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Subversion of conventional construction: Building 3D printing technology

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Abstract. As a rapid prototyping technology, 3D printing technology has been successfully utilized in medical treatment, jewelry, precision parts manufacturing, aviation and other fields. Meanwhile, owing to its feature of energy saving and emission reduction, it is attached high importance to in recent years. However, due to the problems of printing equipment and materials, and evaluation standards, the research progress of building 3D printing technology is far from sufficing the practical demand of large-scale manufacture in the construction industry. This paper starts with an introduction to the classification and development history of building 3D printing technology, explains its current research and application status, and propose outlooks for the prospective development.

1. Introduction

Traditional numerical control manufacturing technology is also known as subtractive manufacturing technology, which is a method that removes excess parts on the basis of raw materials by cutting, grinding, corrosion, melting, etc. to obtain the final product. In contrast, 3D printing technology, also known as additive manufacturing[1], is an advanced method of overlaying printing materials into three-dimensional solids layer by layer through via numerical control technology and the obtained 3D models. In short, 3D printing is a method of "layered processing and superimposed molding" to finally produce a three-dimensional solid object.

Since the 21st century, foreign governments have gradually implemented plans and policies to promote the development of 3D printing technology. In May 2011, the German Photonics Research Plan released by the German Federal Ministry of Education and Research included financial support for the development of 3D printing technology[2]. In August 2012, the US government expended $ 30 million to set up a national 3D printing research center in Ohio[3].

In recent years, China has also paid special attention to the research and application of 3D printing technology. In 2015, the Ministry of Industry and Information Technology officially launched the National Additive Manufacturing Industry Development Promotion Plan—the first special promotion plan for 3D printing technology. In 2016, Outline of Construction Industry Informatization Development 2016-2020 released by the Ministry of Housing and Urban-Rural Development stated that research on 3D printing equipment and materials in the construction industry should be actively carried out, and the application of 3D printing technology in building production should be explored in conjunction with BIM technology.

With the gradual advantage weakening of China's demographic dividend, the demand for the construction industry to change from a labor-intensive industry to a technology-intensive industry is becoming more urgent. Traditional construction methods have high labor intensity, high safety risks, excessive material waste, and long construction cycles. In contrast, the employment of 3D printing technology in the construction industry owns significant advantages such as resource conservation, safety, environmental protection, and customization. 3D printing technology put forward effective solutions and technical support for the major problem.

However, a integral and effective evaluation standard and index system aren't existent in the field, and there are still issues in many aspects like technical process, printing materials, equipment and supportive software, design methods, and model optimization. The formation of its application promotion and industrial chain is severely restricted. Therefore, it is particularly crucial to formulate and improve a unified standard and evaluation system, and to develop more advanced and applicable 3D printing process equipment and materials.

2. Building 3D printing

Due to the late start in China, research on 3D printing technology in the construction field is still relatively lagging behind. In contrast, the United States and some developed European countries have begun to explore the concept of "automated building manufacturing" as early as the 1970s.

In the true sense, automated 3D printing technology was first applied to construction by Joseph Pegna in 1997. He accumulated and selectively cured binding materials in layers, and finally made free-form building components[4]. In 2001, Contour Crafting, a novel building 3D printing technology, was proposed by Behrokh Khoshnevis from the University of Southern California. It achieved layered printing of concrete through nozzles with spatula and large extrusion equipment. In 2007, the British company Monolite came up with D-shape. Different from Contour Crafting, this technology uses cementing agents to selectively cement each layer of powders, and to form a reliable entity layer by layer. In 2008, the Centre for Innovation and Architecture Research at Loughborough University proposed the Concrete Printing. This process involves layering and superimposing the concrete in a semi-flow state by spraying. The most obvious difference from the contour process is that the trowel is no longer set on the nozzle for auxiliary leveling.

In the past two decades, scholars in the field of architecture have explored the development of 3D printing technology from various angles and through various methods. According to the materials and processes exercised, this paper divides the major building 3D printing technology into two categories for introduction, namely the layered bonding technology based on sand and stone powder and the layered spraying technology based on concrete.

2.1. Layered bonding technology based on sand and stone powder—D-shape

D-shape is a method of stacking and molding of various layers of grit powder by spraying an adhesive (the printing device is shown in figure 1 and the process flow is shown in figure 2). In 2009, Italian engineer Enrico Dini managed to print a sculpture with a height of 1.6m. Later, he printed a 4m-high hollow egg-shaped building structure called the "radiation hall". Its messy layout can strongly prove and test this breakthrough of construction technology.

Printing starts from the building bottom. The equipment moves back and forth along the horizontal axis beams and 4 vertical columns. Thousands of nozzles will simultaneously spray grit and magnesium-based glue, when it's printing upward layer by layer. The glue will firmly bind the sand into a hard solid resembling marble, and eventually forms the required shape. Due to the strong microcrystalline structure, the new material has excellent tensile strength and compactness.

Figure 1. The printer for D-shape.

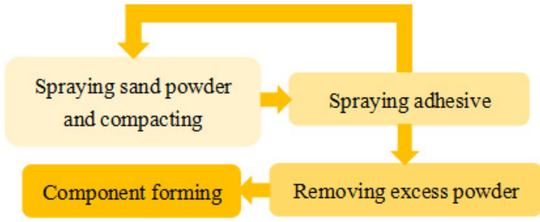

Figure 2. The flow chart of D-shape.

In addition, D-shape has the potential to print buildings on extraterrestrial planets. Enrico Dini has partnered with the European Space Agency (ESA), Foster + Partners and Alta Space to explore construction technologies using lunar soil to print. In 2014, Cesaretti [6] used lunar soil as a raw material and explored the feasibility of in-situ printing of residential buildings on the lunar surface based on the D-shape, which was convenient for future development of extraterrestrial space.

The advantages of D-shape are: (1) faster speed; (2) material consumption which is only 1/3-1/2 of traditional construction; (3) good strength and integrity; (4) high print resolution ratio and smooth surface. D-shape is especially suitable for buildings with complex shapes and high precision requirements, such as cavities and overhangs. However, D-shape also has disadvantages: (1) the printer covers a large area and the component size is limited by the volume of the printer; (2) the molding process is relatively slow compared to other 3D construction technologies; (3) Due to the need for outdoor printing, it is greatly affected by bad weather; (4) The printing cost is higher [7].

2.2. Concrete-based layered spray extrusion technology

2.2.1. Concrete printing. Concrete printing is a process of spraying concrete to form layers by layer (see figure 3 for the printer and figure 4 for the process). In 2009, the research team of Loughborough University utilized a self-developed polypropylene fiber concrete to successfully print a 2m×0.9m×0.8m concrete backrest chair with 128 layers. The entire printing process lasted 41 hours. Then, in order to check the mechanical properties such as the compressive strength of the cube, the chair was peeled in situ [9,10].

Figure 3. The printer for Concrete Printing.

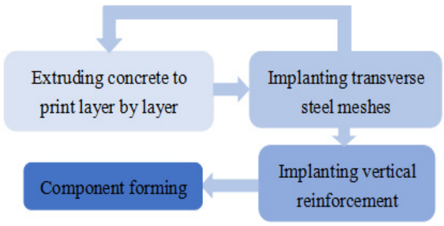

Figure 4. The flow chart of Concrete Printing.

In 2008, Yingchuang Building Technology Co., Ltd. used building 3D printing technology to print walls for the first time. In 2014, 10 physical buildings were printed in Qingpu, Shanghai [12] and the whole process lasted only 24h. The key of the technology is to ensure that the test body does not collapse when the ink is layered and the process of ink intensity growth is matched with the printing process. However, since the concrete materials currently used for 3D printing still have low bending and rupture strength, the walls are brittle and easy to crack, which has largely limited the application of 3D printing to high-rise buildings. Then, in order to explore the safety of 3D printed building technology, in January 2015, the company, in conjunction with Tongji University and CSCEC Eighth Engineering Bureau Co., Ltd., built the first multi-layer building in Suzhou Industrial Park, which used 3D printed reinforced masonry structure and possessed 15.3m in actual printing height. All the *vertical and horizontal walls of the building were printed at the factory and then transported to the construction site for assembly. Then, although the combination of 3D printing technology and reinforced masonry shear wall structure solved the problem of adaptability of the structural system to a certain extent, the seismic performance of the experimental building still needs to be verified [12].*

Concrete Printing is relatively simple and highly efficient in printing, and has a considerable degree of freedom [5], nonetheless printed product surface which is rough and has layered ripples, and the size of finished products is also limited by the size of the printer [7]. Therefore, this technology is suitable for buildings with large volume and relatively simple structure.

2.2.2. Contour crafting. Contour Crafting is a building 3D printing technology that realizes the construction of buildings by layering concrete through computer-controlled nozzles [11] (Figure 5), which has now become the mainstream building 3D printing technology nowadays[8].

The printer of Contour Crafting is supported on the gantry (Figure 6), which can complete the plane movement on the guide rail, and extrude the semi-fluid concrete through the nozzle capable of vertical expansion and contraction to realize printing. If a pre-designed 3D model is imported, the printer can draw the outline of the 3D model on the site. Meanwhile, the printer will automatically extend the two trowels with its nozzle to flatten the shape of the concrete strip. However, the bulky gantry hanger is not conducive to the installation and disassembly of the equipment. After improvement, some scholars have replaced the gantry with a lightweight rigid frame, which makes the printer more flexible and portable and more feasible to print the construction site using contour crafting technology [13].Side pressure is the decisive factor restricting the filling speed of the contour kernel and the printing height [8]. Therefore, the best printing can be achieved only by coordinating the correlation between the injection speed, the core filling speed, the concrete hardening and the effect of strength development speed.

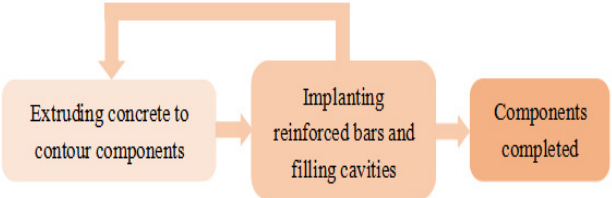

Figure 5. The flow chart for Contour Crafting.

Figure 6. The printer for Contour Crafting.

A research team at the Eindhoven University of Technology has successfully developed a four-degree-of-freedom 3D printer of 9m×4.5m×2.8m based on Contour Printing. The printer consists of a truss robot, a control unit, a stirring device, and a pump [14-16]. In 2017, the world's first 3D printed prestressed concrete bicycle bridge was successfully erected by TU/e. The bridge has a designed lifetime of 30 years, and the bridge is 8m long and 3.5m wide [17, 18]. The printing material of the bridge is special fiber-reinforced concrete, and high-performance steel wire was added when the concrete was sprayed layer by layer to increase the bearing capacity.

Like D-shape, the Contouring Crafting also has the potential to print buildings on extraterrestrial planets. Recently, NASA is actively assisting the research of contour technology to build a space base on the moon surface in the future [19]. Contour crafting makes it possible to print space bases and roads directly from extraterrestrial in-situ materials.

Compared with Concrete Printing, the advantage is that the surface of the printed component is leveled with a trowel, so the surface of the finished product is relatively smooth. In addition, rebars can be configured in the cavity generated during the printing process to strengthen the structure and make printing of high-rise buildings easier [20]. However, there are also some shortcomings in using contour crafting, such as low efficiency (the rate of wall print is about 3min/m^2), the size of the finished product is limited by that of the printer [7], the adhesion strength between layers is low, and the printing accuracy depends on post-processing. When printing, printing out cavities at the *beginning and then pouring core concrete in layers can be prone to forming construction joints with reduced long-term service performance.*

3. Outlook

In recent years, building 3D printing technology has gradually transformed from imagination to practice and from concept to production. In the upcoming future, 3D printing will be widely used in the construction industry. However, there are still some key points to note before that.

3.1. Printing method

Albeit D-shape, Contour Crafting, and Concrete Printing have been gradually put into practical production, they are currently mostly used in the production of building components, and the components are printed and then assembled. However, the goal of building 3D printing will never be prefabrication, but full-size printing at one time and this limitation is still obvious; the larger the device size is, the more difficult the control and the worse the printing accuracy are. But in the future, full-size printing technology is bound to mature.

3.2. Printing material

Because of its high strength and good formability, concrete is widely used in the research and application of building 3D printing. However, the rheological properties of traditional concrete materials can't meet the requirements, and the seismic performance of printed houses is insufficient, which has caused great restrictions on the application and promotion of 3D printing technology. Therefore, the use of new admixtures in printing concrete to improve its comprehensive properties, and even the use of smart materials, fiber, and composite materials instead of concrete to complete printing are important trends in 3D printing research.

3.3. Supporting software

The accuracy of the supportive software determines that of 3D printed building to a certain extent. Therefore, the development of more efficient and accurate supporting software to effectively convert three-dimensional models into computer languages is also a topic worth exploring.

3.4. Test method and evaluation indicator

Compared with traditional concrete, the concrete used in building 3D printing have significantly different work performances, mechanical properties and durability. Therefore, the concrete performance test methods and evaluation indicators specified in the previous specifications are no longer applicable. In order to better characterize the performance of 3D printing concrete, it is particularly important to establish effective and applicable calculation models and service life prediction models, and to implement unified national and industry norms and standards.

4. Conclusion

Building 3D printing technology is the fruit of multidisciplinary collisions in architecture, civil engineering, materials science, computer science, and automatic control. It exerts the most advanced scientific research results to bring subversive influence to the field of building construction. But at the same time, due to the intersection of multiple disciplines, the problem of acting blindly is inevitable. Only by strengthening the exchange and cooperation of various disciplines and paying attention to the actual capabilities and demands of the construction industry can we promote the vigorous development of 3D printing technology in construction.

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