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Geometric Inspection in 3D Concrete Manufacturing: Comparison of Data Capturing Techniques

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Abstract

Geometric quality inspection is an essential process in digital construction that provides insight into the conformity of the fabricated components to their designed models. It is even more important and challenging in modern 3D concrete printing processes where the realization of complex and intricate objects is possible. Using the right sensors for data capture is one of the key factors in the success and reliability of inspection results. Geometric inspection after printing makes it possible to update the digital model, adjust the next production step, or reject the fabricated objects if the deviation exceeds tolerances. This research investigates three different approaches, namely Terrestrial Laser Scanning (TLS), Terrestrial Photogrammetry (TP), and hand-held Structured Light Scanning (SLS), for the quality inspection of two medium-sized digitally fabricated concrete components. We compared the results of the data captured by each sensor with the respective other two sensors using cloud-to-mesh (C2M) distances. In all cases, the Root Mean Square Error (RMSE) is less than 1 mm which is acceptable for the majority of applications within the realm of digital construction. Considering the geometric performance and other parameters –such as time, cost, and flexibility–to name a few, we conclude that hand-held SLS is an optimal choice for geometric inspection of small to medium-sized objects.

1. Introduction

Construction defects can result in various problems, including financial strain, safety risks, and environmental impacts. Such defects might impose a cost escalation of 4%–5% on construction projects (Mills et al., 2009; Kim et al., 2016). Therefore, quality control from the early stages of fabrication is strictly mandated. Geometric quality inspection is a critical step to gain knowledge about the current state of construction components and their quality in terms of dimension, surface, and position. Although it is going to remain important in cast-in-place construction and precast concrete production, it is getting more important and challenging in modern 3D concrete printing processes (Figure 1) where complex objects can be realized. There are many studies that address geometric quality control at various stages of concrete fabrication (Puri et al., 2018; Mechtcherine et al., 2022; Ma et al., 2023; Wolfs et al., 2024; Farrokhsiar et al., 2024). In this study, we focus on geometric inspection after manufacturing that makes it possible to update the digital model, adjust the design model of adjacent components, or reject the printed objects if the deviation exceeds the expected tolerances.

Sensors play a crucial role in the creation of digital replicas of concrete components, whether for documentation or further geometry and texture inspection. In the conventional construction industry, especially when assessing single points like bounding corners, or regular geometries like planar, and right-angled faces, classic surveying techniques such as the tacheometry are employed. One advantage of digital fabrication is that more complex geometries, such as nonplanar walls or non-straight bounding edges, can be realized. In those cases, area-based data capture is necessary for quality control (QC) of the concrete components. We briefly describe three data capturing sensors and related techniques that are used in our study and we will continue this section with related works.

Figure 1. Digital fabrication of a concrete component (Hack et al., 2022)

Terrestrial Laser Scanning (TLS) uses an active sensor system to capture 3D point cloud by receiving the backscattered laser beams of the emitted signal from a sensor. Usually, it estimates the range utilizing Time-of-Flight (ToF) or Phase-Shift (PS) measurement principles. By rotating the optical axis in vertical and horizontal planes in predefined angular intervals, a panoramic scene view accompanied by intensity of the received backscattered signal and/or RGB data from the augmented camera (Suchocki, 2020; Marsch et al., 2020) is captured.

Terrestrial photogrammetry (TP) –here we mean a single hand-held camera– is a passive data-capture technique that refers to the process of obtaining 3D information about objects by utilizing a set of unordered images captured from different positions. In theory, a minimum of one image pair that covers the same scene is required. Nevertheless, in practice, additional images are necessary to generate a reliable and accurate 3D geometry of the surface. Photogrammetry is subject to scale ambiguity, which requires external information for scale estimation (Maboudi et al., 2021).

Structured Light Scanning (SLS) is an active sensing technique, that is widely employed for high-quality reality capture of small to medium-sized objects (Çapunaman and Gürsoy, 2024; Xu et al., 2020). Generally, a projector of an SLS projects a fringe pattern onto the scene with coded stripes. The projected light sequence undergoes deformation on the object's surface and a calibrated camera or multiple cameras record the projected pattern. Analyzing the correspondence between the projected frames and captured frames yields 3D data of the scene (Luhmann et al., 2020).

One important difference between the three techniques is that TLS and SLS directly derive 3D information of the scene, while in TP several steps from image sequence acquisition, image orientation using structure from motion (SfM) –usually followed by bundle block adjustment– and dense image matching are necessary. Therefore, the image acquisition and the quality of all following steps do have a direct impact on the final point cloud quality. The opportunities and challenges of current surveying methods in additive manufacturing in construction (AMC) are discussed in (Maboudi et al., 2020). The authors used a Leica P20 TLS and terrestrial photogrammetry to capture a 2m×2m double-curved wall. In this preliminary study, the capabilities of these approaches for measuring the deviation of as-built geometry from its as-designed 3D model are investigated.

Structured Light Scanning has widely been used for the geometric inspection of concrete elements. Wang et al. (2024) employed a GD-3dScan SLS for QC of a prefabricated concrete column to analyze the global and local deviation of the object from its designed model. In a related study, Mendřický and Keller (2023) used SLS to monitor the aging and shrinkage phenomena of a concrete wall, which was manufactured using 3D concrete printing (3DCP). A digital caliper tool was utilized to assess the dimensional changes in the 3DCP wall based on the cloud-to-model (C2M) distance within several months for a different level of inspection details. The geometric accuracy of seven hand-held SLSs is investigated in (Kersten et al., 2018).

A wide spectrum of digital cameras is becoming more accessible and affordable, making them a common tool for data capture in various fields, including the construction sector (Farrokhsiar et al., 2024). Images captured by the cameras of modern smartphones offer the capability to produce accurate 3D reconstruction models. This hypothesis is supported by a study conducted by Kersten et al. (2024). For four small objects, 3D models reconstructed using the images captured from a variety of smartphone images are compared with corresponding reference 3D models.

TLS is used in (Kim et al., 2016) for dimensional quality assurance of two precast slab concrete elements with the size of around 11m×2m×0.2m. The authors reported the dimensional and positional accuracy of 3 mm. For two objects that are printed with different printing techniques and materials, Mawas et al. (2022) examined different distances, namely C2M, cloud-to-cloud (C2C) and multiscale model-to-model cloud comparison (M3C2) between point cloud data (PCD) captured by TLS and digital models. The utilization of distance measures, particularly C2M, is prominent among researchers due to the accessibility of the digital model in digital construction. This method is favored for its ease of use and capacity for global analysis of the current status of the object of interest (Buswell et al., 2020; Hack et al., 2022; Buswell et al., 2022; Wolfs et al., 2024).

Based on our literature review, terrestrial laser scanning, conventional close-range photogrammetry, and structured light scanning, are the most common techniques used for QC in digital construction (Aryan et al., 2021; Maboudi et al., 2020; Buswell et al., 2020). Therefore, we employed these technologies to capture and compare the geometry of two digitally fabricated concrete components. Our main aim was to prepare a setup to investigate the pros and cons of each technology for QC of 3D manufactured concrete objects, especially medium-sized objects (less than 1 m^3).

2. Materials and methods

In this section, we describe the objects that are inspected and the sensors utilized with their setup in our experiments.

2.1 Objects

We selected two digitally fabricated concrete components (Figure 2) with specific shapes and geometries to test three data-capturing methods. We selected these two objects for their particular geometric characteristics. They consist of flat surfaces, holes, circular shapes of different sizes, and other geometric entities with complicated boundary shapes.

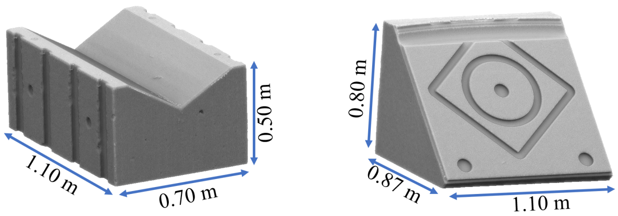

Figure 2. Two digitally fabricated concrete components that are used in this experiment

As it is visible in Figure 2, the objects are around 1 m or less in all directions, and all of our investigations and conclusions are referred to objects of this size. Very small or larger objects might need another setup and experiment.

2.2 Sensors

Advanced non-destructive sensing technologies provide opportunities to integrate diverse sensors, such as TLS, SLS, and conventional cameras for 3D reconstruction of objects.

Figure 3. Sensors used in this study

In our experiment, a Z+F IMAGER® 5010X laser scanner is utilized. According to the specifications, the TLS has a beam divergence of less than 0.3 mrad and a linearity error of better than 1 mm. In addition, the vertical and horizontal resolutions are 0.0004° and 0.0002°, respectively, with an accuracy of 0.007°. Notably, both objects are captured with an average distance of 3 m and an angular resolution of 0.018°, resulting in an average point spacing of approximately 0.8 mm. The TLS coordinate system is our reference coordinate system and all data captured by other sensors are transferred to this system. The different TLS stations registration results are achieved through the utilization of both target-based and plane-based registration using Scantra (Wujanz et al., 2018). The mean positional accuracy of the stations was 0.4 mm.

For image data capturing, we used a Canon EOS 5DS camera which is equipped with a 50 MP, 36 × 24 mm, CMOS sensor and a 28 mm focal length lens. For the left object in (Figure 2), 110 images are captured and a top-view of the setup is illustrated in Figure 5. Five checkerboard targets from TLS measurement are considered for solving the scale as well as transformation to the TLS point cloud. In this way, we ensure that the two datasets are in the same coordinate system with sufficient accuracy for our experiment. Three points are used as control points and two remaining points serve as check points. The total RMSE of the control points is 0.5 mm and the RMSE of the checkpoints is 1 mm. Since we had enough high-quality images, this discrepancy originates from the low number and non-optimal configuration of the reference points. In the next step, we compared the photogrammetric point cloud to the TLS point cloud. The photogrammetric setup for the second object was similar but with more images to enable 3D reconstruction of the details of that object.

As a fast 3D hand-held portable SLS, we employed Artec Eva to capture the geometry of the case study objects. This scanner has an angular field of view of 30° × 21° and provides a textured 3D mesh of the object with a *nominal* accuracy of up to 0.1 mm while capturing up to 18 million points per second. We used six very small targets on each of the objects captured by photogrammetry to transfer the SLS data to the reference coordinate system for further analysis. In both cases, the RMSE of the transformation was around 0.5 mm.

3. Experimental results and discussion

Considering the pros and cons of different comparison strategies (Mawas et al., 2022), we computed the C2M distance

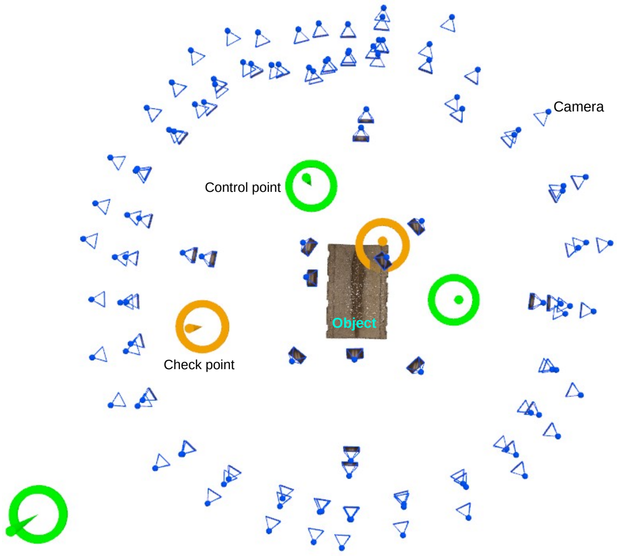

Figure 5. Constellation of cameras and reference points around an object

between the TLS point cloud and the meshes provided by the SLS and TP. Moreover, SLS and TP results are compared using a mesh-to-mesh comparison, where the C2M distances can be considered as the distance between the SLS mesh vertices and the mesh generated by photogrammetry or vice versa. Furthermore, to exclude the effect of outliers and non-correspondent points (Partovi et al., 2021), we use a cut-off threshold (99.7% of the distances). We applied the same procedure for all comparisons in our experiments.

The results of the C2M comparisons of both objects are illustrated in Figure 4 and are listed in Table 1. Since we do not consider one of the datasets as a ground-truth, in the context of C2M distances, the error is considered as the distance of a point cloud to a mesh.

It is worth mentioning that by considering the point cloud or mesh as the final product of photogrammetry, we ignore their capability to provide accurate information about the edges as well as the texture of the object.

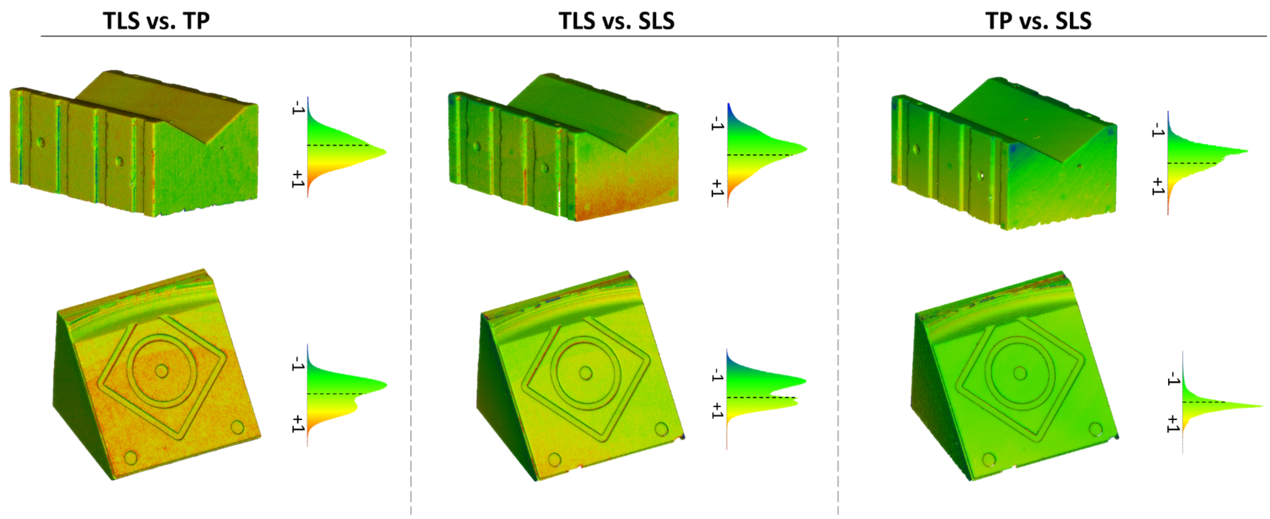

Figure 4. C2M comparison of data captured by different sensors for the objects in Figure 2

		TLS vs. TP	TLS vs. SLS	TP vs. SLS
Object 1 (Figure 2-left)	Mean	0.2	-0.1	-0.2
	Median	0.2	-0.2	-0.3
	Std. Dev.	0.5	0.6	0.6
	RMSE	0.6	0.6	0.7
Object 2 (Figure 2-right)	Mean	0.0	-0.4	0.2
	Median	-0.1	-0.5	0.2
	Std. Dev.	0.6	0.8	0.5
	RMSE	0.6	0.9	0.5

Table 1. Quantitiative measures of the C2M distances between the data captured by different sensors: all numbers in mm

Considering Figure 4 and Table 1 we can highlight the following findings:

- The results show an RMSE<1 mm in all cases, indicating the capability of all three techniques when the QC application requires such a level of accuracy.
- For the first object (Figure 2-left), the C2M distances follow a Gaussian distribution with $\mu \approx |0.2|$ mm and $\sigma \approx 0.6$ mm. However, for the second object, with a more complex geometry, the results are not completely consistent and the RMSE values vary in the range of 0.5 mm to 0.9 mm.
- Although the metrics in Table 1 provide an overall summary of the comparison results, a visual inspection of the C2M distances –as shown in Figure 4– is necessary for a better understanding of the distribution of the deviations.
- For the second object (Figure 2-right), looking at the second row of Figure 4, it is evident that there are two peaks when TLS is involved. This implies a registration error in TLS data. The last column in the second row of Figure 4 shows a better consistency between photogrammetry and SLS data with $\mu = 0.2$ mm and $\sigma = 0.5$ mm.

One error source in TLS data is the mixed-pixel effect particularly evident at edges where the laser beam splits, leading to the recording of multiple backscattered signals (Figure 6). This error could be more pronounced when inspecting objects with intricate details or before surface finishing, as it is often the case in QC after core printing in 3DCP (Hack et al., 2022).

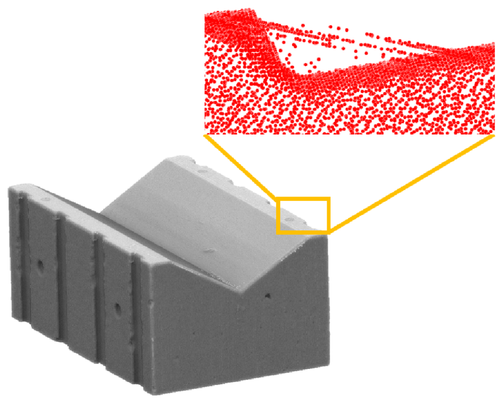

Figure 6. Mixed-pixel effects on TLS point cloud

While SLS and TP also encounter challenges with complex parts of the object, e.g. corners on intrusions and extrusions, their maneuverability allows for capturing higher-quality data on these parts. For example, SLS needs cautious movement around these areas to record the details, precisely. For photogrammetry, more images from different viewpoints and closer distances to these areas might be required. Generally, the availability of an as-designed model of the components in digital construction facilitates effective and efficient data capture planning to reach the required level of detail.

Beyond the mentioned metrics, some other parameters should be considered. We describe the main aspects that could be limited by the requirements and constraints of the projects. A big picture of these aspects is illustrated in Figure 7, schematically. For each parameter in this radar plot, a relative rough comparison is shown and the best solution for each parameter is considered as a reference on the border.

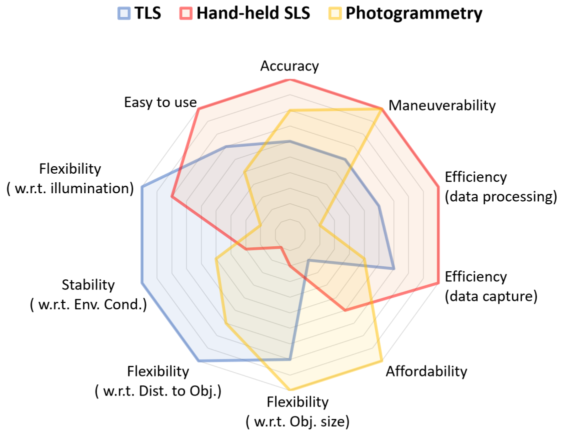

Figure 7. A schematic guide for selecting the proper data capture method for geometric inspection

SLS provides precise data for small to medium-sized concrete objects, like our case studies. However, it can struggle with surface reflectivity and transparency. On the other hand, TLS can deliver a mm level precision but the results are highly affected by the distance between the sensor and object. TLS is more useful for scanning medium to larger size objects and is not suitable for small objects with complex geometry. Photogrammetry can handle objects of different sizes, but the quality of the data depends on many parameters like the quality of the images, the network's geometry, and the algorithms used for camera calibration and 3D reconstruction.

TLS is a fast data collection tool, especially for large objects, but needs careful planning for the scanner locations and their co-registrations that might be limited by maneuverability. SLS is very fast for small objects but might not even work for large objects. The hand-held SLS is designed to be portable, allowing for easy movement during use. The data capture requires cautious movement around the object of interest. Photogrammetry can handle objects of different sizes. Its data capturing is fast but needs a longer processing time to solve the block adjustment and create 3D output.

SLS is suitable for controlled environments and photogrammetry is very sensitive to lighting conditions. Although all these sensors might be affected by surface features, like texture and color, usually it is not a big issue when scanning concrete objects.

TLS is more expensive while SLS and photogrammetry (with consumer-grade cameras) are by far more affordable. SLS and TLS software are usually integrated with the sensor. SLS software usually provides real-time processing and visualization and requires less post-processing. Photogrammetry needs special software for data processing but open-source software are also available. Photogrammetry provides accurate information about the edges as well as texture of the object. However, the pseudo-random sampling nature of the TLS leads to information loss along the edges.

4. Conclusion

Geometric quality inspection plays a crucial role in digital construction to verify the conformity of as-built concrete objects to their as-designed model. Using the proper sensors for data capture is one of the key factors in the success and reliability of inspection results. We investigated the capabilities of three different data capture approaches, namely Terrestrial Laser Scanning, terrestrial photogrammetry, and structured light scanning for the quality inspection of medium-size digitally fabricated concrete components. Based on our experiments, the deviation (RMSE) of 0.5 mm to 0.9 mm is achieved. Considering the registration error of TLS as the reference coordinate system and also the co-registration of the two respective other sensors to that, almost half of these errors originate from the relative registration errors. However, less than 1 mm error is acceptable for most applications in digital construction. We also discussed other aspects like efficiency, cost, shape, and geometric properties that can affect the choice of the sensor for geometric inspection tasks. Supported by our experiments, we conclude that hand-held SLS is an optimal choice for geometric inspection of small to medium-sized objects, i.e., not more than 1 meter on each side of the object. Photogrammetry can achieve comparable results but it needs more domain knowledge and processing effort. TLS provides good results when the object's geometry is not too complicated, otherwise it needs many data capture stations to cover the details of the objects of this size, where the registration of the stations would be more challenging.

In future work, we plan to establish a reference coordinate system with one higher level of accuracy to benchmark the results of the sensors and related processing methods. Two possible candidates are precision photogrammetry solutions (e.g. Aicon DPA system) and a more accurate SLS (for small objects with complex geometry). We also aim to investigate objects with different sizes and geometries. Long-term inspection and analyzing the effect of concrete maturity on the results could be a direction for future investigations. Geometric quality control for recent fabrication techniques, such as shotcrete 3D printing is also our current research topic, which is highly relevant to this study but necessitates special considerations to meet the requirements of such specific fabrication projects.

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