Large-Scale Extrusion-Based 3D Concrete Printing Extruder System Design

Subjects: Engineering, Civil

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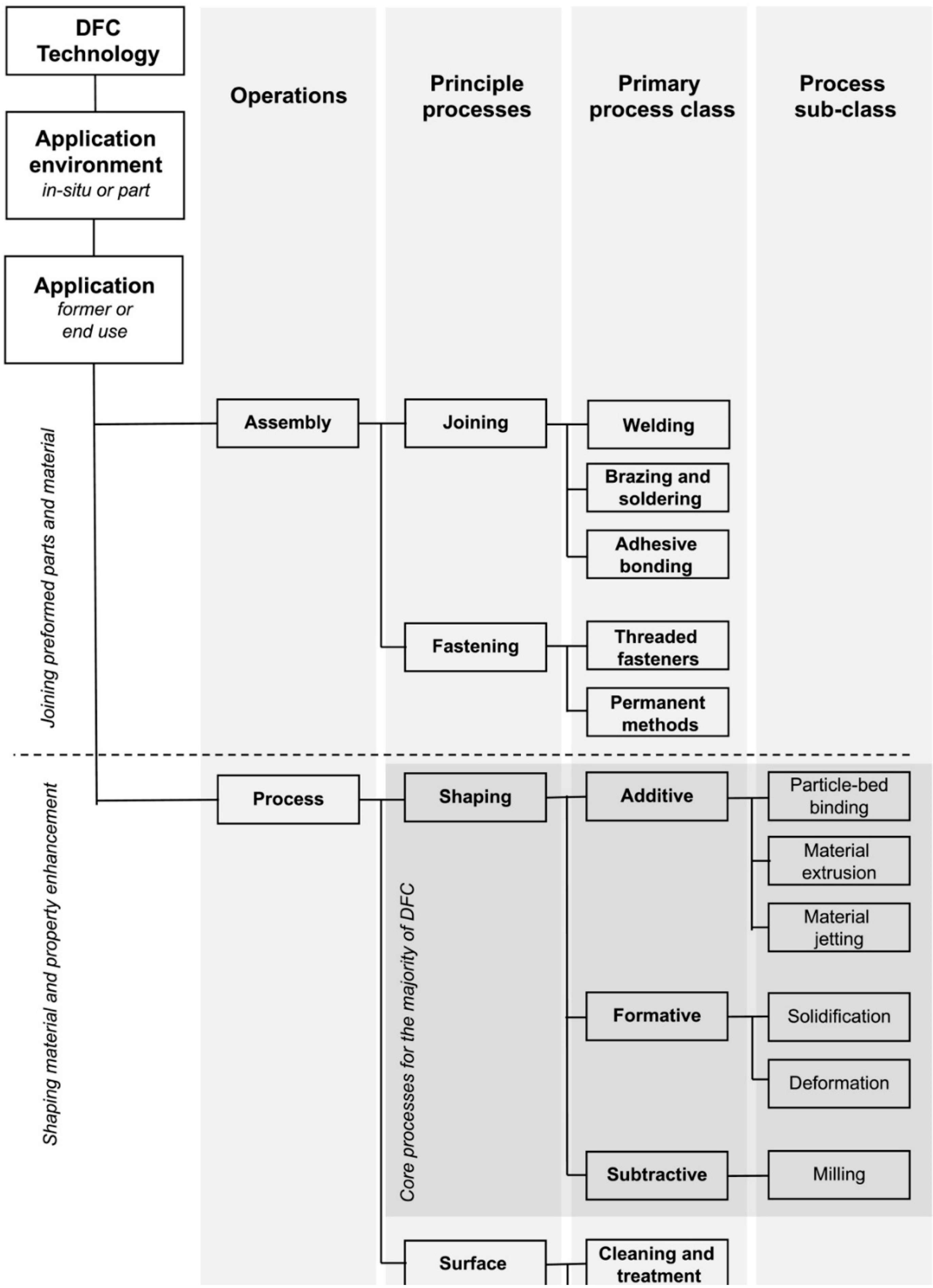
Extrusion-based 3D concrete printing (E3DCP) has been appreciated by academia and industry as the most plausible candidate for prospective concrete constructions.

concrete extrusion 3D concrete printing ram extrusion extruder system design

1. Introduction

The traditional formwork-casting method inherited from the ancient Romans underpins the foundation of modern concrete construction. However, the shortcomings of the method have been acknowledged with centuries of practice. Because of its inability to fulfill the increasing structural, sustainable, economic, social and aesthetic requirements, the concrete industry has begun to explore candidate technologies that could revolutionize concrete construction. Buswell et al. [1] outlined a classification framework for the feasible digital fabrication of concrete (DFC) technologies, as shown in **Figure 1**. 3D concrete material extrusion—referred to as extrusion-based 3D concrete printing (E3DCP) in this entry— is a subclass of 3DCP and has been appreciated by academia and industry as the most plausible candidate for prospective concrete construction. Its commercialization potential has been well-validated in various industrial projects undertaken by construction companies such as XTree [2], COBOD [3], WASP [4], and Sika [5]. Notice that sometimes equivalence is drawn between E3DCP and 3D concrete printing (3DCP), which should be avoided, as the latter is more appropriately referred to as “additive” according to the classification of [1]. In addition, the scope of E3DCP inherently excludes injection 3D concrete printing [6], smart dynamic casting [7], and shotcrete 3D concrete printing [8].


DFC Technology
Application environment
in-situ or part
Application
former or end use
Operations
Principle processes
Primary process class
Process sub-class
Joining preformed parts and material
Assembly
Joining
Welding
Brazing and soldering
Adhesive bonding
Fastening
Threaded fasteners
Permanent methods
Shaping material and property enhancement
Process
Shaping
Core processes for the majority of DFC
Additive
Particle-bed binding
Material extrusion
Material jetting
Formative
Solidification
Deformation
Subtractive
Milling
Surface
Cleaning and treatment

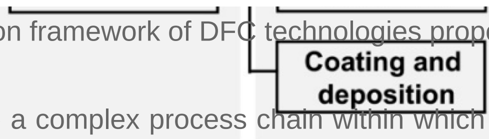


Figure 1. The process classification framework of DFC technologies proposed by [1].

According to [1], any DFC technology can involve a complex process chain within which a single principal process (i.e., shaping or assembly) and a series of sub-processes (i.e., an indispensable process that occurs while executing the principal process) can be identified. In the case of E3DCP, the principal process is the shaping, which consists of the extrusion and deposition processes. However, the sub-processes of E3DCP are more difficult to generalize, as various customizable fittings can be adapted to the E3DCP mechanical system. Based on the sub-processes outlined by [9] and extensive reviews of the literature, the authors have recognized two categories of sub-process for E3DCP: (1) basic sub-processes: those inherited from the traditional formwork-casting process, including the mix proportioning, primary mixing, transport/pumping and curing processes; and (2) advanced sub-processes: those requiring advanced fittings to improve the printing quality or augment the functionality of E3DCP, including the secondary mixing, setting-/fluid-on-demand, in-process reinforcement, interlayer bonding enhancement, finishing, support placement and monitoring and feedback processes.

While the concrete research relating to the basic sub-processes is abundant, the research relating to the principal process and the advanced sub-processes is scarce due to the fact that they are rarely applied to traditional concrete construction projects [10]. With the advent of E3DCP, more research interest has been paid to these two topics in this recent decade. Considerable research efforts are dedicated to the material design (e.g., water-to-cement ratio) of E3DCP, and there have been several prominent review papers [11][12][13][14] that summarize the insights in this regard. However, at the time of writing this entry, there is still a lack of a review paper that highlights the significance of the mechanical design (e.g., nozzle shape, nozzle diameter) of E3DCP.

The complex process chain of E3DCP inevitably entails sophisticated mechanical systems, as shown in **Table 1**. The purpose of this entry is to provide a comprehensive review of the mechanical systems of the principal process and advanced sub-processes for E3DCP applications. The mechanical systems of basic sub-processes are not included since they are well-established in the concrete industry through decades of practice. Therefore, this entry only concerns the printing system (for the principal process) and advanced fittings (for the advanced sub-processes). The printing system consists of two components: (1) the extruder system, also known as the printhead or manipulator, which performs the extrusion action.; and (2) the positioning system, which enables the deposition action (i.e., extruder movement). Advanced fittings can be added to the printing system to introduce additional advanced sub-processes into the E3DCP process chain.

Table 1. E3DCP mechanical system.

	Mechanical System	
Principal shaping process	Printing system	Extruder system
		Positioning system

Mechanical System		
Basic sub-process	Basic fittings	Mix proportioning system
		Primary mixing system
		Pumping system
		Curing system
Advanced sub-process	Advanced fittings	Secondary mixing system
		Setting-/Fluid-on-demand system
		In-process reinforcement system
		Interlayer bonding enhancement system
		Finishing system
		Support placement system
		Monitoring and feedback system

2. Extrusion Process and Extruder System

The extrusion process is a crucial process of E3DCP wherein the concrete undergoes plastic deformation by passing through an outlet to obtain the desired cross-section profile [15]. To ensure a successful extrusion process, the process requirement of extrusion (i.e., extrudability, which describes the capability of fresh cementitious paste (FCP) to be extruded smoothly throughout the outlet without considerable cross-sectional deformation and with an acceptable degree of splitting/tearing of filament ([12][16]) has to be fulfilled.

References

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3. COBOD. Available online: www.cobod.com (accessed on 3 August 2022).
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Depending on the material design, mechanical design (i.e., extruder system design), and operational design, different extrusion behaviors can be observed. A general extruder system is shown in **Figure 2**, which consists of (1) a piston (ram extrusion mechanism); (2) an axis-symmetric chamber with a diameter of D_c and a length of L_c; and (3) a nozzle (outlet) with a diameter of D_n and a length of L_n. The studies [17][18][19][20] allow the authors to generalize the extrusion behavior of FCP using such a ram extruder system. To enable a successful extrusion, the extrusion driving force, F_e (in this case, ram extrusion force, Fram), has to overcome extrusion resistive forces that are responsible for the extrusion pressure drop [21][22][23], which may include: (1) the chamber wall shear force F_{cf} (or friction force) in the billet zone; (2) the shaping force F_{pl} in the shaping zone, also known as the die entry pressure, which is responsible for the plastic deformation of FCP between the chamber and outlet; (3) the nozzle wall shear force F_{nf} (or friction force) in the shaping zone, also known as die land pressure; (4) the dead zone shear force F_{dz} (or friction force) in the dead zone; and (5) the layer pressing force, F_{lp} needs to be taken into account when the layer pressing extrusion mode is adopted.

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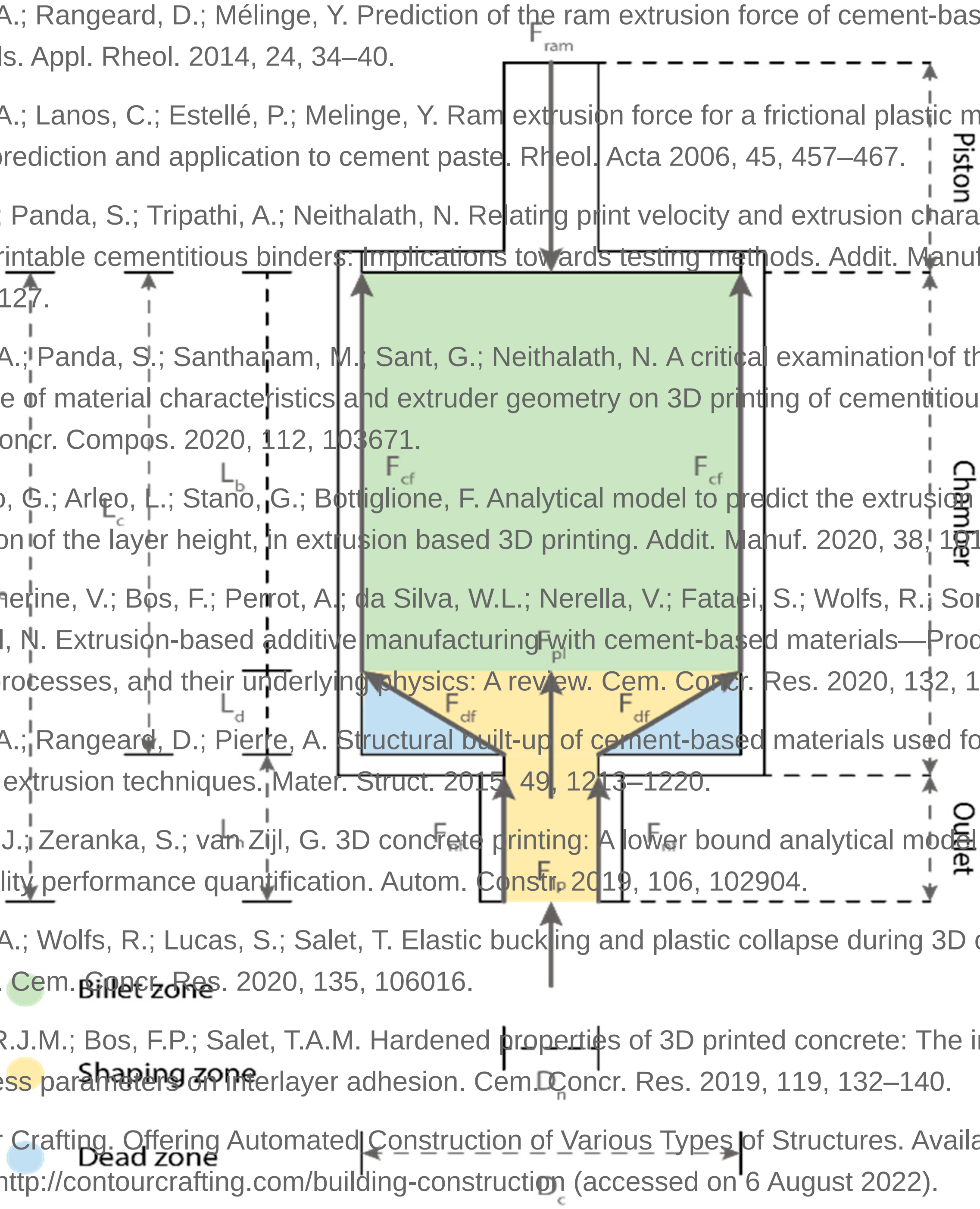

Figure 2. The printhead of a typical ram extrusion for E3DCP.

The presence and magnitude of these extrusion forces, which are dependent on the material design, mechanical design, and operational design of the extruder system, can affect the extrusion behavior (e.g., shearing, consolidation and phase separation and dead zone formation), thereby determining the extrusion pressure and the fulfillment of the extrudability requirements [24].

3. Deposition Process and Positioning System

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Deposition is an additive process where a material is layered onto another layer of the material. During the E3DCP deposition process, the most important property is the buildability, which is defined as the ability of the deposited concrete filament to self-support and resist deformation without formworks [12][25]. The buildability stipulates that the concrete filament should provide sufficient resistance against plastic material failure, elastic buckling failure as well as excessive deformation [26]. However, the mechanical design of the positioning system has a relatively insignificant impact on the buildability compared to the material design. Therefore, the following section presents the mechanical design of the positioning system from a more practical perspective.

Four types of E3DCP positioning systems can be identified: gantry system, robotic arm system, delta system, and swarm system. Each category is characterized by a different degree of freedom and build volume.

The gantry system is the most common positioning system for E3DCP applications due to its ease of operational and cost-effectiveness. A gantry system is generally characterized by three DOFs of translational movements in x, y, z directions (Cartesian coordinate), but sometimes an additional rotational DOF can be added at the extruder to have four DOFs [27][28]. The build volume of the gantry system is constrained by the physical dimensions of the supporting frames in x, y and z directions, and it could range from desktop-scale for laboratory purpose to industrial-scale for construction purposes, see **Table 2**. To overcome the limited dimension of the gantry system, COBOD [3] has developed a flexible modular gantry concrete printer, BOD2, which could be assembled from multiple modular units of 2.5 × 2.5 × 2.5 to fit different construction scenarios. The contour crafting company [29] and IconBuild [30] retrofitted the gantry concrete printer with sliding rails to expand the workspace in one horizontal direction. From a practical standpoint, the robustness of the gantry system can sustain the on-site harsh conditions, however, it could be associated with considerable manual works in assembly and disassembly [31]. Additionally, the accuracy and repeatability of gantry printers are sufficient to complete large-scale E3DCP projects but they are not comparable to the robotic arm system.

The robotic arm system printer generally consists of multiple links connecting altogether at rotary joints, which provides the system with more DOFs (six or more) and allows it to print more sophisticated designs. For example, Lim et al. [32] have pointed out that the staircase effect that typically associates with the extrusion-based 3DCP can be mitigated by adopting the curved-layer printing strategy instead of flat-layer printing. Concretely, in this approach, the extruder nozzle is positioned perpendicular to the target surface throughout the extrusion process so that the surface roughness and geometric accuracy can be improved. To fully exploit the potential of this approach, a position system with four or more DOFs is essential. Similarly, Gosselin et al. [33] recommended utilizing a six-axis robotic arm to realize the tangential continuity method for toolpath planning, which could produce non-planar layers with locally varying thicknesses, thereby unleashing the geometrical freedom of E3DCP to a greater extent. The approach has been used to 3D print multifunctional structures such as the thermal insulation wall and acoustic damping wall. Motamedi et al. [34] utilized a six-axis ABB robotic arm to print an overhang structure without support, which is only possible with the capability of the robotic arm to adjust the angle between the nozzle and printing surface.

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However, most industrial robotic arms (e.g., Kuka, ABB and Fanuc) have limited workspace. Once set up, they can only print structures within a fixed area confined by the arm reach (generally less than 5 m), which will not suffice for conducting large-scale 3DCP projects. There have been various strategies proposed to extend the reach of the robotic arm: (1) installation of the extension arm at the extruder end [35]; (2) lifting of the robotic arms: the construction company Apis Cor [36] employed a crane to lift the pillar-like robotic arm printer after finishing printing tasks at one point; (3) provision of mobility to the robotic arm: the construction company Cybe [37] and the research team from NanYang Technical University [38] have both installed a mobile base underneath the robotic arm to enable theoretically infinite workspace in horizontal direction, and the research team from TU Dresden conceptualized the adaptation of a truck-mounted pump for E3DCP. However, such an approach imposes more strict requirements on the spatial localization of robotic arm, site conditions (e.g., flatness) as well as the weather conditions (e.g., low wind); (4) carrier system: ETH Zurich researchers [39] installed a six-axis ABB IRB 4600 robotic arm on a Gudel 3-axis gantry at ceiling to increase both the horizontal and vertical workspace; and the team from Tsinghua University [40] provided an elevator platform to extend the workspace; and (5) multiple robotic arms: Zhang et al. [41] employed two mobile robotic arms to print structure simultaneously. Such an approach requires complex robotic path planning as well as collision checks before printing. Despite the multitudinous benefits of robotic arms, compared to the robustness of the gantry system, the delicacy of the robotic arm system has raised the suspicion of its suitability for rough on-site conditions, which explains why the majority of robotic arm printers are used under off-site conditions [31].

Apart from the mainstream gantry and robotic arm systems, there have been some innovative systems developed for E3DCP applications. For example, the construction company WASP [4] has customized a Delta 3D concrete printer called BigDelta with a dimension of 7 × 7 × 12 m. The printer consists of three cable-arms connected to joints at frame supports, and each arm could move independently in the Z-direction, forming a navigation based on the polar coordinate. The German Fraunhofer Institute [42] also developed a similar delta 3D concrete printer based on eight cable arms. The delta system also has dimension constraints within the frame, and it also suffers from a higher risk of collision with the already printed parts compared to the gantry system [31]. The Institute for Advanced Architecture of Catalonia [43] has designed three swarm 3D concrete printers that could work collaboratively to produce structures: (1) the base robot, which deposits the first ten layers of concrete filaments to create a foundation; (2) the grip robot, which rests on the previously built foundation and continues deposition to finish the structure, and (3) the vacuum robot, which climbs on the surface of the finished structure and deposits concrete filaments in z-direction. Theoretically, without considering the layer cycle time, such a swarm system can be used to construct large-scale concrete structures without dimensional limitation, especially in horizontal directions. Nonetheless, the technology remains relatively nascent and needs more exploration.

Table 2. Some examples of 3D concrete printers in terms of position system, build volume, horizontal printing speed, layer height and layer width.

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Reference	Positioning System	Degree of Freedom	Build Volume (L × W × H m)/Reach (m)
[44]	Gantry	3-axis	20 × 18 × 18
[45]	Gantry	3-axis	1.2 × 1.2 × 1.0
[46]	Gantry	3-axis	0.5 × 0.39 × 1.1
[47]	Robotic arm	6-axis Fanuc R-2000iC/165F	-
[48]	Gantry	3-axis	-
[49]	Gantry	3-axis	3.0 × 3.0 × 3.0
[50]	Robotic arm	6-axis KUKA KR60 HA	-
[51]	Gantry	3-axis	1.8 × 1.8 × 1.5
[52]	Gantry	4-axis	9 × 4.5 × 2.8
[53]	Gantry	3-axis	0.15 × 0.15 × 0.12
[54]	Robotic arm	6-axis Denso	-
[55]	Robotic arm	6-axis FANUC R-2000iC/165F	-
[56]	Gantry	3-axis	-
[39]	Robotic arm and	6-axis ABB IRB 4600 robotic arm hanging on a	-

Reference	Positioning System	Degree of Freedom	Build Volume (L × W × H m)/Reach (m)
	gantry	Güdel 3-axis gantry	
[57]	Gantry	3-axis	10.36 × 2.74 × 3.05
[58]	Gantry	3-axis	0.40 × 0.30 × 0.30
[59]	Gantry	4-axis	-
[27]	Gantry	4-axis	-
[3]	Gantry	3-axis	Infinite × 14.6 × 8.1
[30]	Gantry	3-axis	Infinite × 8.53 × 2.59
[37]	Robotic arm	6-axis	2.65–3.50
[37]	Robotic arm	7-axis	Infinite × Infinite × ~3
[42]	Delta system	-	17 × 12 × 5
[4]	Delta system	-	7 × 7 × 12 m

secondary
, support
within the
printing system generally increase the energy, machine and maintenance costs (in the passive systems, the energy increase may be insignificant). Additionally, they may increase the energy and material costs as well as the technical complexity of the overall system, as shown in **Table 3**.

Table 3. The material costs and technical complexity of the advanced fittings.

Advanced Fittings		Material Cost	Technical Complexity *	
Secondary mixing system	Static mixer	• Higher (additives)	• Low	• The compatibility of different static mixers with

Advanced Fittings		Material Cost	Technical Complexity *	
(with secondary dosage)				different concrete materials.
	Dynamic mixer	• Higher (additives)	• Medium/High	• The optimization of mechanical parameters, operational parameters, concrete material property, chemical admixture type and dosage and printing path.
	Thermal heating	• Non	• Low/Medium/High *	• Thermal gradients that can lead to non-uniform modifications of concrete properties. • Numerical modelling of the thermal effects during concrete extrusion.
Setting/Fluid on demand system	Electro/permanent magnet	• Higher material (magnetic particles)	• Medium/High *	• Compatibility of magnetic particles with concrete materials. • The guidelines for operational parameter control.
	Vibration	• Non	• Medium/High *	• Impacts of vibration on the material extrudability.
In-process reinforcement system	Entrainment	• Higher (reinforcements)	• Medium/High *	• The control of the feed-in speed of the reinforcement materials.

Advanced Fittings		Material Cost	Technical Complexity *	
				• The correct alignment of the reinforcement with respect to the concrete layer cross-sectional centroid to prevent anisotropic properties and ensure uniform covering
	Placing between layers		• High/High *	• Concrete materials with appropriate rheological properties to seal the horizontal weak interface which would be otherwise susceptible for moisture and chemical invasions. • Precise positionings of the reinforcement
	Cross-layer encasement		• High/High *	• Concrete materials with appropriate rheological properties to seal both the vertical and horizontal weak interfaces • Precise positionings of the reinforcement in terms of the centerline alignments.
	Cross-layer penetration		• High/High *	• Precise positionings of the reinforcement in terms of the spacing and centerline alignments.

Advanced Fittings		Material Cost	Technical Complexity *	
Interlayer bonding enhancement system	Bonding agents	• Higher (bonding agents)	• Medium	• Compatibility of the bonding agents with the concrete materials.
	Physical	• Non	• Medium/High	• The implementations of the physical means without affecting the extrusion process.
Finishing system		• Non	• High	• More precise precision according to the printing path
Support placement system		• Higher (supports)	• High	• Precise positions of the supports. • The effects of pause on the printing time and open time of the concrete materials.
Monitoring and feedback system		• Non	• Medium/High	• The monitoring itself is not complex, however, the real-time analysis, feedback and adjustment can significantly increase the complexity

Low, when the system is a passive system; medium, when the system is automated but independent of the printing path and programming; high, when the system needs to be integrated and programed with the printing path definition to perform its intended task; high *, when the system could be coupled with the printing path to achieve functional-graded materials.