# State of Advances in Reality Capture for Construction Progress Monitoring and Documentation

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#### Abstract

Construction documentation is necessary on every project. Information captured must be accurate, timely and actionable. With several technologies and techniques available, the aim of this study is to determine the current state of the industry on this topic. The objectives of this study are to investigate the status of construction documentation, understand different technologies efficiency and practicality for their deployment to monitor construction progress. A mixed methods approach used a survey and interview instrument to distribute to professionals within the construction industry. Data from surveys was analyzed and later validated with thematic analysis of interview data. Main findings include that a single documentation technique or technology is not available to fit all scenarios and solve all documentation problems. Most of the documentation is done on the job site by project team members that are there, including superintendents and project managers. Still imagery and video are being captured daily on almost every job site. It takes more technically trained professionals to deploy more advanced technologies like laser scanning and drones. The primary decision for when a technology is deployed is determined by the type of data to be collected or the problem to solved. Within each of these groups, the decision is made based on four key issues including cost, speed, data value, and training required.

#### Keywords -

Progress Monitoring; Reality Capture; As-Built Documentation; 360 photography; Drones; Laser Scanning

#### **1** Introduction

Progress monitoring is a critical and challenging task required of a project manager. Inspections of construction progress are often manual and time intensive. Delivering a project on time and within budget requires active management of unique trades, all operating on different timelines toward a common goal. Therefore, it is imperative to have constant progress data available to ensure a project is on schedule and within budget [1]. Progress monitoring data must be accessible, actionable, and easily comparable so that corrective steps can be taken when problems arise. Progress monitoring is ineffective if its review cannot result in accurate remedial action.

Capturing the data required comes in many formats. Several technological advances have moved the industry away from the original method of progress tracking of doing it manually and recording it on paper. These include Light Detection and Ranging (LiDAR), photogrammetry, static imagery, and radio-frequency identification (RFID). Research by Omar and Nedi [2] classify technologies used for progress monitoring data collection into four categories: Enhanced IT, Geo-spatial, Imaging, and Augmented Reality [2]. These disciplines have matured over the past several years through increases in accuracy, reduction in time, and decreased cost. However, there is not a consensus on what technologies solutions solve which specific construction problems [3].

As-built documentation is an important part of the construction ecosystem. Being able to document the location of key systems within a building with supplemental data is a huge asset for owners and facilities managers. Being able to communicate that information with all the stakeholders in a project is equally valuable. How this is best accomplished has not been agreed upon within the AEC industry. There is a lack of standardization in how this data is collected, stored, and distributed to various stakeholders. This is a result of the numerous variables used to determine how progress monitoring data in captured. The sheer quantity of data is also a hindrance to valuable data collection and dissemination. It is estimated that the average construction project will generate more than 400,000 images [4].

The ever-evolving nature of technology necessitates periodic review of best practices and recommendations from previous research. Sensors become more accurate, computers calculate faster, and storage has moved to the cloud. The recent attention on technological solutions to the construction industry's problems has stimulated the growth of progress and improvement. Companies that specialize in reality capture are competing for better accuracy, range, and speed which is driving down costs. Leica, a prominent manufacturing of LiDAR technology, now sells a laser scanner for \$18,000, compared to an entry level model sold three years ago for £30,000 [1]. Technologies have the potential to be combined as they continue to mature. For example, the combination of small unmanned aerial systems (sUAS) and LiDAR. sUAS are currently being used for photogrammetry, because the photography industry is mature enough to combine high resolution in a small form factor. Research is being conducted on improving the navigation and autonomy of sUAS [5]. How all these technologies come together to solve problems in progress monitoring is not standard. The progression of technology and its integration into construction progress monitoring needs to be evaluated and understood.

## 2 Literature Review

Construction progress monitoring is a core component to managing any construction project. Knowing the progress of a project is integral to its success, much like managing quality standards and a budget. Construction progress monitoring gives project managers the ability to control schedule, budget, and unforeseen problems by comparing current conditions with a benchmark [1]. This task is often manual, involving multiple personnel from various disciplines. Not only does it require the attention of the general contractor, but also the design team and owner. All parties involved in a construction project require accurate and timely information on the status of the project to make informed decisions. How this data is collected and shared is constantly evolving due to the strides in advancing technology. Kopsida et al. [1] present a review of literature on the status of progress monitoring technologies by evaluating the following metrics: utility, time efficiency, accuracy, level of automation, required preparation, user's training requirements, cost, and mobility. They conclude that due to all metrics being considered and the complexity of construction projects, no general approach to construction progress monitoring can be recommended at this time [1].

Untimely detection of discrepancies between as-built conditions and as-designed plans are far too common on construction projects. Managing reliable progress data and integrating it into other project management systems is critical to remaining on schedule and avoiding delays. Unfortunately, traditional manual approaches do not integrate well [2]. Traditional methods are being replaced by various technologies, which are benefiting from the move toward automation. Laser scanning and photogrammetry are promising for indoor applications, but due to the lack of automation in object recognition they do not meet the researcher's threshold for an ideal use case [2]. "The future of the construction industry is of a highly automated project management environment integrated across all phases of the project lifecycle" [2].

Categorizing the various progress tracking technologies allows for greater comparison and application for their potential problem-solving ability. These categories each have their strengths and weaknesses, but all lack in automation. Manual input is required at some level in each of these areas [2]. Further advances in holistic automation and integration with current construction monitoring systems is required.

Collecting data for progress monitoring creates the secondary problem of data storage and collaboration. Multiple independent systems are utilized on construction projects creating enormous amounts of digital data. For example, on a 20,000m<sup>2</sup> building project in Champaign, IL, the construction management team collects an average of 250 photos per day [6]. Storing and sharing data when the file count is in the hundreds of thousands become a problem in and of itself, separate from progress monitoring [4]. With several file formats and interested parties, sharing data that is easily organized and distributed is a problem. "The AEC industry does not have a comprehensive visual dataset" [4]. Finding a universally accepted format and organizational structure is paramount to continue down the path of automation in progress monitoring. Taking photos or video on a jobsite is essential, as well as the use of BIM. However, there is not a systematic way for integrating the two. Several factors were found causing this problem: image to BIM alignment, unordered images, and distortion. Han [4] also notes several issues with point cloud to BIM technologies trying to integrate big visual data, object detection and agent localization. Specifically, solving the perspective-n-point problem would allow for greater automation in processing visual data from multiple sources [4].

## 2.1 Automation

Part of automating progress monitoring is recognizing work activities. Difficulties in distinguishing various stages of work activities create problems when automating the process of assessment. "It is difficult to differentiate between forming, placing, and back-filling a concrete foundation wall and inferring the current state of progress" [7]. Recognizing what is happening in collected data and comparing to what was designed is still being developed. Yang et al. [7] discuss two methods, occupancy-based assessment and appearance-based method. The first method uses point clouds of as-built conditions and overlays the data on the design model to detect discrepancies as well as utilize 4D BIM to track scheduling progress. The second method uses photogrammetry to create point clouds from images to identify materials, their quantities, and compare to the schedule [7].

Structure-from-Motion (SfM) is another technique used to automate progress monitoring. SfM uses as-built point cloud data and automatically registers photographs over the mesh model [6]. "SfM aims to reconstruct the unknown 3D scene structure and estimate camera positions and orientations from a set of image feature correspondences" [8]. This technique is key to the registration of photos to visualize progress compared to as-planned models. All of the methods presented by Golparvr-Fard et al. use this technique [8].

#### 2.2 Challenges

One of the main obstacles to as-built documentation and progress monitoring is the accuracy of the data collectors. Laser scanning is becoming more precise and photogrammetry algorithms are processing point clouds with greater detail [4]. However, different scenarios require various levels of accuracy. Photogrammetry is not ideal for interior work [1]. Fine details that distinguish various levels of completeness of interior work are not easily determined from photogrammetry data. Laser scanning is better suited for high accuracy and range [4]. "If the accuracy and quality level desired for a particular application is not high (i.e., error < 10 cm, and completeness rate > 80%), image-based methods constitute a good alternative for time-of-flight-based methods" [3].

The second obstacle in effective progress monitoring is the lack of consistency in data collection. Not only does the accuracy of the data collection vary, so does the type and frequency of data collection. Individuals collecting the data must interpret in real time what needs to be captured, how it needs to be captured, and the way it should be presented [6]. Progress monitoring data can be collected through numerous types of equipment such as cellphone photography, LiDAR, 360 photography, sUAS, and written daily reports. All of these methods require extensive as-planned and as-built data extraction from construction drawings, schedules, and daily construction reports produced by superintendents, subcontractors, and trade foremen [6]. All of these variables combine to create a unique situation on every constructions site based on the people involved, type of project, and equipment available. Not only is the data itself inconsistent, but so is the interpretation of the information. Data may be collected with the intent of highlighting one thing while it is interpreted in another way as it is distributed to various stakeholders.

The third obstacle in effective progress monitoring is the level of automation of a system. Scan to BIM lelve of automation is currently being researched in the industry [9]. It is cumbersome and resource intensive to interpret visual data manually [10]. Bosché et al. [9] introduced a system to further automate the Scan-vs-BIM technique, specifically for MEP components. The original approach of Scan-vs-BIM can only recognize objects within 5 cm of their as-planned locations. The new approach proposed by Bosché et al. [9] is more accurate, and lends itself to higher degrees of confidence at greater distances. The second finding of the study is in regard to "pipe completeness recognition". Recognition is defined as, "the type of object can be discerned. More specifically here, this mean that the analysis of the features enables discerning objects of a specific type (e.g. pipes with circular cross-sections)" [9]. The new method proposed by the researchers can match cross-sections with greater degrees of confidence by matching at regular intervals of 10 cm. Other methods do not measure at regular intervals, which can lead to errors in detection and recognition. The new method performed better and validated elements at higher levels of confidence compared to the original method in identifying as-built MEP pipes to as-planned. Scan-vs-BIM or any proposed approach to compare asbuilt conditions vs a BIM model assumes a model that is continually updated with every architect's supplemental instructions (ASIs), requests for information (RFIs), requests for proposal (RFPs), or change orders [6]. An incomplete model will sabotage any attempt at progress monitoring that relies on BIM to produce timely and informative decisions. Additional work is needed in this area to reliably interpret visual data in complex environments such as a construction jobsite [11].

## 2.3 **Progress Monitoring**

Progress monitoring of construction activities takes on many forms. Karsch et al., [10] conducted interviews of experts and describe a method of progress monitoring consisting of notes and photos taken on smart phones. Their participants describe this method of documentation "subjective" or "unreliable" [10]. With the prevalence of smartphones, it can be reasonably concluded that pictures and video in combination with email is the most common form of documentation and progress monitoring because of its familiarity and deployment among the general population. However, this does not mean this system is the most effective. Several interview participants commented the need for a much higher level of automation and analysis [10].

Image based systems have become the primary technology for progress monitoring of construction sites. Several LiDAR based methods have been proposed by previous researchers, but the most recent research reveals a turn toward image-based methods. The low cost of digital cameras and the implementation of highresolution cameras on smartphones has enabled the capture and sharing of construction photography to become more relied upon [6]. Prices on laser scanners will, drop yet they are unlikely to catch up with those on cameras soon since their manufactures do not respond to the competitive mass market of digital cameras [6]. In general, many recent methods for monitoring construction projects have moved to image-based techniques. Just like laser scanning techniques, imagebased methods capture occlusions during the documentation stage. Static occlusions, which are a product of progress itself, and dynamic occlusions, which are the capture of moving objects such as people, vehicles, and equipment [6].

### 3 Methodology

The research methodology used for this study is mixed methods. A sequential explanatory design was chosen to further explain and interpret the quantitative data from survey via semi-structures interview based qualitative data. This approach is in two phases, first a survey instrument to collect quantitative data and then semi-structured interviews to collect qualitative data. Interview participants were chosen from those who participated in the survey in order to further investigate the motivations behind the survey results. Preliminary data for this research was collected through a literature review. Literature review main findings were used to develop a survey instrument. The survey was first distributed to a small group of five industry professionals as a pilot to receive feedback. The survey was then distributed by email with an anonymous link to industry Virtual Design and Construction (VDC) personnel to determine the deployment of specific technologies. This survey was web-based and included questions that were open-ended and scaled. A snowball method was used to distribute the survey to construction professionals. The survey did not include personal demographic questions to maintain confidentiality and limit any potential of matching responses with participants. Two definitions were given to participants for consistency in terminology, construction documentation - data captured in various formats that describes the current status of a construction activity and progress monitoring - the process of comparing current construction documentation data with past data to compare and identify the progression of construction activities. The survey consisted of thirtytwo questions covering the themes of departmental demographics, technology specific questions, progress monitoring, value, and general remarks. Once survey data was analyzed, main findings were used to develop questions for a semi-structured interview format.

## 4 **Results and Discussion**

#### 4.1 Quantitative Results

The survey portion of the mixed method study was answered by 56 respondents, 48 of whom answered all the questions. 53% of respondents were employed at companies larger than \$1.5 Billion in revenue per year. This indicates that a majority of the respondents worked in large companies. Survey participants showed a high level of experience with 32% indicating more than 10 years' experience and another 25% between 5 and 10 years of experience in the construction industry. Due to space restrictions, limited amount of data is presented here.

The importance of progress monitoring is underscored by responses to a survey question asking respondents about on how often they document it, as shown in Figure 1. The overwhelming majority of the participants, 28 out of 48 indicated that they updated the progress schedule on a daily basis.



Figure 1. Frequency of Project Progress Monitoring

Survey participants were given the choice to select all of the technologies that they use to document construction project progress. This was mapped against how often they use them on a project. Not surprisingly, still imagery and video were chosen as the technology that is most commonly used on a daily basis, as shown in Figure 2. Those participants who noted they document daily, also reported that they use drone footage about half of the time. One respondent noted that they use laser scanning on every project, and document about 2-3 times per week.



Figure 2. Frequency of project progress monitoring and technology tools used

Respondents were asked to rate how satisfied they were with the data collected by various methods to capture construction progress. The choices presented to the respondents were on a 5-point Likert scale ranging from 'Extremely Satisfied' to 'Extremely Dissatisfied'. The numbers of respondents who indicated 'Extremely Satisfied' about a particular technology/tool is shown in Figure 3. Results indicate that respondents felt that laser scanning and drone mapping provided the most accurate data to document construction progress monitoring. The results are in keeping with other researchers' findings that indicate project managers prefer a variety of ways to document visual project data [12].



Figure 3. Respondent satisfaction with progress monitoring technology tools used

Respondents were further probed about what technologies they used to document construction progress, based on the scope of work being recorded. The technologies chosen by scope of work varied and no single technology available currently was identified by the respondents as the best solution for documenting all areas of a project. Concerning the documentation of site work, drone mapping/scanning was selected as the best technology for this scope of work.

The technology selected by participants for the documentation of structure was laser scanning, followed by 360-degree photography. Documenting the skin of a structure produced the choice of still imagery followed

by drone photo/video and then 360-degree photography. For interior framing, participants selected 360-degree photography as the best technology with 11 total responses and still imagery with 10 was a close second. For finishes, participants selected still imagery as the best technology with 17 responses followed by 360-degree photography with 8 responses.

Participants noted several different software platforms they use for monitoring progress of construction projects. The two mentioned most frequently were Procore and StructionSite. These platforms allow for seamless dissemination of information, especially media to various stakeholders. This is useful as the majority (91%) of participants commented that they do share documented activities with other project stakeholders. Participants did note that they have not received feedback from project stakeholders on a preferred format for documentation data, 58% vs. 42%. However, more participants chose that they do not use any form of documentation in lieu of in-person visits to the jobsite, 61% vs. 39%. Conversely, 73% of participants said they do use digitally documented data for inspections or verification of work performed, while 23% said they did not.

Survey participants ranked their preference on the technology that provided the best cost/benefit ratio. Only 2 responses separated the first three choices, still imagery, 360-degree photography, and laser scanning. 56% indicated that choosing a third party is the worst choice based on a cost/benefit ration. Not surprisingly, 59% of survey participants chose still imagery as the technology that requires the minimum amount of effort to produce a finished product for documentation. Almost 50% of respondents said laser scanning provides the most valuable information for documentation see Figure 4.



Figure 4. Most valuable information for documenting project progress

Participants were asked about which tool seemed to be the most promising one for future development to document project progress monitoring. The results indicate drone mapping, laser scanning and 360-degree photography are expected to get better and have the greatest potential to document construction progress in future projects.



Figure 5. Most promising technology to document construction progress in future

#### 4.2 Qualitative Results

Eight participants were selected from the researchers' established professional network, who had completed the survey to be interviewed. Research has shown that 8-interviews are appropriate to reach 80% saturation rate in qualitative interview based studies [13]. Interview questions were designed to explore in further detail the reasons behind certain choices being made by VDC personnel in the construction industry. No attempt was made to connect survey responses with interview participants to maintain confidentiality of survey results.

Interviewees responded to which currently is best for documenting construction by saying laser scanning and 360-degree photos. Laser scanning is the most comprehensive technology while 360-degree photos and videos are good for easily digestible data. One interviewee said, "Laser scanning is best overall. But a lot of people aren't willing to pay, you know, \$30,000 for a laser scanner. The 360-degree photos are a quick and simple tool that is a lot cheaper. And you can have normal people look at the data that you get from it and they understand what it is."

When interview participants answered what is lacking from current documentation technology, two themes that arose are training and education. Both of these are in regard to construction industry personnel and other project stakeholders. Interviewees commented that while the technology could be better, there is slow adoption and training on how to implement the technology within the construction industry. They also commented that project stakeholders are unaware of the capabilities of current technology and how to leverage the data collected to improve their projects.

When asked about waste, three themes were discovered, time, money, and labor. Time is being wasted in processing captured data, especially laser scan data. Post processing and point cloud registration is consuming value time and requires skilled and trained professionals to handle and interpret the data. Trained personnel cost money to imbed on site with a project team, or to travel to and from the project to collect and process data

Several problems are able to be solved through technology available for documentation. Primarily, referenced by interviewees, were work verification and as-built point clouds. Work verification is primarily being done with 360-degree cameras as a fast way to capture the status of a scope of work for quality assurance and quality control (QA/QC) purposes. One interviewee even mentioned using the information capture for determining liability of a problem. Several interviewees mentioned using laser scanning for verifying slab penetrations before concrete is poured. They compare scan data with models previously built to verify the work is correct. Another use of laser scanners mentioned by participants is in scanning and verify overhead mechanical, electrical, and plumbing (MEP) rough-ins. One interviewee said they specifically use laser scanning to verify overhead MEP on their large healthcare projects. Another example of problem-solving laser scanners are being used for is documenting as-built conditions for renovations. Several interviewees mentioned using laser scanners to document buildings they were doing renovations on. However, they were able to successfully leverage that information, but other project stakeholders they shared the scan data with were less capable.

Interview participants gave several reasons why they think project stakeholders do not utilize documentation data. The primary reasons given were a poor of the technology understanding and poor communication between project stakeholders about the technology and data. While tech savvy project stakeholders are able to leverage the data, the typical stakeholder cannot. This leads to a lack of understanding about what the technology is and does, but importantly the value it brings to justify its cost. Poor communication between stakeholders also leads to them not leveraging the data collected. One interviewee mentioned he has worked with very few architects who can take laser scan data he provides from a renovation project and model off of the data. Another told the story of an owner who hired a third-party laser scan the entire project several times, but through conversations with the owner, he realized the owner did not fully understand why he was having the building laser scanned.

The two major improvements described by interview participants about how to make laser scanning more accessible are cost reduction and time reduction. Every interviewee mentioned the high cost of laser scanning. The equipment is expensive as is the training and time required to use it properly. This was described as the main hurdle of implementing laser scanning on smaller projects because it simply costs too much.

When describing what could improve the progress

monitoring process, interviewees spoke about data integration and training. Data is currently fragmented throughout different formats and platforms that it is difficult to digest the information, especially when it is not in one place. One interview participant described a scenario where subcontractors and trades were better involved in the documentation process to better capture data. He said having trades document their own work would enable a less adversarial relationship between the subcontractor and general contractor while also enabling better information sharing. Another interviewee spoke about lowering the burden on technically trained people to perform the data collection by training others to perform the work.

Interview participants had several ideas on where they wanted the documentation process to be in the next five years. The primary responses included better automation, greater speed of data capture, better data integration, and greater jobsite connectivity to enable all of these advances.

All technologies are currently being utilized on construction projects, often multiple technologies on the same project. There is not a one size fits all solution for construction documentation technologies. Projects are being documented on a daily or multiple time per week basis with technologies that are the most accessible. Superintendents and project managers or combination thereof are the most common project team member to document construction. Therefore, less technically trained team members are using the technology they are most familiar with and comfortable using, their phones to capture still imagery and video. This leads to a disconnect between the cost of more advanced capture methods and the value of the data they provide. Technically trained team members are documenting projects that require technical solutions provided by more advanced Laser equipment. scanning and drone mapping/scanning/photo/video are being performed less regularly by highly trained professionals because high effort is required to plan, perform, and post process data collection with these methods.

Low acceptance and deployment of highly technical equipment is more common with smaller companies. The hurdles of cost and low understanding of value from project stakeholders is limiting deployment with all company sizes. Simpler technologies are more efficiency because they require less training, the equipment is less sensitive to the job site, and they are cheaper. Practicality of highly technical equipment has not reached a sustainable level due to the lack of understanding of the value of those technologies and the lack of data integration.

A graphic is proposed to better understand the situation of numerous documentation technologies available, as shown in Figure 6. Technologies are initially

split into two groups, status/progress and technical solutions. These categories inform the reader based on the type of data they are attempting to collect. This leads the user down the path to technologies that can satisfy their data needs while also informing them of the effort required and quality of data provided by each technology. The graphic also shows the technology best suited for their scope of work, as indicated by the participants of the study. By working from the outside in, a scope of work is selected which leads to the appropriate technology determined by industry survey and interview data.



Figure 6: Summary of thematic analysis of interview data

## 5 Conclusions and Recommendations

Progress monitoring and construction documentation are vital to every project. Monitoring progress to update budgets and schedules help project stay on track. Successful documentation must be accurate, timely, and actionable. Unfortunately, no single documentation technique or technology fits all scenarios and solves all problems. Each technology has its strengths and weaknesses. The majority of documentation is done on the job site by project team members that are there, superintendents and project managers. They often reach for the most accessible technology that is comfortable for them, their phones. Still imagery and video are being captured on a daily basis on almost every job site. It takes more technically trained professionals to deploy more advances technologies like laser scanning and drones. The primary decision for when a technology is deployed is determined by the type of data to be collected, technical solutions or status/progress. Within each of these groups, the decision is made based on four key issues including cost, speed, data value, and training required. Smaller companies trend to not use the most advanced and expensive technologies compared to large.

Further investigation is recommended for the integration of construction documentation data. Data is currently fragmented based on data type and capture

method. While individual platforms have reduced the burden of access for the non-technically trained professions, there is not consensus or common access. A type of cloud-based dashboard to host different data formats with one common access would be the goal.

Several platforms and devices are presently being developed and deployed in the construction industry for 360-degree photography. The potential value of data collected in 360-degree photography might not fully be realized until the technology has had more time to mature, but data captured now could be mined in the future. How this data could be applied to construction documentation needs to be further investigated.

Further investigation into why there is a lack of buy in and understanding of documentation by the architect and engineering community is needed to identify the problem and develop a strategy for better include this group with the valuable information being collected. The data being collected in valuable, but if it is not easily used by project stakeholders its costs cannot be justified. Over coming this hurdle would be a step forward in standardizing the technology and techniques used to documentation construction projects. Finally, further investigation into computer vision and machine learning is needed to address the capability of autonomously identifying construction material, equipment, and activities. This area of research is being advanced in other industries and needs to be applied to construction. With greater processing power and artificial intelligence, identifying problem areas and scopes of work that are behind schedule autonomously will become the future.

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