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AS-BUILT DATA ACQUISITION FOR VISION-BASED CONSTRUCTION PROGRESS MONITORING: A QUALITATIVE EVALUATION OF FACTORS

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ABSTRACT

The accuracy of computer vision-based progress monitoring of construction projects depends on the quality of data acquired. The data acquisition can be conducted through different vision-based sensors combined with several options for sensor mounting. Several factors affect this combination and considering these factors in selecting the acquisition technology and sensor mounting combination is critical for acquiring accurate vision-based data for the project. Currently, their definition and impact of these factors on the selection of these technologies are both subjective, and there are no formal studies to evaluate the impact. Hence, in this study, we first identify and define twelve key factors affecting data acquisition technology and eight factors affecting sensor mounting. Next, a questionnaire survey was designed, and responses from professionals were used to evaluate the Relative Importance Index (RII) for the individual factors for these technologies and methods. The obtained ratings were compared to the author's initial assessment, and the cause for a few variations obtained was justified. This study provides a clear assessment of these factors and forms a basis for selection based on the factors involved with the project requirements.

Keywords: *As-built modelling; Data Acquisition; Reality Capture; Scan-to-BIM; Technology Selection.*

1. INTRODUCTION

Progress monitoring is critical to the project's success. Computer vision and its subdomains are being explored for effective and real-time progress monitoring (Paneru and Jeelani, 2021). Computer Vision-Based Construction Progress Monitoring (CV-CPM) involves three steps, namely – data acquisition, as-built modelling, and progress estimation (Bhadaniya, et al., 2021; Reja, et al., 2021). Our recent study presented the integrated CV-CPM framework, which defines the three steps in detail while discussing the tools, technologies, algorithms and the methods involved in each step (Reja, et al., 2022).

The fundamental concept is to acquire spatial data and convert it to develop a 3D as-built model. Finally, this model is compared with the equivalent as-planned model at a specific

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time to compute the project's progress. The data acquisition step is critical because the quality of the acquired data affects the next steps involved in the CV-CPM pipeline (Rebolj, et al., 2017). There are two critical components for data acquisition: (a) selection of technology and (b) selection of sensor mounting method. The selection of these two depends on various factors, which can depend upon the characteristic of the project being monitored and the level of progress monitoring to be conducted. Identifying and evaluating these factors is critical for data acquisition and further steps of CV-CPM. In our recent study (Reja, et al., 2022), we identified these factors through an in-depth literature review through the PRISMA methodology. It was found that there is a critical need to evaluate these factors to guide the selection of technology and mounting method for implementation on construction projects. Therefore, this paper aims:

- To identify the factors affecting the selection of data acquisition technology and sensor mounting method for progress monitoring at projects.
- To qualitatively evaluate these factors and provide a basis for selection based on a structured questionnaire survey.

The scope of the work includes data acquisition technologies and sensor mounting methods used specifically for computer vision-based construction progress monitoring.

Section 2 reviews various data acquisition technologies and sensor mounting methods used for CV-CPM. Section 3 shows the methodology adopted for this research study. Section 4 identifies and defines the factors affecting acquisition technologies and sensor mounting methods. Section 5 presents the details of the questionnaire survey. Section 6 presents the results obtained from the survey analysis and compares them with the author's primary assessment. Finally, conclusions are presented in Section 7.

2. DATA ACQUISITION FOR CV-CPM: LITERATURE REVIEW

Table 1 shows the literature summary of the data acquisition step in the existing CV-CPM pipelines. It can be observed that several combinations of acquisition technologies and sensor mounting methods have already been tested.

For acquisition technology, most methods have used photogrammetry/ videogrammetry (based on images/videos) or laser scanning; only a few studies have used RGB-D based data capture. For sensor mounting, it can be noted that most studies have used manual methods of device traversing instead of UAV or UGV. The selection also considers the scope of progress monitoring, which can include interior reconstruction, exterior façade, or both because ongoing construction sites may not be entirely open or closed. Figure 1 shows the available data acquisition technology and sensor mounting methods. These have been discussed in detail in the following sub-section.

2.1 ACQUISITION TECHNOLOGY

As shown in Figure 1, cameras, video cameras, Laser scanners, and Range Imaging (or RGBD cameras) are the vision-based technologies used to collect progress monitoring data. These are discussed in detail below:

2.1.1 Cameras (Images and Videos)

Two camera variants are used to capture images and videos, i.e., monocular and binocular (or stereovision cameras). The monocular camera captures a single frame from a single lens, while a binocular camera has two lenses separated by some distance and captures two frames at an instance. This binocular disparity helps the stereo camera to compute the depth of the corresponding captured points. The videos are first decomposed to separate image frames, and then these frames are selected for further processing. Cameras are cheap, portable, easy to use, and available on almost all mobile devices, making them a preferred alternative over other technologies. However, processing camera images using SfM have a relatively high computational cost if the images are not in sequence and also requires acceptable capturing conditions like lighting, distance, and adequate and obstacle-free field of view for accurate results (Reja, et al., 2022).

Table 1: Literature summary data acquisition for CV-CPM pipelines

Data Acquisition			
Reference	**Acquisition Technology**	**Mounting Method**	**Indoor/ Outdoor**
(Khairadeen Ali, et al., 2021)	Laser Scanning and Photogrammetry	Manual	Indoor
(Pour Rahimian, et al., 2020)	RGBD Camera	Manual	Both
(Braun, et al., 2020)	Digital Images	UAV	Outdoor
(Vincke, et al., 2019)	Laser Scanning or Photogrammetry	Manual	Both
(Han, et al., 2018)	Photogrammetry/Laser Scanning	UAV	Both
(Arif and Khan, 2021)	Videography	Fixed	Both
(Kim, Kim and Lee, 2020)	Laser Scanning and Photogrammetry	UAV	Both
(Wang, et al., 2021)	Video Camera	Fixed	Outdoor
(Kopsida and Brilakis, 2020)	RGBD Camera	Manual	Indoor
(Mahami, et al., 2019)	Photogrammetry	Manual	Both
(Maalek, et al., 2019)	Laser Scanning	Manual	Both
(Bognot, et al., 2018)	Videogrammetry	UAS	Outdoor
(Omar, et al., 2018)	Photogrammetry	Manual	Outdoor
(Pučko, et al., 2018)	RGBD Camera	Manual	Both

2.1.2 Laser Scanners

Laser scanners (or LiDARs: Light detection and ranging) directly capture the 3D cartesian or spherical coordinates of the surrounding points and deliver 3D point cloud data directly with internal processing. They can be controlled by either phase-based or time of flight-based methods. They are best used for automated data retrieval as they do not require much processing and can capture high-resolution spatial data. Their major disadvantage is that they require a clear line of sight requiring a frequent change of scanning positions to capture 3D data, making them tedious to use and having a high purchase cost (Omar and Nehdi, 2016).

2.1.3 Range Imaging Devices

Range imaging cameras (or RGBD cameras) compute the pixel point's depth by calculating the distance of points in a scene concerning a specific point with the help of a sensor. They capture the spatial as well as depth information simultaneously. They generally output a point cloud or surface mesh directly with the help of their in-built algorithm. Their major disadvantage is their low range of capture, but they are easy to use.

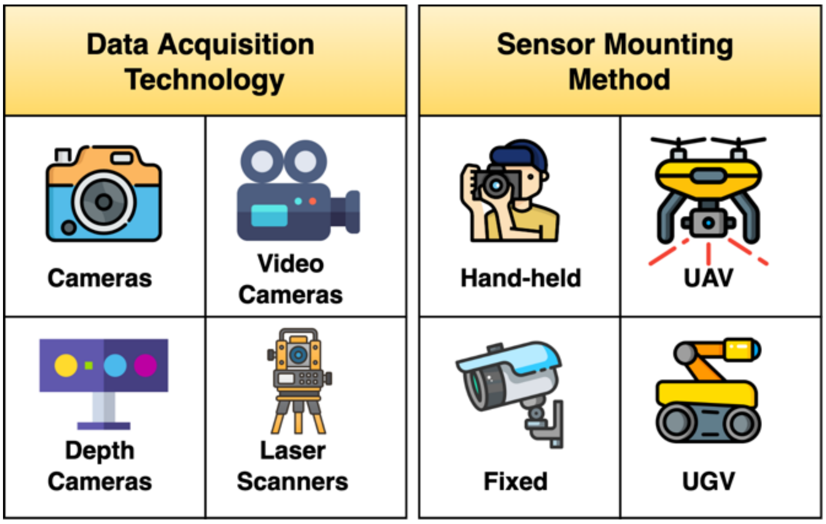

Figure 1: Data acquisition technology and sensor mounting methods

The sensor mounting methods are discussed in the following sub-section.

2.2 SENSOR MOUNTING METHOD

As shown in Figure 1, the acquisition can be by a static device (as in the case of laser scanners), hand-held devices (like mobile cameras and Tablets), UAV or UGV mounted robotic systems (like 2D-Cameras or Range imaging devices) or even a combination of these systems (Asadi et al., 2020). The integration of these robots deployed for manoeuvring with the desired technology creates different acquisition dynamics, including robotic path planning, obstacle avoidance, capture speed, automation, etc. The recent development of light air-borne LiDAR sensors and SPOT by Boston Dynamics (Boston Dynamics, 2019) with high data transmission speed (Reja and Varghese, 2019) has paved the way for unmanned data acquisition in dynamic construction scenes, which can be used in the future pipelines.

2.2.1 Hand-held

The manual method of capturing the data includes holding the acquisition device in hand and traversing along the site to capture the relevant data. These require human effort, are tedious and subject to errors.

2.2.2 Fixed

The fixed method mounting is when the data capturing device location is static on a construction site, and the capture frequency is set. It is mainly in the form of fixed cameras. The major disadvantage of being fixed is that they suffer occlusions due to moving objects and can capture only the specified field of view (FOV). Hence, multiple fixed devices are required to capture the construction site.

2.2.3 UAV

Unmanned Aerial Vehicles (UAVs) include drones that can fly autonomously or manually on the planned path to capture data. Their primary advantage is enabling automatic data capture if the path is planned. They have navigational disadvantages as they require a clear and collision-free route, which is challenging to plan at construction sites. If they are manually operated, an operator with navigation skills is required. It is generally required to meet the statutory laws applied to use them on projects commercially.

2.2.4 UGV

Unmanned Grounded vehicles (UGVs) include robotic vehicles embedded with various sensors to move on the ground. These generally use obstacle avoidance algorithms for autonomous navigation. Their major disadvantage is that they have specific terrain requirements for movements.

This section presented various data acquisition and sensor mounting methods with their strengths and challenges. The following section identifies various factors which affect the selection of these.

3. METHODOLOGY

Figure 2 shows the methodology followed for this research. Since multiple factors affect the selection of these data acquisition technologies and sensor mounting, the factors were identified and documented based on the author's practical experience and supported by the literature. A questionnaire survey-based method was used to calculate the Relative Importance Index (RII) for selection for a qualitative evaluation of the factors.

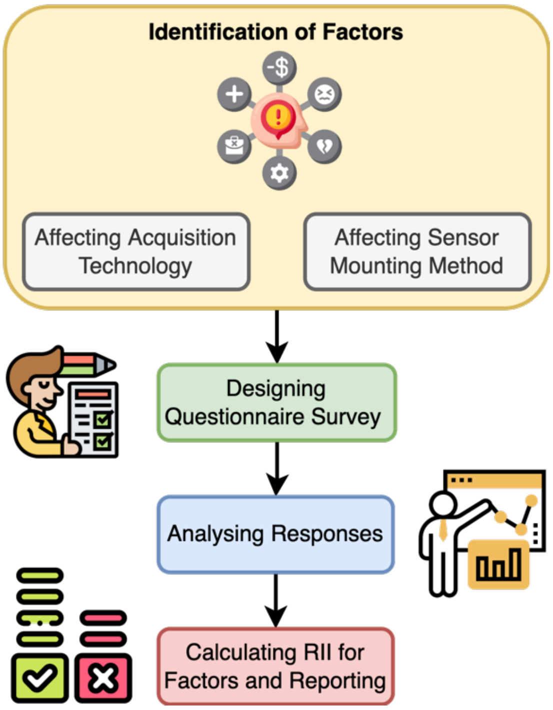

Figure 2: Methodology

4. FACTORS AFFECTING DATA ACQUISITION TECHNOLOGY SELECTION

Evaluating the technology and methods is critical for selecting the combinations for on-site implementation. Several factors govern the selection criteria. Therefore, this study identifies the factors based on their use in literature while choosing the technology and method and the authors' experience in this field. Our recent study identified these factors (Reja, Varghese and Ha, 2022) by a thorough review of the literature using a well-defined PRISMA methodology.

Table 2 shows twelve key factors for data acquisition technology that have been identified. They are equipment cost, equipment portability, automation for data capture, real-time data availability, range of equipment, spatial resolution, spatial accuracy, lightning requirement, user training requirement, time for data capture, preparations for data capture and computation cost for processing.

Likewise, Table 3 shows eight key factors that have been identified for the sensor mounting method. They include accessibility, manoeuvre speed, navigation skills, operator training, statutory requirements, sensor mounting cost, range of operation and preferred use-case.

The initial relative assessment of factors based on the author's perspective supported by field experience and literature has been shown in Tables 4 and 5. The colour codes green, yellow, and red represents low, medium, and high. As this is a subjective evaluation, a questionnaire survey was designed to make it more objective, and responses were analysed. The following section presents the details of the questionnaire statistic and survey results.

Table 2: Definition of various factors that affect data acquisition technology selection

Sl. No	Factors affecting data acquisition technology selection	Definition
1	Equipment Cost	It is the measure of the cost of purchasing the equipment.
2	Equipment Portability	It is the ease of moving the technology (device) around to capture another location.
3	Automation for Data Capture	It is the degree of automation in the process for capturing data like images and depth of the point cloud.
4	Realtime Data Availability	It is the measure of the speed of raw data capture and availability.
5	Range of Equipment	It is the measure of distance up to which the device can be used to capture data.
6	Spatial Resolution	It is a measure of the smallest object that can be resolved by the sensor or the linear dimension on the ground represented by each pixel.
7	Spatial Accuracy	It is the measure of the degree to which information on an image or point cloud matches real-world values.

Sl. No	Factors affecting data acquisition technology selection	Definition
8	Lightning Requirement	It is the measure of the degree of illumination required for data capture.
9	User Training Requirement	It is the degree of training required to use the technology to capture data.
10	Time for Data Capture	It is the measure of time required to capture the data.
11	Preparations for Data Capture	It is the degree of preparation required to capture data.
12	Computational Cost for Processing	It is the time required to process the raw data to point cloud data.

Table 3: Definition of various factors that affect sensor mounting method selection

Sl. No	Factors affecting sensor mounting method selection	Definition
1	Accessibility	It is the ability to reach a place with respect to another place.
2	Manoeuvre Speed	It is the speed at which the device can be manoeuvred to capture data.
3	Navigation Skills	It is an act of directing the course of sensing technology to capture data.
4	Operator Training	It is the amount of training required to operate the mounted technology.
5	Statutory Requirements	It is the number of requirements to be met which are set by the central or state government of a country for the use of these methods.
6	Sensor Mounting Cost	It is the measure of the cost of purchasing the sensor mount.
7	Range of Operation	It is the measure of distance up to which the device can be manoeuvred using the mount
8	Preferred Use-Case	It can be preferred either for interior or exterior data capture.

5. QUESTIONNAIRE SURVEY

A questionnaire survey with project description and factors definition was sent to 40 experienced professionals from the construction industry[4]. The participants were postgraduate engineers working on different construction projects across India in several organisations with at least two years of field experience. The survey participants were selected so that each participant had relevant experience in using and implementing the data acquisition technologies and sensor mountings methods on construction projects. Finally, 33 responses were received from the participants of the survey.

[4] The link to the questionnaire is available at: https://docs.google.com/forms/d/e/1FAIpQLSeh-NoWReaYDBEfBnRd_aY1viumwEo4u8mhWYvQjIcHUaJCyw/viewform

Below are the results after analysing the Relative Importance Index (RII) as calculated from Eq. 01. RII is used to analyse the survey results for factors.

$$RII = \frac{\Sigma(W_n)}{A*N} \qquad \text{(Eq. 01)}$$

Where,

W = Constant expressing the weighting given to each response

A = Highest rating (In our case, A=3)

n = Frequency of responses

N = Total number of responses

Based on the ranks obtained from the analysis, the factors were categorised as high, medium, and low levels with colour codes as red, yellow, and green, respectively. The criteria for the values of 0.55 and 0.75 were set so that the classification best reflects the variation in the factors. For example, for equipment costs, a digital camera costs in the range of $200, a range imaging camera about $1000 and a laser scanner about $15000. Hence the ratings were set so that these are divided into low, medium, and high values to show relative comparison wherever possible.

Low ~ ($RII < 0.55$)

Medium ~ ($0.55 < RII < 0.75$)

High ~ ($RII > 0.75$)

Tables 6 and 7 show the relative ranks of the factors received for the data acquisition technology and sensor mounting method, respectively.

Table 4: Matrix for data acquisition technology selection - Author's perspective

Sl. No	Evaluating Factors	Cameras	Range Imaging	Laser Scanner
1	Equipment Cost	Low	Medium	High
2	Equipment Portability	High	High	Low
3	Level of Automation for Data Capture	Medium	High	High
4	Realtime Data Availability	High	High	Low
5	Range of Equipment	Medium	Low	High
6	Spatial Resolution	Low	Medium	High
7	Spatial Accuracy	Medium	Medium	High
8	Adequate Lightning Required	High	High	Low
9	User Training Requirement for Data Capture	Low	Low	High
10	Time Required for Data Capture	Low	Low	High
11	Pre-Preparations Required for Data Capture	Low	Low	High
12	Computational Cost for Data Processing	High	Low	Low

Table 5: Matrix for sensor mounting - Author's perspective

Sl. No	Evaluating Factors	Fixed	Hand-held	UGV	UAV
1	Accessibility	Low	Medium	Medium	High
2	Manoeuvre Speed	Low	Low	Medium	High
3	Navigation	NA.	User	RC & Automated	RC & Automated
4	Operator Training	Low	Low	Medium	High
5	Statutory Requirements	Medium	Low	Low	High
6	Sensor Mounting Cost	Low	Low	High	High
7	Range of Operation	Low	Medium	Medium	High
8	Preferred Use-Case	Interior and Exterior Scenes	Interior and Exterior Scenes	Interior Scenes	Exterior Scenes

6. RESULTS AND DISCUSSION

It can be observed that there is a slight difference in the survey results of the values in Tables 6 and 7 in comparison to Tables 4 and 5, which were based on the author's perspective. The deviations have been highlighted using bold font and an asterisk symbol. However, most of the factors and their relative importance ratings matched, and that affirms our preliminary assessment. The deviations found are discussed in the following subsections.

Table 6: Matrix for data acquisition technology selection - Survey results

Sl. No	Evaluating Factors	Cameras	Range Imaging	Laser Scanner
1	Equipment Cost	Low	Medium	High
2	Equipment Portability	High	**Medium***	Low
3	Level of Automation for Data Capture	Medium	**Medium***	High
4	Realtime Data Availability	High	High	Low
5	Range of Equipment	**Low***	Low	High
6	Spatial Resolution	Low	Medium	High
7	Spatial Accuracy	Medium	Medium	High
8	Adequate Lightning Required	High	High	Low
9	User Training Requirement for Data Capture	Low	**High***	High
10	Time Required for Data Capture	Low	Low	High
11	Pre-Preparations Required for Data Capture	Low	**Medium***	High
12	Computational Cost for Data Processing	High	Low	Low

Table 7: Matrix for sensor mounting - Survey results

Sl. No	Evaluating Factors	Fixed	Hand-held	UGV	UAV
1	Accessibility	Low	Medium	Medium	High
2	Manoeuvre Speed	Low	Medium*	Medium	High
3	Navigation	NA.	User	RC & Automated	RC & Automated
4	Operator Training	Low	Medium*	Medium	High
5	Statutory Requirements	Medium	Low	Low	High
6	Sensor Mounting Cost	Low	Low	High	High
7	Range of Operation	Low	Medium	Medium	High
8	Preferred Use-Case	Interior and Exterior Scenes	Interior and Exterior Scenes	Interior Scenes	Exterior Scenes

6.1 COMPARATIVE RESULTS FOR DATA ACQUISITION TECHNOLOGY SELECTION

As compared from Tables 4 and 6, slight deviations are realised in the ratings for range imaging technology. Equipment portability is medium in the case of range imaging (compared to low in Table 4). This can be because, compared to digital cameras, RGB-D cameras can be bulky due to additional accessories provided.

The level of automation has been reported as medium for range imaging (in comparison to high in Table 4). This may be because the reconstruction requires manual input compared to laser scanning, which automatically produces a point cloud.

The range of equipment is low in the case of digital cameras (in comparison to the medium in Table 4). This can be because taking images from far may result in lower reconstruction accuracy; therefore, accurate reconstruction can be done if the objects are clear from a specific range.

User training requirements and preparations for data capture for range imaging are found to be high and medium, respectively (in comparison to low and low in Table 4). This may be because of the calibration process required before starting the data capture.

6.2 COMPARATIVE RESULTS FOR SENSOR MOUNTING

The manoeuvring speed and operator training requirements have been reported to be medium (in comparison to low and low in Table 5). This variation can be because it depends on the data capturing skills of the operator and his technical knowledge of using the device.

All the other relative ratings match the author's perspective, affirming that the comparison and the ratings provided are appropriate.

7. CONCLUSION

The paper presented a qualitative evaluation of the factors affecting the data acquisition step of CV-CPM. For achieving the first objective, the factors affecting technology and mounting method selection were first identified and defined. For the second objective in this study, an objective evaluation was conducted based on a questionnaire survey circulated among experienced professionals.

The results were compared with the author's preliminary ratings, and it was noted that few variations were seen. Individual deviations were discussed by providing possible reasons. The ratings obtained through this study can be utilised for technology and mounting method selection, which is a valuable addition to the existing method of selection, which is entirely dependent upon the use case. In addition to these ratings, project-specific requirements should be evaluated against these factors to select an appropriate technology for collecting data for CV-CPM.

The study contributes primarily by comparing the factors for data acquisition and sensor mounting qualitatively, which has not been done before, which adds to the theory of construction progress monitoring. The current limitation of this study is that the comparison shown here is relative to the three technologies and the four mounting methods. Some of the factors can be better evaluated by directly a quantitative comparison of values, which will be a part of future research in this area.

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