Identification of Factors and Metrics to Compare Vision Based Data Acquisition Devices

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Abstract –

Construction projects rely on several technologies for progress monitoring of projects. Among these technologies, Computer Vision (CV) based technologies are gaining popularity as they enable direct acquisition of physical site data. There are numerous devices available using vision-based technologies. Several studies have attempted to compare these technologies to identify appropriateness to meet the project requirements. However, there is no structured framework to compare and select a CV-based data acquisition device based on the requirements of a project. To develop a framework, it is critical to identify the factors and associated metrics that enable a systematic device comparison. Through a systematic review of literature of comparative studies on CV-CPM technologies this work identifies several factors and defines the metrics that form the basis for a structured framework. An approach to forming the framework based on these factors is also proposed.

Keywords –

Progress monitoring technologies; Computer Vision; Data acquisition; Comparative framework; Literature review

1 Introduction

Effective progress monitoring is crucial during a construction project's life cycle to control cost and time overruns. Further, prompt and accurate progress updates from a site avoids stakeholder disputes and related complexities by eliminating unexpected circumstances.

Data acquisition is a crucial step in progress monitoring process, which contributes for accurate project control. Project control data is increasingly being obtained through automated data acquisition technologies. Among these, Computer Vision (CV) based technologies are gaining significance as they have the potential to capture the physical state of a site [1,2].

There are several devices in the present-day market for acquiring as-built status based on CV-based data inputs. These devices range from hand-held portable – low-resolution ones to tripod-mounted high-resolution ones. Correspondingly, the outputs of these devices can be used for different levels of progress monitoring. These levels could vary from basic visualization to detailed quantification of as-built components. Four levels of progress monitoring have been defined by earlier studies [1]. Identifying a suitable device suitable for the required level of progress monitoring specified for a project is an important requirement.

Existing papers have focused on the comparison of specific technologies, [3] or devices [4]. For a robust implementation, first, there is a need to systematically structure this comparison of the data acquisition devices and, secondly, create a framework to select the suitable device given an intended level of progress monitoring for a project. Hence, this paper aims to:

1. Review the existing studies on the comparison of various devices and technologies.
2. To identify the factors that enable a systematic comparison of automated data acquisition technologies for Computer Vision based Construction Progress Monitoring (CV-CPM).

The paper is structured as follows. In Section 2, the review methodology is initially discussed and then a table listing the various comparative studies and factors considered for technology comparison is presented and discussed. In Section 3, the metrics for each of the factors are defined and an approach to develop a structured framework is outlined. Discussion on the work is presented in Section 4 and followed by summary and future work in Section 5.

2 Review of Literature

2.1 Methodology

The reference literature for the review was collected from the Scopus database using a keyword search-based method followed by snowballing technique. Out of 312 results from the Scopus database and 24 papers from the snowballing technique, a total of 42 papers were identified through the PRISMA methodology [5], and an exhaustive review with analysis was performed. In this review, the papers that focuses on CV-CPM and specific comparison of data acquisition devices were included. The chronological distribution of the selected papers varies from 2011 to 2023, with majority concentrated in the years 2021, 2022 and 2023.

The search attributes used in the review with the keywords used and search scope are 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.

Table 1. Search attributes

Search attributes	Values used in the search
Databases	Scopus
Language	English
Duration	2012-2023
Type	Journal and conference articles
Keywords	Construction, Automated progress monitoring

2.2 CV-based data acquisition devices

As mentioned in Section 1, CV-CPM is an emerging field focusing on information retrieval through visual inputs. These inputs include digital images, videos, thermal images, as-built point clouds (PCs), panoramas, and photospheres.

Major CV-based techniques include fixed surveillance, photogrammetry, videogrammetry, range or depth imaging and 3D laser scanning, each with their own advantages and limitations [1,2]. In all these technologies, the acquired data as image frames or point clouds are retrieved in multiple file formats compatible with corresponding processing software.

These technologies are combined with suitable mounting options including Unmanned Aerial Vehicles and Unmanned Ground Vehicles to enable progress monitoring for construction projects. There are numerous popular devices of varying combinations of the above-mentioned technologies and mounting options being used in the industry for efficient progress monitoring.

To develop a framework for comparing CV-based device for varied requirements of progress monitoring, the first step is to perform a detailed literature review of existing specific comparative studies.

As presented in Table 2, eighteen studies are reviewed in detail to identify the devices being compared along with the technology categorization of these devices. The devices that are included consists of 3D laser scanners (Terrestrial- TLS and Mobile- MLS), iPhone or iPad LiDAR sensors, digital cameras, depth camera, etc.

It is to be noted in the reviewed studies that some of the researchers identified a third reference in their study as a benchmark [3,4,6–15], whereas others evaluated a particular device in comparison to another device, keeping the latter as a reference [16–19]. In a few studies, both the above cases are evaluated [20,21]. In all three cases, the benchmark or reference is mentioned in the table. The table is further organized based on the technologies compared, grouping the similar technology comparisons together.

Most of the studies focused on comparing devices working on the same CV-based technology [3,6–8]. However, in studies where cross-technology comparisons were done, the images captured using depth or digital cameras were subjected to photogrammetric reconstructions where the input data is converted to as-built point clouds [12–14]. Further, these point clouds were compared to the directly obtained point clouds from the laser scanners or LiDAR sensors.

Various quantitative and qualitative factors, based on which the comparison is performed in the studies, are also stated in Table 2 along with the methodology adopted for comparison in the studies. It is interesting to note that a significant portion of the studies focuses only on quantitative factors [4,6,8,13,16–21] with a comparatively lesser studies taking into account both the factors [3,7,9–12,14,15].

The results from these studies are not included in the table, as the focus of the work is to identify and document the factors that were used for comparison and define suitable metrics than can be used to quantify the factors.

Both the quantitative and qualitative factors, listed in the table, must be suitably quantified based on their context. This will form the basis for a structured comparison framework. However, the scope of this article is limited to the characterization of quantitative factors, as provided in Section 3.

3 Metrics for quantitative factors

The major quantitative factors identified earlier are summarized in Table 3. These factors include resolution; accuracy; time; surface coverage; cost; system storage and device moving speed. The corresponding metric that can be used for quantification of these factors are also mentioned in the table along with the description to quantify them.

It can be noted that different studies use one or more factors to compare the devices along with different terminology for the same methods. All studies examined accuracy for comparison, with the majority also addressing resolution and quantifying them using various metrics, as depicted in Table 3. Accuracy ensures the reliability of data capture, while resolution determines the level of detail and clarity in the output. Given their

Table 2. Detailed review for comparison of devices

Papers	Data Acquisition				Comparison			
	1st Device		2nd Device		Benchmark/ Reference	Quantitative Factors	Qualitative Factors	Methodology
	Name	Technology	Name	Technology				
[3] (2017)	Paracosm laser scanner	Handheld mobile laser scanner	Faro Focus 3D S120	Terrestrial laser scanner	Manually collected field measurements	Accuracy, time, cost	Workflow, quality of scans	• Accuracy is compared using variance calculation • Comparison of total time
[4] (2018)	DotProduct DPI-8 and GeoSLAM ZEB1 scanner	Handheld mobile laser scanner	Faro Focus3D X330, Leica Nova MS50 MultiStation, Leica ScanStation C5	Terrestrial laser scanner	Standard tape measuring tool	Accuracy, scanning time, post-processing time	-	• Error in distances is calculated
[6] (2022)	Leica BLK360	Terrestrial laser scanner	RIEGL-VZ-400i	Terrestrial laser scanner	Topographic equipment (total station and laser distance measurer)	Accuracy, points density, distance & orientation deviation	-	• Cloud-to-cloud (C2C) distance analysis using CloudCompare software • Number of points in 5×5 cm^2
[7] (2023)	iPad Pro LiDAR (App 1)	Handheld mobile laser scanner	iPad Pro LiDAR (Three other Apps)	Handheld mobile laser scanner	Two TLSs (Faro Focus 3D and the Leica HDS 7)	Accuracy, number of points, scanning times	Visual quality	• C2C distance analysis using CloudCompare software • Total number of points within the object
[8] (2023)	iPad Pro LiDAR (App 1 - 3D Scanner)	Handheld mobile laser scanner	iPad Pro LiDAR (App 2 - RTAB-Map)	Handheld mobile laser scanner	Leica Disto D810 ranger (distance measurement), GeoSLAM ZEB Horizon scanner (MLS), Leica RTC360 (TLS)	Accuracy, point density, point spacing	-	• Distance analysis between points and their best-fitting plane • C2C distance analysis using CloudCompare software • Scan-to-BIM Model and compare dimensions to the reference dimensions
[9] (2022)	iPhone 12 Pro LiDAR (App 1)	Handheld mobile laser scanner	iPhone 12 Pro LiDAR (two other apps)	Handheld mobile laser scanner	Terrestrial laser scanner (Faro Focus3D X330)	Accuracy	Visual quality, influence of lighting and object materials	• C2C distance analysis using CloudCompare software • Error in distances is calculated

Papers	Data Acquisition				Comparison			
	1st Device		2nd Device		Benchmark/ Reference	Quantitative Factors	Qualitative Factors	Methodology
	Name	Technology	Name	Technology				
[10] (2017)	Google Tango tablet	Mobile range camera (Infrared-based scanning)	ZED camera	Mobile range camera (passive stereo vision)	Leica Laser Disto (for distance measurement)	Preparation time, scanning time, post-processing time, accuracy	Rescanning effect, ease of use, influence of lighting, and object materials	• The deviation in dimensions of scan values and actual values are compared and the average percentage error is calculated
[11] (2015)	Kinect v1	Mobile range camera (Infrared-based scanning)	Kinect v2	Mobile range camera (Time-of-flight sensor)	NextEngine 2020i Desktop laser scanner, laser meter for distance	Accuracy	Influence of sunlight	• C2C distance analysis • Error in distances is calculated
[12] (2011)	Nikon D-80 camera	Structure from Motion (SfM) for unordered photos	Leica ScanStation 2	Terrestrial laser scanner	Standard tape measuring tool	Accuracy, number of points, cost, storage space on computer	Applicability, automation, training need, extra effort required	• PCs are converted to 3D CAD objects. The percentage error in ratios for each dimension (x, y, z) was used for comparison.
[13] (2013)	e Canon Vixia HF S100 camera & Point Grey Flea-2 camera	Photogram-metric and videogram-metric recon-struction	Leica ScanStation C10	Terrestrial laser scanner	Total station (SOKKIA 30R)	Accuracy, completeness, number of points	-	• Error between a point from the surface of the reference model • Dividing the surfaces of the reference model into small regions and the existence of points is checked • Number of points per square meter
[14] (2022)	DSLM-type camera	Photogram-metric re-construction	iPad Pro LiDAR (Scaniverse App)	Handheld mobile laser scanner	Laser scanner, CAD model (measuring with a laser range finder and tape), set of calibration balls	Accuracy, number of points	Quality (discontinuity, deformation, displacement, duplication)	• C2C distance analysis using CloudCompare software • Total number of points within the object
[15] (2021)	Canon EOS 6D DSLR camera	Photogram-metric re-construction	iPad Pro LiDAR (SiteScape & EveryPoint App)	Handheld mobile laser scanner	Terrestrial laser scanner (Faro Focus X330)	Accuracy, completeness cost	ease of use, Influence of lighting	• Multiscale Model to Model Cloud Comparison (M3C2) analysis • Mesh to cloud distance analysis

Papers	Data Acquisition				Comparison			
	1st Device		2nd Device		Benchmark/ Reference	Quantitative Factors	Qualitative Factors	Methodology
	Name	Technology	Name	Technology				
[16] (2012)	Kinect Sensor	Mobile range camera (Infrared-based scanning)	Faro LS 880	Terrestrial laser scanner	2nd device	Accuracy	-	• C2C distance analysis • Distance analysis between the points and their best-fitting plane
[17] (2014)	Kinect Sensor	Mobile range camera (Infrared-based scanning)	Riegl VZ-400	Terrestrial laser scanner	2nd device	Accuracy	-	• Error between the object parameters with respect to the reference model • C2C distance analysis
[18] (2021)	iPad Pro LiDAR (SiteScape App)	Handheld mobile laser scanner	Faro Focus3D X330	Terrestrial laser scanner	2nd device	Accuracy, number of points, storage space on the system	-	• Distance between the points and their best-fitting plane • C2C distance analysis • Total number of acquired points • Distance between two consecutive points
[19] (2014)	iPhone 3GS	Photogram-metric re-construction	FARO Photon 120/20	Terrestrial laser scanner	2nd device	Accuracy, number of points	-	• C2C distance analysis
[20] (2014)	Canon EOS 300D, SONY DSC-HX20V, Smartphone SONY Z1	Photogram-metric re-construction	Konica-Minolta VI-9i	Terrestrial laser scanner	Quadrics, 2nd device	Accuracy	-	• Distance between a point from the surface of the reference model • C2C distance analysis
[21] (2022)	iPad Pro LiDAR (3D Scanner app)	Handheld mobile laser scanner	Faro Focus3D X330	Terrestrial laser scanner	2nd device and manual 3D BIM model	Local precision, global correctness, surface coverage	-	• Distance analysis between the points and their best-fitting plane • Distance between Apple PC and the closest point into the TLS PC • Distances between the PC and the closest surface in the 3D BIM • Orthogonally projecting the points on the corresponding surface to construct a 2D alpha-shape

fundamental importance, they emerge as pivotal factors in device selection. Factors like surface coverage, cost, system storage, and device moving speed are explored only by a few studies for comparison.

Table 3. Quantitative factors and corresponding metrics

Factors	Metrics	Description	Papers
Resolution	3D density of points	Number of points per unit volume / Total number of points in the target object	[7,9,12,14, 18,19]
	Number of points / 2D density of points	Number of points per unit square / Total number of points in the target area	[6,8,9,13,18]
	Average percentage completeness	Dividing the surfaces of the reference model into small regions and the existence of points is checked	[13,15]
	Consecutive point distance / Point spacing	Distance between two consecutive points (Absolute/average)	[8,9,18]
Accuracy	BIM/mesh to cloud distance analysis	Average distance between one PC and the closest surface in 3D BIM/mesh	[15,21]
	C2C distance analysis	C2C distances are determined by calculating the mean of all Euclidean distances between the nearest neighboring points of two-point clouds	[6–9,11,14, 16–21]
	Local precision / roughness	Distance analysis between the points and their best-fitting plane	[8,16,18,21]
	M3C2 analysis	Multiscale Model to Model Cloud Comparison	[15]
	3D BIM distance analysis	Building the BIM model from the PC (Scan-to-BIM) and comparing its dimensions with reference dimension	[8]
	Error in distance measurement	Percentage/absolute/average error in measurement of distances as compared to the reference	[3,4,9–12]
	Average error / Average percentage error	Distance between a point from the surface of the reference model where this point is supposed to be located / error between the object parameters with respect to the reference model	[10,13,17,20]
Time	Total time per setup	-	[3,12,13]
	Preparation time	-	[3,10]
	Scanning time	-	[3,4,7,10]
	Post-processing time	-	[3,4,10,13]
Surface coverage	-	Points are orthogonally projected on the corresponding surface to construct a 2D shape	[21]
Cost	-	Costs of actually purchasing or renting the devices (May also add man-hour cost as per time)	[3,12,13]
System storage	File size on the system	-	[12,18]
Device moving speed	Range of the speed	The speed of moving the device at which errors are least	[10]

3.1 Device Comparison

To compare devices, the factors identified in Table 3 can be weighted based on the project requirements such as project type and complexity, required level of progress monitoring, and level of details to be captured. Using these, the weighted average of factors can be calculated for a particular device, and this can be used to compare devices and select the appropriate option for the project.

The methodology for device comparison and selection is shown in Figure 1. Table 4 illustrates an example for the comparison approach, with a few factors as an example for selecting between two devices. The weights can be determined using the Analytic Hierarchy Process (AHP). However the weights presented in the table are hypothetical, and the specifics of weight estimation are not addressed in this paper, but are a part of ongoing research. The third and fourth columns of the table denote High, Medium, or Low values for each device, with corresponding numerical values of 3, 2, and 1 respectively. For factors where lower values are preferable, such as time, the numerical values are inverted to appropriately represent High, Medium, or Low. Finally, a weighted average of factors is computed for each device and compared, leading to the conclusion that Device 1 should be selected in the given example.

Table 4. Example of the comparison approach for device selection

Factor	Factor Weight	Device 1	Device 2	Weighted value Device 1	Weighted value Device 2
Resolution	0.2	3 (High)	2 (Med)	0.6	0.4
Accuracy	0.5	2 (Med)	1 (Low)	1.0	0.5
Time	0.3	1 (High)	3 (Low)	0.3	0.9
Weighted Average				1.9	1.8

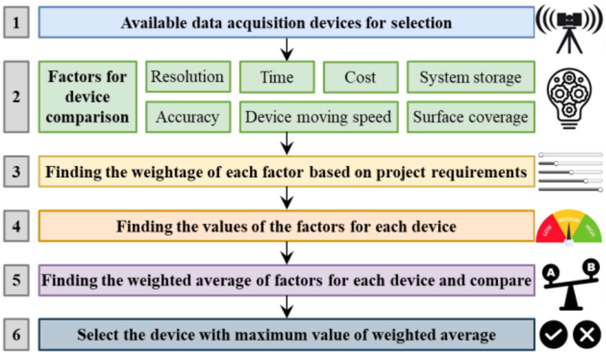

Figure 1. Methodology for device selection

4 Discussion

In the reviewed literature, a notable gap exists as the range of the devices are not evaluated Range of the device is one of crucial quantitative factors that should be considered based on field study and site conditions.

Most of the literature reviewed in this paper has conducted the field experiments to compare the devices on a site that is available based on convenience. These sites vary in monitoring requirements and physical conditions. As a result, developing a standardized benchmark for the devices is not possible. There is a need to develop a standardized testbed that would allow for the systematic comparison of devices under controlled physical conditions, including factors such as lighting and different types of construction. This will ensure a more comprehensive and reliable evaluation, of data acquisition devices.

The qualitative factors are discussed by lesser studies as compared to the quantitative factor. However, several significant qualitative factors have been identified, including ease of use, influence of lighting, influence of object materials, visual quality, training need, and more. These factors play crucial roles in assessing the overall performance and suitability of devices. While this paper has addressed quantitative factors, more work is required to characterize the qualitative factors. Using both the quantitative and qualitative factors, a holistic framework for CV-based device comparison to meet progress monitoring requirements of a project can be developed.

5 Summary and further work

This paper provides a systematic review of comparative studies on CV-based data acquisition technologies and devices from the relevant publications to understand the state-of-the-art in this domain.

Based on the comparative studies reviewed, key quantitative factors and the measurement metrics are identified. However, qualitative factors should also be included in developing a systematic device comparison and selection framework.

It is proposed that these factors can be weighted based on project requirements and scores for devices being considered for a project can be computed. These scores can assist in selecting the appropriate device.

Ongoing work is focused on developing a decision support system using this holistic framework. As a part of this framework, models for comparing performance of a mobile hand-held device with a terrestrial laser scanner is also being developed through a field-based study.

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