Bagh-e Nazar

Bagh-e Nazar, 20(127), 69-82/ Jan. 2024
DOI: 10.22034/BAGH.2023.394730.5371

Persian translation of this paper entitled:
فرم‌هایی با هندسهٔ پیچیده و رویه‌های منحنی در چاپ سه‌بعدی بتن
published in this issue of journal

Original Research Article

Complex Geometry Forms and Curved Surfaces in 3D Concrete Printing*

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Received: 06/05/2023 ; accepted: 27/09/2023 ; available online: 22/12/2023

Abstract

Problem statement: One of the most critical issues in architectural design is form, which has become more complicated in computational design. To overcome such problems nowadays, digital manufacturing methods such as additive manufacturing could be used. For a long time, concrete has been considered one of the primary materials in architecture. In recent decades, concrete 3D printing has made significant progress and practical samples such as pedestrian bridges, residential units, and urban furniture have been made with this technology. One of the most important advantages of 3D printing is the creation of complex geometries including curved surfaces. In 3D concrete printing, due to its large scale, some defects of the printed surfaces, such as the staircase effect are more visible. One of the methods that could be used to make the final finish of the printed surface smoother and closer to the original digital design is the application of curved (non-flat) layering in the production process. This method could produce surfaces with a better finish only by intervening at the software level and using the existing hardware.

Research objective: This paper seeks to investigate the methods presented in the additive manufacturing of cementitious materials and attempts to find their advantages and limitations in published articles.

Research method: In this review article, the documentary data collected from published scientific documents like articles, books, and theses, have been analyzed using a descriptive-analytical method.

Conclusion: Three main methods in additive manufacturing of concrete materials have been investigated, and the advantages and limitations of each have been listed. The main challenges for additive manufacturing of concrete in the three categories: properties of printable concrete, supporting structures for concrete printing, and the presence of cold joints were investigated, and finally, the methods presented for the construction of curved surfaces with 3D concrete printing technology were mentioned.

Keywords: *3D concrete printing, Additive manufacturing, Curved surfaces, Form with complex geometry, Curved (non-planar) Layering.*

* This article is extracted from Ph.D. thesis of "Khodayar Bondarian" entitled "Developing Computational Tools for Geometry Design in Additive Manufacturing Digital Fabrication" that is in progress under the supervision of Dr. "Saeed Haghir" and Dr. "Karen Abrinia", and in consultation of Dr. "Mohammad Reza Matini" at University of Tehran, Faculty of Fine Arts, School of Architecture, Tehran, Iran.

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Introduction

Additive manufacturing (AM), which is also referred to as 3D printing (3DP), has gained wide acceptance in the last two decades and is used in a variety of applications, from the automotive and aerospace industries to the pharmaceutical and biosystems and food industries. The roots of this technology could be found in photo sculpture (in the 1860s) and topography modeling (in the 1890s) (Gao, et al., 2015).

Among the most important advantages that additive manufacturing has over conventional methods such as subtractive manufacturing, which was the reason for the increasing popularity of this field, are: design flexibility (Karunakaran, Bernard, Suryakumar, Dembinski & Taillandier, 2012) and manufacturing complex geometries at a lower cost. Also high dimensional accuracy, no need to assemble parts (Gao, et al., 2015), less energy consumption, more sustainability, faster prototype production especially in low volumes, and lower cost in low quantities (Hopkinson, Hague & Dickens, 2006).

For rapid prototyping (RP) or additive manufacturing, various types of digital files have been produced by different CAD software packages, but the most widely used and accepted type is called STL1, which is basically a tessellated (triangulated) surface model (as opposed to a solid model). This file is used by the layering software and after applying the layering process, the tool path for the printer is extracted in the form of G-code language commands (Brown, De Beer & Conradie, 2014).

Fig. 1. Deitingen service station, Solothurn, Switzerland by Heinz Isler. Source: Kleis, 2009.

The CAD geometry created in the modeling software is converted into an STL file, and then this file is in turn compiled into a language that the printer can understand, and the printer starts making parts based on the settings that exist in its firmware. Also, some settings are included in the file, and then after the construction is completed, the part is carefully removed from the printer and, if needed, post-processing is performed to prepare it for final use (Gibson, Rosen & Stucker, 2010, 4-6).

Concrete has long been used as a building material in the Achaemenid Empire (Bakhshi, 2003) and the Ancient Roman Empire (Moore, 1995). Due to special features such as high formability and resistance to compressive forces, resistance to abrasion and corrosion, and lower price compared to structural steel, concrete has always been a favorite material of construction for architects and civil engineers. Concrete has also been widely used in the production of complex geometric forms with curved surfaces, such as the works of architects Eero Saarinen, Antoni Gaudí, Félix Candela, and Heinz Isler (Fig. 1).

The big disadvantage of using concrete in the production of such forms is the complexity of formwork design and setup and of course its high cost. In addition to the long time required for formwork setup and concrete pouring and curing, in some cases, the design is not capable of being built with conventional methods. In the last decade, there has been a lot of interest in using concrete as a material in large-scale 3D printing. Different goals have been listed for this technology: building shelters on the moon, building temporary shelters in emergencies, lowering the cost and construction time of buildings, using mass customization in the production of diverse forms such as urban furniture, high-quality control in construction (Buswell, Leal de Silva, Jones & Dirrenberger, 2018).

Automation in the construction industry could also bring additional benefits. Increased safety for construction workers, coping with a shortage of skilled labor (Bos, Wolfs, Ahmed & Salet, 2016), reduction of on-site construction time, greater freedom in architectural design (Lim, et al., 2012), and less production of environmental pollutants.

In this article, various methods of large-scale 3D printing are reviewed along with their advantages, limitations, and applications such as the construction of pedestrian bridges, residential units, the production of urban furniture, and temporary shelter after a disaster (Mathur, 2016; Holt, Edwards, Keyte, Moghaddam & Townsend, 2019). In the next section, the challenges of additive manufacturing with concrete materials are discussed in three sub-sections: "printable concrete properties and its constituents", "printing of cantilevered parts and supporting structure for concrete printing" and "the existence of cold joints".

Modern AM techniques are studied in four research areas (Gao, et al., 2015): (1) geometry design (2) material design (3) computational tools and interface development (4) manufacturing tools and process development. Concrete 3D printing could also be examined from these four perspectives and its latest findings and achievements could be enumerated. The construction of complex geometries by 3D printing with concrete materials is in the field of geometry design of AM technologies, which itself is divided into five subcategories: (1) multiple representations of 3D models (2) geometric processing for AM fabrication (3) verification, repair, and enhancement of the 3D model (4) High-performance computing (HPC) for AM (5) Optimization for special effects. The investigated research area in the next part of the article is curved (non-flat) layering, which is in the subcategory of geometric processing for AM fabrication. This type of layering is a new type that is used in the production of forms with complex and curved geometry so that the printed piece has a good quality.

The research questions in the curve layering method are:

Is flat layering an optimal method for printing complex geometries containing freeform shapes with low resolution, for example with a larger filament in FDM?

What options are there to minimize the roughness of curved surfaces produced by the staircase effect in the flat layering method?

How best could the roughness of curved surfaces be minimized in the pre-processing step (digitally designed print path) than in the post-processing step (surface finishing with abrasion or plating)?

Research Method

This article is a descriptive-analytical review of common methods of 3D printing with concrete materials as well as curved (non-flat) layering methods in additive manufacturing. The data collection method is documentary and library research. The documents used include research and review articles, conference papers, theses, dissertations, and books. The search keywords include 3D concrete printing, additive manufacturing of concrete, additive manufacturing of cementitious materials, curved layering, and non-flat layering, which are searched in the title and abstract of the articles, the results of which were analyzed from 1997 onwards and based on the number of citations. The most cited articles were selected to be used in this article.

- **Large-scale 3D printing**

3D printing could be divided into two small-scale (desktop) and large-scale groups. Using 3D printing to produce the final product in the construction industry requires large-scale printers. More than 30 groups of researchers have been engaged in research in this field in the last 10 years (Buswell, et al., 2018).

For different structural purposes, there are two main groups of large-scale printers, and all printing methods were included in these two groups: (1) Contour Crafting (CC) method and (2) Particle-bed method (Farzin, Mostofinejad & Ghahremani, 2019).

More than half of the processes use the material extrusion method (such as Contour Crafting) in which a small filament (between 6 and 50 mm in diameter) is typically pumped continuously from a nozzle mounted on a gantry robot or robotic arm. Usually, the material used is mortar with a high percentage of cement and aggregate with maximum dimensions of 2 to 3 mm. The extruded cross-sectional shape is variable and could be circular, elliptical, or rectangular, and the linear speed of extrusion is in the range of 50 to 500 mm/s (Buswell, et al., 2018).

- **3D printing by contour crafting**

One of the first pioneers in the development of large-scale 3D printing technology using cement paste is Dr. Behrokh Khoshnevis, a professor at the University of Southern California. The 3D printer of Contour Crafting is a gantry robot on which a head is installed that is connected to a concrete pump with a hose and like desktop 3D printers, cement paste is extruded along the contour curves whose coordinates are given to the robot controller, and the final product emerges by overlapping these layers. In Contour Crafting, the printer extrudes two layers of cement paste to produce a mold, and the top of the extruded part is smoothed with a trowel built into the machine. This technology is designed to be used in on-site construction as well (Fig. 2) (Khoshnevis, 2004).

This technology has several limitations: (1) it is limited to vertical extrusion and two-and-a-half-dimensional (2.5D) topologies (2) the initial mold and trowel system are too complex to be used in manufacturing of any part depending on the size and shape of the part. (3) The successive interruption of

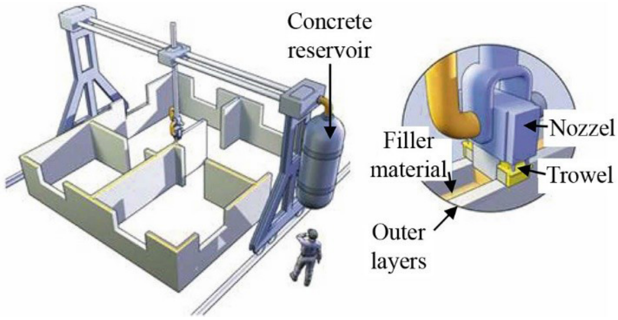

Fig. 2. Contour Crafting. Source: Allouzi, Al-Azhari & Allouzi, 2020.

concrete in the mold, due to the hydrostatic pressure and the weak mechanical characteristics of the extruded cement paste, the appearance of weakened interfacial areas are observed between the layers, as was experimentally in Le, et al. (2012b) shown.

- **D-Shape 3D printing using the powder bed method**

D-Shape technology was developed by an Italian engineer named Enrico Dini. Unlike the other two methods which were 3D printing based on material extrusion, this technology was a 3D printing based on powder bed technology (Cesaretti, Dini, De Kestelier, Colla & Pambaguian, 2014).

The D-Shape printer is a gantry robot that is located in a chamber and can spread layer by layer powder materials (spectrum of stone powder, sand, and ceramic particles) on the surface and then glue the powder particles together by spraying a special adhesive and integrate them. In the end, it is necessary to remove the excess powders from the printer chamber so that the final product can be seen (Farzin, et al., 2019).

Excess sand powder in this method could be reused in the process. Although this technology was initially designed for the off-site production of panels and structural elements with complex geometry, it is currently being tried to show the possibility of using it on-site (Fig. 3) (Gosselin, et al., 2016).

The advantages of this method are (1) the possibility of producing complex geometries without supporting structures and (2) the high resolution of the printed part (Farzin, et al., 2019). The limitations that exist in this method are (1) low speed for mass production (2) differences in the amount of binder penetration and the degree of bleeding around the injection point (Lim, et al., 2012).

- **3D Concrete Printing (3DCP)**

The concrete printing (CP) method is based on the Contour Crafting method, and it is a type of 3D printing based on material extrusion. The difference from the Contour Crafting method is the three-dimensional freedom and greater resolution of the printed part, which allows better control of the internal and external geometry (Fig. 4) (ibid.).

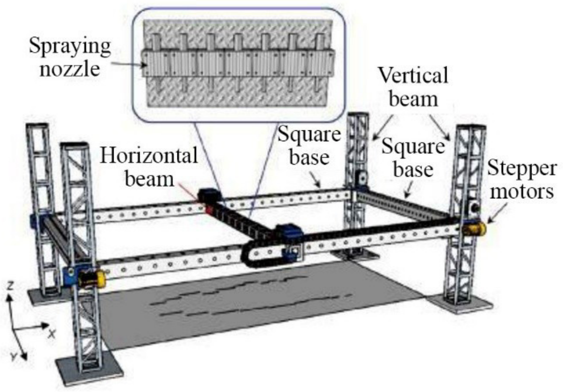

Fig. 3. D-Shape 3D printer. Source: Al-Safy, 2019.

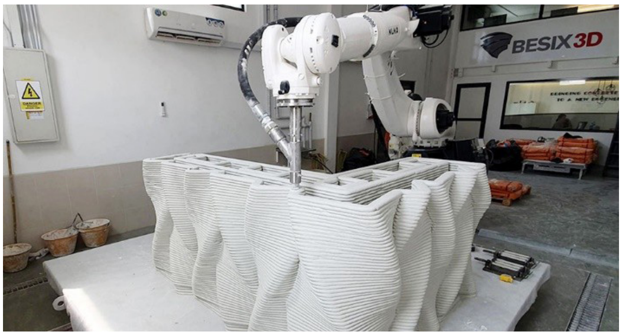

Fig. 4. 3D Concrete Printing. Source: www..kuka.com.

The advantages of this method are (1) the possibility of using the second material and (2) higher resolution than Contour Crafting (ibid.). The limitations of this method are: (1) the need for a supporting structure to print cantilevered and free forms (2) the need for a concrete pump and its maintenance and cleaning and control (3) separating the supporting structure and cleaning using post-processing (ibid.).

Samples of Additive Manufacturing of Concrete

From the large-scale 3D printing technology with cement paste, several samples have been produced as final products around the world. The Eindhoven University of Technology in the Netherlands is one of the pioneers of using this technology in the construction of pedestrian and bicycle bridges in the world (Fig. 5) (Salet, Ahmed, Bos & Laagland, 2018; Everett, 2021). A project with several residential units is also being built by the Dutch company BAM in Eindhoven (Fig. 5) (Boffey, 2021). The Concreative company in the United Arab Emirates has produced urban furniture, including tables, benches, and vases (Fig. 5) (Concreative, 2018). The American company ApisCor has been able to produce several buildings with a 3D printer in Masdar City in the United Arab Emirates (Fig. 5) (Emre, 2022).

Challenges of Additive Manufacturing of Concrete

• Characteristics of printable concrete and its ingredients

For 3D printing, cement paste must have certain characteristics, and this cannot be done with commonly used concrete. The desired mixing design, such as shotcrete, should be able to be pumped and retain its shape without deformation or with minimal deformation after extrusion (Buswell, et al, 2018).

Qualitative features such as “pumpability”, “extrudability” and “buildability” have been introduced by (Le, et al., 2012a). Pumpability describes the ease of transfer of cement paste from the pump to the extrusion nozzle (ibid.). Positive displacement pumps are commonly used in concrete 3D printing technologies (Buswell, et al., 2018). For conventional concrete, the workability of concrete means the ease of mixing and transporting it to the desired point, which is similar to the concept of pumpability in 3D concrete printing, and mixing ratios such as cement-to-aggregate ratio, water-to-cement ratio, and the number of additives also affect it.

In conventional concreting, the term “open time” is related to slump loss. In concrete 3D printing, “open time” is related to maintaining the viscosity and yield stress of the concrete, which is critical to the printing process. This parameter is related to the operation window in which a certain volume of material should be extruded (ibid.).

With the material deposition speed, another parameter called “cycle time” is defined, which is the time to print each layer and move to the next layer. This parameter determines the time delay between placing fresh concrete on the underlying layer (ibid.).

Fig. 5. (1) The longest bridge (in 2018) printed with concrete, Nijmegen, Netherlands. Source: 3www.dprintingindustry.com (2) Residential unit with printed concrete, Eindhoven, Netherlands. Source: www.guim.co.uk (3) Urban furniture including tables, benches, and vases by Concreative in the United Arab Emirates. Source: www.concreative. me (4) Concrete Printing, Masdar City, United Arab Emirates. Source: www. dezeen.com.

Extrudability means the ability to extrude the cement paste through the nozzle without significant deformation in the cross-section and an acceptable level of splitting/tearing of the filament. There is no formal reference test to estimate extrudability and this parameter is now evaluated by visual inspection (ibid.).

The buildability of the cement paste is determined by considering extrudability, pumpability (or workability), and a certain open time (e.g. 100 minutes) to determine the amount of superplasticizer that affects the shear strength of the cement paste. In the research by Le, et al. (2012a), the range of 0. 3 kPa to 0.9 kPa was determined for the cement paste used, which is neither too soft nor too stiff.

In printable concrete, fine aggregates usually up to 2 to 3 mm in diameter are used (Buswell, et al., 2018) and polymer fibers (Panda & Tan, 2018) as well as other components such as superplasticizers, retarders, and accelerators are also added to them. (Le, et al., 2012).

The strength of printed concrete depends on the direction of printing (Paul, Tay, Panda & Tan, 2018). Because this concrete is not reinforced, its tensile strength can only be increased by adding fibers to it (Panda, Paul, Mohamed, Tay & Tan, 2018). Of course, one of the research trends in this field is reinforcing printed concrete. Methods such as printing on the supporting structure, using conventional reinforcements in a post-tension form after printing the piece, and inserting the reinforcement during concrete printing perpendicular to the layer or along the layers are among these methods (Paul, Van Zijl & Gibson, 2018). In the research by Asprone, et al. (2018) a comprehensive review has been done about reinforcing printable concrete.

- **Printing of cantilevered parts and supporting structure for concrete printing**

Among the other challenges encountered are the printing of curved parts and the use of a supporting structure to print them. Since the strength of concrete increases with time, in concrete printing, minimum time is needed for the lower layer to have enough resistance to withstand the higher layer. It is possible to make the cantilevered parts in two ways: (1) by corbeling (Gosselin, et al., 2016; Bos, et al., 2016) (2) by adding temporary support on which to print the cantilever and then removing it afterward (Lim, et al., 2016).

For the support structure, many researchers have proposed ideas such as printing a polymer structure with a time interval compared to concrete printing, using powder materials such as sand, printing the support structure with concrete (ibid.), or adaptive moulds like the example of the Danish company Adapa (Fig. 6).

- **Cold joint formation**

Due to the time interval between the printing of layers, there is a possibility of a cold joint between both layers, which can reduce the strength of the structure at the place of formation. Adding polymer fibers (Panda, Chandra Paul & Jen Tan, 2017) or placing reinforcement between layers as well as optimizing printer tool paths according to printing parameters are ways to reduce or prevent this phenomenon (Buswell, et al., 2018).

Manufacturing curved surfaces with 3D printing technology

For layering, the 3D model file, which could be either solid or surface, is converted to a tessellated model (STL). Although layering is possible directly on the original model file, STL files have become the standard in AM technologies (Mohan Pandey, Venkata Reddy & Dhande, 2003).

The main limitation of the STL file, due to the first-order approximation of the surface, is the lack of precise geometrical information of the original model. The maximum deviation between a piece of the original surface and the STL model is called chordal error. Despite this error, the STL model has advantages such as ease in layering, changing the orientation of the model, and adding supporting structures.

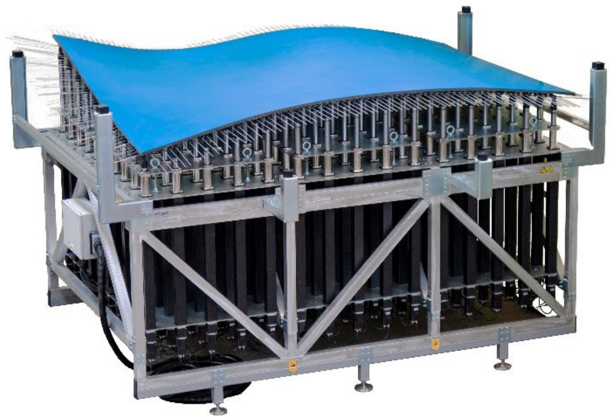

Fig. 6. Adaptive mould by Adapa company. Source: www.adapamoulds.

Placing parallel layers on top of each other leads to a staircase effect as shown in Fig. 7. According to the stepped edges in the part, three situations may arise; first, all layers are placed inside the volume of the original model, second, all layers are outside it and third, some part inside the volume and the rest outside it. This phenomenon is called “confinement problem” (Fig. 7).

Curved (non-flat) layering is a dynamic method for toolpaths in 3D printing by fused deposition modeling (FDM) or fused filament fabrication (FFF). In this method, unlike conventional flat layering, the values of vertical alignment (z) are variable for each layer (Allen & Trask, 2015).

The use of this layering method can also help to improve the mechanical properties of the part because the tool path follows the top surface.

Curved (non-flat) layering also has limitations. In most cases, to print a curved surface, it is necessary to build a support structure for the final product, something similar to a mould, so that the final print can be built on it. The amount of slope that the surface could have is related to many

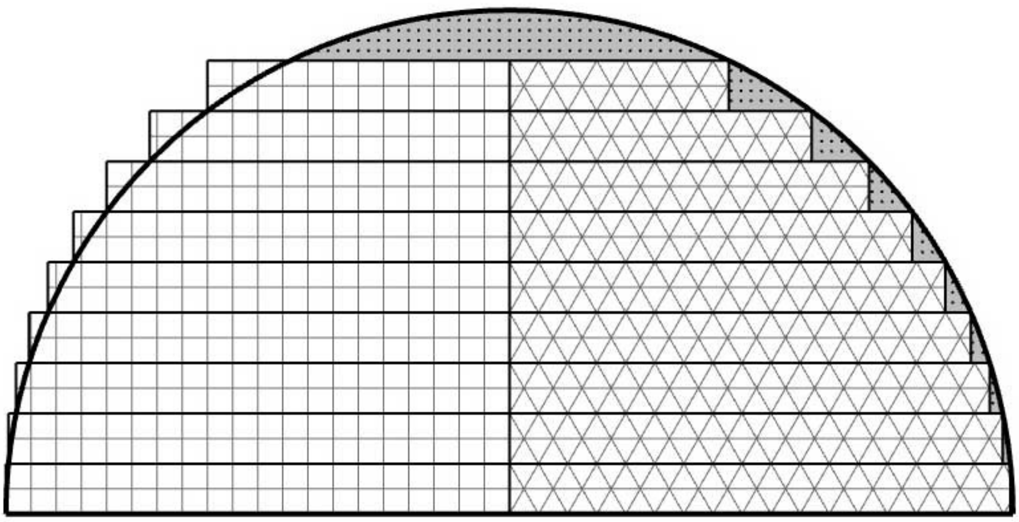

Fig. 7. Staircase effect in extrusion-based additive manufacturing, parts with vertical hatches (left side) are outside the 3D model, and parts with diagonal hatches (right side) are placed inside the 3D model. The gray areas show the difference between the printed part and the 3D model. Source: Authors.

variables, including concrete efficiency, printing speed, and nozzle dimensions. One of the most common problems is the collision of the nozzle with previously printed layers (Nisja, Cao & Gao, 2021).

In conventional construction that relies on formworks, geometric limitations arise as (1) casting angles (2) non-re-entrant shapes (3) complexity (Hague, Campbell & Dickens, 2003).

Familiar disadvantages of printing flat layering are: (1) more layers are required for higher resolution and precision in curved surfaces, which leads to unacceptably long printing times (Sabourin, Houser & Bøhn, 1996) (2) the anisotropic properties of the final part, especially In the FDM method (Lee, Kim, Kim & Ahn, 2007) (3) staircase effect on the surface (Hong, Lee & Gong, 2005).

The reason for the appearance of the staircase effect on the surface is the geometrical estimation of the curved section of the surface with layers of the same thickness. This effect is mainly dependent on the thickness of the filament and is measured by the area or height of the cusp, which is the same length as the height of the error triangle.

To solve this problem in D-shaped, powder-bed printing, the top surface is ground to the desired finish in a post-processing operation. In Contour Crafting, a special trowel is used to smooth the surface during printing. In general, the surface finish requirements enforce additional work and the main difference in the method used is "net-shape and grind" or "under-print and apply" (Lim, et al., 2016).

Improving tool paths for a printer is a pre-processing operation that minimizes surface roughness and reduces additional post-processing tasks such as grinding and plastering.

Curved layering seeks to improve the aesthetic and mechanical properties of FDM technology by developing the flat layering process from 2D to 3D to print materials on a non-flat layer. This means that regardless of the degree of curvature, to deposit the material at a consistent angle such as 90 degrees, the nozzle must be perpendicular to the surface of the substrate. These conditions will significantly reduce the staircase effect compared to flat layering, because the material deposits on the curved cross-section of the surface, and as a result, the staircase effect is prevented at least in one direction. It also minimizes the possibility of peeling layers because (1) the top surface is covered with a single layer, compared to multiple edges of flat layers (2) the total number of layers required for printing is much less than with flat layering.

The idea of curved layering was first proposed in the 1990s for "Layered Object Manufacturing" (LOM) technology. (Kalmanovich, 1996) by presenting the idea of a "Height Grid" which divided the xy planes into a grid with regular intervals, and the height value (z) was used as an element of this grid to represent curved layer profiles. Also, with the "Open Loop" method, the curvature difference of each layer was adjusted, was as the offset of the curved layers. The research by Klosterman, et al, (1999) developed this idea to achieve optimal mechanical performance in fiber-reinforced ceramics and composites, which occurs by enabling fibers to join continuously in the curved plane, especially at the top surface.

Researchers later published articles about the use of the superposition method in curved layer fused deposition modeling (CLFDM) and the ability to produce more strength than flat layering by applying longer length filaments, larger contact area per layer, and anisotropy between filaments (Lee, et al., 2007; Bellini & Guçeri, 2003).

In the research by Chakraborty, Aneesh Reddy & Roy Choudhury (2008) an algorithm was presented to solve the problem of bonding between filaments, this problem was especially prominent in large-scale printing due to the large size of the filament (Lim, et al., 2016). Most of the research studies conducted in this field were summarized in Table 1, in these works have only studied algorithms or simulations and few applications have been reported with this method.

Regardless of the variety of methods in Table 1, rows 1 to 6 and 9 have used the mathematical solution method. Therefore, there are always exceptions that algorithms cannot guarantee proper tool paths depending on the geometric complexity of the part. One of the appropriate methods of using an implicit solution method is to use a programming language (script) in modeling software such as Rhino (Robert McNeel & Associates, 2023) and its plugin, Grasshopper. In this way, the user could utilize the software's geometric modeling capabilities and the programming language to create an algorithm for generating tool paths that conform to the curve process. The research projects mentioned in rows 7, 8, and 10 in Table 1 have used these implicit methods. Some examples of parts printed with these methods are shown in Fig. 8. Part (1) in Fig 8 was printed at Loughborough University, and the printer toolpaths were generated in Rhino software and Visual Basic programming language. Part (2) in Fig 8 was printed

Table 1. Published research in curved layer additive manufacturing. Source: Authors.

No	Research	Year	Method	Application/(Material)
1	(Kalmanovich, 1996)	1997	Height Grid + Open Loop	Net shape fabrication (Monolithic ceramic/ Ceramic matrix composite)
2	(Klosterman, et al., 1999)	1999	Laminated Object Manufacturing (LOM)	
3	(Chakraborty, et a.l, 2008)	2008	Curved Layer Fused Deposition Modeling (CLFDM)	Biomedical engineering (Biocompatible PMMA-resin)
4	(Diegel, Singamneni, Huang & Gibson, 2010)	2009	CLFDM with triple-material deposition head (CLFDM)	3D PCBs (ABS/Fab-epoxy/conductive polymer)
5	(Huang & Singamneni, 2015)	2015	Curved Layer Adaptive Slicing (CLAS)	Layer-engineered net shaping (FDM materials)
6	(Allen & Trask, 2015)	2015	Curved Layer Fused Filament Fabrication (CLFFF)	3D objects (PLA)
7	(Lim, et al., 2016)	2016	Curved Layer 3D Concrete Printing (CL3DCP)	Concrete freeform surfaces (Concrete)
8	(Borg Costanzi, et al., 2018)	2018	Curved Layer 3D Concrete Printing (CL3DCP) on adaptive mould	Dome-like concrete surfaces (Concrete)
9	(Lim, Weng & Pham, 2020)	2020	Curved Layer 3D Concrete Printing (CL3DCP) on adaptive mould	Synclastic and Anticlastic concrete surfaces (Concrete)
10	(Li, Nguyen-Xuan & Tran, 2023)	2023	Curved Layer 3D Concrete Printing (CL3DCP)	Concrete cylinder with non-flat layers (Concrete)


(1) (2) (3)

Fig. 8. (1) Concrete printed doubly-curved four-part sandwich panel (1.5m×1.5m×0.1m). Source: Lim, et al., 2016 (2) Doubly-curved concrete surface with four different surface finishes (1.0m×1.0m×0.03m). Source: Lim, et al., 2016 (3) Dome-like concrete printed surface (2.5m×2.5m×0.030m). Source: Borg Costanzi, et al., 2018.

at Loughborough University, and the printer toolpaths were obtained in Rhino software and the Grasshopper plugin. The bottom bright color piece is coated with plaster, the top piece is a radial pattern, the right piece is printed based on curved layering toolpaths, and the left piece is produced as a support structure by flat layering. Part (3) is the dome-like surface, which was printed using an adaptive mould at the Eindhoven University of Technology. In this piece, first, the perimeter paths of each piece are printed, and then their inner space is manually filled with concrete.

Results

In the last two decades, with the accelerating use of additive manufacturing technologies (3D printing) in most industries, the construction industry has not been an exception. With the development of two types of additive manufacturing technologies, "extrusion-based" and "powder-bed" on a large scale, it is possible to produce all or part of the building's structure and components. Both mentioned types produce the desired piece in a layerwise process.

The first type, the "extrusion-based" method, has gained more acceptance, and most researchers have focused on this technology. "Contour Crafting" and "3D Concrete Printing" are technologies that belong in this category. Contour Crafting has more history in this field and is offered for on-site or off-site use, including a gantry robot and concrete pumping equipment. In this method, due to the complexity of the printer head, it is generally not possible to produce complex geometries. 3D Concrete Printing is usually used off-site. The printer could be a gantry robot or a six-degree-of-freedom robotic arm with concrete pumping equipment that pumps cement paste to its head and nozzle. In this method, it is possible to have more control over the printed geometry, and it is possible to produce complex geometries with curved surfaces.

The second type of large-scale additive manufacturing technology is "powder-bed" called D-Shape. The 3D printer consists of a gantry robot that spreads the powder material on the surface and then the binder is poured from nozzles at the desired points. The similarities of these two types of large-scale 3D printing and the three mentioned methods are shown in Fig. 9.

The cement paste used in two manufacturing methods based on extrusion contains a high percentage of cement and the maximum diameter of the aggregates is 2 to 3 mm. Qualitative properties such as "pumpability", "extrudability" and "buildability", which are influenced by parameters such as mixing ratios like cement-to-aggregate ratio, water-to-cement ratio, and the amount of additives, are defined for printable concrete.

One of the limitations of 3D printing with cement paste is the construction of cantilevers, which is usually done in two ways: "corbeling" or using a support structure and "adaptive mould". The main weakness in the produced parts is the presence of cold joints between the layers. Ideas for placing reinforcements between the layers or adding metal

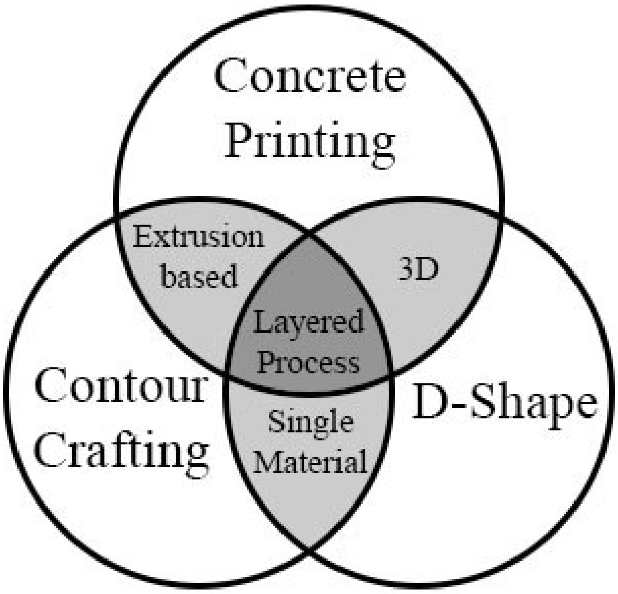

Fig. 9. Similarities of large-scale additive manufacturing technologies. Source: Authors.

and polymer fibers to the cement paste have been proposed to solve this weakness.

One of the limitations of extrusion-based 3D printing is the final quality of the surface of the printed piece. In the usual way that the 3D model file is layered flat by the layering software, the final surface of the part, especially in complex and curved geometries, looks stepped. A computational method to correct this defect is to use curved (non-flat) layering. Most of the researchers in this field are looking for an explicit mathematical solution for this problem, which is not very effective in cases where the geometry of the part is very complicated. For complex geometries, coding in 3D modeling software could be used to extract tool paths for the printer. In this way, by implicitly solving this problem, curved (non-flat) layering is possible for a wider range of complex geometries.

Conclusion

The ability to produce complex geometries in large-scale additive manufacturing technologies has enabled designers to use new geometries. On the other hand, the possibility of mass customization in additive manufacturing technologies, faster production, the need for less human labor, and better quality control have made this category of technologies ideal for automation in the construction industry. Real examples produced with these technologies across the globe include a wide range of residential units, temporary post-disaster shelters, pedestrian bridges, and urban furniture.

To improve the finishing quality of the final surface of the products, a group of researchers are looking for the application of the curved (non-flat) layering method so that they can achieve this with the existing printers and only by intervening in the pre-processing part of the 3D printing process.

Applying curved (non-flat) layering can have results such as (1) better surface finish quality (2) shorter printing time (3) higher mechanical strength for the surface.

In novel curve layering methods, the use of programming languages in software such as Rhino has made it possible to produce tool (printing) paths in such a way that they are interactively compatible with complex geometries.

Currently, these methods are not fully automatic, and it is necessary to extract suitable tool paths for the 3D printer with user intervention. In future research, one could expect this automation process to progress to the point where user intervention is eliminated.

Endnote

1. Standard Tessellation Language

Reference list

• Al-Safy, R. A. (2019). Myths and reality of implementing three-dimensional technology in construction. *Journal of Engineering and Sustainable Development*, 23 (5), 71–94.

• Allen, R. J. A. A. & Trask, R. S. (2015). An experimental demonstration of effective Curved Layer Fused Filament Fabrication utilising a parallel deposition robot. *Additive Manufacturing*, 8, 78–87.

• Allouzi, R., Al-Azhari, W. & Allouzi, R. (2020). Conventional Construction and 3D Printing: A Comparison

Study on Material Cost in Jordan. *Journal of Engineering,* 2020, 1-14.

• Asprone, D., Menna, C., Bos, F. P., Salet, T. A. M., Mata-Falcón, J. & Kaufmann, W. (2018). Rethinking reinforcement for digital fabrication with concrete. *Cement and Concrete Research,* 112, 111–121.

• Bakhshi, L. (2003). *Yadvare-ye Haftadomin Salgard-e Sanat-e Siman* [Memorial to commemorate the 70th anniversary of the cement industry]. Tehran: Employers' union of cement industry.

• Bellini, A. & Güçeri, S. (2003). Mechanical characterization of parts fabricated using fused deposition modeling. *Rapid Prototyping Journal*, 9 (4), 252–264.

• Boffey, D. (2021). *Dutch couple become Europe's first inhabitants of a 3D-printed house.* Guardian News & Media Limited. https://www.theguardian.com/technology/2021/apr/30/dutch-couple-move-into-europe-first-fully-3d-printed-house-eindhoven#:~:text=The new house consists of,fitted%2C and finishing touches applied.

• Borg Costanzi, C., Ahmed, Z. Y., Schipper, H. R., Bos, F. P., Knaack, U. & Wolfs, R. J. M. (2018). 3D Printing Concrete on temporary surfaces: The design and fabrication of a concrete shell structure. *Automation in Construction*, 94, 395–404.

• Bos, F., Wolfs, R., Ahmed, Z. & Salet, T. (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping*, 11 (3), 209–225.

• Brown, A. C., de Beer, D. & Conradie, P. (2014). Development of a Stereolithography (STL) input and Computer Numerical Control (CNC) output algorithm for an entry-level 3-D printer. *South African Journal of Industrial Engineering*, 25 (2), 39–47.

• Buswell, R. A., Leal de Silva, W. R., Jones, S. Z. & Dirrenberger, J. (2018). 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 112, 37–49.

• Cesaretti, G., Dini, E., De Kestelier, X., Colla, V. & Pambaguian, L. (2014). Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronautic*a, 93, 430–450.

• Chakraborty, D., Aneesh Reddy, B. & Roy Choudhury, A. (2008). Extruder path generation for Curved Layer Fused Deposition Modeling. *CAD Computer Aided Design*, 40 (2), 235–243.

• Concreative. (2018). *Architectural products.* https://www.concreative.me/architectural-product

• *Dezeen.com.* (n.d). Retrieved March 6, 2023, from https://static.dezeen.com/uploads/2019/12/apis-cor-worlds-largest-3d-printed-building-dubai-architecture-news_dezeen_1704_col_11-852x566.jpg

• Diegel, O., Singamneni, S., Huang, B. & Gibson, I. (2010). *The future of electronic products: Conductive 3D printing? Conference proceedings of 4th International Conference on Advanced Research in Virtual and Physical Prototyping,* VRAP 2009, Leiria, Portugal, 397–403. https://www.scopus.com/inward/record.uri?eid=2-s2.0-78649836781&partnerID=40&md5=c46c6e3c2b1ac738c35e6f6a99bf2cb4

• Emre, M. (2022). *Apis Cor Completes The Dubai Municipality, Largest 3D-Printed Construction.* ParametricArchitecture. https://parametric-architecture.com/apis-cor-completes-the-dubai-municipality-largest-3d-printed-construction/

• Everett, H. (2021). *World's Longest 3D Printed Concrete Pedestrian Bridge Unveiled In Nijmegen.* 3D Printing Industry. https://3dprintingindustry.com/news/worlds-longest-3d-printed-concrete-pedestrian-bridge-unveiled-in-nijmegen-195951/

• Farzin, M., Mostofinejad, D. & Ghahremani, S. (2019). Fabrication of concrete 3D printer and investigation of print effective parameters. *Third Congress on Development of Infrastructure of Civil Engineering, Architecture and Urban Development of Iran with Road & Construction Approach.* https://civilica.com/doc/915934

• Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S. & Zavattieri, P. D. (2015). The status, challenges, and future of additive manufacturing in engineering. *CAD Computer Aided Design*, 69, 65–89.

• Gibson, I., Rosen, D. W. & Stucker, B. (2010). *Additive manufacturing technologies: Rapid prototyping to direct digital manufacturing.* In Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. New York: Springer US. https://doi.org/10.1007/978-1-4419-1120-9

• Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J. & Morel, P. (2016). Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders. *Materials & Design*, 100, 102–109.

• Hague, R., Campbell, I. & Dickens, P. (2003). Implications on design of rapid manufacturing. Proceedings of the Institution of Mechanical Engineers, Part C: *Journal of Mechanical Engineering Science*, 217 (1), 25–30.

• Holt, C., Edwards, L., Keyte, L., Moghaddam, F. & Townsend, B. (2019). *Construction 3D Printing. 3D*

Concrete Printing Technology, Oxford, United Kingdom: Elsevier, 349–370. https://doi.org/10.1016/B978-0-12-815481-6.00017-8

• Hong, W., Lee, Y. T. & Gong, H. (2005). A study of the staircase effect induced by material shrinkage in rapid prototyping. *Rapid Prototyping Journal*, 11 (2), 82–89.

• Hopkinson, N., Hague, R. J. M. & Dickens, P. M. (2006). *Rapid Manufacturing: An Industrial Revolution for the Digital Age.* Rapid Manufacturing: An Industrial Revolution for the Digital Age, Chichester, United Kingdom: John Wiley & Sons, 1–285.

• Huang, B. & Singamneni, S. B. (2015). Curved layer adaptive slicing (CLAS) for fused deposition modelling. *Rapid Prototyping Journal,* 21 (4), 354–367.

• Kalmanovich, G. (1996). " Curved-Layer" Laminated Object Manufacturing. *Conference proceedings of 1996 International Solid Freeform Fabrication Symposium,* Austin, USA.

• Karunakaran, K. P., Bernard, A., Suryakumar, S., Dembinski, L. & Taillandier, G. (2012). Rapid manufacturing of metallic objects. *Rapid Prototyping Journal,* 18 (4), 264–280.

• Khoshnevis, B. (2004). Automated construction by contour crafting—related robotics and information technologies. *Automation in Construction*, 13 (1), 5–19.

• Kleis, C. (2009). *Deitingen Sued Raststaette*. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Deitingen_Sued_Raststaette,_Schalendach_04_09.jpg

• Klosterman, D. A., Chartoff, R. P., Osborne, N. R., Graves, G. A., Lightman, A., Han, G., Bezeredi, A. & Rodrigues, S. (1999). Development of a curved layer LOM process for monolithic ceramics and ceramic matrix composites. *Rapid Prototyping Journal,* 5 (2), 61–71.

• Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Gibb, A. G. F. & Thorpe, T. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures*, 45 (8), 1221–1232.

• Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Law, R., Gibb, A. G. F. & Thorpe, T. (2012). Hardened properties of high-performance printing concrete. *Cement and Concrete Research*, 42 (3), 558–566.

• Lee, C. S., Kim, S. G., Kim, H. J. & Ahn, S. H. (2007). Measurement of anisotropic compressive strength of rapid prototyping parts. *Journal of Materials Processing Technology*, 187–188, 627–630.

• Li, S., Nguyen-Xuan, H. & Tran, P. (2023). Digital design and parametric study of 3D concrete printing on non-planar surfaces. *Automation in Construction*, 145, 104624.

• Lim, J. H., Weng, Y. & Pham, Q. C. (2020). 3D printing of curved concrete surfaces using Adaptable Membrane Formwork. *Construction and Building Materials,* 232, 117075.

• Lim, S., Buswell, R. A., Le, T. T., Austin, S. A., Gibb, A. G. F. & Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21 (1), 262–268.

• Lim, S., Buswell, R. A., Valentine, P. J., Piker, D., Austin, S. A. & De Kestelier, X. (2016). Modelling curved-layered printing paths for fabricating large-scale construction components. *Additive Manufacturing, 12, 216–230.* https://doi.org/10.1016/j.addma.2016.06.004

• Mathur, R. (2016). 3D printing in architecture. International J*ournal of Innovative Science, Engineering & Technology*, 3 (7) , 583-591.

• Mohan Pandey, P., Venkata Reddy, N. & Dhande, S. G. (2003). Slicing procedures in layered manufacturing: A review. *Rapid Prototyping Journal*, 9 (5), 274–288.

• Moore, D. (1995). *The Riddle of Ancient Roman Concrete.* Retrieved from http://www. romanconcrete.com/

• Nisja, G. A., Cao, A. & Gao, C. (2021). Short review of nonplanar fused deposition modeling printing. *Material Design and Processing Communications,* 3(4).

• Panda, B., Chandra Paul, S. & Jen Tan, M. (2017). Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material. *Materials Letters*, 209, 146–149.

• Panda, B., Paul, S. C., Mohamed, N. A. N., Tay, Y. W. D. & Tan, M. J. (2018). Measurement of tensile bond strength of 3D printed geopolymer mortar. *Measurement*, 113, 108–116.

• Panda, B. & Tan, M. J. (2018). Experimental study on mix proportion and fresh properties of fly ash-based geopolymer for 3D concrete printing. *Ceramics International,* 44 (9), 10258–10265.

• Paul, S. C., Tay, Y. W. D., Panda, B. & Tan, M. J. (2018). Fresh and hardened properties of 3D printable cementitious materials for building and construction. *Archives of Civil and Mechanical Engineering*, 18 (1), 311–319.

• Paul, S. C., van Zijl, G. P. A. G. & Gibson, I. (2018). A review of 3D concrete printing systems and materials properties: current status and future research prospects. *Rapid Prototyping Journal*, 24 (4), 784–798.

• *Robert McNeel & Associates.* (2023). Rhino. https://www.rhino3d.com/

• Sabourin, E., Houser, S. A. & Bøhn, J. H. (1996).

Adaptive slicing using stepwise uniform refinement. *Rapid Prototyping Journal*, 2 (4), 20–26.
- Salet, T. A. M., Ahmed, Z. Y., Bos, F. P. & Laagland, H. L. M. (2018). Design of a 3D printed concrete bridge by testing. *Virtual and Physical Prototyping*, 13 (3), 222–236.

HOW TO CITE THIS ARTICLE

Bondarian, Kh.; Haghir, S; Abrinia, K. & Matini, M .R. (2024). Complex Geometry Forms and Curved Surfaces in 3D Concrete Printing. *Bagh-e Nazar*, 20(127), 69-82.

DOI: 10.22034/BAGH.2023.394730.5371
URL: https://www.bagh-sj.com/article_180308.html?lang=en