3D SCANNING TECHNOLOGY AS A KEY FOR QUALITY CONTROL AND PRECISION IN CIVIL ENGINEERING 3DCP CONSTRUCTION

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Abstract

This paper focuses on new application methods, with an emphasis on Additive Manufacturing and especially on 3D Concrete Printing. As concrete printing is a “living material”, there is a need for continuous quality and accuracy control, with an emphasis on the verification of finished rigid structural elements made by 3DCP. The paper presents different methods and technologies for the use of 3D scanning, analyses the use of scanning in practice and discusses the main challenges and future directions.

Keywords

3D Concrete Printing, 3DCP, 3D Scanning Technology, 3DST, Laser Scanning, Photogrammetry

1 INTRODUCTION

The research and development of additive manufacturing (AM) is moving forward at a brisk pace in all sectors, including healthcare [1], mechanical engineering and civil engineering [2]. AM brings new, sophisticated and complex structural solutions using different materials, be it recycled plastics [3], metals [4] or their variations in the form of paste materials [5]. New structural solutions need to be subjected to structural and material analysis performed by numerical models, into which the material and structural properties of the objects are fed [6]. These models are based on the Finite Element Analysis (FEA) method, which uses elements that are connected by "nodes" to link multiple elements together [6]. Stiffness equations are then determined between these nodes and, when deformed sequentially, they can, for example, represent the tensile stresses in an element, depending on what type of equation is used in that element [7]. In the construction industry, the shapes of structures for FEA calculations are very similar; mostly, rectangular, square and circular shapes are produced. Slightly abnormal shapes are produced only occasionally , making up a very small proportion to the previously mentioned geometries. However, when using 3D Concrete Printing (3DCP) in civil engineering structures [8], these special shapes cannot be easily converted into simulation programs, nor can the dimensions of the final structures be accurately measured by conventional methods.

3D Scanning (3DST) includes various methods of collecting data on remote objects that are measured by using Light Detection and Ranging (LIDAR) [9], photogrammetry [10] or Sound Navigation and Ranging (SONAR) [11]. These methods are imperative for the structural surface detection of any structures, and, in all such measurements, even in the context of 3DCP measurements of structures, the ability to detect as much detail as possible in the structures and to establish a correlation between the idealized body and the real test feature of the measured 3DSTs is essential [12].

The effectiveness of scanning methods is significantly influenced by ambient lighting, surface characteristics and the type of used material mixture. For instance, reflective or wet surfaces may cause artefacts during structured light scanning, while porous or dusty surfaces may reduce the accuracy of LIDAR. Measurements conducted in controlled indoor conditions typically yield higher accuracy compared to outdoor environments [10], [13].

Thus, it can be concluded that AM has the potential to fundamentally impact and innovate the construction industry and beyond. However, there is a need to continuously validate material properties, and especially the geometric distribution of the individual parts, through experimental testing, numerical simulations based on the Finite Element Analysis (FEA) or the Finite Element Method (FEM) and 3DST. This review paper focuses on this particular topic; Fig. 1 shows a typical scan of a small structure. The obtained results will subsequently lead to

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the creation of safer, more efficient, economical and environmentally and aesthetically attractive building elements and eventually objects.

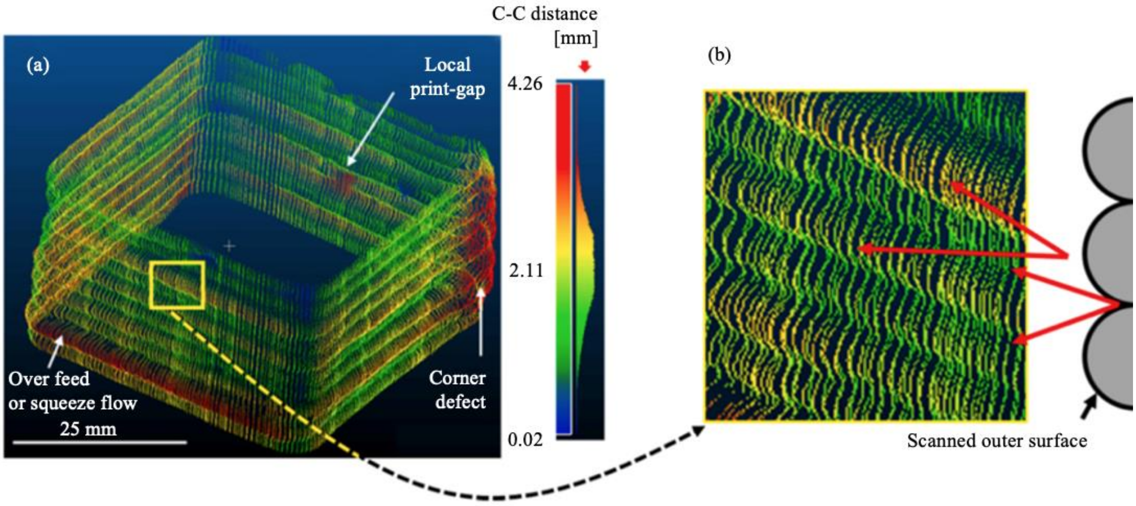

Fig. 1 3D scan of a 3DCP segment which shows differences between the input and output from a scanner [14].

2 METHODOLOGY

General Principles of 3D Scanning Technology

3DS is based on sensing of remote objects without actually connecting them using a physical body. For scanning of 3D structures in general, LIDAR or photogrammetry technology is most commonly used.

LIDAR is a device that emits laser light at distant objects, from which it is then reflected to measure the position and distance , in the Cartesian coordinate system, from the original source of the radiation [15]. Nevertheless, there are limitations to this technology which may cause it to be unusable, such as reflectivity of the surfaces being imaged, high purchase price and detailed imaging on distant objects [16]. Basic applications may include basic sizing of features or whole building objects for conversion to CAD programs [17], [18].

Photogrammetry is nowadays a rather inexpensive affair as high resolution cameras are available. Photogrammetry has, in comparison to laser scanning, the advantage of sampling and is also more continuous than laser scanning. However, the problem is acquiring enough pixels to produce a good quality image. This technology is very sensitive to lighting conditions, closer objects, multiple photos needed of the same object from different angles, and so on [19].

In addition to LIDAR and photogrammetry, structured light scanning is increasingly used for laboratory-case or small 3DCP element analysis. While LIDAR is better suited for long-distance scans and coarser detail, structured light offers high resolution for close-range inspection. On the other hand, it is much more sensitise to lighting and surface reflectivity [12], [13]. A comparative overview is provided in Tab. 1:

Tab. 1 Comparison of different 3D scanning technologies.

Technology	Sensitivity to light	Resolution	Range	Usage
LIDAR	low	medium	long	large-scale or outdoor model
Photogrammetry	high	medium	medium	general purpose
Structured light	very high	high	short	laboratory-scale model

General Principles of 3DCP Technology

The production of structural elements and parts using 3DCP technology is based on a *X*, *Y* and *Z* coordinate system. The print head moves in the *X* and *Y* coordinate plane and successively prints individual layers of concrete. The *Z*

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coordinate determines the height of the product as each layer is formed. The *X* axis determines the direction of printing, the *Y* axis is perpendicular to the direction of printing and the *Z* axis remains the height axis [20].

There are several different methods of 3DCP structures and parts, including methods performed by robotic arms, large format frame printers, special cranes adapted for brick block placement, or printers on rail travel [21]. These methods are suitable for both indoor and outdoor applications (in-site printing) [22].

When creating concrete structures, it is important to choose a suitable material, for example MASTERFLOW 3D 100 [23] precast concrete mix. The method of production depends on the nozzle (extruder) used, which may or may not be able to control the material flow [20]. The design hardware can be further modified by software that controls the print speed, the rotation of the extruder and the addition of accelerating components to the material [24]. This software is also used to divide the whole object into "slices" and to modify the printing path [25].

3D printing of concrete structures and parts is a demanding discipline and problems, such as print breaks caused by too many accelerators, inappropriate aggregate fraction or unwashed conveying hoses, can arise. Maintenance of the technology is key to successful operation. However, the technology is significant and has many potential applications.

From the economic perspective, implementing 3D scanning in 3DCP projects involves initial costs (equipment, software training etc.). Nonetheless, the early pilot studies demonstrate potential returns through reduced material waste, lower rework rates, and improved geometric precision. For example, integrating Terrestrial Laser Scanner (TLS) into prefabrication processes has led to repair cost reductions of up to 15 % [16], [18].

3 DISCUSSION

Integration of Laser Scanning Technology into 3DCP

3DST in civil engineering is carried out on a daily basis, with high resolution, as a passport of objects with rounding in centimetres is considered. However, for 3DCP structures made by AM, it is necessary to control all the processes that will be performed during the building, treatment and subsequent post-processing.

The first stage is the execution of these constructions. In most cases, the printed material is pasty and cohesive. These parameters can be further exploited during the actual printing process, where the deformations produced can be observed using laser scanning. These deformations, imperceptible to the human eye, can then be corrected during the printing process and do not damage or destroy the structure at all [26].

The second phase of the production of 3DCP structures, the 3DST can be used to examine the whole printed structures. In the process of refinishing, deformation of the element may occur and that is why an inspection is necessary. . The surface quality control must be done with higher detail where shrinkage cracks, individual shapes of the printed layers, regularity of the layers and also the overall shape of the produced structure should be checked. However, the structures do not have to be only printed concrete; if 3D printed stiffening elements, such as concrete reinforcement, are used (see Fig. 2), , they will have to undergo laser inspection in the precast production [27].

The final application for large structural elements is the inspection of experimental specimens, where the exact area of the test specimen needs to be calculated. These areas should be measured with as much accuracy as possible so that the behaviour of the individual test specimens can be described [13].

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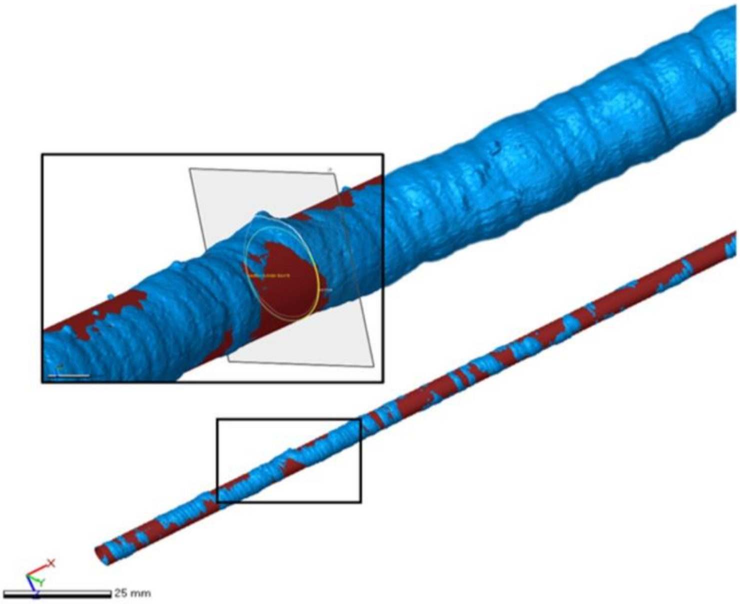

Fig. 2 Demonstration of experimentally measured 3D sinking against its digital twin, the cylinder [27].

Case Studies

So far, these technologies have been used for basic applications in a few examples, as described in the previous sections. These are, for instance, adaptive feedback during the actual printing of the 3DCP design, inspection of parts of the printed 3DCP design and assessment of the finished 3DCP design.

During printing, changes in temperature, humidity, solar radiation, and other natural or mechanical influences may occur that may affect the resulting print quality. Test sensors were developed and interfaced with the active print head and subsequently the nozzle. The nozzle then adjusted the height of each printed layer [28].

The structures could be printed separately or consistently whole. Study [29] gives an example of a partial design where a part of the design was scanned. Laser scanning and photogrammetry were used, where 80 3DCP images of the structure were taken for the photogrammetry. T Subsequently, the structure was scanned using a Leica P20 TLS which took measurements from 6 measurement points. The structures were inter-assessed against each other, and the experimentally printed samples were further assessed against the numerical model.

It appears that incorporating Artificial Intelligence (AI) for real-time quality control could help to provide even better results. Machine learning algorithms can process scan data on the fly, as well asdetect geometric deviations and adjust printing parameters dynamically. Having beentested in metal additive manufacturing, such techniques are expected to significantly enhance 3DCP workflows [17], [30].

The structures, as mentioned, were stacked into individual building blocks to produce the final structure. The structures can then be scanned with e. g. a DJI Phantom 4 plus drone and they should also be scanned with conventional stationary measuring devices. The main objective of the observation is for example the settlement of the structure or the size deviations of the individual parts. The structures scanned in this way are entered into CAD programs and compared with oneanother [30].

Challenges and Future Developments

Currently, laser scanning or photogrammetry applications are possible for 3DCP structures. However, it is necessary to determine how these applications could be further extended. For example, higher applications in active printing and control with other natural and mechanical variations that may occur during printing could be considered. The applications are mainly needed in the verification of large-scale constructions. However, smaller test specimens should not be neglected either, taking into account the layer sizes and their uniformity, as well as

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the overall final construction, which nowadays is needed to verify the deformations during the use of the building, as these are mostly prototype constructions.

4 CONCLUSION

Additive Manufacturing (AM) is increasingly used in the construction industry and is gaining more and more popularity. 3D Concrete Printing (3DCP) is mainly used for load-bearing vertical structures but it can also be used to a limited extent for horizontal load-bearing structures, such as beams or staircases. Subsequently, the use of 3D Scanning Technology (3DST) as a remote sensing technique, for example, is required for verification, whereby laser scanning or photogrammetry can be used. These methods are partly used to adjust the height of the layers during application, to verify the experimental specimens against the models and the numerical model. Overall, it can be concluded that some work regarding 3DCP exploits the benefits of 3D Scanning, but there is still great potential for further applications.

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