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Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders

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ABSTRACT

In the present paper a new additive manufacturing processing route is introduced for ultra-high performance concrete. Interdisciplinary work involving materials science, computation, robotics, architecture and design resulted in the development of an innovative way of 3D printing cementitious materials. The 3D printing process involved is based on a FDM-like technique, in the sense that a material is deposited layer by layer through an extrusion printhead mounted on a 6-axis robotic arm. The mechanical properties of 3D printed materials are assessed. The proposed technology succeeds in solving many of the problems that can be found in the literature. Most notably, this process allows the production of 3D large-scale complex geometries, without the use of temporary supports, as opposed to 2.5D examples found in the literature for concrete 3D printing. Architectural cases of application are used as examples in order to demonstrate the potentialities of the technology. Two structural elements were produced and constitute some of the largest 3D printed concrete parts available until now. Multifunctionality was enabled for both structural elements by taking advantage of the complex geometry which can be achieved using our technology for large-scale additive manufacturing.

1. Introduction

Until recently, additive manufacturing (AM) techniques were confined to high value adding sectors such as the aeronautical and biomedical industries, mainly due to the steep cost of primary materials used for such processes. In the last decade, the development of large-scale AM in such domains as design, construction and architecture, using various materials such as polymers [19], metals [20] and cementitious materials [16]. The deposition process introduced in this paper is designed for cement-based 3D printing.

Historically, the first attempt at cement-based AM was made by [21] using an intermediate process between the classical powder bed and inkjet head 3D printing (3DP) [25] and fused deposition modeling (FDM) [8], in order to glue sand layers together with a Portland cement paste. Many groups have been involved with the development of large-scale AM for construction applications, all of which have been using processing routes derived from FDM or 3DP, although varying depending on the chosen material and targeted application.

Among the literature available, three projects stand out over the last decade.

- The pioneering Contour Crafting (CC) project [14] is based on the extrusion of two layers of cementitious materials in order to generate a formwork. The extruded piece surface roughness is smoothed out using a trowel while performing the extrusion. The 3D printhead is mounted on an overhead crane as the system is designed for on-site construction operations. There are several drawbacks with the technology developed by [14]: the CC technology is limited to vertical extrusion, hence yielding 2.5D topologies (vertical extension of a planar shape); the initial formwork and trowel system can be rather complex to implement for production, depending on the size and shape of the object being printed. Furthermore, the interrupted sequential casting of concrete within the formwork due to hydrostatic pressure and weak mechanical properties of the extruded cement ensure the occurence of weakened interfacial zones between the layers, as shown experimentally by [17].
- The on-going concrete printing project at Loughborough University [6] is to a certain extent similar to the CC project since the printhead used for deposition of cementitious materials is also mounted on an overhead crane [18]. The material used in this project is a high-performance concrete [17], yielding better material properties than was obtained in the CC project. The high mechanical performance of the material combined with the relatively small diameter of the extrudate (4 – 6 mm) [16] allow for a good geometrical control. However, the trade-off necessary for maintaining its dimensional accuracy

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makes the process quite slow with regards to the envisioned industrial application. Although the project initially aimed at developing a processing system enabling for the generation of 3D topologies rather than 2.5D, the proposed solutions made use of supports, as in many other AM technologies, hence reducing the efficiency and flexibility of the process while increasing its material cost. Finally, dimensions and possibilities in terms of shape-design are prescribed by the use of an overhead crane.

- The D-Shape project [7], developed by Enrico Dini, is based on a 3DP-like technology. A large-scale sand-bed locally solidified by deposition of a binding agent, which is done using a printhead mounted on an overhead crane. This is done sequentially layer by layer; once the printing process is over, the printed piece is taken out of the sand bed; the remaining sand can be readily reused in the process. Although initially designed for the off-site production of panels as well as structural elements with complex geometries, the D-Shape project is currently aiming at demonstrating the feasibility of their process locally on-site, where only local construction material, i.e. sand, and binder materials can be used.

Based upon an understanding of the limitations identified in the above cited projects, the research project introduced in the present paper deals with the large-scale additive manufacturing of selective deposition for ultra-high performance concrete (UHPC). The 3D involved printing process is based on a FDM-like technique, in the sense that a material is deposited layer by layer through an extrusion printhead. The present work also explores the possibilities offered by computer-aided design (CAD) and optimization, and their integration within the product design process in the case of large-scale AM. Thus, the introduced technology succeeds in solving many of the problems that can be found in the literature. Most notably, the process introduced in the present paper enables the production of 3D large-scale complex geometries, without the use of temporary supports, as opposed to 2.5D examples found in the literature for concrete 3D printing. As a side remark, let us emphasize that the examples presented in this paper are among the largest 3D printed concrete parts ever produced. Multifunctionality enabled by arbitrary complex geometry is studied for a large-scale structural element. The research project presented in this paper was designed upon the following challenge: developing a large-scale additive manufacturing technology capable of producing multifunctional structural elements with increased performance. With this work, the aim of the authors is also to take part in the redefinition of architecture and design in the light of integral computation and fully automated processes.

The paper is organized as follows. First, the design and processing chain is described. The material considered for validating this new process route is presented and tested in Section 3. In Section 4 examples of complex shape structural elements produced with large-scale UHPC 3D printing are given. The obtained results are discussed in Section 5, as well as the techonolgy potential. Finally, in Section 6 a few concluding remarks are drawn.

2. Processing setup

2.1. Computational design

Generating and modeling shapes for additive manufacturing has to be done following specific sets of requirements, coming from both the processing constraints, e.g. layer thickness, product dimensions, etc., and the functional properties of the produced part, e.g. mechanical strength, thermal conductivity, etc. Both types of constraints will have to be considered synergetically at three different time and spatial scales: the material scale, the building path scale, and the global shape scale. In the present work, the processing constraints consist mainly in controling the rheology of the extruded paste and the setting kinetics of the material in interaction with the continuous building path and global shape of the object, e.g. a quickly setting mortar and/or a larger global shape allows for faster building path for a given layer. Functional requirements depend mostly on the properties of the hardened material and the structural geometry for effective mechanical properties, as well as other geometrically induced properties such as thermal insulation, soundproofing, etc.

Various approaches can be adopted for generating the robotic building path. An usual and straightforward method for generating a building path is to use a 3D-to-2D slicing software. It consists in slicing the 3D shape of an object in flat thin layers of constant thickness which can be layered one up onto the other. This results in a cantilever-method strategy, as shown on Fig. 1 (left). Each layer is then made of a contour line, as well as a filling pattern such as a honeycomb structure or a space-filling curve (Peano curve, Hilbert curve, etc.); the filling density can be adjusted for given requirements. This method is well-established for small-scale AM and 3D printing polymer- or metal-based processes. It is however not appropriate for large-scale AM since it does not take into account the processing constraints and their impact on the performance of the printed object. The building path should be adapted and optimized based on simulation results in order to take into account constraints and to exhibit more robustness for complex geometries.

These drawbacks are avoided in the present work by relying on a different method for generating a building path. The tangential continuity method (TCM) shown in Fig. 1 (right) is better for large-scale AM since the building paths are actually 3-dimensional, i.e. made of non-planar layers with locally varying thicknesses, hence better exploiting the geometrical potentialities of 3D printing technologies. The obvious advantage of such strategy is to keep contact surfaces constant between two layers, hence avoiding the geometrical gaps between two layers which often limit the possibilities of AM processes, most notably FDM and powder-bed-based processes. The layered structures obtained using the tangential continuity method can thus be mechanically loaded as classical masonry vaults, i.e. in pure compression, perpendicularly to the layer interface plane. Both methods are presented on Fig. 1: with the cantilever method the heigth of layers (grey) is preserved but the surface of contact varies (red), while the TCM preserves the surface of contact (red) and changes the height of layers (grey). From a structural mechanics viewpoint, the TCM yields more efficient and mechanically sound constructions.

2.2. Controlling the 6-axis robotic arm and printing system

For spatial displacement, an industrial ABB 6620 6-axis robotic arm was used. The remaining processing hardware parts were designed inhouse. It consists in a printhead mounted on the robot as well as two peristaltic pumps, one for the premix and one for the accelerating

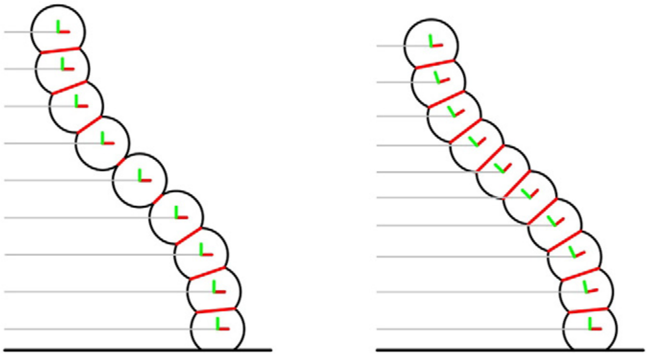

Fig. 1. Schematic cut perpendicular to layers 3D printed using the cantilever method commonly found in commercial 2D slicing software (left) and the tangential continuity method (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)