3BUILD – First 3D Printed Structure in Greece

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Abstract. Digital fabrication, including construction of buildings with use of 3D printers is gaining significant momentum for the construction sector. Benefits such as free form architecture, reduction of building time, labor costs and waste material, freedom of geometry can be taken advantage in such building techniques. 3D Printing Concrete (3DCP) is a wet manufacturing process where layers of extruded mortar are bound by successive material deposition. Most common equipment for this type of application are the gantry printers, which are based on the cartesian robotic systems technology. 3BUILD is the research project, co-funded by the "Ereyno-Dimiourgo-Kainotomo" program by the Greek Ministry of Development, with participation from TITAN, SIKA, COS and NTUA. The project main objective is the design and construction of a gantry type 3D printer and furthermore the use of the printer for the construction of a structure of dimensions up to 8 × 8 × 3 m. Development of works for the certain project included the design and construction of a middle-sized printer and printing of 2 m high structures of various shapes, investigation of sensitivities of mortar properties to different printing parameters (printing speed, printing geometry, layer dimensions) and relevant adjustments, the design and final construction of the full scale 3D printer and all challenges encountered and resolved before finally printing in real scale.

Keywords: 3D printing · gantry printer · concrete · mortar · 3BUILD

1 Introduction

3D printing of cementitious materials was introduced by Khosvenis et al. [1] and [2] back in the early 2000s by setting the fundamental technological and engineering aspects that led to today's rapid growth of the additive construction industry. Parameters such as pumping rate, layer thickness, linear velocities as well as construction parameters including the layer width, height and morphology were established and discussed thoroughly.

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The fundamental and most critical aspect of construction 3D printing is the material properties of concrete, both in terms of chemical composition and mechanical properties. Zareiyan and Khoshnevis [3] investigated the parameters involved in various defects namely the existence of cold joints between successive layers of deposited material while Le et al. [4] examined the maximum number of layers that can be deposited without excessive deformation of the bottom layers. Various methods have been proposed to counter this effect namely the dynamic control of the printing head height [5] and the control of height increase rate [6]. The above defects and restrictions result in special chemical composition of the used materials including accelerators that allow the material to develop the strength required to withstand the weight of the top layers. Moreover, the aggregate size significantly influences the pumping method. Moreover, classical reinforcements do not exist in 3D printed structures which would result in decreased strength of since cement cannot withstand tension. However, this disadvantage is partially countered by the use of chopped fibres (i.e., polymeric) that are randomly dispersed inside the printed material increasing their tensile strength. Other methodologies have also been proposed including adding reinforcements post printing or simultaneously printing both the cement and reinforcements [7] and [8].

In terms of printer hardware, various layouts have also been proposed and developed, with gantry-type machines (fixed base or moving on rails) [9, 10] and various robotic arm layouts [11] dominating the current state of the art, while other more exotic solutions such as swarm and autonomous robots are still too premature to provide competitive alternatives.

The printing head is also critical. Alternative printing head designs can facilitate controlled pauses of the printing process allowing for elaborate printing schemes or incorporate additional rotary degrees of freedom especially useful for rectangular shaped nozzles.

The present work aims to introduce the first ever large-scale construction 3D printer in Greece. The layout of the printer is fixed base, gantry type with three degrees-of-freedom. The gantry type layout was selected in order to be able to accommodate multiple functions other than the printing process such as low weight, installation, assembly and transportation phases, while the printing head comprises a simple nozzle for continuous printing. The design of the printer allows for easy adaptation to the construction area being able to successfully accommodate envelopes ranging up to 20 × 10 m and up to 6m high simply by increasing the number of the fixed columns. The design process and basic characteristics of the printer are presented and extensively discussed in the following sections. Finally, the first 3D printed house in Greece is presented and discussed upon.

2 Design of the 3D Printer

As already stated, the design of the 3D printer aimed to result in a low-weight and modular layout meaning adjustability in terms of printing area dimensions. Moreover, printer dynamics are also taken into consideration aiming to a stiff design minimizing eigenvibrations induced either from inertia effects or from wind loads.

In order to do so, the gantry type design of the printer was performed considering two main sub-systems; the XY stage carrying the printing head fixed on the X-axis and the lifting mechanisms. The absence of a slender extendable Z-axis mounted on the XY stage as in most small to medium scale machines already in use, ensures increased stiffness especially during rapid direction changes. Furthermore, relying on lifting mechanisms and fixed columns guarantees upgradability of the printer to construct higher buildings while ensuring stiffer behaviour, particularly at the beginning of the printing process compared to the extendable Z-axis alternative.

Considering future upgrades and full automation of the complete process (i.e., including the pumping unit), the control unit of the printer is able to drive at least eight axes (DOFs). The controller takes as input a series of standard G-code commands defining the toolpath of the printing head to produce the end product. The G-code can be generated using either CAM or Slicer commercial software providing similar results.

2.1 XY Stage

The XY stage comprises of a closed rectangular truss that guides the XY movement. The printing head is fixed on the X axis. The selection of the closed frame was performed to increase the bending resistance of the mechanism minimizing the load transferred on the columns and allowing for a lightweight design. The overall layout of the XY stage is shown in Fig. 1. Another aspect that increases the modularity of the design and significantly decreases the overall weight and construction cost is the choice to implement the XY stage using fixed-length 2 m long modules made of aluminium profiles. The lightweight structure shown in Fig. 2 was modelled using 1D beam elements to facilitate fast and efficient optimization and dimensioning. The main objective was to minimize the deflections at the position of the printing head being able to achieve deflections in the order of 2 mm (Fig. 3) for a 100 kg printing head over a 10 m long simply supported X axis, while the module weight is around 65 kg. Maximum deflection for the same load is almost 4mm (Fig. 4) considering the full 12 × 10 m XY stage supported on all four corners. The actual printing head weighs far less than the nominal value of 100 kg considered for the initial design iteration and calculations should be able to predict future upgrades allowing for more intricate printing head designs. The XY motion of the

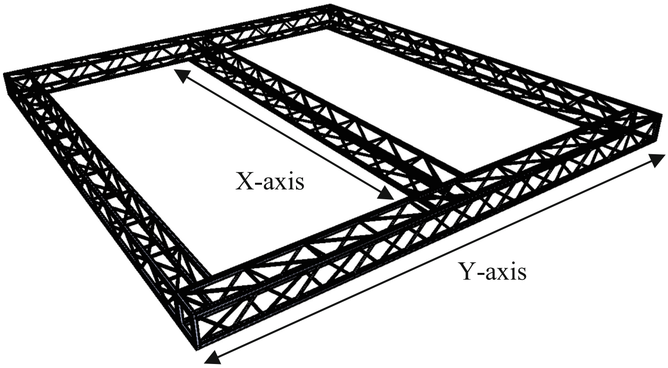

Fig. 1. Basic layout of the XY stage. The Y axis closed rectangular frame encompasses the moving X axis.

printing head is performed using rack – pinion transmissions driven by servo motors. The XY stage components are installed on rails for smooth low friction movements.

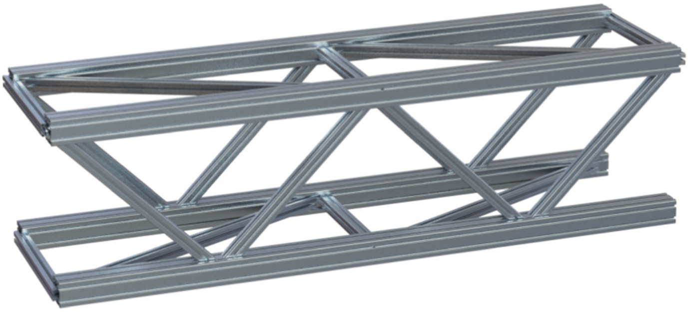

Fig. 2. Structural module of the XY stage consisting of aluminium profiles.

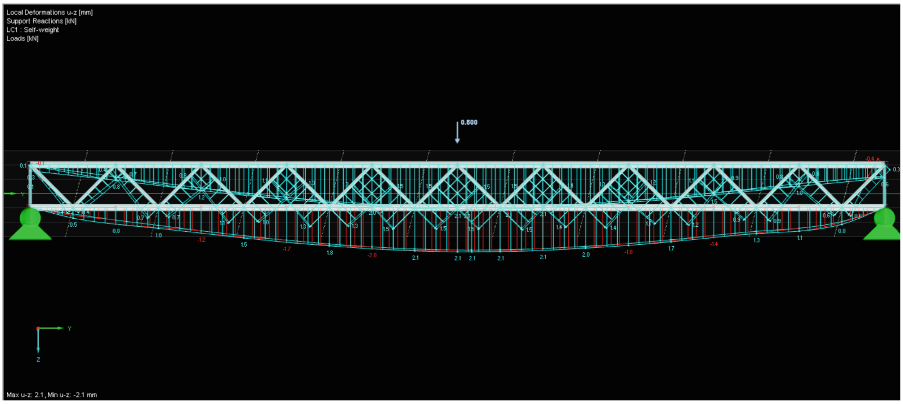

Fig. 3. Deformation of the X axis modelled as a simply supported structure using beam elements.

2.2 Z Axis

As explained the XY stage is positioned on four vertical columns that comprise the Z axis. The XY stage is guided onto the vertical columns in order to maintain its positioning over the printing plane. The lifting mechanism consists of vertical lead screws that are kinematically connected using angular gear drives. This allows for a significant differentiation compared to existing solutions as a single motor is used to drive all four lifting screws simultaneously and with low power consumption. This is performed with an expense of speed and power as the vertical motion is performed at a small fraction of the XY speed. However, since motion on Z axis – thus changing printing layers – does not require high speeds compared to the XY motion, the low Z speed is not considered as a deficiency. Furthermore, the vertical lead screw system apart from its facile controllability was also able to ensure high position accuracy, despite the high

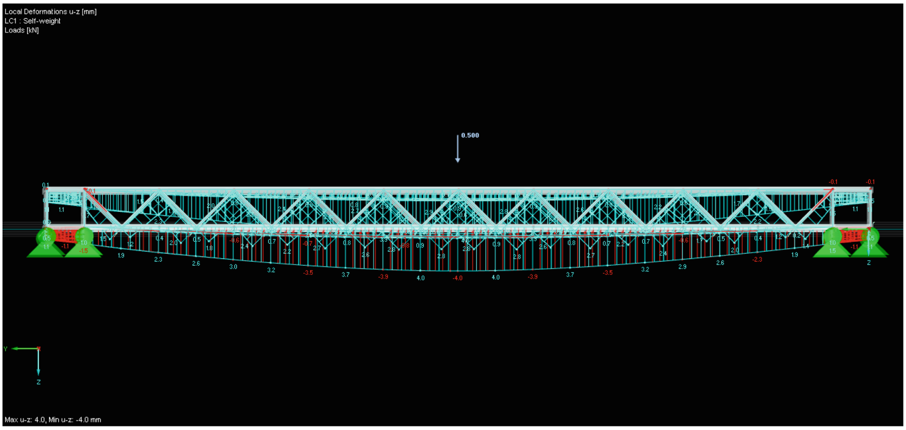

Fig. 4. Deformation of the XY stage pinned on the four corners using beam elements.

lifting loads. This feature was able to allow the below described ramp-method printing. The same aluminium profiles as for the XY stage were used for the supportive columns significantly improving the assembly and logistics efficiency.

2.3 Pumping Unit

The pumping unit consists of an automated two-stage mixing pump that uses a progressive cavity pump (PCP) directly feeding wet mortar on the Ø1.5-inch pipe that leads to the printing head. The pump provides the ability to alter the condition of the wet mortar in real time in order to cope with the variations in environmental conditions (i.e., temperature change, humidity) and the demands of the printing specimen (area and height). This way it is possible to counter the negative effects described above and further enhance the quality of the printed specimens. The mortar used throughout this work was tailor-made to match the specifications of the building, the printer and the process in the context of the 3BUILD project. The dry mortar composition did not require any extra aggregates to be inserted in the mix and therefore did not require an extra dry mixing phase.

2.4 Printing Material

The printing material used is a cement-based mortar that contains limestone aggregates and special additives. It was developed for large-scale 3D printing operations with the indicative specifications, presented in Table 1.

Table 1. Indicative specifications of the printing material.

Specification	Time	Value	Standard
Compressive strength	1 day	20–25 MPa	EN 12190
Compressive strength	28 days	60–110 MPa	EN 12190
Flexural strength	1 day	3–7 MPa	EN 196-1
Flexural strength	28 days	8–12 MPa	EN 196-1
Elastic modulus "E"	28 days	20–40 GPa	EN 13412
Adhesive strength	28 days	>1.5 MPa	EN 1542
Initial setting time		60–90 min	EN 480-2
Final setting time		150–210 min	EN 480-2
Early age shrinking	1 day	Max 700 µm/m	(internal)
Shrinking	28 days	Max 1200 µm/m	EN 12617-4
Maximum aggregate size		Max 2mm	EN 12192.01
Bulk Density (fresh mortar)	10 min	~2.2–2.3 kg/lt	EN 1015-6
Air content	10 min	3–6%	EN 13395-1
Density	28 days	~2.0–2.1 kg/lt	EN 12190
Resistance of capillary absorption		<0.5 kgm−2h−0.5	EN 13057
Freeze-thaw		Within range	EN 13687-1
Resistance to carbonation	3 months	<reference value	EN 13295
Temperature range		10–30 °C	
Colour		Varies	

3 Design of Specimens

As explained earlier, the printing process is continuous and non-intermittent. Therefore, in order to ensure smooth and efficient printing operation closed loop shapes must be used for the walls. The exterior walls have hollow shapes and are printed using double row filaments as illustrated in the images below. Nevertheless, this very hollow shape results also in increasing the flexural stiffness and strength of the wall as well as its ability to withstand shear forces and attain good thermal insulation. Figure 5a to 5d demonstrates various parametric wall designs for both exterior and interior walls. Figure 5a to 5c rely on the neighboring filaments touching and thus creating solid joints whereas Fig. 5d demonstrates the use of external stiffening members such as steel rods that are placed manually during the printing process. The determination of the characteristic length L between the joints results from the calculation of the bending stresses on the wall. The various shapes shown in Fig. 5 can follow a curved path in a conformal way as to produce curved walls T and X junctions, which is particularly useful for the design of interior walls.

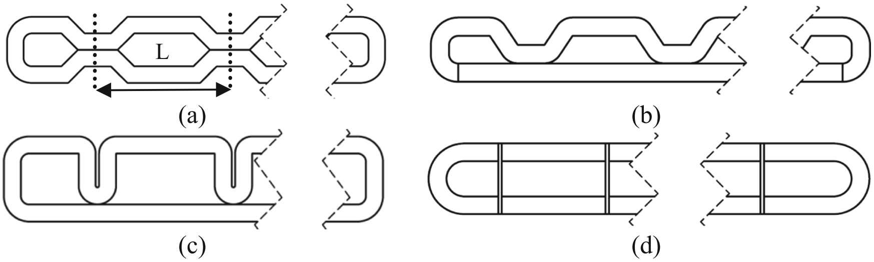

Fig. 5. Various closed loop wall formations. (a) artistic elements on both sides of the wall, (b) artistic element on one side versus smooth outer surface, (c) similar to (b) although steep directional change ensures quasi smooth finish in both surfaces although is prone to increase the jerk motions of the printer and (d) slot type wall with external stiffening elements, ensuring minimum material use for given wall dimensions.

Apart from the specimen layout, the vertical motion pattern is also important. The two major vertical motion patterns include a constantly rising ramp or consecutive parallel layering at fixed vertical position (3-axis or 2 + 1/2 axis motion respectively). The constant ramp method was used throughout the test since it is thought to provide smoother end surfaces as opposed to consecutive layering. Intermittent printing can accommodate parallel layering more safely.

A variety of test specimens was designed and printed prior to printing the full house, in order to fine tune the performance of the printer mainly in terms of dynamic phenomena such as jerk motions (steep linear velocity drop that leads to defects in the deposed filament).

4 The First 3D Printed House in Greece

The full-scale tests were conducted in the facilities Elefsina Plant of TITAN SA. The house built covered an area of approximately 50 m^2 and consisted of a total of three rooms. The total printing volume was estimated at 40 m^3 while the total printing time was less than 24 h. A series of designs were proposed and rated with aesthetic criteria. The floor plan of the selected house was converted to CAD model that in turn was used to create the toolpath for the printing process by extracting the corresponding G-code.

As shown in the simplified floor plan of Fig. 6a the printed structure consists of three parts. They are connected through the use of external components such as doors and glass panels that are to be installed at a later date. Each of the three parts (shown in different colors in Fig. 6b) was printed and transported outside to the exhibition area. The assembled house is shown in Fig. 7. Figure 8 shows some close-up snapshots during the printing process. No defects were observed while the visible wall parts exhibit low roughness characteristics in the order of a few millimeters that is highly comparable to similar printing projects elsewhere. Smoothness of the visible walls allows the facilitation of surface treatments such as plastering.

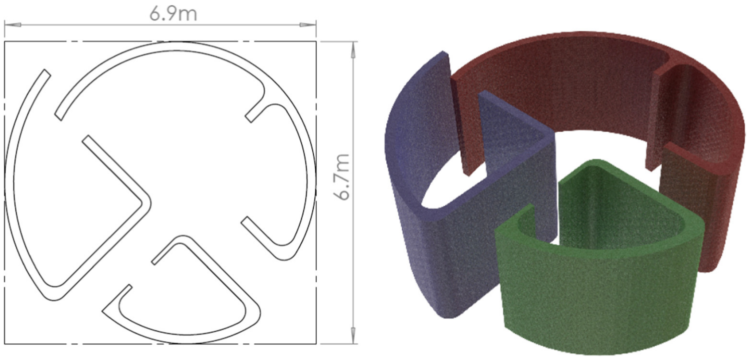

Fig. 6. Floor plan of the printed house (a-left) and CAD model of the printed house (b-right).

Fig. 7. First full-scale printed house in Greece.

Fig. 8. Snapshots of the printing process.

As seen in Fig. 7 the printed structure does not include windows or other openings incorporated into the design. Windows or doors can be added either post-printing and after the material reaches adequate structural integrity, or by utilizing intermittent printing. Employment of intermittent printing will allow the continuous printing of the windows without the need to remove the excess material thus increasing productivity and specimen design freedom.

5 Discussion and Conclusions

The first large-scale construction 3D printer was developed and manufactured in Greece within the 3BUILD project. A complete structure that can be adapted to everyday use has been printed, providing the proof of concept for the printer design and the tailor-made mortar. Significant observations have been made in terms of the overall printer performance and process optimization. The intrinsic high stiffness of the printer resulted in the absence of large amplitude vibrations ensuring smooth completion of all printing tests. The quality of the printed specimens was at par with results available in literature.

Moreover, there are improvements that can be implemented in order to allow for deployment of the printer design. Incorporation of intermittent printing through redesign of the printing head is expected to allow for incorporation of openings (windows, doors) during the printing process. Smart automation of the process remains an open topic, while standardization is at early stage of adaptation in most locations globally.

Additionally, the 3D printed prototype house requires additional work in order to be utilized for everyday use, including placement and connection of a fabricated roof, setting foundations, as well as introducing utilities, among others. Pre-determination of the routing of plumbing and electrical installations could be included in the original CAD file in order to further facilitate faster deployment.

Finally, the legislative framework will most likely need to be revised, before introducing 3D printing as a construction method. Such revisions will most likely need to consider performance of 3D printing structures in terms of mechanical stability, structural integrity and durability, in conditions relevant to each location separately.

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