

Large-Scale 3D Printing: The Way Forward

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Abstract. Research on small-scale 3D printing has rapidly evolved, where numerous industrial products have been tested and successfully applied. Nonetheless, research on large-scale 3D printing, directed to large-scale applications such as construction and automotive manufacturing, yet demands a great a great deal of efforts. Large-scale 3D printing is considered an interdisciplinary topic and requires establishing a blended knowledge base from numerous research fields including structural engineering, materials science, mechatronics, software engineering, artificial intelligence and architectural engineering. This review article summarizes key topics of relevance to new research trends on large-scale 3D printing, particularly pertaining (1) technological solutions of additive construction (i.e. the 3D printers themselves), (2) materials science challenges, and (3) new design opportunities.

Keywords: Additive Construction; Large-Scale 3D Printing

1. Introduction

The hype of large-scale 3D printing was largely triggered by a Chinese Company called ‘Winsun’, who claimed in the public domain that it was able to print “10 full-sized houses in a day”, which only costed \$5,000 each, using a ‘top-secret’ cement recipe made “entirely from recycled materials” [1]. WinSun used Contour Crafting (i.e. gantry-based large-scale 3D printing; see Figure 3), a technology pioneered by Professor Khoshnevis from the University of South California [2]. Despite that Contour Crafting was first announced in 2004, it has only received enormous wide-spread media coverage in 2014 through WinSun. Nonetheless, WinSun’s claims in the media were confronted by severe criticisms and doubts on whether the technology is mature enough to go that far [3], especially that the Chinese company did not release any details about the technical characteristics of the used materials [4]. Regardless of WinSun’s credibility, the company was surely successful at making large-scale 3D printing a ‘hot-topic’, and managed to convince governments about it.

Following that hype, the Egyptian Government signed a deal for printing 20,000 single-storey housing units with WinSun [5], the UAE government signed a contract to print the ‘Office of the Future’ with WinSun, and more recently, Saudi officials studied the use of 3D printing to build 1.5 million housing units with WinSun [6]. Above all, the government of UAE has made a serious stride towards expediting the spread of technology by announcing its target to have 25% of UAE’s construction built using large-scale 3D printing, as well as signing a MoU with Autodesk with an investment of 100 million U.S. dollars to boost large-scale 3D printing start-ups. Simultaneous to governmental initiatives, large-scale 3D printing has been dramatically grasping the interest of scientists and technical specialists, as indicated by the evolution of publications during the past five years (Figure 1).

Figure 1 summarises a review of publications relevant to large-scale construction-oriented 3D printing as till September 2015, which the authors refer to as “additive construction”. Based on our track of the topic’s evolvement, year 2016, which was not included in [7] review, experienced an even more dramatic increase in the number of journal and conference proceeding articles, as more scientists began



investigating the technology. Attention to large-scale 3D printing is expected to further grow at an exponential rate.

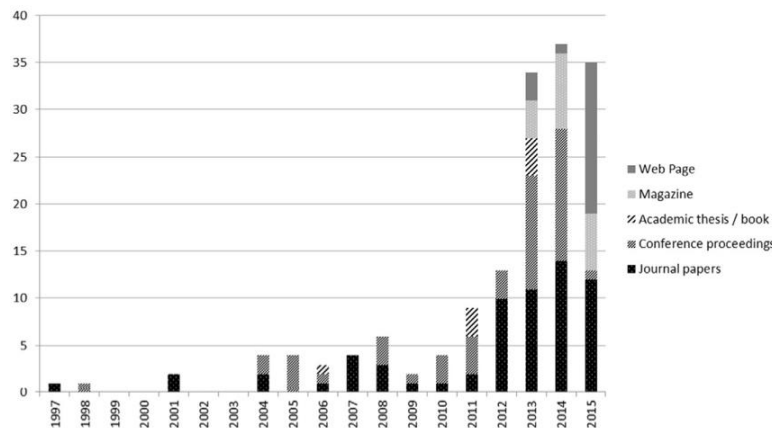


Figure 1. Evolution of number and type of publications relevant to ‘large-scale 3D printing’ during the last twenty years [7]

2. Overview

Large-scale 3D printing is a special type of *additive manufacturing* that specialises on erecting large-scale, heavy, and often permanent structures. Some authors prefer using the term *additive construction*, in reference to the principle of *additive manufacturing* scaled up for construction [7]. *Additive manufacturing* itself is defined by ASTM as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” [8]. This is what has recently become known as *3D printing*.

3D printing has a relatively long history of development, traced back to the 1980’s at which time it was used for rapid prototyping of products in manufacturing. The technology advanced to an extent that it may now replace conventional subtractive manufacturing, and has become accessible to the public. Today a 3D printer is priced as low as \$250. Throughout the past 3 decades, numerous approaches to additive manufacturing were invented, including stereolithography, selective laser sintering, fused deposition modeling, and inkjet powder printing. Each is outlined in the Appendix.

While these technologies has been successful for small scale purposes, scaling-up 3D printing for the use of construction, and to replace conventional building methods, is yet a challenge.

According to Labonnote et al. [7], research efforts in large-scale 3D printing has been devoted to three main aspects:

1. technological solutions of additive fabrication (i.e. the 3D printers themselves),
2. material science challenges,
3. and new building design opportunities

The following sections will review current state of research in each of these aspects and will discuss areas of further investigation and potential improvements.

3. Large-scale 3D printing technologies

Research on large-scale 3D printing technologies could be classified as either gantry-based, robotic-arm based, or swarm-based.

3.1 Gantry Solutions

A gantry-based solution is simply a scale-up of additive manufacturing to additive construction. In short, it is “a giant 3D printer”, with an actuator controlled in translation to any direction along the X, Y, Z-axes in cartesian coordinates [7]. The most noticeable and noteworthy gantry-based developments are D-Shape and Contour crafting:

- *D-Shape* is a process similar to the inkjet powder bed method (refer to Appendix) where a binder is selectively sprayed on the printing material [9]. When the binder contacts the powder printing material, the solidification process starts and a new layer is added. It takes 24 hours for the solidification process to be completed. D-Shape is a factory gantry-based powder-bed 3D printer that has the ability to print architectural structures with dimensions up to $6 \times 6 \times 6$ m (Figure 2). The products printed using D-shape technology can have a compressive strength up to 235–242 MPa [9]. Surplus powder that is not a part of the structure acts as a support to the structure while the solidification process takes place. Once the printing of an object is completed, it is removed out of the loose powder bed [10]. The surplus powder can be reused for other structures as well. D-Shape technology was mainly designed for factory (off-site) production of structural elements having complex geometries. However, using the technology to print on-site is currently being studied, where construction material available on site, like sand, and binder materials can be used [11].



Figure 2. D-Shape 3D Printing Technology.

- *Contour crafting (CC)* is the most recent and the most promising gantry-based 3-D printing technology developed for the construction industry [9]. CC is an in-situ process where the material (usually cement-based paste) is extruded successively layer by layer [10]. The CC system consists of a gantry system and a nozzle. The gantry system used in CC is very alike to that used in precast concrete fabrication. However, on-site employees are—theoretically—not needed in contour crafting as the process is fully automated, unlike in precast concrete fabrication where on-site employees are required during production to make sure that the discharge system is working properly. A set of actuated and computer-controlled trowels are used to trowel the printed material extruded from the nozzle. This is done to ensure a smooth and accurate planar and free-form surfaces. One of the main issues related to contour crafting is maintaining a uniform level of viscosity. A uniform level of viscosity is required for an improved structural strength and a smoother surface finish [9].

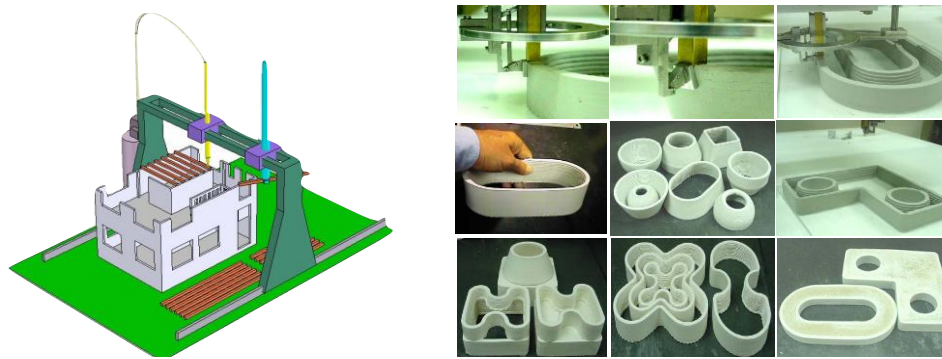


Figure 3. (left) initial Contour Crafting conceptualisation, and (right) first realisation attempts of 2.5D printed concrete shapes [2]

3.2 Robotic Arm Solutions

Although D-Shape and Contour Crafting were successful in scaling up additive manufacturing for the use of construction, they yet suffer from significant limitations. D-Shape is criticised for being unreliable due to the difficulty of hydrating cementitious powder in a satisfactory and regular manner; It is also unpractical as one has to eventually remove the powder and clean the product, adding significant time and effort to the process.

On the other hand, Contour Crafting is criticized for being limited to vertical extrusion. Hence CC does not literally yield 3D, but rather 2.5D typologies (vertical extensions of a planar shape) [11]. As in small-scale 3D printing techniques, the extrusion path in CC uses 3D-to-2D slicing software. The software slices a 3D shape into layers of constant thickness, which are then extruded one up onto the other. Each layer is then made of a contour line and a filling pattern that looks like a honeycomb; whereas the filling density is adjusted on the basis of given requirements. The drawback of such technique is apparent when attempting to print a cantilevered structure; i.e. a structure that sways horizontally from the base layer, as shown in Figure 4 (left). Clearly, weak interfacial zones (red) between the printed layers (grey) are created [11].

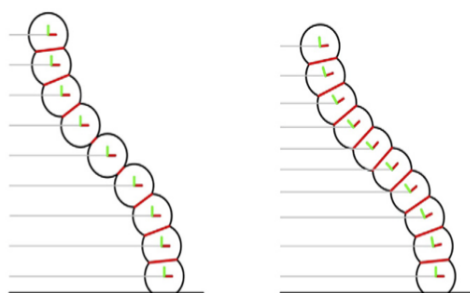


Figure 4. The Tangential Continuity Method (TCM) implemented used a 6-axis robotic arm by Gosselin et al. [11]

In response to the aforementioned limitations, [11]invented the Tangential Continuity Method (TCM) illustrated in Figure 4 (right). The method makes use of the increased degrees of freedom of a 6-axis robotic arm to generate a building path that are, accordingly to [11], truly three dimensional. The paths are made of non-planar layers with locally varying thicknesses (grey). The obvious advantage of such strategy is to increase areas of contact between two layers (red), hence avoiding the geometrical gaps between the layers; This eventually yields more efficient and mechanically sound constructions [11].

As aforementioned, the invention of the Tangential Continuity Method (TCM) would have not been possible without the use of the increased degrees of freedom offered by 6-axis robotic arms. For this purpose, and for their high software and hardware versatility and flexibility, robotic arms has now become the dominant tool for large-scale 3D printing research and development. Industrial robots like Kuka or ABB are accompanied with accessible software and scripting languages that ease the task of planning and controlling robotic trajectories. Designers and artists has further developed workflows to bridge the gap between digital and material worlds, with an aim to automate the materialisation of CAD/CAM (computer-aided design and computer-aided manufacturing) files. Automatic ‘File-to-factory’ is not a barrier anymore [12], but at the same time it is a subject of further research and development.

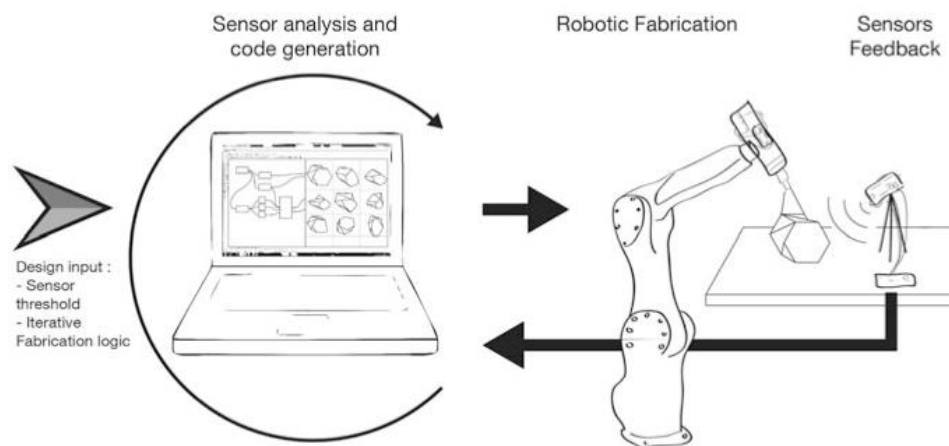


Figure 5. Ideal robotic-arm fabrication (or 3D printing) workflow [12]

An ideal workflow for robotic-arm fabrication is as following (Figure 5):

- Design and model the product using CAD parametric design software; for this purpose *Rhinoceros3D* is often used. *Grasshopper3D* plug-on is simultaneously used to visually program *Rhinoceros3D* models and build generative algorithms (or generative art). Through *Rhinoceros3D+Grasshopper3D* (Figure 7), the design is flexibly generated based on adjustable parameters and algorithmic rules.
- Convert the *Rhinoceros3D+Grasshopper3D* CAD model into robotic instructions through CAM plugins, e.g. KUKA|prc. The plugin generates accurate simulation of robotic trajectories, which allows the designed to virtually explore the potential and limitations of robotic fabrication processes.
- Extrude and receive real-time feedback from the end-effector, using micro-controllers (e.g. Arduino) and sensors to control material-specific parameters. This becomes especially crucial when extruding non-static materials such as clay, polymer or concrete. Precise sensor feedback is needed to enable tracking, fine-tuning and synchronisation between material, machine and design [12]. Control parameters include: (1) environmental conditions (e.g. air temperature, relative humidity), (2) sheer viscosity at the extrusion point, (3) feed rates, and (4) displacement speed. All these parameters will help predicting the final deposition location of the extruded material. Plenty of feedback sensors could be used for this purpose, such as thermometers, water flow meters, cameras (through image-pixel based analysis), fast laser scanners, Infrared (for light

sensitive material), and more. Such feedback may thence feed an artificially intelligence logic to adapt the extruders behaviour on real-time basis (refer to Figure 6).

To sum up, the current main challenge confronting large-scale 3D-printing research is the design of a smart end-effector that intelligently bridges digital and fabrication worlds, while finding optimum material properties under optimum environmental set-ups. Clearly, all this requires competences in material science, mechatronics, artificial intelligence and structural engineering. Section 3.2 reviews material science research in particular.

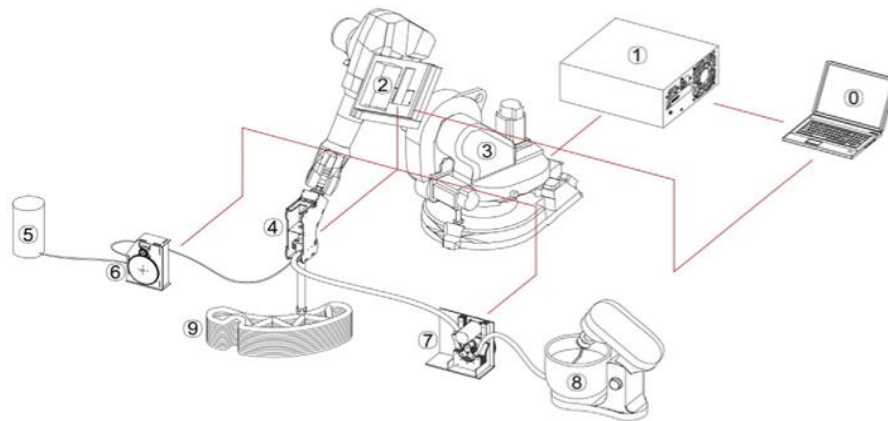


Figure 6. Concrete-type 3D-printing system components consisting of (0) System command, (1) Robot controller, (2) Printing controller, (3) Robotic arm, (4) Printhead, (5) Concrete accelerating agent, (6) Peristaltic pump for accelerating agent, (7) Peristaltic pump for premix, (8) Premix mixer, and (9) 3D printed object.

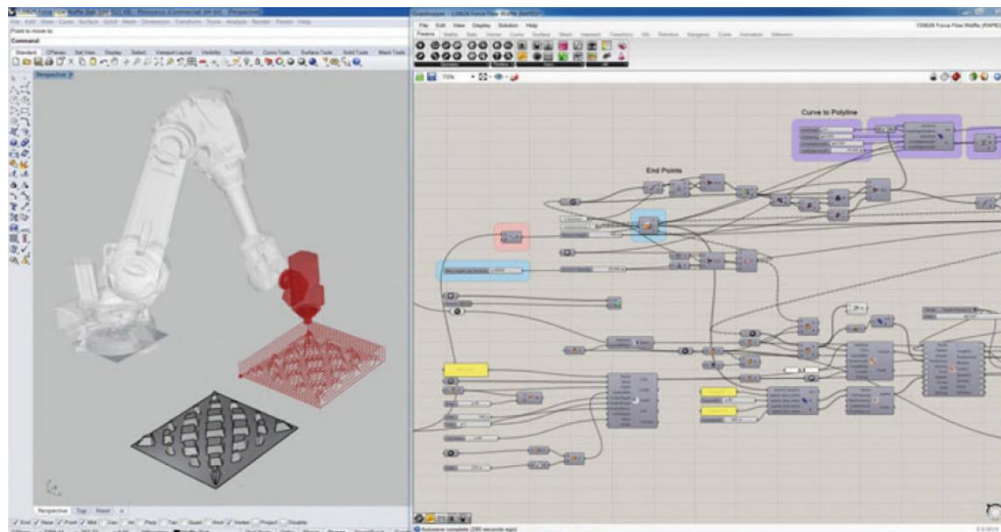


Figure 7. Grasshopper plugin for simulating robotic trajectories translated from a CAD model [13]

3.3 Swarm Solutions

Swarm approach is a radically different solution. It rejects the use of a single giant printer, in favour of the collective performance of several and smaller mobile robots: “swarm” [7]. In 1997, Pegna [14] has envisioned the approach as constructing large structures by an army of mechanical ‘ants’, spilling one

grain of sand at a time. The motive is to extend the concept of additive construction to areas where human exposure, payload and transportation activities are dangerous [14]. Ceccanti et al. [15] proposed a swarm-based solution to build moon habitats; and argued that a smaller wheeled printer controlled by a rover responsible for collecting and depositing the regolith would be more efficient than D-shape in that case.

Swarm approach was implemented by a research team from MIT who introduced the concept of building architectural structures using a swarm of single, independent robots. The research team envisaged the robots' capability to build and then climb tabular structures, which successively form single threads within a larger network constituting the developing structure. Similarly, students in California College of the Arts in San Francisco designed autonomous robots to carry out construction work in hostile environments, which used sawdust to perform additive construction [16]. The application of swarm approach depends highly on the robots' ability to climb. Moreover, the ability of robots to communicate within a swarm is key to the success of this approach, which requires real-time sensor feedback to support algorithmic decision making processes [7].

Sasa Jokic and Petr Novikov from the Institute of Advanced Architecture of Catalunya created a group of three small robots called “mini-builders” for executing large scale structures [17]. Mini-builders constitute three types of robots:

- Foundation Robot, which uses tracks for movement, and a line follower sensor put in front of the robot for positioning. This robot places the base layer so that the grip robot could proceed with the additive construction process.
- Grip Robot, which is self-attached to the structure and fastened between four rollers. Each one of the rollers is connected to a steering actuator to allow the robot to position itself within and above the structure. This method allows the robots to carry out horizontal and curved printing of components. Material curing times are accelerated by the use of heaters.
- Vacuum Robots, which are used to strengthen the shell printed by the previously mentioned robot types. Those robots consist of a vacuum generator and a suction cup, can travel over surfaces at any angle and reinforce the shell by attaching themselves to it and printing extra layers over it.

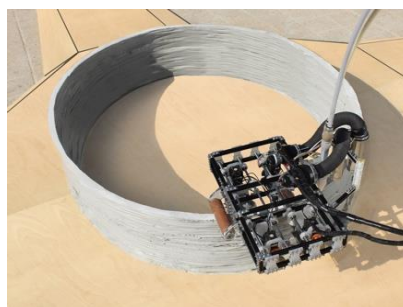


Figure 8. Grip Robot [17].

Another interesting swarm-based large-scale 3D printing uses flying robots, which are intended to overcome height limitations. Hunt et al. [18] has tested the practicality of “aerial additive construction” through a flying quadcopter robot capable of depositing polyurethane expanding foam in mid-flight.

Limitations include flight stability, materials availability, battery life of quadcopter and regulation restrictions.

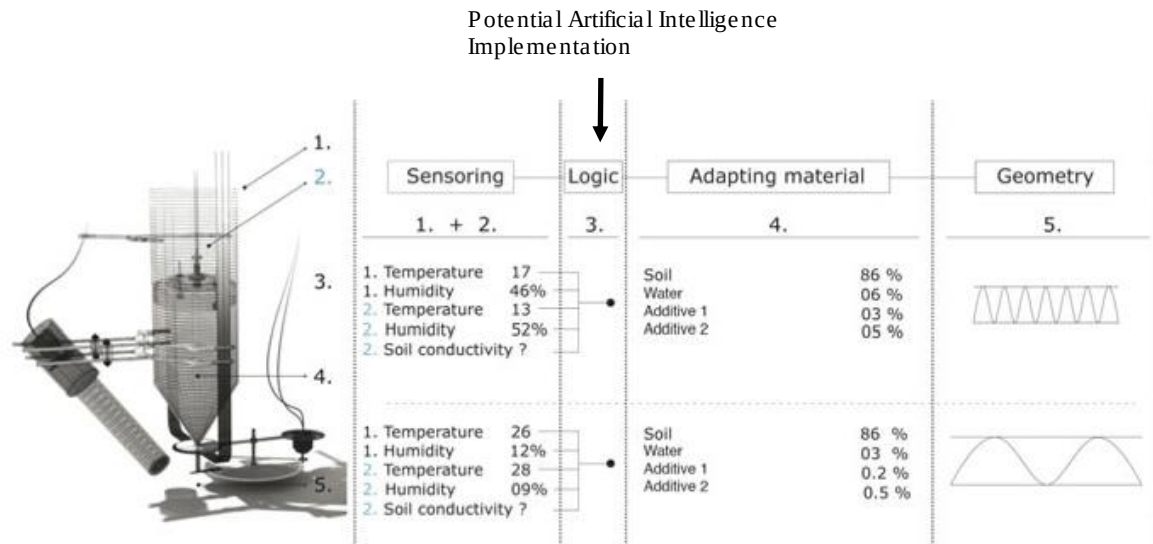


Figure 9. 3D printing process informed by sensors [12]

4. Material science challenges

Materials used in 3D printing (or additive manufacturing in general) can either be solid-like, viscous-like, powder-like or liquid-like. 3D processes based on solid-like materials involve layering the material in solid form. The different layers are bind by a number of techniques, like using a glue-like material to hold the successive layers together. 3D processes based on viscous-like materials involve extruding a viscous liquid from a printing nozzle. The materials are cured after extrusion in order to solidify. Contour Crafting, Fused Deposition Modelling and Inkjet processes are examples of 3D processes that are based on viscous-like materials. 3D processes based on powder-like materials involve the transformation of a material from a powder to a solid state using melting or sintering. D-Shape, Laser Sintering, Power Binding Printing, Selective Laser Melting and Selective Laser Sintering are all processes that are based on powder-like materials. 3D processes based on liquid-like materials involve the transformation of a material from a liquid to a solid state, such as Stereolithography where a light source is used for curing [7].

4.1 Concrete-type Materials

Most recent large-scale 3D printing research efforts has focused on concrete-type materials (e.g. Contour Crafting). For cementitious (or any viscous-like) 3D-printing to succeed, the extruded material should meet specific, sometimes contradictory requirements. Lim et al. [10] identified four extrusion-based process-related characteristics that need to be considered and optimised. These are namely: (1) pumpability, (2) printability, (3) buildability and (4) open time. *Pumpability* is the ease with which a material travels through the printing system. *Printability* is the ease with which a material is deposited from an extruder. *Buildability* is the resistance of the wet deposited material to deformation when the upper layers are printed on it. Finally, *open time* is the time in which the previous properties remain within the acceptable limits. Balancing the printability and buildability has always been known as the

most critical property. This is because, the adhesion between layers which affects the bond strength, is a function of the time interval between layers. Hence, the process should be designed such that the individual layers are able to adhere with one another (an open time that is short enough), and yet which still have time to cure (an open time that is long enough) [10,19–21]. This can be done by calibrating input parameters, including: the rate of extrusion, the thickness of layers, linear speed, part diameter, number of layers and the output parameters, including: layer width, part height, vertical profile and surface roughness [22].

Recently Feng et al. [23] studied the mechanical behaviour of a concrete-type 3D printed element, and revealed through microscopic observations, mechanical test of cubes and small beams, and Finite Element modelling, the effect of the printing process on the structural behaviour. Their study indicated that the layer-on-layer printing process led to an apparent orthotropic behaviour that was relevant to compression strength and elastic modulus, but not to failure mode. Their results confirmed that due to the anisotropic nature of material distribution, all extrusion-based processes are likely to create components that are strongly anisotropic [21], and that this will have a significant effect on the load-bearing capacity of the construction in question. The same conclusions were reached by Le et al. [20] who measured the effects of voids that appeared between deposited filaments on the orthotropic compressive and flexural strengths of extruded concrete. Moreover, FE analysis conducted by Feng et al. [23] showed that the printing direction has a significant influence on the load bearing capacity of the structure.

For these reasons, one may not rely on the structural performance of 3D printed elements, as their mechanical properties may be highly unpredictable. Although some researchers attempted to add glass fiber to the printing concrete to increase its strength, the material was yet too brittle to be used as load bearing components, or components that span horizontally such as slabs and staircases [9]. Nonetheless, the material was proven reliable enough to print moulds in which conventional concrete are poured into (Figure 10). The 3D printed moulds in that case becomes part of the final product; as such a great advantage is obtained through the elimination of de-moulding [9]. Above that, the most attractive advantage of 3D printed moulds is the ability to produce complex 3D shapes in comparison to casting processes [11]. More about geometric advantages and design opportunities are discussed in Section 3.3.



Figure 10. 3D printed moulds [9]

4.2 Beyond Load-bearing Properties

As mentioned above, the state-of-the-art of large-scale 3D printing is largely dominated by concrete-type research efforts, with an immense focus on the bearing capacity of the printed material. However, a sound building material cannot merely depend on good load-bearing capacity. Other essential qualities of materials that should be investigated include durability, water vapour diffusion resistance, thermal properties, and/or fire-resistant properties. Additionally, it is required that the selected materials does not pose risk on the health, safety and environment [24]. Material storage is also considered an issue as large-scale construction requires large volumes of material. Thus, one should also consider that the material used for 3D printing is inexpensive and have lightweight to facilitate storage [25]. This challenge can be addressed by using locally-derived materials that does not require transportation or storage. For instance, some authors proposed an “off-grid” 3D printer that can work using sand as the raw material for building.

Striding beyond sole bearing capacity investigations would probably entail moving out of the box to explore materials other than concrete for large-scale 3D printing applications. Labonnote et al. [7] argue that recent large-scale 3D printing efforts were largely influenced by the heritage of construction in which buildings are composed of combination of materials, each exhibit specific properties serving different requirements. For example, a wall may be composed of multiple materials including timber studs to provide adequate load-bearing properties, mineral wool to provide good insulation properties, and vapour barriers to provide good water vapour diffusion resistance properties.

Current large-scale 3D printing efforts seem to follow the same heritage of focusing on uni-functional material properties. This makes it unlikely to significantly favour large-scale 3D printing ahead of traditional construction methods. For this reason Labonnote et al. [7] except that today's standard use of extruded concrete in large-scale 3D printing will be disqualified in favour of other materials and/or processes. The authors argue that future opportunities for the application of material science in large-scale 3D printing are two-fold:

- Development of innovative materials that exhibit an optimal combination of all essential properties. Such inventions would increase the efficiency of construction through the reduction of material usage and the elimination of the extra work and time devoted for installing numerous materials. An example of such material science invention is developed by the Engineering Excellence Group Sydney [7]. The group invented an approach to print moulds made of wax, which they refer to as FreeFab Wax (Figure 11). The FreeFab is a replacement to the conventional timber-made, steel-made, or more recently concrete-printed moulds. FreeFab Wax exhibits both load-bearing properties, as well as sustainability properties. The wax is 3D printed to yield the required tolerance and surface finish; thereby, it is placed after use in a recycling station that melts the wax off the finished element and collects it for re-use again in other mould printing processes [24]. Figure 14 presents a conceptual overview of the FreeFAB Wax printing and recycling process.
- Investigation of large-scale 3D printing processes that support the extrusion of non-homogeneous Functionally Graded Materials (FGMs) whose properties smoothly vary along an axis (e.g. Figure 12). FGMs are inspired by the natural formation of bones and teeth in which the microstructure of a composite material varies from one material to another through a specific gradient. These would facilitate the production of versatile building materials. FGMs have already been investigated for the use of small-scale 3D printing [26] and should be also considered for large-scale 3D printing.

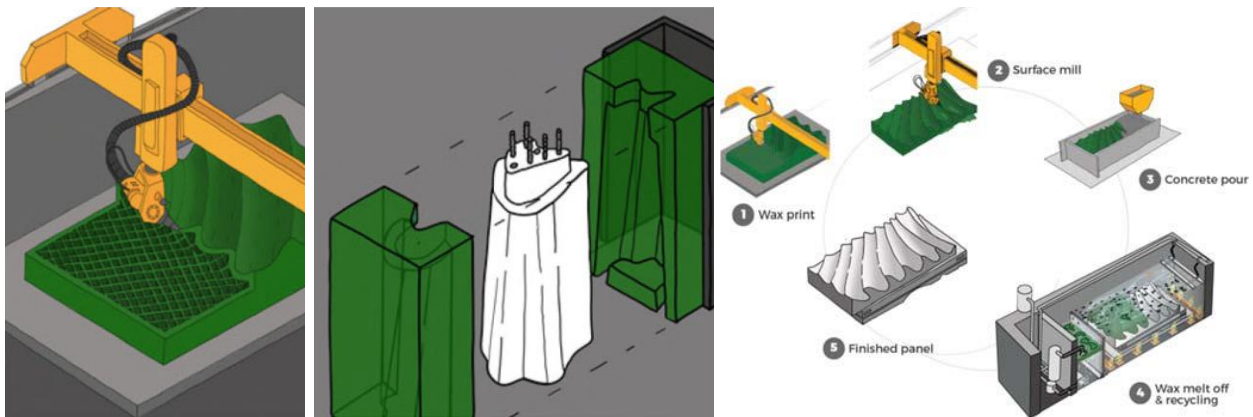


Figure 11. A conceptual illustration of the FreeFAB wax mould fabrication and recycling process [27]



Figure 12. FGM 3D-printed structures by MIT Medial Lab [28]

5. New building design opportunities

In the field of architectural design, a significant trade-off exists between the will to save cost, which entails producing simplistic and straight walls, and between the desire to produce novel and non-standard buildings, which entails producing customised moulds and formwork for one-time use, thus generating large amounts of waste materials and unforeseen construction delays. Large-scale 3D printing offers unlimited potential for producing complex geometries that can't be identified by basic geometrical notions and were only accomplished for limited projects [29]. Now that it is mathematically proved by Anatsioui et al. [30] that any 3D structure can be created by means of layer by layer. Structures can be made into almost any shape [15] regardless of their difficulty, expenses or possibility [14].

5.1 Smart Design and Building Performance Optimization

Furthermore, large-scale 3D printing provides the opportunity of optimising topologies at no extra costs. Optimised components results in material savings and reductions in weight [31] and aids in other types of optimisation such as those linked to thermal or acoustic properties. Gosselin et al. [11], for instance, experimented on the production of complex 3D printed concrete elements to attain ultra-high performance buildings. An example of their work is illustrated in Figure 14. The research team compared the shown complex 3D printed wall (Figure 13a) against a typical conventionally-built wall (Figure 13b). They found that a gain in thermal insulation performance of 56% was obtained in comparison to a conventional wall, only by optimising the geometry of the internal reinforcement. The wavy shell results in reducing the amount of heat (i.e. heat flux Φ) flowing through the whole structural element. Additionally, the authors argue that the wavy shell is structurally efficient as it contains straight

bars acting as a stable truss, suited to support loadings; the shell also acts as a doubly-corrugated reinforcement, enhancing the element's flexural rigidity [11].

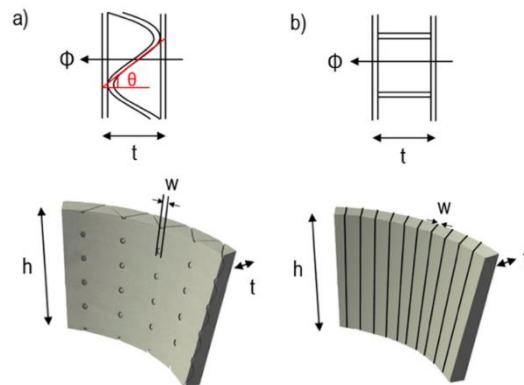


Figure 13. (a) complex 3D printed wall with wavy internal reinforcement, versus (b) wall with conventionally built internal reinforcement [11].

Moreover, large-scale 3D printing provides a better and more flexible methodology than mass customisation for meeting customer and/or architectural requirements for individualised products. Mass customisation depends on the use of diverse combinations of pre-assembled units and/or hindered differentiation methods. However, Strauss [21] offers a controlled individualisation level. Gardiner [24] considered flexibility regarding individualisation as a possible future niche market for large scale 3D printing. It actually represents a great interest to architects as 3D printing may be a true game-changer for architectural design and for future rich cooperation between engineers and architects. 3D printing's added value exceeds the possibility to embed "increased functionality" [32]. In fact, it can also contribute to the building of "smart structures" which embrace various properties such as solar responsively, technologies for monitoring and maintenance of buildings, self-healing materials and seismic forces dissipation. More potentials of large scale 3D printing were investigated like façade construction and predicted innovative smart applications [21].

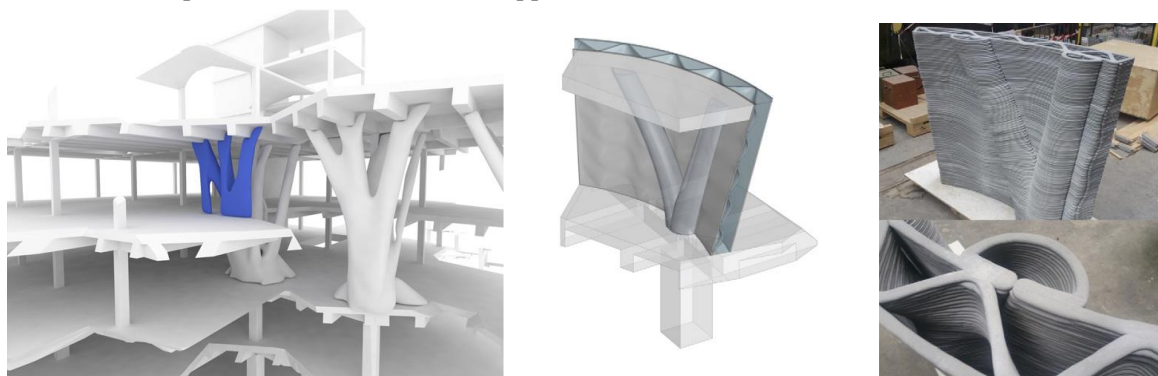


Figure 14. Architectural context for the multi-functional wall element (left), CAD model for the multi-functional wall (centre) and the 3D printed high-performance concrete multi-functional wall (right), designed and constructed by Gosselin et al. [11]

6. Conclusions

The articles reviewed three core inter-disciplinary research themes pertaining large-scale 3D printing: (1) technological solutions of additive construction (i.e. the 3D printers themselves), (2) material science challenges, and (3) new building design opportunities.

Improving the 3D printing technology: State-of-the-art large-scale 3D printing technologies could be classified as either gantry-based, robotic-arm based, or swarm-based. Gantry based solutions served well for materialising the concept of large-scale 3D printing, but yet suffer significant drawbacks. Swarm

based solutions seem promising as for approaching unreachable construction zones, but are too conceptual so far. There is a great potential for robotic-arm solutions to push the future of large-scale 3D printing forward, given their well-established workflows, aside with their high versatility and flexibility. The main challenge is to design a smart robotic-arm end-effector that intelligently bridges digital and fabrication worlds, while finding optimum material properties under optimum environmental set-ups.

Tackling Material Science Challenges: Most recent large-scale 3D printing research efforts has focused on concrete-type materials. For cementitious (or any viscous-like) 3D-printing to succeed, the extruded material should meet specific, sometimes contradictory requirements. These are namely: (1) pumpability, (2) printability, (3) buildability and (4) open time. Recently employed large-scale 3D printing systems were successful in achieving a right equilibrium between these requirements, and hence attained satisfactory load-bearing capacity parameters for full-scale real-world structures. Nonetheless, one may not rely on the structural performance of 3D printed elements, as their mechanical properties are yet highly unpredictable. This is due to the effect of voids that appear between deposited filaments on the orthotropic compressive and the flexural strengths of the extruded concrete. Nonetheless, till day the printed material were proven reliable enough to develop moulds in which conventional concrete are poured into. 3D printed moulds have a significant advantage over conventional moulds in their ability to produce complex 3D shapes. Despite this advantage, 3D printed elements is unlikely to significantly become favoured ahead of traditional construction methods, unless researchers stride beyond the uni-functional material heritage of construction towards the innovation of multi-functional material. A multi-functional material is that which not only exhibits one property (e.g. load-bearing), but rather multiple properties.

Exploring New Design Opportunities: Designers are often confronted with a trade-off between cost savings, which entails producing simplistic and straight walls, and between novel and non-standard buildings, which entails producing customised moulds and formwork for one-time use, thus generating large amounts of waste materials and unforeseen construction delays. Current large-scale 3D printing state-of-the-art allow constructing complex geometries that were not possible in the past. Future research may investigate this opportunity aside with its implications on the future of building design, not only from an aesthetic perspective, but also from the perspective of (thermal, acoustic, etc.) performance of structures. Also the value of large-scale 3D printing may exceed “increased functionality”; It can also contribute to the building of "smart structures" which embrace various properties such as solar responsively, technologies for monitoring and maintenance of buildings, self-healing materials and seismic forces dissipation. All in all, large-scale 3D printing would create a paradigm change in the field of building design. Future architects are expected to become robotic-aware, in which they would consider robotic arm constraints for the design of a given building element.

7. Acknowledgement

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8. References

- [1] S. Griffiths, Giant 3D printer creates 10 full-sized houses in a DAY: Bungalows built from layers of waste materials cost less than £3,000 each., DailyMail. (2014). <http://www.dailymail.co.uk/sciencetech/article-2615076/Giant-3D-printer-creates-10-sized-houses-DAY-Bungalows-built-layers-waste-materials-cost-3-000-each.html> (accessed December 28, 2017).
- [2] B. Khoshnevis, Automated construction by contour crafting—related robotics and information technologies, *Autom. Constr.* 13 (2004) 5–19.
- [3] J. Brandon, Don't Believe the Hype: WinSun Unveils Bland Multi-Story 3D Printed Buildings, SolidSmack. (2015). <https://www.solidsmack.com/fabrication/dont-believe-hype-winsun-unveils-bland-multi-story-3d-printed-buildings/> (accessed January 2, 2018).

- [4] I. OBERTI, F. PLANTAMURA, Is 3D printed house sustainable?, in: Proc. Int. Conf. CISBAT 2015 Futur. Build. Dist. Sustain. from Nano to Urban Scale, LESO-PB, EPFL, 2015: pp. 173–178.
- [5] N. Davison, 3D-printed cities: is this the future?, Guard. (2015). <https://www.theguardian.com/cities/2015/feb/26/3d-printed-cities-future-housing-architecture> (accessed January 2, 2018).
- [6] Alec, Saudi Arabia plans to 3D print 1.5 million houses with WinSun's construction 3D printing tech, 3Ders. (2016). <https://www.3ders.org/articles/20160802-saudi-arabia-plans-to-3d-print-15-million-houses-with-winsuns-construction-3d-printing-tech.html> (accessed January 2, 2018).
- [7] N. Labonnote, A. Rønnquist, B. Manum, P. Rüther, Additive construction: State-of-the-art, challenges and opportunities, Autom. Constr. 72 (2016) 347–366.
- [8] The American Society for Material and Testing, Standard Terminology for Additive Manufacturing Technologies, in: ASTM Int., West Conshohocken, United States, 2009.
- [9] P. Wu, J. Wang, X. Wang, A critical review of the use of 3-D printing in the construction industry, Autom. Constr. 68 (2016) 21–31.
- [10] S. Lim, R.A. Buswell, T.T. Le, S.A. Austin, A.G.F. Gibb, T. Thorpe, Developments in construction-scale additive manufacturing processes, Autom. Constr. 21 (2012) 262–268.
- [11] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, Large-scale 3D printing of ultra-high performance concrete—a new processing route for architects and builders, Mater. Des. 100 (2016) 102–109.
- [12] A. Dubor, G. Camprodom, G.B. Diaz, D. Reinhardt, R. Saunders, K. Dunn, M. Niemelä, S. Horlyck, S. Alarcon-Licona, D. Wozniak-O'Connor, Sensors and workflow evolutions: developing a framework for instant robotic toolpath revision, in: Robot. Fabr. Archit. Art Des. 2016, Springer, 2016: pp. 410–425.
- [13] J.B. Gardiner, S.R. Janssen, FreeFab, in: Robot. Fabr. Archit. Art Des. 2014, Springer, 2014: pp. 131–146.
- [14] J. Pegna, Exploratory investigation of solid freeform construction, Autom. Constr. 5 (1997) 427–437.
- [15] F. Ceccanti, E. Dini, X. De Kestelier, V. Colla, L. Pambaguian, 3D printing technology for a moon outpost exploiting lunar soil, in: 61st Int. Astronaut. Congr. Prague, CZ, IAC-10-D3, 2010.
- [16] B.B. Millsaps, 3D Printing Robots Capable of Building in Outlying Areas, 3D Print. (2015). <https://3dprint.com/32903/swarmscapers-robots/> (accessed January 2, 2018).
- [17] Institute of Advanced Architecture of Catalunya - IAAC, Minibuilders: small robots printing big structures, (2017). <http://robots.iaac.net/> (accessed January 2, 2018).
- [18] G. Hunt, F. Mitzalis, T. Alhinai, P.A. Hooper, M. Kovac, 3D printing with flying robots, in: Robot. Autom. (ICRA), 2014 IEEE Int. Conf., IEEE, 2014: pp. 4493–4499.
- [19] A. Perrot, D. Rangeard, A. Pierre, Structural built-up of cement-based materials used for 3D-printing extrusion techniques, Mater. Struct. 49 (2016) 1213–1220.
- [20] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G.F. Gibb, T. Thorpe, Mix design and fresh properties for high-performance printing concrete, Mater. Struct. 45 (2012) 1221–1232.
- [21] H. Strauss, AM Envelope: The Potential of Additive Manufacturing for facade constructions, TU Delft, 2013.
- [22] B. Khoshnevis, R. Russell, H. Kwon, S. Bukkapatnam, Crafting large prototypes, IEEE Robot. Autom. Mag. 8 (2001) 33–42.
- [23] P. Feng, X. Meng, J.-F. Chen, L. Ye, Mechanical properties of structures 3D printed with cementitious powders, Constr. Build. Mater. 93 (2015) 486–497.
- [24] J. Gardiner, Exploring the emerging design territory of construction 3D printing-project led architectural research, RMIT University, Melbourne, Australia, 2011.
- [25] E. Barnett, C. Gosselin, Large-scale 3D printing with a cable-suspended robot, Addit. Manuf. 7 (2015) 27–44.
- [26] S. Chianrabutra, B.G. Mellor, S. Yang, A dry powder material delivery device for multiple material additive manufacturing, Univ. Southampton, UK. (2014).
- [27] J.B. Gardiner, S. Janssen, N. Kirchner, A Realisation of a Construction Scale Robotic System

- for 3D Printing of Complex Formwork, in: ISARC. Proc. Int. Symp. Autom. Robot. Constr., Vilnius Gediminas Technical University, Department of Construction Economics & Property, 2016: p. 1.
- [28] Functionally graded printing, MIT Media Lab. (2012).
[http://matter.media.mit.edu/tools/details/3d-printing-of-functionally-graded-materials#prettyPhoto\[3d-printing-of-functionally-graded-materials\]/1/](http://matter.media.mit.edu/tools/details/3d-printing-of-functionally-graded-materials#prettyPhoto[3d-printing-of-functionally-graded-materials]/1/) (accessed January 2, 2018).
- [29] I. Vizotto, Computational generation of free-form shells in architectural design and civil engineering, *Autom. Constr.* 19 (2010) 1087–1105.
- [30] A. Anastasiou, C. Tsirmpas, A. Rompas, K. Giokas, D. Koutsouris, 3D printing: Basic concepts mathematics and technologies, in: *Bioinforma. Bioeng. (BIBE)*, 2013 IEEE 13th Int. Conf., IEEE, 2013: pp. 1–4.
- [31] H. Valkenaers, D. Jansen, A. Voet, A. Van Gysel, E. Ferraris, Additive manufacturing for concrete: a 3D printing principle, in: *Proc. 14th Euspen Int. Conf., euspen*, 2014: pp. 139–142.
- [32] R. Soar, Additive manufacturing technologies for the construction industry, *Rapid Manuf. An Ind. Revolut. Digit. Age.* (2006) 249–273.