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Design and Implementation of Highly Robust Gantry-Type and Low-Cost 3D Concrete Printer for Construction

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Abstract The advances of additive manufacturing by a 3D printing method such as complex geometry building, time-consuming, worker labor, and materials cost, support this new type of construction method to become promising for future applications. This study presents the development of a customized and large-size concrete 3D printer with low cost, ease of operation, and scalable design. The 3D printer gantry-type structure was designed with a dimension of 2,580 x 3,600 x 2,800 (mm) and driven by high-precision AC motors in three independent X, Y, and Z axes. A customized feeding-extrusion system was designed for either automatic or manual material feeding continuously and automatically. The low-cost concrete mixture was used with the use of by-products from a local thermal power plant which allows to reduce the material cost. After a number of experimental trials, an optimized set of parameters has been established such that a printing cycle of 25 layers was printed consecutively at a single run. Several concrete-based construction patterns have been printed and applied in practice. The results can be applied in many aspects of civil construction and produce affordable buildings worldwide.

Keywords 3D Printing, 3D Printing in Construction, Concrete Printing, Manufacturing

1. Introduction

Concrete is one of the most important materials widely used in construction worldwide for centuries [1-4]. The key characteristics of concrete such as strong in compression, durable, fire resistant, and transformable in various types of shapes make concrete more dominant than other materials in construction. In modern civil engineering, a concrete-based building can be made by typical non-traditional methods such as contour crafting, D-shape, and concrete printing [5-15]. 3D Concrete Printing (3DCP) has been attractive in manufacturing engineering for many years. These days, the application of 3DCP of different materials such as biomaterials [16], cement-based materials [3, 17], and reinforced concrete elements [12] is attractive to researchers and engineers worldwide. As a new cutting-edge revolutionized manufacturing process in construction, 3DCP enhances the process of digitalization and automation in construction in a large variety of particular scenarios. The reduction of time-consuming, human resources such as labor workers, civil engineers, etc. increases the cost-efficiency so that a small building using

3DCP can be built within a limited time and budget. D. Asprone *et al* [12] proposed the fabrication of reinforced concrete (RC) members based on 3DP which was the first step to building structures such as beams, roof-top, etc (Fig. 1a). T. Salet *et al* [18] designed and tested a full-size bridge (Fig. 1b). In 2016, Apis Cor company successfully finished the first residential house printing project in 24 hours [19]. These days, a number of buildings have been used worldwide at an affordable cost.

(a)

(b)

Figure 1. (a) 3D printed beam structures (reprinted from [12]) and (b) 3D printed beam bridge (reprinted from [18])

3D concrete printers are now available in the market and capable of printing walls and houses with lots of benefits and drawbacks compared to traditional building methods. The 3D printing construction market was valued at \$1.4bn in 2021 and is expected to rise to \$750.8bn by 2031. The key benefits of 3DCP are automation, fast completion, improved sustainability, and design freedom. With 3DCP technology, up to 60% of the time on the job site and 80% in labor can be saved. However, there are trade-off costs relating to the cost of the system and implementation. A commercialized 3D concrete printer may cost from 150,000 euros to 450,000 euros (Cybe Construction Company, Netherlands) or 120,000 USD (Beijing NELD Intelligent Technology Co. Ltd, China). In 2019, ICON (Texas, USA) released the Vulcan II model with a printed size of 260 x 850 x 260 cm. The machine uses an ICON's dedicated material, namely *Lavacrete* and the cost for the machine is \$250,000 (Table 1). Along with the cost of the equipment, operator training is also a bottleneck of 3DCP because of the complexity in use to obtain robust and reliable products. On the other hand, standards relating to the equipment, system, material used, and fabrication process are still ongoing to be established by organizations such as the American Society for Testing and Materials (ASTM) and the International Standards Organization (ISO).

Along with the current 3DCP products available in stock, several advanced trends in robotics applications have been applied in 3DCP such as cable-driven parallel robots, image processing-based robots, etc. In 2015, Barnett et al [20] introduced a large-scale 3D printing system with the use of a cable-suspended robot. Tuong Phuoc Tho and Nguyen Truong Thinh analyzed and verified the control mechanism of a 3DCP cable-driven parallel robot by theoretical and experimental approaches [21]. David Hahlbrock *et al* [22] implemented a cable-driven parallel robot to extrude cementitious material to create a 3D-printed façade. Xuchu Xu *et al* [23] proposed a point-cloud-based approach for real-time 3D construction printing defect detection using a 3D camera and cloud-to-plane distance. However, it is rather difficult to scale up these results to a large scale with ease.

Table 1. Specifications of several 3DCP machines available in the market and the reported 3DCP

Model	**CyBe Gantry Robot (Netherlands)**	**WASP Crane 3D Printer (Italy)**	**Vulcan II (USA)**	**Customized 3DCP (Vietnam)**
Specification	• Speed: 500mm/s in horizontal, 40mm/s in vertical • Dimension: 7000 x 10,000 x 4000 mm • Weight: 13 tons • - training: 10 days	• Speed: 200mm/s • Dimension: ϕ8000 mm – H 3200 mm • Printer weight: 500kg • Pumping system weight: 300kg	• Speed: 200 to 300 mm/s • Dimension: 8.5 x 8.5 x 2.6 m • Weight: 1.7 tons	• Speed: 100 mm/s • Dimension: maximum 6000 x 6000 x 4500 mm • Weight: 200kg
Price	€485,000	€ 132,000	\$250,000	\$50,000 (estimate)
Note	Gantry-type CyBe software and CyBe motar (dedicated)	Robotic arm WASP software	Gantry-type Material: *lavacrete* (dedicated)	Gantry-type Common 3D software Common concrete mixer

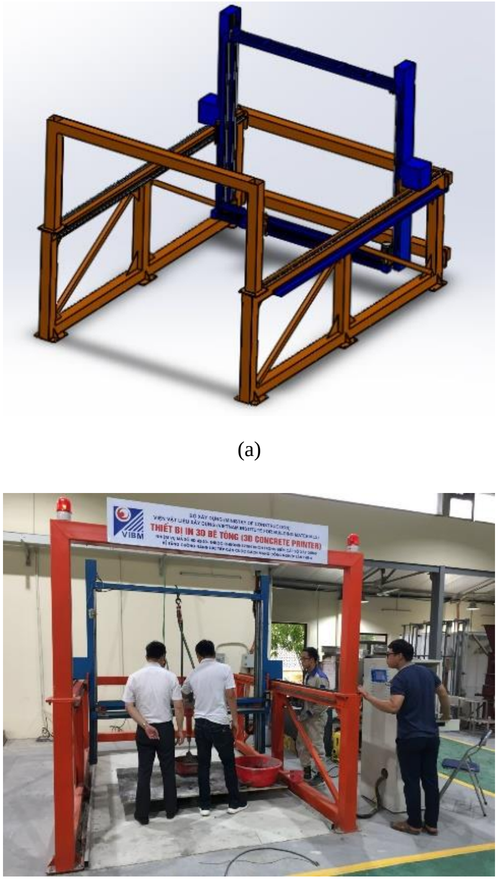
Compared to traditional construction technology, 3DCP can overcome many problems related to environmental issues such as noise, dust, resource-saving problems, etc. Up-to-date, the trend in 3DCP in research is about improving the stability of the printing process, advanced materials, and optimization of the printing process. However, even though the outlook of 3DCP is remarkably promising, there remain lots of challenges to commercializing a 3DCP system. Some of the most critical problems of 3DCP are the high cost of equipment, material limitations, and high-skilled human resources to operate the construction process. In this paper, the authors presented a customized and fully automated large-size 3DCP system with low cost, ease of operation, and common material characteristics of which the mechanical properties of the concrete can be adapted to the construction criteria at the local. The system had been used in practice and operated by common workers after a short training course. The customized 3DCP is capable of scale-up for large buildings while maintaining the high capability of maintenance and stability. A composition of by-products and low-cost materials was used to evaluate the performance of the 3DCP. The research results show that the developed 3DCP system was low-cost equipment, low-cost and common local ingredients, ease of implementation, and scalability with low-skill workers. The products have a high potential to be commercialized in low-income and developing countries.

2. Materials and Methods

A typical 3DCP system is composed of four major modules: mechanical frame structure, human-machine interface application, control system, and mixed material composition. In the scope of this research, the control system regarding the hardware and control algorithms was supplied by third-party developers (Marlin hardware and Simplify3D respectively). The hardware and control applications are common in use in the 3D printing community and support the users with constructive and informative interfaces. In the scope of this study, the two customized main modules were the mechanical frame structure and the material composition.

2.1. Design of Mechanical Frame Structure with High Robustness and Precision

The frame structure is a vital module of any 3DCP system because it warrants the stability, accuracy, and scalability of the system. Two of the most common mechanical frames for 3DCP systems are the robotics arm and gantry type [24]. By analyzing and comparing both the advances and drawbacks, A. Putzatova *et al* [24] noted that the gantry-type printers are more suitable for large-scale buildings because of the high flexibility in both size configurations and preparation of construction surface compared to the robotics arm-type printer. With the gantry structure, axes X, Y, and Z can move independently and robustly (Fig. 2). The details of actuators and power transmission mechanisms are described in Table 2. The belt and rack-pinion power transmission mechanisms were selected because of their high robustness, and high scalability for large buildings while the ball screw power transmission mechanism guarantees the precision of the deposited layer in printing. The ball screws mechanism is used widely in a variety of high-precision systems such as computer numerical control (CNC) machines in which motion accuracy is one of the most criteria factors.



(a)

(b)

Figure 2. The design and assembly of the 3D printing system: (a) design in Solidworks and (b) onsite implementation

Table 2. Specifications of 3 axes

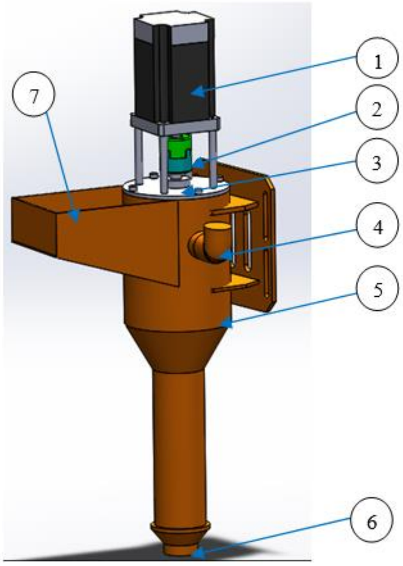
Axis	Actuator	Power transmission mechanism	Printing dimension (mm)	Overall dimension (mm)	Motion accuracy (mm)
X	1x AC servo motor	Belt	1800	2580	0.1
Y	2x AC servo motors	Rack and pinion	3000	3600	0.05
Z	2x AC servo motors	Ball screws	1800	2800	0.05

The prototype 3DCP system was 2,580 x 3,600 x 2,800 mm in length x width x height which leads to the maximum printing dimension was 1,800 x 3,000 x 1,800 mm respectively. The X and Y axes motors' power was 1.5kW so that the printing motion at high speed and high acceleration could be quarantined for long-term operation. With such power, the customized 3DCP system is upgradable to print a maximum size of 6,000 x 6,000 x 4,500 mm dimension. In the case of larger buildings, actuators must be changed while the axis dimensions are customized with modular parts.

2.2. Design of the Feeding-Extrusion Systems

The feeding-extrusion system might be called the end-effector or printer head of the 3DCP. In the process of printing concrete, the composition of concrete and additives is fed from a reservoir via a hose system by several methods such as compressed air, piston, or screw extrusion [6, 7, 25]. The feeding system working by compresses-air has a simple mechanism, however; the air pressure must remain stable to produce force evenly. The piston-based mechanism has the benefit of large generated force and ease of maintenance. The major drawback of both of these two methods lies in their inability to sustain continuous material feeding without the need for reloading [7, 26]. On the other hand, an AC motor-driven screw extrusion method can function as both feeding and mixing materials. The screw extrusion does not require a reverse procedure to reload the material. The feeding force and speed can be controlled via an AC servo motor. Therefore, the screw extrusion mechanism is the most preferable mechanism used in 3DCP for concrete in construction.

The cylindrical feeding-extrusion system components are described in Fig. 3. The mixing materials (concrete and additives) can be fed either manually through a manual inlet (Part No.7) or automatically through an inlet (Part No.4). The barrel (Part No.5) was made from Aluminum with nano-coating for ease of cleaning and maintenance while the Nozzle (Part No.6) can be changed for cleaning or upgrading purpose. Depending on the size of the grain, materials, or components of the concrete mixing, different configuration nozzles can be used. The nozzle was designed for versatile usage for different materials and morphology so that the user can change the nozzle easily.



(a)

(b)

Figure 3. The design of the screw-type feeding extruder: (a) the design of the feeding extruder, and (b) the screw extruder after fabrication

2.3. Development of Mixing Materials for Printing

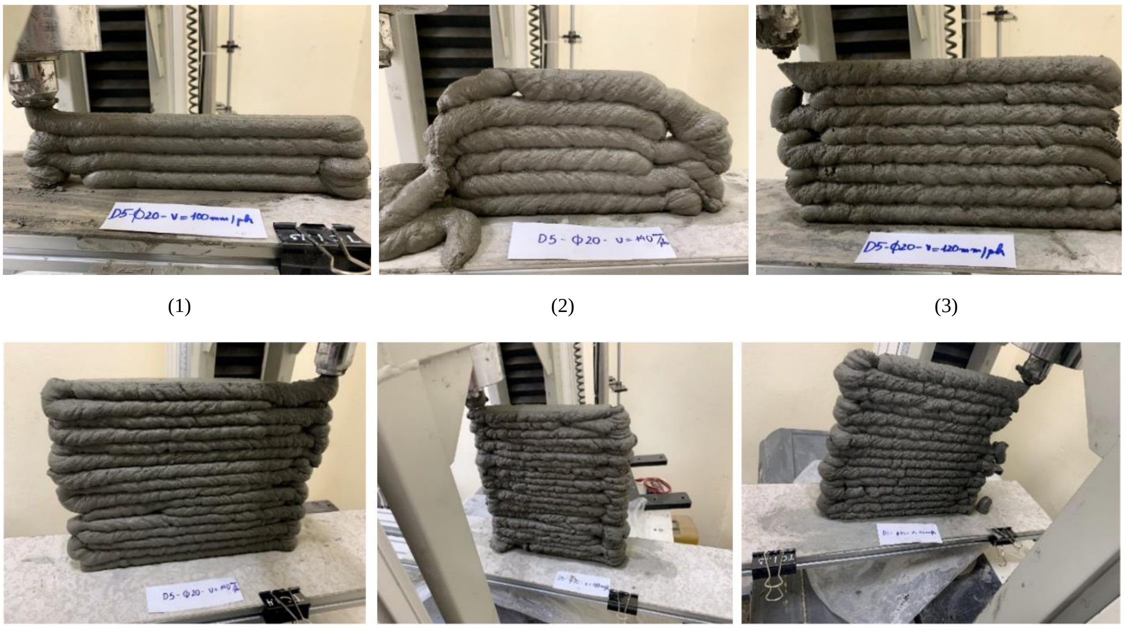
The Material for 3DCP is one of the ongoing challenge tasks for researchers these days because of its multi-variable dependence. The concrete-based materials in 3DCP must adapt the requirement of both the printed pattern properties such as drying shrinkage, curing time, interlayer bond, etc., and the printing parameters such as printing speed, nozzle geometry, etc. [27]. In general, the concrete mixture used for printing consists of a blend of cement, water, aggregates, admixtures, and reinforcements in specific proportions [9]. From preliminary experiments, a set of ingredients was selected as Table 2 where viscocrete is a polymer-based high-performance superplasticizer for producing soft consistency high-grade concrete [17, 28]. To determine the optimized printing condition, several major parameters such as the ratio of water/superplasticizer, and sand grain size were varied together with the printing parameters. Fly ash is a by-product of coal combustion from Quang Ninh thermal power plant in Vietnam. Fly ash is usually used as a supplementary cementitious material in the production of concrete because of its advanced benefits such as reduction of the heat of hydration, improvement of workability, enhanced durability, reduced permeability, and environmental impacts [29].

3. Experiments and Results

The process of 3DCP is influenced by a variety of parameters which can be categorized into materials composition and printing configuration. However, these parameters are cross-correlated to each other and contribute greatly to the printability of material including fluidity, extrudability, buildability, and setting time. For example, fluidity refers to the ability of concrete mixing materials to be pumped, transported, and smoothly extruded over the print head. The fluidity is affected by water content and/or the grain size of sand. The sand of grain size D = 2.5mm was first selected because of its popularity in construction at local. The ratio of sand with respect to Viscocrete ranged from 0.67 to 1.5 and the ratio of water/Viscocrete varied from 0.35 to 0.4. A Design of Experiment (DOE) was planned as Table 3 to determine the extrudability and the buildability in different cases. The value ranges were selected by preliminary experiments at local. The results are shown in Fig. 4.

Table 3. Specification of the materials for concrete printing

Materials	Detail	Density
Cement	PC50 cement by Nghi Son Ltd. Co (Vietnam)	2.94 g/cm^3
Aggregate	Silica fume	2.1 g/cm^3
Fly-ash	Fly-ash (by-product) from Quang Ninh Thermal Power Plant (Vietnam)	2.4 g/cm^3
Sand	Sand with grain size Dmax = 2.5 mm	2.617 kg/m^3
Viscocrete	Sika Viscocrete 3000-20 M	



(1) (2) (3)

(4) (5) (6)

Figure 4. Experimental verification at different printing conditions

Table 4. The DOE table to determine the extrudability and buildability

Case number	Water/viscocrete ratio	Sand/viscocrete ratio	Viscocrete (wt% over viscocrete)	Fly-ash (wt% over viscocrete)
1	0.35	0.67	10	20
2	0.35	1.0	10	20
3	0.35	1.5	10	20
4	0.40	0.67	10	20
5	0.40	1.0	10	20
6	0.40	1.5	10	20

Based on the experiments as DOE table 4 and the same printing parameters, the printed patterns collapsed in case No. 2 and became non-uniform distribution in case No.1. The disconnection happened at the end of each cycle such as in the case of No. 1 with the sand/viscocrete being 0.67 revealing that there was less sand in the mixing composition. As more viscrocrete was added, the mixture binding became stronger so that more printing layers could be printed in a single cycle. As a result, No. 3 and No. 6 with a ratio of 1.5 showed the highest printed pattern while the ratio of 0.67 sometimes caused disconnection at the end of the printing cycle because of dryness. However, in the case of 1.5, the mixture's viscosity reduced and affected to the flowability and formation of the printing layers. The No. 3 experiment showed a good interlayer bond and ease of extrudability in operation. As the amount of water increased, the results showed that the continuity in a single printing was enhanced slightly, however, the buidability also reduced.

It was concluded that a water/viscocrete ratio of 0.4 produced poor capability of extrusion and layer-deposition while in the case of that ratio of 0.4, a sample with the ratio sand/viscocrete of 1.5 produced the most promising result. However, the height of the printed patterns still cannot be over 1 meter with a number of layers below 20 layers. In the case of the water/viscocrete ratio below 0.4, for instance, 0.35 (Fig. 5), the maximum deposited layers were over 25 and the adhesiveness between consecutive layers is strong enough to maintain the structure. Therefore, the proper water/viscocrete ratio of 0.35 was selected.

After a number of trials, an optimal ratio and printing parameter were achieved in Table 5. A set of concrete furniture was designed and printed for testing the optimal dataset (Fig. 5).

Table 5. The optimal condition for printing concrete

Water/viscocrete	Sand/viscocrete	Fly-ash (wt%)	Viscocrete (wt%)
0.35	1.0	20	10

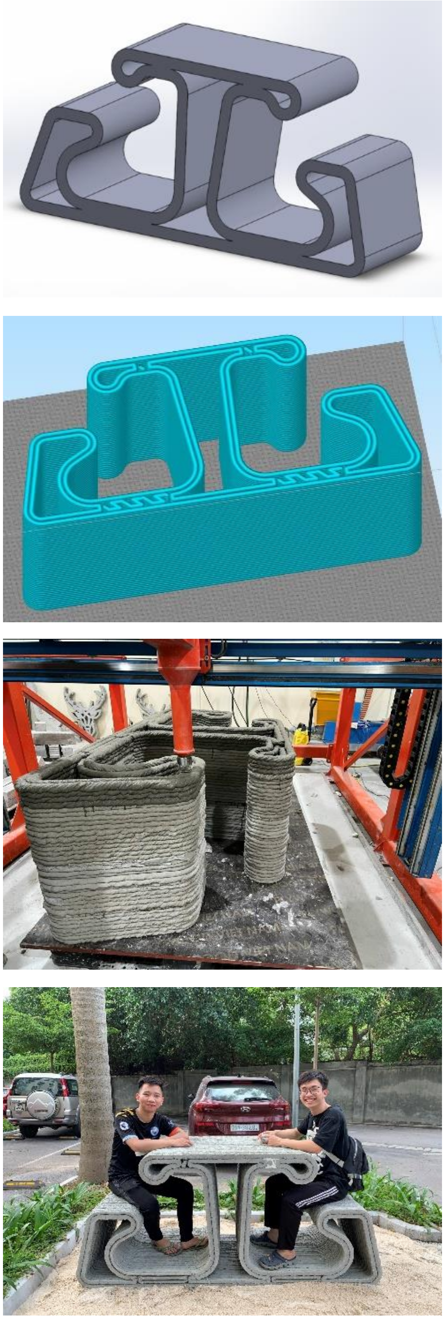


Figure 5. Printed patterns with the optimal condition described in Table 5

4. Conclusions

The printed structures revealed promising applications of the 3DP in construction. Several factors are required for further experiments such as the mechanical stiffness, fatigue test, and life-long of the building after hardening. The materials used for the test are from a local brand, or by-products from a thermal power plant (fly-ash), hence; the cost for materials is reduced. Some more advanced additives and/or aggregates will be tested in the future for better-printed patterns.

In summary, a 3D printing system for concrete-based materials was designed, manufactured, and tested with promising results. By applying the gantry structure, the mechanical structure is more robust than other structures such as the robot arm structure. Another important advanced characteristic of module-based design gantry structure is the scalable to large-scale building with fast maintenance and assembly process. The system was composed of AC servo motors -driven power transmission mechanisms that can produce high force and high accuracy. The printing dimension of the current design was 1,800 x 3,000 x 1,800 (mm) and can be scaled up on demand easily. Material composition and printing parameters were tuned and optimized for better performance. The final results showed that 25 consecutive layers can be printed in a single run. The reported 3DCP together with low-cost mixing materials has the potential to be used in many aspects of civil construction and it is expected to produce affordable and fast buildings in the future.

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