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Applicability and Limitations of 3D Printing for Civil Structures

Mostafa Yossef
Iowa State University, myossef@iastate.edu

An Chen
Iowa State University, achen@iastate.edu

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Mostafa Yossef
Department of Civil, Construction and Environmental Engineering
Iowa State University
Ames, Iowa, 50011
myossef@iastate.edu

An Chen
Department of Civil, Construction and Environmental Engineering
Iowa State University
Ames, Iowa, 50011
achen@iastate.edu

ABSTRACT

Three Dimensional Printing (3DP) is a manufacturing process that builds layers to create a three-dimensional solid object from a digital model. It allows for mass customization and complex shapes that cannot be produced in other ways, eliminates the need for tool production and its associated labor, and reduces waste stream. Because of these advantages, 3DP has been increasingly used in different areas, including medical, automotive, aerospace, etc. This automated and accelerated process is also promising for civil structures, including building and bridges, which require extensive labor. If successful, it is expected that 3D structural printing can significantly reduce the construction time and cost. However, unlike applications in other areas, civil structures are typically in large scale, with length or height spanning hundreds of feet. They are subjected to complex loadings, including gravity, live, wind, seismic, etc. Therefore, it is challenging to develop suitable printing tools and materials. As a result, although there are limited 3D printed buildings, 3DP of civil structures is still at a primitive stage. This papers aims to explore the applicability of 3DP for civil structures. The first part is devoted to a review of 3DP in different areas, including 3D printed buildings. Based on the state of art, the weakness and opportunities of 3DP are identified. Finally, future directions for 3DP in civil structures are discussed.

Key words: 3D Printing—review—civil structures—applicability—limitations

INTRODUCTION

Three Dimensional Printing (3DP) was evolved from automated production, which started in the early twentieth century. It was first applied in manufacturing and automotive industries. Recently, its applications were expanded to other industries, including medical, aerospace, construction, etc. This automated and accelerated process is also promising for civil structures, including building and bridges, which require extensive labor. However, many factors have limited its further development. As a result, although there are limited application of 3DP in civil construction, 3DP of civil structures is still at a primitive stage. This paper first reviews the latest development of 3DP in construction and other areas. It then identifies the limiting factors and challenges of 3DP. Finally, future directions of 3DP in civil engineering are discussed.

BRIEF HISTORY OF 3D PRINTING

According to 3DPI (2014), 3DP started in the late 1980's. It was known as Rapid Prototyping (RP) technology developed by Kodama in Japan. Six years later, Charles Hull invented Stereo Lithography Apparatus (SLA). In 1987, SLA-1 was introduced as the first commercial RP system. In 1989, a patent for Selective Laser Sintering (SLS) was issued for Carl Deckard at University of Texas. Through the 1990's until early 2000's, SLS has been developed to focus on industrial applications such as casting. New terminology, Casting and Rapid Manufacturing (RM), was introduced for such applications. In 2005, the terminology evolved to include all processes under Additive Manufacturing (AM). The term *Additive Manufacturing* (AM) is defined by ASTM as "a process of joining materials to make objects from 3D model data, usually layer upon layer" (ASTM Standard 2012). Unlike *Subtractive* term which means machining away the material from a block to form the required object. Casting or shaping the material in a mold is often called *Formative* process. Table 1 shows a summary of different techniques used in AM (Buswell et al. 2007).

Table 1 –Summary of AM techniques (Buswell et al. 2007)

Process	Description
Stereolithography (SLA)	Liquid photopolymer resin is held in a tank. A flat bed is immersed to a depth equivalent to one layer. Lasers are used to activate the resin and cause it to solidify. The bed is lowered and the next layer is built.
Fused Deposition Modelling (FDM)	Extrudes a narrow bead of hot plastic, which is selectively deposited where it fuses to the existing structure and hardens as it cools.
Selective Laser Sintering (SLS)	Utilises a laser to partially melt successive layers of powder. One layer of powder is deposited over the bed area and the laser targets the areas that are required to be solid in the final component.
3D Printing (3DP)	Based on inkjet printer technology. The inkjet selectively deposits a liquid binder onto a bed of powder. The binder effectively 'glues' the powder together.

3DP is based on AM process. It is a process where a 3D model is created using Computer Aided Drafting (CAD) software. The model is then transferred to the 3D printer as a standard data known as stereolithography language (STL), where the model is converted into layers that can be applied consecutively. Each layer is formed where the printer head deposits an activating agent, and premixes it with a power material. The layers are bonded together consecutively to form the 3D object. In 2009, the first commercial 3D printer was offered for sale. In 2012, an alternative 3D printer was introduced at entry level of the market with affordable price.

APPLICATIONS OF 3D PRINTING

3DP has been increasing used in different areas. Architectural modelling is one of the major areas that uses 3DP for developing prototypes that facilitate the communication between the architect and customer. Architect can print now complex structures and color it as well for better representation (Gibson et al. 2002). In medical area, 3DP is used to create high quality bone transplant, modelling of damaged bones for better fracture analysis (James et al. 1998; Murray et al. 2008). 3PD can also be used to print complex shapes, such as human tissue or artificial blood vessels that are used in coronary bypass surgery (Wong and Hernandez 2012). Dentists are using 3DP to create a plaster model of the mouth or to replace patient's teeth (van Noort 2012). In aerospace industry, 3DP is used to print airfoils (Thomas et al. 1996). In automotive field, Song et al. (2002) used RP technology to manufacture the die of an automobile deck part.

3DP FOR CIVIL STRUCTURES

Warszawski and Navon (1998) pointed out the following problems concerning construction industry: low labor efficiency compared with automated machines, high accident rate, low quality work due to insufficient skilled workforce, and difficulty of applying control of construction site. Applying automation or 3DP can overcome these problems.

Automation in construction industry started in terms of robotics [Gambao et al. (2000); Kuntze et al. (1995); Lorenc et al. (2000); Williams et al. (2004)]. Buswell et al. (2007), (2008) conducted a review over RM technologies for construction, based on which they developed a Freeform Construction method. The term of Freeform Construction was defined for methods that deliver large-scale components for construction without the need of formworks using AM. They concluded that Freeform Construction could reduce the construction cost and provide freedom of selecting desired geometry with better performance than traditional method. Lim et al. (2009) stated that Freeform Construction methods are currently limited to CC (US); Concrete Printing (UK); and D-shape (Italy).

Khoshnevis (1998) introduced the Contour Crafting (CC) which later become an effective method of printing 3D houses. Khoshnevis (2004) defined CC as "*an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surface*". The idea of CC was to use two trowels to form a solid planar surface for external edges. Filler material such as concrete can then be poured to fill the extruded area. They demonstrated that CC can be used in building structures as shown in Figure 1, where a nozzle is supported by a gantry system which moves in two parallel lanes. The nozzle is capable of full 6-axis positioning and can extrude both sides and filler material. CC nozzle can also be used for forming paint-ready surface, placing reinforcement before pouring concrete, plastering and tiling, plumbing and installing electrical modules and communication line wiring.

Zhang and Khoshnevis (2013) developed an optimized method for CC machine to efficiently construct complicated large-scale structures. Extensive research was done to avoid collision between multiple nozzles. Three approaches were compared, namely: path cycling, buffer zone path cycling and auxiliary buffer zone. The results indicated that the path cycling and buffer zone cycling provided the maximum optimization. They concluded that using CC method is significantly faster than traditional methods and implementation to multi-story building is possible by climbing as shown in Figure 3.

According to Roodman and Lenssen (1995), the construction industry consume more than 40% of all raw materials globally. CC can reduce the material waste from 7 tons to almost none for a single-family home. And the speed of the construction can be increased to one day per house. Although the ability of using this method in luxury structures or complex structures is still limited, implementation of CC can help with fast construction of low income housing and emergency shelter.

Despite the many advantages of CC, Lim et al. (2009) listed some limitations of CC as follows. The mold is not disposed and becomes a part of the wall. CC method requires excessive steps including molding, installing reinforcement, and placing concrete to build layers up to 20 mm high. These limitations encouraged them to develop another Freeform Construction method called Concrete Printing. Similar to 3DP idea, the concrete printing machine has a frame of 5.4m x 4.4 m (footprint) x 5.4 m (height) and a printing head moving on a mobile beam. A 9 mm nozzle is supported with the printing head to provide the material extrusion. Later, Le et al. (2012) conducted experimental program to figure out the optimum mix design of a high-performance fiber-reinforced fine-aggregate concrete for printing concrete.

The 3D printed houses can provide a cheap and efficient homes of low-income families. The printed houses consist of different printed parts assembled together to form the house. It can take less than 24 hour to build one house. However, no details are provided about 3DP of wiring, plumbing and HVAC, etc.

The latest development of 3DP was from WinSun, a Chinese company. They printed five-story apartment block using 3DP as shown in Figure 4 (Charron 2015). They stated that the houses were in full compliance with relevant national standards, which overcomes one of the main issues that face 3D printed houses. WinSun also printed a decorated house as shown in Figure 5.

3DP can also be used for non-conventional structures. DUS, a Dutch architecture company used 3DP to design facades integrated with solar panels, where the angle of the solar panel could be optimized automatically for any location. This can eliminate the need of manufacturing a mold for every different location (Jordan et al. 2015).

Other automation effort was done by the industry sector. For example, Shimizu Corporation in Japan developed an automated system that included erection and welding of steel-frames, laying concrete floor planks, installation of exterior and interior wall panels, and installation of various other units (Yamazaki and Maeda 1998).

Lim et al. (2012) compared CC, D-shape, and Concrete Printing. They concluded that Concrete Printing could optimize strength prior to manufacturing, which resulted in less material. It could also create complex concrete shapes without the need of labor-intensive molding as shown in Figure 2.

CHALLENGES OF 3DP FOR CIVIL STRUCTURES

As described above, 3DP allows for mass production, uses less labor, increases the construction speed and produces less waste compared to traditional construction methods. 3D printed structure is a layered structure, which is not new in civil engineering. Concrete Masonry Unit (CMU) structure is a typical layered structure, where the CMU units are installed by pieces and bonded together with mortar. The author of this paper has designed CMU buildings up to 13 stories and 125 feet high. The integrity of 3D printed structure is better than CMU structure. Therefore, 3D printed structure should be able to exceed the height of CMU structure. However, the tallest building that has been printed so far was the 5-story apartment building. Khoshnevis (2004) and Buswell et al. (2007) stated multiple issues that slowed down the growth of automation industry in construction. It can be summarized as follows:

- automated fabrication is often not suitable for large scale products and conventional design approaches;

- smaller ratio of automated products in comparison with other industries;
- only limited material can be used by automated machines;
- expensive automated machines tend to be unfeasible economically; and
- managerial issues and the increasing pressure towards environmental issues of construction materials in developing countries (Guthrie et al. 1999).

CONCLUSIONS AND FUTURE DIRECTIONS OF 3DP FOR CIVIL STRUCTURES

It can be shown from this paper that the application of 3D printing in civil engineering is promising. It can not only help to improve communication among designers by creating prototypes of the desired projects, but also be used in high-stress performance testing and end-user applications. Considering the limitations described above, in the authors' opinion, the following directions of 3DP for civil structures deserve further attention.

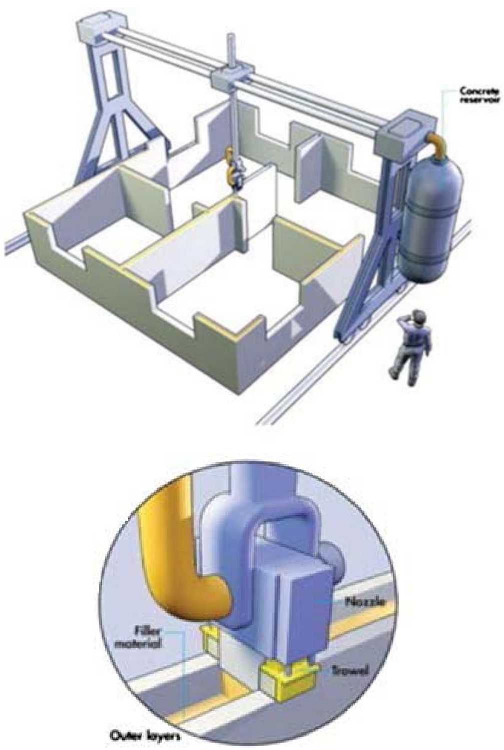
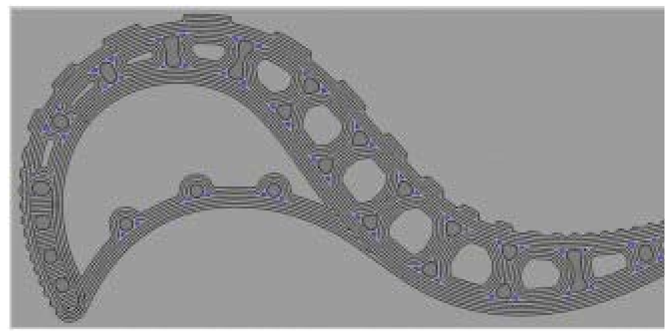
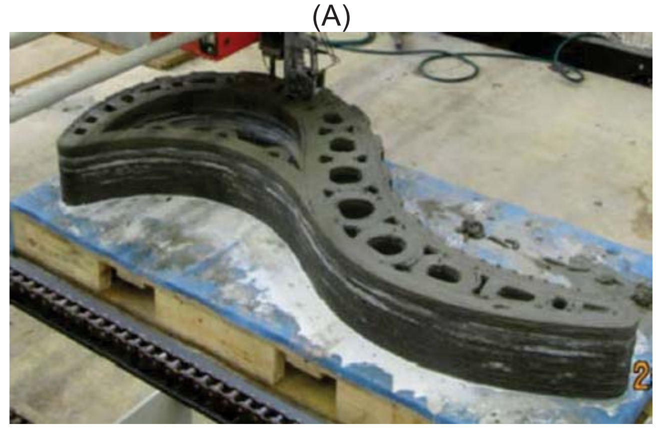


Figure 1 - Schematic view of construction of conventional buildings using CC (Zhang and Khoshnevis 2013)



(A)



(B)

Figure 2 – Complex Concrete Printing Product
(a) 3D Model (Lim et al. 2012),
(b) During printing (Le et al. 2012)

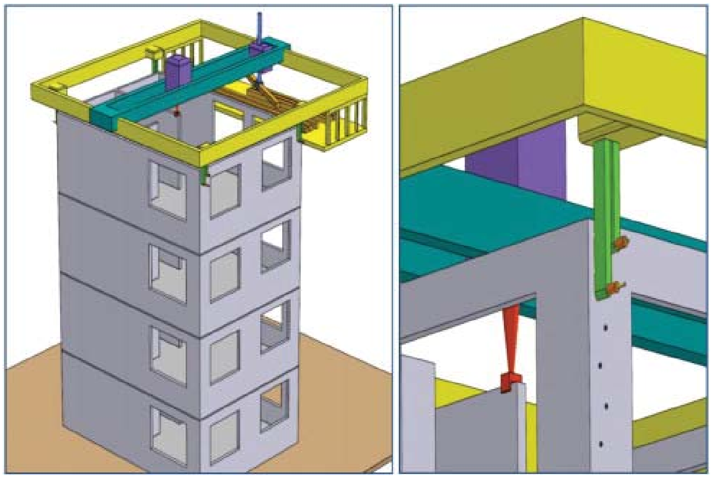


Figure 3 – Construction of multi-story buildings using Contour Crafting method (Zhang and Khoshnevis 2013)

Figure 4 – A 3D printed five-story apartment block (Charron 2015)

Figure 5 – A Decorated 3D printed house (Charron 2015)

Construction components of significant size are heavy, typically being up to 5 tons. Suitable equipment needs to be developed in order to lift and move heavy component. However, before suitable equipment can be developed for large scale structure, in-situ deposit approach, i.e., printing lighter parts on site followed by assembly would be an alternative option.

3DP can be especially useful for structures with complex shapes. For example, rubber can be used to print shock absorbers in a large scale which can help in reducing the seismic effects on buildings. A prototype is shown in Figure 6.

3DP can also open up a frontier to use new materials. These new materials need to satisfy specific requirements from 3DP. For example, they need to have proper curing time since the lower layer needs to support the upper layer. The bonding between different layers should be strong. These materials also require extensive testing to determine their mechanical properties, including the properties of the materials, inter- and intra-layers.

Figure 6 - 3D Printed Rubber Shock Absorber (http://3dprinting.co.uk/)

Jordan et al. (2015) stated that automated industry will take over the constructions process. This requires revising building codes to ensure that additive machines are operating within limits and meet performance criteria. For example, the 3D printed structure should be able to take complex loads, including gravity, live, wind, seismic, etc., and satisfy the performance requirements, such as fire, smoke and toxicity. In addition to that, current safety factors are high due to the consideration of human mistakes. Such factors can be lowered in case of using automated machines instead of human workforce.

Development of a complete process from the parametric design until printing the building is needed to control the whole process and eliminate any wasted time during printing. Khoshnevis (2004) proposed a planning system that shows each component of future automated system. Figure 7 shows a brief explanation for the proposed plan.

Further research is also needed in connections for 3D printed structures, where few studies are available. These include, but not limited to, beam-column, column-footing, wall connections, etc.

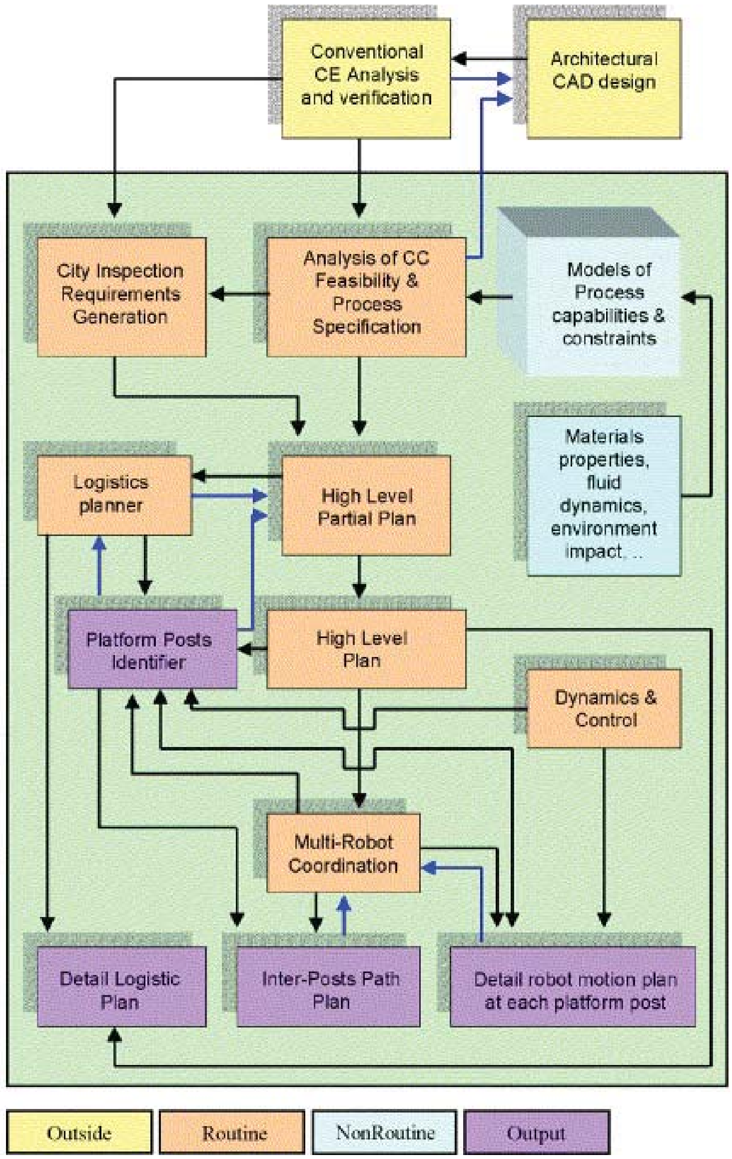


Figure 7 – Components of future automated construction (Khoshnevis 2004)

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