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Inspection methods for 3D Concrete Printing

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Abstract. 3D Concrete Printing (3DCP) is being used for off-site manufacture of many elements found in the built environment, ranging from furniture to bridges. The advantage of these methods is the value added through greater geometrical freedom because a mould is not needed to create the form. In recent years, research has focused on material properties both in the wet and hardened state, while less attention has been paid to verifying printed forms through geometry measurement. Checking conformity is a critical aspect of manufacturing quality control, particularly when assembling many components, or when integrating/interfacing parts into/with existing construction. This paper takes a case study approach to explore applications of digital measurement systems prior to, during, after manufacture using 3DCP and after the assembly of a set of 3DCP parts and discusses the future prospects for such technology as part of geometry quality control for the procurement of 3DCP elements for the built environment.

Keywords: 3D Concrete Printing; Geometric inspection; Quality control; Additive manufacturing

1 Introduction

The construction industry has been slower than other industries to adopt automation and digitalization in its manufacturing [1,2]. This remains the case and the current drive for ‘Industry 4.0’ standards promote the adoption of automation in manufacturing [3,4]. As a result, many Digital Fabrication processes that form Concrete (DFC) are emerging, with additive methods being the most common [5]. Many demonstrators on the building scale have been realised, and the science behind the materials continue to be investigated [6-9].

There has been less exploration of the geometric conformity of manufactured parts. Early work that recognised printing resolution issues for 3DCP was presented by Buswell et al. [10], and Buswell et al. [11], with examples of error measurement using photogrammetry in Lim et al. [12]. More recent research has been presented by Xu et al. [13] in real-time varying the bead size to reduce geometric errors, and by Ketel et al. [14] in developing a printability index to link mortar rheology to the geometrical attributes.

Quality inspection is an essential part of quality control [15], based on drawings and specifications detailing the requirements for materials and workmanship, mostly fulfilled via idiographic field testing in casting concrete products [16,17]. The quality required for reliable assembly of several parts becomes more challenging [18] and in manufacturing, such geometric inspection is often performed on a batch of products using statistical measures [19].

Inspection through digital geometric measurement has become common in construction and manufacturing [20-22], and will play an increasingly significant role, due to the fact that 3D printed components tend to be geometrically more complex and are hence difficult to measure with traditional means. There are different approaches for reality capture that can be applied in 3DCP, which depend on component scales, shape complexity, construction stages, ambient environmental conditions and other technical or economic demands. Classic approaches like using a Total-station are applicable just for simple components. However, 3D laser scanning and photogrammetry-based approach also including structured light-based methods are expressed as the most dominant data capturing approaches [23,24].

In order for Additive Manufacturing (AM) to find its way into the construction industry in the long term, geometric conformity of 3DCP components to the planned model and specified tolerances of the final products will need to be quantified efficiently using the aforementioned inspection techniques. This applies both to in-situ printed structures on which further building elements, as well as to prefabricated elements that are assembled at the construction site. This paper explores applications of digital geometric inspection methods applied to four stages of the manufacturing and assembly process using 3DCP:

- determining process capability prior to manufacture;
- adaptive fabrication during production;
- evaluating of form for postprocessing; and,
- building documentation after assembly.

2 Background

2.1 Additive Manufacture with Concrete

There are two approaches that utilise the placement of premixed cement-based mortar in a layerwise under digital control. Extrusion-based 3D concrete printing (3DCP) [25] is similar to the Fused Deposition Modelling (FDM), where fine grain concrete is extruded in filaments and deposited in a layer superposition manner to reach the target geometry [26,27]. Fig. 1 a, b and d present examples. Fig. 1c presents a material jetting process based on the principles of shotcrete [28] to deposit the material in a similar single nozzle toolpath approach. Both techniques are reported in the case studies presented, although the methods discussed apply to many other processes.

(a) (b) (c) (d)

Fig. 1. Typical 3DCP demonstrations: (a) doubly-curved panel (Loughborough University); (b) pedestrian bridge (TU Eindhoven); (c) doubly-curved reinforced wall (TU Braunschweig); (d) COHESION pavilion (University of Innsbruck).

2.2 Geometric inspection methods and tools applied in 3DCP

Data acquisition. The data acquisition methods can be affected by parameters like geometric deviations, visualization capabilities, the level of the inspector's experience, and degree of automation [29]. A systematic study and review on this is presented by Kim et al. [24].

3D laser scanning. 3D laser scanning and especially Terrestrial Laser Scanning (TLS) has become a common technology to acquire accurate 3D point clouds [1] in many engineering fields. High accuracy, ability to measure long ranges and low dependency on usual atmospheric conditions (lighting in particular) are the main advantages. However, material reflectivity, high cost, level of detail (LOD) dependency on the distance to the object, low portability and operational difficulties in congested areas and possible noise due to moving machinery and personnel in the construction site are limitations [30]. Typical applications of using laser scanned as-built data of components and structures for geometrically dimensional inspection (in comparison to design CAD

[1] The point cloud is a term used for a set of unordered points, which are spatially sampling an object.

models) can be found in Akinci et al.[31], Gordon et al. [32], Bosche [33], and Kim [34].

Photogrammetry. The availability of inexpensive digital cameras has significantly increased the number of photos that are being captured on construction sites on a daily basis [35]. Photogrammetric techniques have an advantage that the sampling is more continuous than laser scanning, although the pixel size is a limiting factor. Challenges of this approach include: the sensitivity to different lighting conditions, especially regarding severe shadow and low textured surfaces and windows; occlusion: capturing at each standpoint is limited to the closest structural part of the component to the camera; and each component must be visible from multiple (at least two) different points of view and those need to resemble a good image ray intersection geometry. Examples of use in construction include observations using unmanned aerial vehicles (UAV) both outside [36] and inside buildings [37].

Structured light scanning. Structured light scanning has been one of the most widely applied optical 3D measurement techniques because of its ease of implementation and fast full-field measurement. Structured light scanners work by projecting a patterned field of light, usually a set of sinusoidal stripes, onto the surface being measured. The set of projected light patterns is then captured using a camera and combined to allow the projected field of light to be unambiguously defined. This allows a process of triangulation to be used to determine the spatial position of imaged pixels to represent points on the imaged surface, creating a point cloud. Short scanning time, high resolution and highly-reduced dependency on material, texture and lighting conditions are the key benefits of this approach. However, this technology only works on relatively small objects located close to the projector.

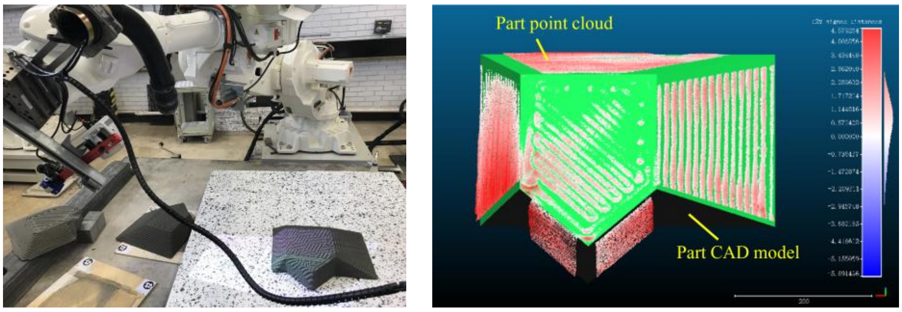
Coregistration. Often it is desirable to compare the printed object with the digital model and so registration of the measurements with the 3D model must be undertaken often with methods like ICP [38]. Although this approach works in many cases comparing two solid objects, its results could contain bias especially in AM products while ICP tries to minimize the difference between the two entities. Other approaches are to register point clouds and the physical object based on clearly defined targets. Some other researchers used a so-called feature based coregistration for this purpose [34].

3 Case studies

The following case studies demonstrate inspection at four stages of manufacture and assembly: pre-printing for process and material evaluation, during printing to compensate for plastic deformation, after printing for application of secondary processes, and post assembly for ‘As Built’ records.

3.1 Determining process capability: prior to printing

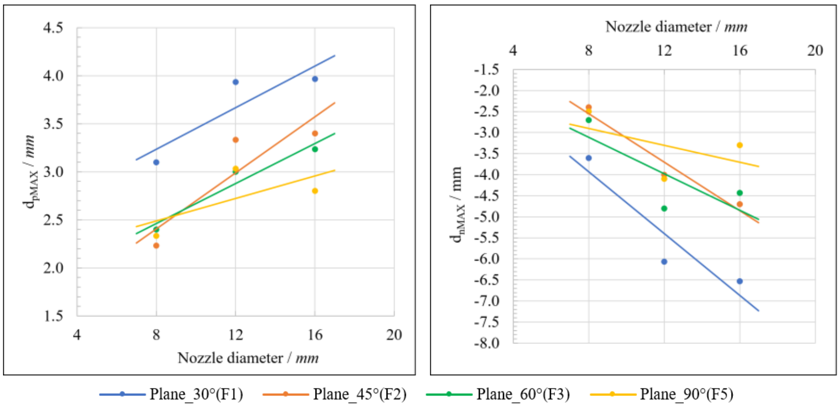
The evaluation of process capability in terms of the manufacturing precision is needed to inform the design of the part and as a benchmark for improvement, or system verification checking. Here a 'standard' test geometry was manufactured using an extrusion based 3DCP process (Further details in [39]). Positioning of the nozzle was via an ABB industrial robot and material was supplied via a worm pump. Several parts were printed using varying nozzle sizes (8 mm, 12 mm and 16 mm), where the layer height was parametrically linked by a ratio of 0.52, giving respective layer heights of 4.2 mm, 6.3 mm and 8.3 mm. Three parts were manufactured for each diameter using the same hatching pattern and step were taken to minimise the impact of mortar rheology, generating an inspection lot. Each part was then scanned using a DAVID SLS-3 structured light scanner for cost effectiveness and reasonable precision. The scanner performed several scans from different directions to capture the whole part geometry (Fig. 2a). Each scan was then processed (denoising, background removal and ICP registration) using *CloudCompare* [40] to obtain the complete point cloud. This systematic approach can be adapted to isolate influences that might affect the final geometry in a systematic test.



(a) (b)

Fig. 2. Structured light-based geometric inspection: (a) data acquisition; (b) flat face profile deviation measurement.

The six flat faces were inspected for flatness and profile errors. For each area, the deviation between each point in the point cloud and the surface of the CAD model was measured (Fig. 2b). The inspected errors allowed the feature tolerances to be evaluated and plotting the data against anticipated effects can help identify unexpected influences. For example, Fig. 3 shows the maximum positive deviation errors as a function of nozzle diameter, for each of the inclined and vertical planes on the part. The well-known 'staircase effect' [41] might be expected to dominate and present a linear relationship. The impact of the consistency in the material, even with care, leads to a lack of correlation. The diagrams also demonstrate that the error tends to reduce as the inclination increases because the layer height exacerbates the approximation errors to the flat surface. These insights might then be reasonably applied as constraints in the design of a component, as a benchmark against which improvement strategies can be measured.



(a) (b)

Fig. 3. Flatness errors variation of flat faces along with the nozzle diameter for different inclined angles: (a) maximum positive deviation; (b) maximum negative deviation.

3.2 Adaptive feedback: during printing

During printing, parameters may be controlled or anticipated a-priori. Others may fluctuate during a printing process, or between printing sessions: environmental conditions or geometric deviations due to cumulative deformations in layers of freshly deposited material for example. Even the exact geometrical properties of the 'print-bed' may be unknown. In such cases, the process conditions deviate from expected, which in turn leads to errors or possibly print failure. To avoid this, one approach is using real-time measurement and adaptive feedback.

Wolfs et al. [42] developed a system to perform continuous adjustment of the nozzle height during printing. A 1D Time of Flight (ToF) distance sensor, with an accuracy of approx. 1 mm and a range up to 200 mm, attached to the nozzle of the 3D printer. The sensor was positioned directly in front of the nozzle and could react instantly to the measurements via a wireless motion controller. Here, the data is collected, and continuously compared to a predefined, desired nozzle height. When deviations occur, a PID (proportional-integral-derivative) feedback system overrules the prescribed 3D print instructions (G-Code) and corrects the nozzle position in real-time.

The adaptive feedback system was demonstrated in a 250 mm radius cylinder wall printing. When the wall was printed with a conventional fixed increment in the z-height (Fig. 4a), deformations resulted in a significant deviation of the nozzle height, leading to poor layer placement and finally collapse. Using the feedback system ensured consisted nozzle position with respect to the working surface and a successful print of 50 layers (Fig. 4b).

(a) (b)

Fig. 4. 3D printed cylinder walls without (a) and with (b) the adaptive feedback system (figures reproduced from [42]).

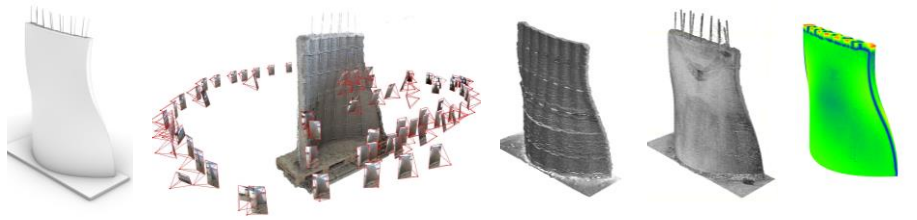
3.3 Postprocessing operations: in between to production steps

AM often results in undesirable level of precision in the surface finish and post-processing is required to bring the part into tolerance. Here the SC3DP technique [43] was applied to manufacture a doubly-curved, fully-reinforced concrete wall of 2.5 × 0.18 × 2.3 m including manual placement of pre-bent horizontal and vertical reinforcement (Fig. 5). The first stage was to print the vertical wall, install reinforcement, and then to spray the vertical surface, prior to a troweling operation to smooth the surface. The initial print was 3D scanned so that the as-printed part could be used to generate the tool path for the second spray process.

(a) (b) (c)

Fig. 5. SC3DP with reinforcement: (a) wall shotcrete 3D printing; (b) manual placement of the pre-bent horizontal bars; (c) threading in the vertical bars.

3D laser scanning and multi-view photogrammetry were used to generate 3D point clouds of the printed components. Data was acquired under different object conditions (dry/wet, with/without reinforcement, before/after surface finishing) in order to take possible conditions on real construction projects into account. Fig. 6 depicts as-planned model of the demonstrator and data capturing in different steps using above mentioned techniques. For multi-view geometry a non-professional digital camera was used and 80 images were captured. Then, PiX4D software was used to align the images and find the key points and perform the image matching. For 3D laser scanning, Leica P20 TLS was used to scan the object from 6 stations (2 stations before reinforcement and 4 stations on final product) with the average distance of 3 meters between the scanner and the object. The average density of the point clouds is less than 2 mm. Considering localization of the instrument in each station, it takes ten minutes to run a scan on each station. As 3D laser scanning is a direct measurement of the points, no special post-processing is required.



(a) (b) (c) (d) (e)

Fig. 6. Geometric inspection of a component: (a) 3D designed model of the wall; (b) photogrammetric block around the fabricated wall; (c) TLS data before reinforcement; (d) TLS data after reinforcement; (e) wall model colourised by C2C distance.

Eight targets were installed on different parts of the printing environment (cf. 2.2 co-registration) and their coordinates were also measured using the robotic arm in order to co-register the designed 3D model and the point cloud data acquired from the printed entity. TLS and photogrammetric point clouds as well as a 3D model were then co-registered using the 3D similarity transformation. Cloud to cloud (C2C) and cloud to mesh (C2M) distances were utilised to measure the deviations of the printed component from its digital twins.

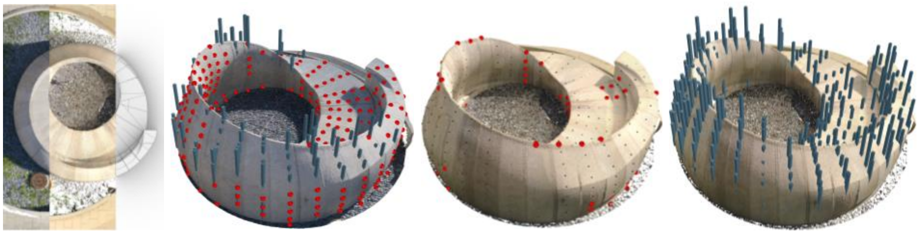
3.4 Assembly verification: after installation

The COHESION pavilion at the University of Innsbruck (Fig. 1d, [44]) comprised of 47 unique components that were assembled into the installation of 6.20 m diameter, 2.70 m height and 12.2 tons of weight. Every layer in each part of the assembly constantly changed in height between 4.50 and 12.00 mm, generating material deposition issues. The challenge here was to verify that the whole assembly was within tolerance using two parallel options for larger-scale measurement: photogrammetry and 3D laser scanning.

For photogrammetry, a drone set-up with a DJI Phantom 4 Plus, 4K sensor and predefined flight paths as well as Agisoft’s Meta Shape for calculations was used. This produced 136 images in 1 hour of flight and took approx. 3 days of calculation with 16-point cloud fragments, containing 13,304,966 points in total.

The 3D laser scanning with a Faro Focus S150 took approx. 1 hour for 8 scans, which yielded varying numbers of points from 468,436 - 12,653,468 in each point cloud, containing 23,924,383 points in total. The different amount of points in the individual scans was caused as some of the scans covered smaller areas on the pavilion exterior; the bigger ones covered more extensive areas (e.g. the interior). The surface area of the outer shell is approx. 88 m², resulting in a density of approx. 27 pts/cm² in the merged point cloud.

Once the orientationally adapted CAD model and the data sets from the two measurement approaches was aligned (Fig. 7a), a detailed data comparison (of 565 points) was achieved by measuring the distances between the CAD model and the scans. The precision of the photogrammetric data was reasonable for the general orientation and the build design evaluation, whilst the laser scanning was far more precise. A limit of 12 mm of deviation was defined to cull out problems of the closest point comparison. In the photogrammetric model, more than half of the points showed deviations above the limit (Fig. 7b). 110 points with more than 12 mm deviations (Fig. 7c) from laser scanning had to be visually checked, where 24 points actually had a deviation and others were at the boundary conditions of the structure which led to closest point comparison problems. 16 of the 24 points were located at the top-crease of the pavilion, which was a logical result because of the 3DCP process that filleted corners and creases. The 458 points with less than 12 mm deviations were visualized with diagrammatic 100 times scaled boxes at the location of the points of interest (Fig. 7d). As the deviation in neighboring areas was very similar, this led to the assumption that the elements still had a slightly offset position to the CAD model.



(a) (b) (c) (d)

Fig. 7. Geometric inspection of an assembled structure: (a) overlay of photogrammetry, 3D laser scan and CAD model; (b) photogrammetry: points (marked in red) with deviations > 12 mm, and points (marked in dark blue, values scaled by 100) with deviations < 12 mm; (c) laser scanning: points (marked in red) with deviations > 12 mm standing out especially on corners and creases; (d) laser scanning: points (marked in dark blue, values scaled by 100) with deviations < 12 mm.

4 Results and discussion

Table 1 presents the measurement system parameters from each case study. The structured light scanning method worked well at the scale explored, however the measurements were undertaken in a clean environment away from the manufacturing equipment. For measuring and verifying printed features, the method was robust. One observation was that the increased number of scans will increase the cloud point processing operations, which might affect the measurement of larger parts and also for a larger component both 3D laser scanning and photogrammetry, proved feasible to capture the large amount of data via multiple stations within acceptable time period. In the case of the assessment of the assembly, these processes also identified the accumulation effect of the manufacturing errors on the conformity of an assembly.

Table 1. Factors related to geometric inspections in the four case studies.

Quality control action	**Machine calibration**	**Adaptive feedback**	**Postprocessing assessment**	**Assembly verification**
Inspection technique	Structured light scanning	1D laser ranging	3D laser scanning/ Photogrammetry	3D laser scanning / Photogrammetry
Object scale	< 0.5 m	Point	< 3.5 m	< 7.0 m
Object surface state	Wet	Wet	Wet-Dry	Dry
Ambient lightning condition	Indoor	Indoor	Indoor	Outdoor, sunny
Measuring distance	1.0 - 1.5 m	≤ 0.2 m	≥ 1.0 m	2.0 - 3.0 m
Measuring (point cloud) resolution	0.3 mm	1.0 mm	> 1.0 mm	2.0 mm (laser scanning) / 4.0 mm (photogrammetry)
Time consumption	For an inspection lot: 15 - 20 min for data acquisition; 2 - 4 hrs for data processing	Real-time	30 - 60 min for data acquisition; 2 - 5 hrs for data processing	60 min for data acquisition; 3 days for data processing
Cost of measurement equipment	3 - 6k €	< 0.2k €	100k € (laser scanning) / 5k € (photogrammetry)	50k € (laser scanning) / 7k € (drone setup + software)

The 1D height measurement used for z-height correction on-the-fly was also promising. Key here is the speed at which the measurements can be processed into machine actions. With only linear distance measurements, this proved to be quite achievable. The method could be developed into 3D surface measurements to achieve 3D adaptive control for more complex applications of 3D curved geometries, which would then increase the required computational capacity.

Overall, the common technical challenges of different stage geometric inspection are time consumption (related to both data processing method and computational capacity), accessibility (inside of the structure), and ambient conditions (dirt, light, working space, etc). Since 3DCP is usually used for creating bespoke one-off large-scale components and structures, it’s critical that the printing parts are right-first-time, which can be achieved through material and process control. Geometrical measurement is a critical part of this process for establishing and checking machine precision, correcting the uncontrollable aspects of the process and for verifying form, either for a secondary process, to establish whether it is to specification or to determine the as built case.

It is likely that, rather than the traditional quality control based on random sampling parts, the bespoke nature of the components manufactured with 3DCP combined with less predictable process factors, is likely to lead to individual part verification. The automation of these quality control procedures throughout machine setup, printing and post-printing are somewhat inevitable, at least until 3DCP processes are demonstrated to be under control such that the uncertainties on geometric tolerance become insignificant.

5 Conclusions and outlook

Additive Manufacturing with concrete offers more freedom in design and this has been demonstrated to lead to the manufacture of more bespoke complex geometries. 3DCP processes are currently not fully predictable because of a combination of material, environmental and process variables that are difficult to determine, isolate and mitigate the effects. The result is that the success of a print in terms of the geometrical conformance to the design drawing needs to be verified at every build.

Equally, it is likely that corrective action will be needed during manufacture to ensure a successful build, i.e. prevent collapse. Additional post-processing is will be important for many practical applications and so verifying the base print prior to the application of a more controllable second process is likely to become routine as a consequence. The expectation coming from this work is that more systematic use of measurement in the 3DCP manufacturing process will be a cornerstone of future systems.

Beyond pure quality control, digital data acquisition enables the creation of extensive databases in which production parameters such as nozzle size, feed rate, material, temperature and geometry etc. are recorded and correlated with the print result. With the participation of a larger research community in feeding such a database, it becomes increasingly possible through the use of sophisticated techniques such as artificial intelligence to make precise predictions about the future print results and potentially to make suggestions for optimized path planning and automated adjustment of the production parameters.

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