:** The level by which a particular technology can be integrated with other technologies or the existing Enterprise Resource

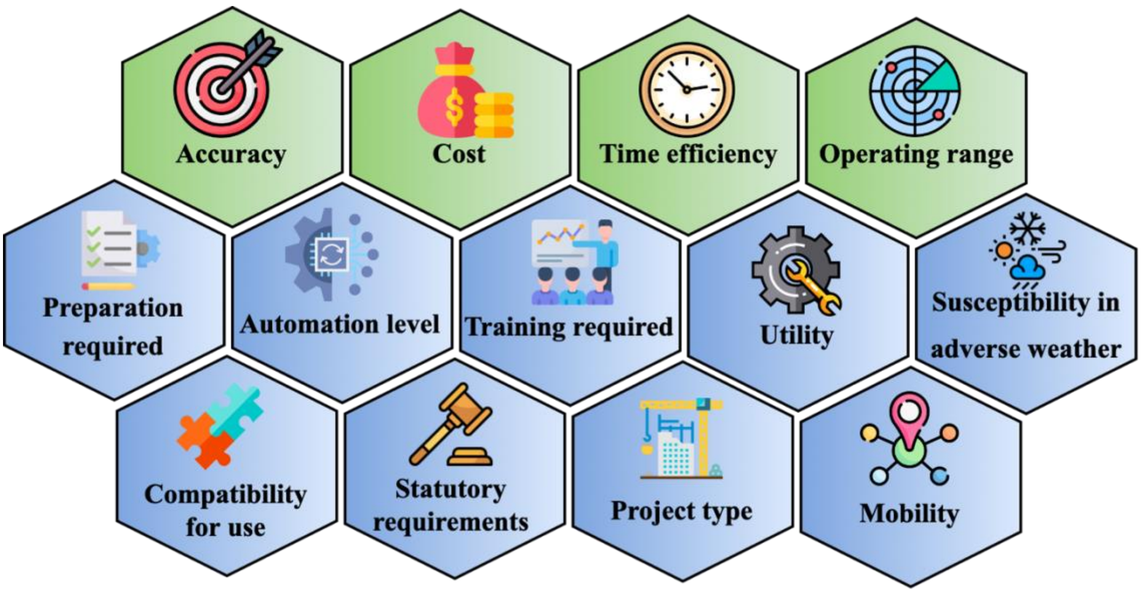

Figure 2 Factors affecting selection of technology: Quantitative (in green) and Qualitative factors (in blue)

Management (ERP) system.

7. **Statutory requirements:** The legal codes and procedures to be followed while using a technique enforced by the authorities.
8. **Mobility:** The ease, flexibility, and portability of the related equipment.
9. **Project type & characteristics**: The type and characteristics of a particular construction project where the technology can be used.

Utilization of these factors for technology selection

To utilize these factors for appropriate technology selection, it is recommended to provide weightage to factors based on the project's constraints on cost, quality, and time. The qualitative and quantitative evaluation of categorized factors should be performed. All the six technologies mentioned in Table 2 can then be evaluated based on these factors for appropriate selection. This demonstration is not in the scope of this paper but will be part of future research.

5 Discussions

Progress monitoring is crucial for accurate project control. Choosing the appropriate automated technology based on required parameters is vital in the monitoring stage of a project. Automated technologies can be integrated based on the requirements and can be highly efficient in reducing project overruns compared to manual methods. The technology must be chosen without overselling, such that the investment returns from the project can be made higher.

An idealized situation would enable a higher efficiency in all these parameters, which is not practically possible in a single technology. Therefore, selecting a suitable technology that produces the maximum output based on these parameters would be the goal in the monitoring phase of a construction project.

Another important consideration is that newer technologies might face challenges about their widespread acceptance, as the construction companies might tend to reject the pilot integrated automation technology proposals. This happens mainly due to a lack of technical knowledge of automated technologies and the tendency to continue adopting conventional techniques. So integrated proposals through research should be added with proper inspection and maintenance guidelines, followed by proper incentives to the enterprises, so that widespread adoption can be facilitated. Moreover, data collection by a single resource tracking is never sufficient for accurate progress monitoring. Hence, applying data fusion techniques is vital to tracking multiple resources on a construction site.

6 Conclusions

This paper provides a systematic review of various automated progress monitoring technologies from 61 relevant publications to understand the state-of-the-art to guide future research. The paper also identifies the benefits and limitations associated with each technology (in Table 2), along with the factors affecting their selection (in section 4). It is to be noted that each construction project is unique and has its specific characteristics. As all the technologies have their advantages and shortcomings, selecting a technology that suits a particular project is extremely important. The technologies can be combined and integrated to minimize cost overruns. This review provides a basis for this selection, as it systematically identifies the scope for each automated technology. In addition, more review efforts are recommended to identify suitable mounting methods that can be used in combination with the techniques. Digital twin based progress monitoring is a potential area of future research [12].

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