Conceptual Design of Advanced Construction Progress Monitoring with Terrestrial and Robotic Laser Scanning Systems

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SUMMARY

Advanced geomatics tools such as robotic and terrestrial laser scanners have the potential to significantly improve the progress monitoring of construction sites throughout their life cycle, particularly in the concrete structures, from the initial stage to cracking the ground for excavation and shoring to outdoor pouring of concrete at above levels and indoor finishing processes. Using 3D laser scanners to collect point cloud data and importing it into a BIM platform can lead to effective construction quality assessment, promoting sustainability in the building industry. By performing a robust BIM-based quality control system, including comparing as-built models extracted from point cloud data with the original as-designed drawings in 3D digital format, discrepancies can be detected and conflicts prevented during construction. Geomatics engineers are the groups of people who are involved in construction projects from the beginning. They now track construction progress using a combination of terrestrial lidar systems and emerging technologies such as robotic lidar systems mounted on autonomous mobile platforms or drones. This paper presents a framework for the effective use of advanced lidar systems to collecting 3D laser scanning data during different construction phases, in order to support the efficient quality control process in a BIM framework.

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1. INTRODUCTION

Though the general public views fossil fuel vehicles and transportation as the primary contributors to global warming and greenhouse gas emissions, in reality, the building sector accounts for 37% of Green House Gas (GHG) emissions, while the transportation sector contributes only 22%. It is also interesting to note almost 9% of the total CO2 emissions that are directly released into the atmosphere come from the construction material producers industry as part of their process to produce concrete, aluminum, steel, glass, and bricks (GlobalABC, 2021) [Figure 1]. Moreover, the construction industry influences the natural environment negatively by consuming almost 17% of the world's freshwater (Sandanayake, 2022).

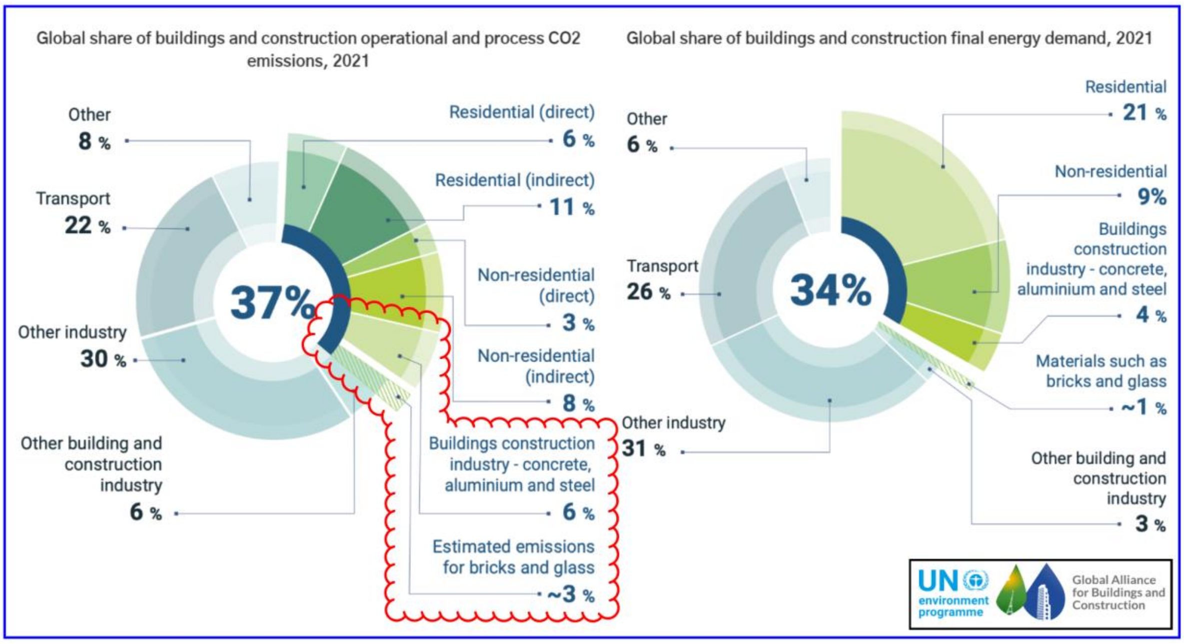

Figure 1. Global share of buildings and construction's energy use and emissions in 2021. Image adapted from (GlobalABC, 2021).

Material waste due to errors and mistakes during construction poses a significant obstacle to cost-effective projects, resulting in a loss of 5 to 25% of the entire construction budget (Forcada et al., 2017). Wimalasena et al. (2010) report that approximately 10% of construction material is wasted during construction, accounting for roughly 1% of the total GHG emissions (GlobalABC, 2021). Quality Assurance (QA) and Quality Control (QC) practices can mitigate the amount of carbon dioxide emissions associated with construction projects.

Quality Assurance is a process to ensure all the construction designs created by different consultants are compatible and match each other prior to implementing them on-site. Architectural, landscape, land surveying, structural, HVAC (Heating, Ventilation, and Air Conditioning), plumbing (mechanical), and electrical drawings are among the primary categories of building drawings. They are produced by a variety of professionals including architects, planners, engineers, and legal land surveyors. Alongside these primary drawings we have subsets of detailed shop drawings for steel embeds, glazing, elevators, and windows which mainly relies on architectural and structural drawings. Lack of effective communication among different designers is one of the main causes of project failure (Lee & Kim, 2018). By implementing an appropriate QA approach, discrepancies and clashes within different construction designs can be detected and rectified by sending Requests For Information (RFI) to the designers before implementation at the construction site. Building Information Modelling (BIM) is a process that enables an effective 3D QA and helps manage construction activities from initial design through operation. It becomes more effective with on-site point cloud data captured by 3D laser scanners.

Quality Control is a process that takes place during construction, where experts ensure that the work being implemented in the fields precisely matches the final drawings extracted from the QA process. This process is challenging as it requires regular monitoring of all on-site activities to ensure they align with the as-design drawings. In construction projects, site superintendents and supervisory teams spend 30-50% of their daily time on manual inspection (Golparvar-Fard et al., 2015). Laser scanners are robust tools to support QC during different construction phases with their exclusive benefits including effectiveness, high accuracy and precision, time saving, safety, and non-invasiveness (Skrzypczak et al., 2022). By performing 3D laser scanning, a precise point cloud can be obtained and used to extract building component parameters. These parameters can then be converted or updated to a BIM model, commonly referred to as the Scan-to-BIM process (Bosché et al., 2015). The Scan-to-BIM-based QC enables robust and efficient monitoring during construction in a timely manner (Maalek et al., 2019). It is also crucial to validate as-built BIM models with as-is BIM models to prevent conflicts and mistakes during construction (Carvalho et al., 2021; Wang et al., 2019). This validation can prevent the huge cost of rework which can account for up to 25% of the entire construction project (Josephson et al., 2002). During the last decade, a significant amount of research has been conducted to monitor the progress and quality of work in construction projects. In this area, (Golparvar-Fard et al., 2015) have used daily images from the construction site to monitor the progress of work. (Panahi, et al., 2022; Panahi, et al., 2023) have used video footage and computer vision techniques to monitor the progress of work and activities of construction workers inside modular construction factories, which can further reduce the costs associated with affordable housing. (Puri & Turkan, 2020) have used LiDAR and BIM to monitor the progress of work and identify discrepancies in bridge construction. Despite these advancements, the state of quality control methods still highly relies on manual intervention which can reduce the frequency of application for these methods in construction projects.

To ensure an efficient data collection process, new Robotic Laser Scanners (RLS) can be utilized with traditional Terrestrial Laser Scanners (TLS). The RLS system, in particular, has become increasingly popular in recent years, as it allows for a faster and more automated data collection process. However, it is crucial to plan appropriately before conducting 3D laser scanning in the field to ensure that the benefits of using those systems are maximized. By understanding the strengths and weaknesses of each type of scanner, construction teams can determine which instrument is best suited for each phase of the project. In this paper we will explore the different types of laser scanning instruments and provide guidance on when and how to use them for optimal results in the QC process.

2. METHODOLOGY

Data collection from the dynamic and complex environments of construction sites poses one of the main challenges in implementing QC in the construction industry. Therefore, it is crucial to choose the right scanning systems in the planning stage to have more coverage and avoid shadows and gaps in the point clouds (Olsen, 2022).

2.1 Lidar instruments

There are various types of lidar tools available for data collection; some are unmanned and autonomous, such as ground and drone robotic laser scanners, and some are manually operated, such as TLS. Lidar tools have five major applications in the construction industry: 3D model reconstruction, object detection, deformation measurement, quality assessment and progress monitoring (Wu et al., 2021). Recent advances in Drone Robotic Laser Scanner (DRLS) and Ground Robotic Laser Scanner (GRLS) technologies [Figure 2] enable real-time collection of a point cloud to monitor construction activities. However, they may not be suitable for some construction monitoring tasks due to their lower accuracy compared to TLS (Kim et al., 2022; Koval et al., 2022).


(a) (b)

Figure 2. An example of (a) a drone robotic laser scanner (DRLS) and (b) ground robotic laser scanner (GRLS).

2.2 Suitable lidar instruments for different construction phases

An appropriate selection of scanning systems should be made during the planning phase of data collection to account for different stages of the construction project, from excavation and shoring monitoring to pouring the foundations and the typical levels above for the concrete structures (Wang et al., 2019). For the QC data collection purposes, we have broadly divided the construction project into three main phases: (1) pre-construction and excavation; (2) outdoor data collection; and (3) indoor data collection, [Figure 3]. For each phase, we have linked a suitable 3D laser scanning instrument based on its performance.

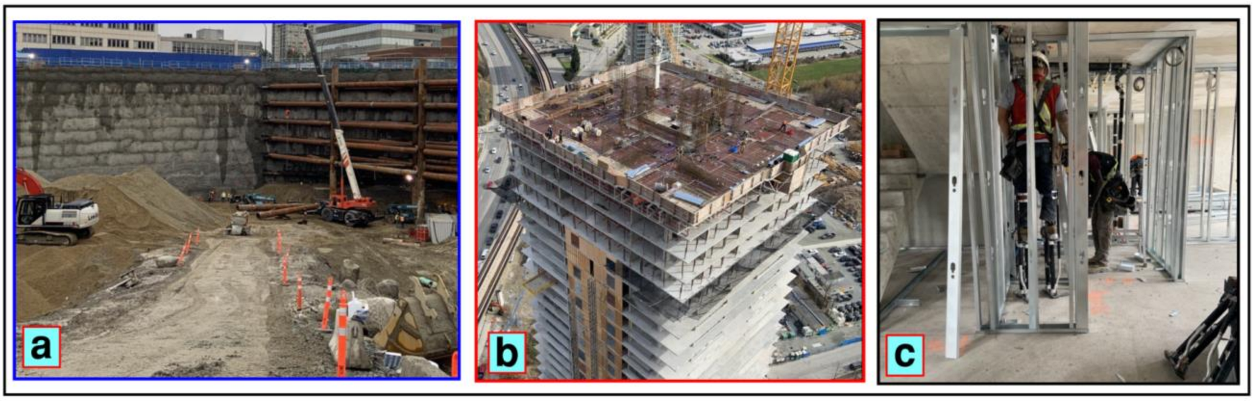

Figure 3. (a) Excavation site (b) outdoor construction (c) indoor construction.

2.2.1 Pre-construction stage

This phase aims to collect 3D laser data to monitor the vertical shotcrete surfaces of deep excavations for underground multistory parking under tall buildings or tunnels. This stage of construction is considered the pre-construction stage, where it is crucial to monitor the shotcrete surfaces conducted by geotechnical teams to ensure they match the design drawings (Olsen et al., 2015). When monitoring deep excavated shotcrete surfaces [Figure 4], it is important to ensure that the main exterior structural walls for high-rise buildings are correctly placed against shotcrete surfaces from the foundation to ground level. Also, in the New Austrian Tunneling Method (NATM) tunneling method, it is important to ensure the shotcrete surfaces are not included within the proposed final lining area for the main concrete layer. In case of these two above scenarios, TLS and Wearable Laser Scanners (WLS) are considered appropriate tools for precise scan data acquisition (Olsen 2022) as it is difficult to use DRLSs to navigate inside. On the other hand, for the monitoring of dirt and earthwork, DRLSs can be suitable for excavation for footings and foundations, as they can fly over the large digging area and heavy excavation machinery to perform scanning data collection safely and quickly (Li & Liu, 2019).

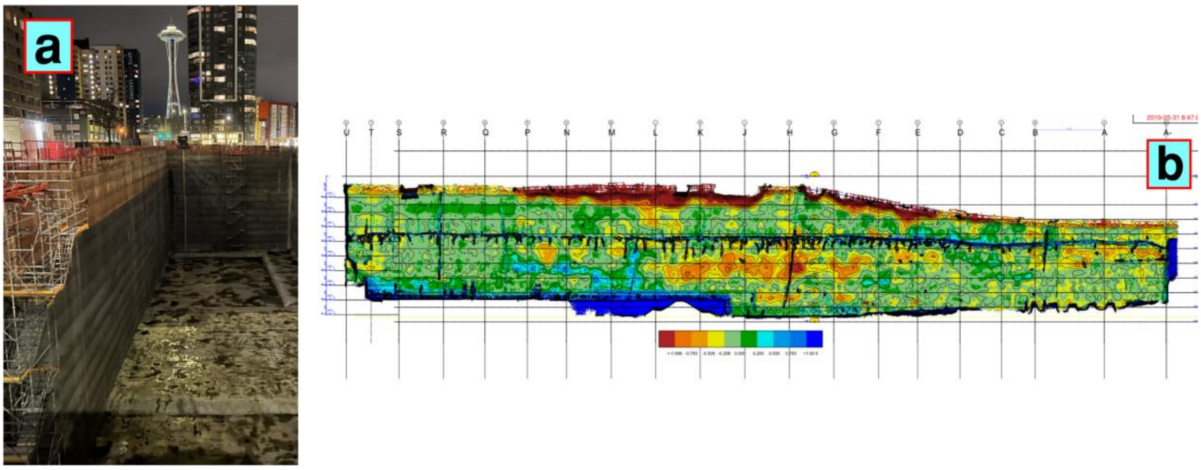

Figure 4. (a) An example of deep excavation for eight levels of underground parking and (b) shotcrete surface data collected with TLS and WLS.

2.2.2 Outdoor construction progress monitoring

The outdoor construction monitoring requires various types of laser scanning instruments. This process can be further divided into two sub-phases: (1) cast-in-place concrete formwork geometric quality control; and (2) as-built surface construction at above levels [Figure 5].

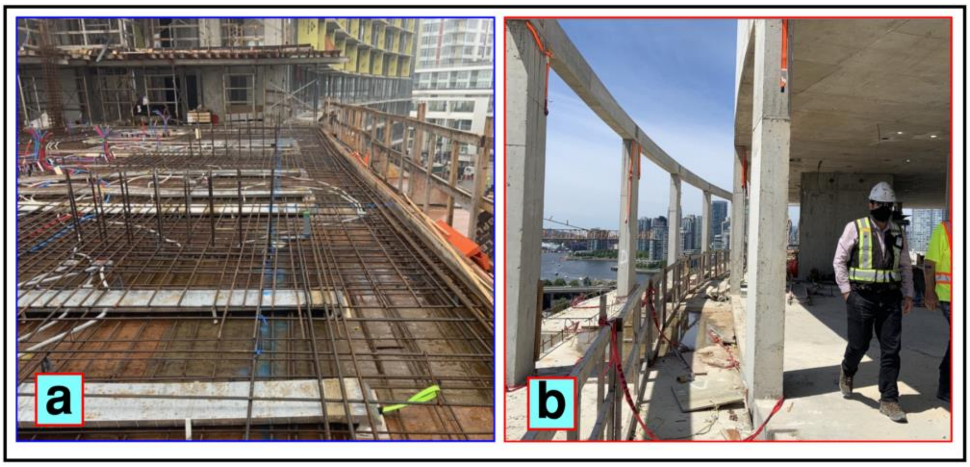

Figure 5. (a) Cast-in-place slab formwork before pouring concrete (b) exposed concrete for as-built monitoring.

Cast-in-place concrete formwork requires robust QC. Typically, scan data is obtained to compare built wooden or steel concrete formworks with as-planned drawings to confirm geometric requirements. Scan data would be helpful for the monitoring of mega concrete structural elements such as a deep structural transfer beam underneath a high-rise building [Figure 6], which must be in the right location with respect to the property lines, especially in dense urban areas. Scan data can also be useful for quality assessment of various construction objects, including installed grid, cage rebars, HVAC ducts, and plumbing pipes. TLSs are the most appropriate tools for these purposes because they produce high accuracy point clouds typically within 10 mm (Niskanen et al., 2020). For example, Maalek et al. (2019) validated an overall extraction accuracy of the point cloud data obtained for column, walls, and slab segmentation with ground truth and as-designed drawings, confirming an accuracy of 6 mm. On the other hand, the use of DRLSs and GRLSs is limited to construction progress monitoring for large objects and outdoor areas not only to ensure safety (Guan et al., 2022) but also because the resulting point clouds are not as accurate as those acquired from TLS. However, to improve the DRLS accuracy, Lassiter et al. (2021) proposed using pyramid geometric targets to increase the absolute accuracy of drone lidar point clouds to the level of accuracy to which the targets were surveyed.

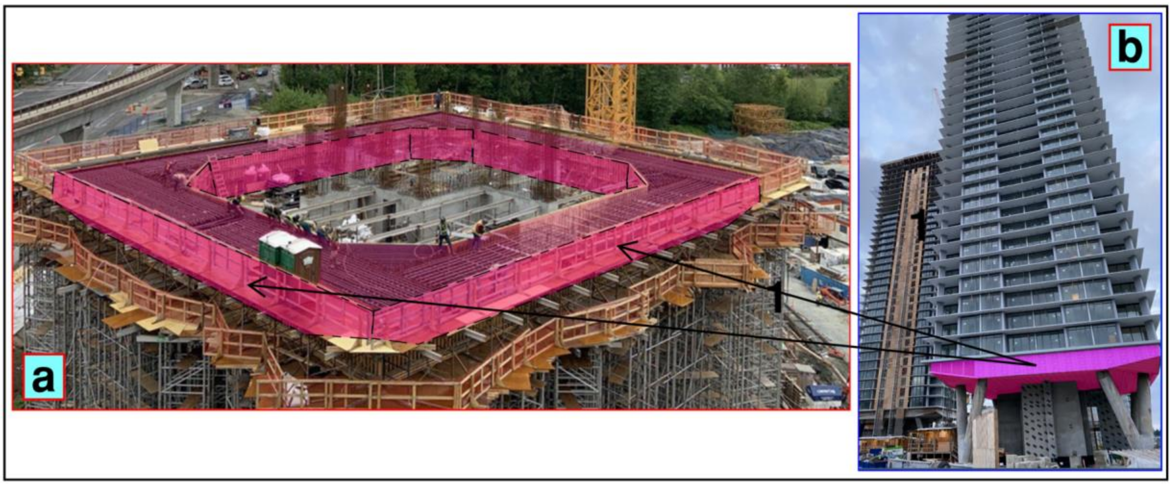

Figure 6. (a) A formwork of a structural transfer beam under a high-rise tower with 8.5 feet deep ready to be poured in 2020 and (b) after the building was constructed in 2021.

2.2.3 Indoor progress monitoring

Indoor progress monitoring is conducted at the final stage of construction projects to monitor finishing and cosmetic progress, such as masonry walls, glazing, and windows installation as well as plumbing and flooring, etc. However, colleting scan data with TLS can be challenging in indoor spaces because the surveyors need to conduct scans from multiple locations to avoid occlusions (Aryan et al., 2021; Jung et al., 2018), which can cause difficulties in registration and affect the quality of the final point cloud. As long as high accuracy is not required, GRLSs can be suitable tools to monitor progress on a regular basis as it enables automated registration without targets (Jung et al. 2015). These robots can also be useful for large object monitoring. For example, Kim et al. (2022) used GRLSs and deep learning techniques for the assessment of scaffolds in a construction site.

GRLS can also play a vital role in ensuring safety as the construction industry has the highest rate of fatalities among other industries, accounting for over 18% of all industrial fatal injuries (Bureau of Labor Statistics, 2016). Safety monitoring for indoor construction with DRLSs & GRLSs can be significantly improved through automated monitoring. On the other hand, TLSs are the most suitable tools for the monitoring deformation of concrete in the interior areas of tall buildings due to the high level of accuracy required (Olsen et al., 2010). According to the American Concrete Institute (ACI), concrete curing needs to be monitored within 7, 28, and 91 days after pouring concrete (Guide to External Curing of Concrete, 2016). This documentation and monitoring are essential to prevent damage to plumbing and HVAC system windows, and flooring due to concrete deformation in high-rise buildings, as well as to prevent the effect of creep and shrinkage in tall concrete buildings (Olsen, 2022).

3. CONCLUSION

For sustainable development in the construction industry, it is important to reduce the negative effects on global warming by minimizing waste of construction materials caused by errors and mistakes during construction. This goal can be achieved by implementing QA and QC in various construction phases within a BIM framework with the aid of advanced geomatics tools. Although there have been significant advancements in laser scanning systems, proper planning is necessary before performing the 3D laser scanning on the field to optimize their usages. TLS is a suitable tool for the QC process, specifically for precision scanning purposes to support structural or geotechnical monitoring. However, TLS has some limitations such as costly maintenance, limited angular coverage, as well as lack of mobility. While GRLS have limitations in terms of accuracy, their autonomous robotic system is a significant advantage. GRLS can be useful for monitoring complex indoor environments or places that are difficult for humans to access for damage assessment. Additionally, they are autonomous scanning systems that can be programmed prior to scanning, allowing them to perform their job without supervision. Lastly, DRLS can play a vital role in outdoor monitoring, especially when it comes to collecting data for vertical objects such as dense exposed rebar cages or deep formwork prior pouring concrete. Despite this, the ability of DRLS to access hard-to-reach areas and collect data quickly and efficiently makes them valuable tools for a range of applications. It is important to note that the accuracy and resolution of DRLS can be an issue, particularly in challenging environments with poor lighting or reflective surfaces. While various scanning systems have their limitations, they are still valuable tools for effective and efficient monitoring. By adopting these tools and techniques in a proper manner, construction professionals can minimize waste and errors, reduce negative impacts on the environment, and improve the overall sustainability of the industry.

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