The Design and Development of an Extrusion System for 3D Printing Cementitious Materials

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Abstract*— *Additive manufacturing (AM), popularly known as '3D printing', is a manufacturing technique that builds physical 3D objects layer by layer using materials such as polymers, metals, and cementitious composites. The widespread popularity of additive manufacturing in most industries ranging from biomedical to aerospace suggests a revolution in manufacturing which has recently emerged to the construction sector. Considered as the future of construction, AM is used in 3D concrete printing due to its benefits in reducing the waste and contributing towards circular economy goals through the use of recovered waste materials from demolition sites. This paper presents an active extrusion system for the 3D printing of cementitious materials for the construction industry. The system has been designed from first principles and therefore can be extended to other materials and scaled up with slight hardware modifications. A robust design has been realized using an unconventional yet simplistic approach. The extrusion system uses some additions to the design to generate a consistent output of material throughout a print. The effectiveness of the extruder is demonstrated through an extensive printing and testing of various printed objects.

Keywords*— *Additive manufacturing, Concrete 3D Printing, 3D Printing, Extrusion Based system, Industry 4.0, Robotics, Automation in Construction, Concrete 3D Printer, Automation.

I. Introduction

Additive manufacturing is fast becoming a key instrument in the construction industry the term Additive manufacturing (AM), popularly known as 3D printing, is the process of additively joining materials to make a physical 3D object from a digital 3D model. The 3D object is created layer upon layer, as opposed to subtractive manufacturing techniques [1]. Some of the most widely adopted AM technologies are fused deposition modelling (FDM), Stereolithography (SLA), selective laser melting (SLM), selective laser sintering (SLS) and digital light processing (DLP) [2]. Regarding materials, a variety of polymers, metals, ceramics and composites can be used. The use of these materials is dependent on the type of AM process used [3].

The widespread popularity of additive manufacturing in most industries ranging from biomedical to aerospace suggests a revolution in manufacturing which have recently emerged in the construction sector and large-scale 3D printing. This takes additive manufacturing to a whole new level of printing dimension. Some of the benefits of deploying AM in the construction sector are it is ability to print complex geometric shapes with minimum waste, which makes it a cost-effective solution for the construction industry. Also, it has the added benefit of creating a circular economy, where buildings can be demolished, and the materials can be reformulated for manufacturing new structures.

The construction industry so far has been developed around two leading AM technologies the extrusion-based AM method, with some effort on developing a scaled-up 3DP technologies for cementitious materials [4]. There are two fundamental components of any extrusion-based 3D printer: the extruder assembly and the positioning system. The extruder's ability to reliably and accurately output the correct quantity of material over varying distances is fundamental to the printing process and the final output. However, the accuracy of the extruded material is insignificant if the positioning system is inaccurate. Therefore, both the extruder and the positioning system are needed to build a visually and geometrically accurate structure. The positioning and delivery system are usually standard machinery, i.e. Gantry or Robotic Arm which are looked into further under the related work section, and a mortar pump for delivering the materials to the nozzle. The extruder and delivery systems have the most significant influence on whether or not extrusion printing will produce a successfully printed object [5]. Hence, this paper proposes a robust active extrusion nozzle system design and a printing platform that enables the 3D printing of various cementitious materials.

II. Related Additive Manufacturing Solutions

Existing additive manufacturing systems were originally devolved for small scale products prototyping. The greatest challenge that the construction sector faces is the scaling up of existing AM technologies. In this section, the hardware configuration aspects of extrusion-based solutions used in the construction industry are investigated.

A. Gantry Based 3D AM Systems

The gantry solution simply represents a direct scaling-up of AM to additive construction – in other words a giant 3D printer. In gantry solutions, a set of motors are controlled in translation in any direction defined by along the X, Y and Z-axes in Cartesian coordinates. Gantry solutions were first developed for concrete extrusion in 2001, and Khoshnevis from the University of South California in the US patented the combination of this solution with the material process under the name "Contour Crafting" [6]. Fig 1a illustrates the counter crafting gantry system concept. Unlike Contour Crafting, where the focus had always been on entire constructions fabricated in one-piece, Freeform Construction focuses on the fabrication of full-scale construction components such as walls and panels [7]. This system works on the same principle as Contour Crafting and includes a printing head digitally controlled by a CNC machine to move in the X, Y and Z directions along three chain-driven tubular steel beams. A material hopper was mounted on top of the printing head and was connected to a pump that carried the

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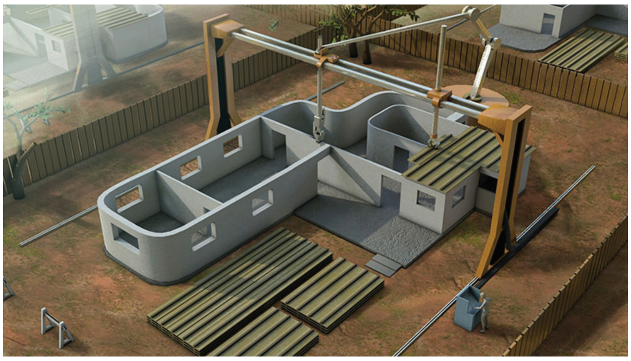
material to the printing nozzle [8]. In addition there are many more emerging companies that are using similar setups such as COBOD who made and sold the largest concrete 3D printer to Saudi Arabia in 2019 [9]. Other companies that also use extrusion based concrete printing and a gantry system includes [10][11].

Other solutions that do not relay on extrusion based system yet uses a gantry system were also made such as the Dini's D-shape printer that deploys slimier technology to the 3DP [12] in large scale, as shown in Fig 1b.



a) Counter Crafting gantry system concept [13]

b) D-shape Printer [14]

Fig 1 Gantry Systems

B. *Robotics Arm Based AM Systems*

Several concrete 3D printer solutions involve the use of robotic arms [15], [16]. In contrast to the typical gantry-based solutions, robotic arm systems offer the promise of broader task flexibility, dynamically expandable workspaces, rapid setup times, and more straightforward implementation with existing construction techniques [17]. These can either extrude materials by themselves [18]–[20], or perform subsidiary construction-related tasks [21] such as surface smoothing and painting.

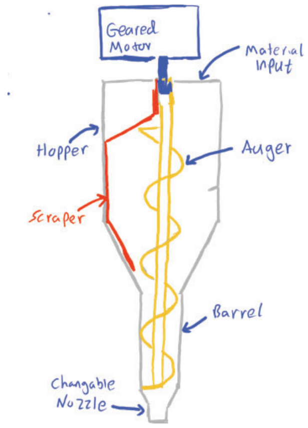
While there are many developments in the robotics and material formulation side, there is a lack of shared knowledge regarding the extrusion system and the setup used. This paper hopes to shed some light regarding the process of developing an extrusion-based AM system for 3D printing cementitious materials such as mortar and geopolymers.

III. Proposed Concrete 3D printing system

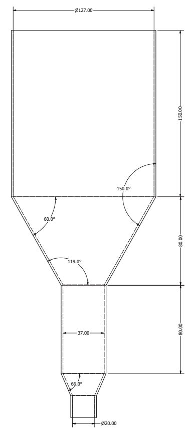
There are two fundamental components of any extrusion-based 3D printer: the extruder assembly and the positioning system. The extruder's ability to reliably and accurately output the correct quantity of material over varying distances is fundamental to the printing process and the final output. However, the accuracy of the extruded material is insignificant if the positioning system is inaccurate. Therefore, both the extruder and the positioning system are needed to build a visually and geometrically accurate structure.

A. *Extrusion System Design*

The first part of the concrete printer is the extrusion system. The design is a result of an iterative trial and error method for both the material formulation and the design of the extrusion system. Fig 2a shows the idea synthesis sketch for the extrusion system. The design includes; a hopper system to feed the material in, an extrusion auger screw to transport the materials down and through the nozzle, the nozzle which shapes the material output and a geared motor to drive the screw. Additionally, a scraper is added to agitate the material and aid with extrusion reliability.



a) Extrusion System Idea synthesis



b) Proposed Extrusion system CAD Drawing with the dimensions in mm.

Fig 2 Proposed Extrusion System Idea Synthesis And CAD Drawing

Fig 2b shows a CAD drawing of the proposed extrusion hopper. The barrel's diameter of 37 mm is chosen based on the auger screw that the author managed to obtain. However, the hopper slopes angles were explicitly designed to try and achieve a mass flow pattern, as illustrated in Fig 3. For many materials, flow problems such as erratic flow, materials segregation, and particle degradation in stagnant regions can be eliminated by ensuring that a mass flow pattern exists in the hopper [22]. Given the nature of the printed cementitious material and the importance of keeping its homogeneity, the hopper design avoids any sharp or steep edges that add unnecessarily pressure to the mixture — ensuring a smooth flow to and out of the nozzle.

Fig 4a illustrates a transparent rendered view of the proposed extrusion system. While Fig 4b shows an assembled rendered view of the extrusion system attached to the Open build rail, which will then be attached the positioning platform.

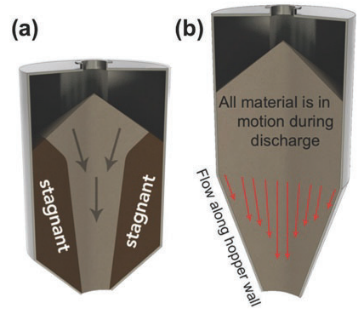
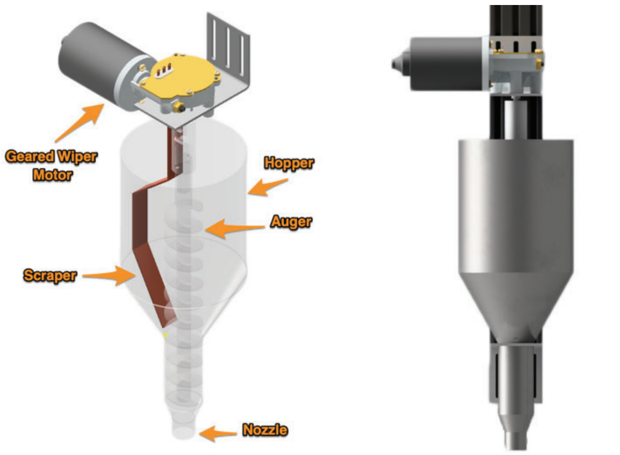


Fig 3 The Two Primary Flow Patterns, (A) Funnel Flow, (B) And Mass Flow [23]



a) Transparent render of the proposed extrusion to show the key components.

b) Assembled Render

Fig 4 Rendered Views Of The Proposed Extrusion System

B. Nozzle Design

Just as the hopper plays a major role in a successful print, the nozzle plays an even significant role in shaping the materials output and determining the buildability of the final structure. Depending on the required output, the nozzle can be varied to achieve detailed print using a smaller nozzle size or a faster and more robust structure by using a larger nozzle. Fig 5 presents a nozzle assembly drawing. The assembly is attached to the hopper's barrel which can easily be attached and removed. Fig 6 shows the prototyped nozzle, which is 3D printed using PETG filaments; various upper nozzle sizes were designed and printed to find the optimum nozzle size for this system and the materials being printed.

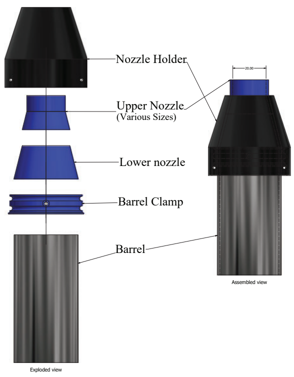


Fig 5 Detailed Assembly Drawing Of The Proposed Nozzle

Fig 6 Prototyped Nozzles Using 3D Printing

C. Hopper Prototype

The implementation of the design was possible by using sheet metal fabrication. The hopper was designed using Autodesk Inventor, and then laser cut using a plasma machine, as shown in Fig 7a The 1.5 mm thick stainless-steel sheet is then bent to shape and welded together, as shown in Fig 7b Furthermore, the scraper was also designed in Inventor and then bent with the correct angles to fit the hopper perfectly as shown in Fig 8. Prior to the addition of the scraper, the materials struggled to completely discharged from hopper without adding more materials or vibrating the hopper. Thus, the scraper became an integral part of the extrusion system. A vibration motor can also be added to further improve the flowability and compactness of the concrete.

a) Plasma Cut Sheet metals for the proposed hopper

b) Proposed Hopper Prototype

Fig 7 The Implementation Process Of The Proposed Extrusion Design

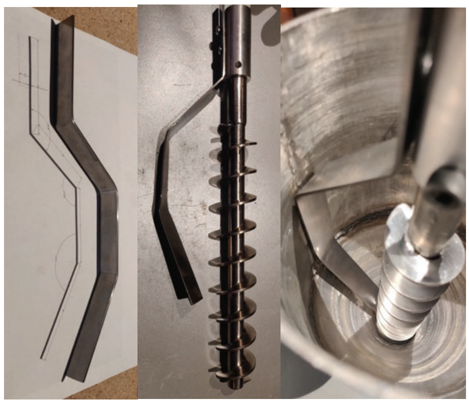


Fig 8 The Implementation Of The Scraper Design Into The Hopper

D. Positioning system design and Prototype

The second fundamental system that is needed to produce a gematrically and vitally correct parts is the positioning system. The positioning system used in this study, is a modified CNC gantry system, based on the opensource extrusion rails Open-Builds platform [24]. The platform is designed to print small to medium concrete samples for the purpose of developing a sustainable concrete mixture for 3D printing. Thus, a reasonable print area is required to print samples and small structure. Hence, the printer working area is; 490x400x300 mm, which is a sufficient area to examine mixtures and print samples that can be mechanically tested. The use of an open source system allows for easier expansion and scaling up of the gantry system when required. The gantry is a cartesian XYZ platform, with the axes driven by NEMA 23 Stepper motors coupled with TB6600 drivers. The drivers are controlled using a RAMP board [25] which is a common 3D printers controller based on an Arduino Mega 2560 microcontroller that communicates to a PC over a serial port. The open source firmware used to control the board is Klipper [26]. Fig 9 shows the final implantation of the positioning system with the control unit.

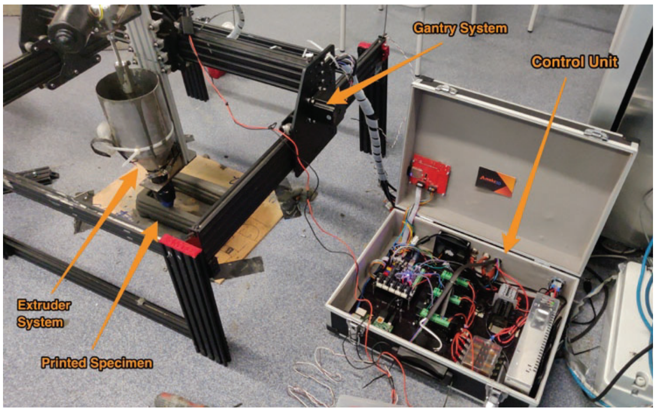


Fig 9 Pproposed Positioning System With The Control Unit

IV. Software Algorithm and print preparation

The proposed concrete 3D printing system pursues the same architecture of other 3D printing systems in the market. Therefore, existing software can be adapted to this platform. Fig 10 shows a high-level block diagram describing the steps taken in an overall software process of an AM system. These steps were taken to produce the printed objects in the results section.

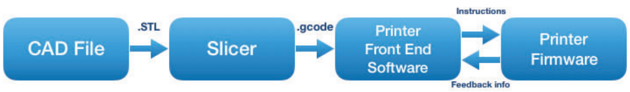


Fig 10 3D Printing High-Level Software Block Diagram

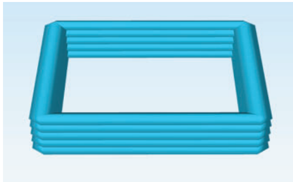
- CAD File - A 3D model made in CAD software (Such as Fusion 360) and exported as an STL file.
- Slicer - Takes an STL file and outputs a GCode, instructions for the printer to understand.
- Printer Front End Software - Controls the printer and displays status, position, temperature, etc.
- Printer Firmware – Installs on the printer's microprocessor (In this case Arduino with a RAMP 1.4 shield with Klipper Firmware [26]), and it is responsible for handling the GCode instructions from the PC.

V. Results and discussion

Before testing the systems, various 3D models were designed using Fusion 360 and exported as an STL file and then sliced using a custom slicer configuration for the developed platform. Furthermore, a ready-mix mortar that has been visually mixed to the right consistency is used. Future studies will look into the use of sustainable concrete mixture for 3D printing.

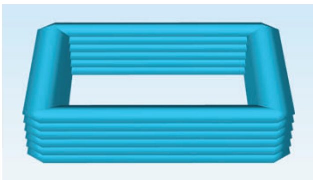
Initially, a rectangular block that is 150x150x100 mm in size (Fig 11a) was 3D printed in order to tune in the printing parameters such as; gantry motion speed, layer height or printing resolution and extrusion rate. The nozzle size was set to 20 mm, as it produced the best flow rate with the ready-mix mortar. Fig 11b shows the first print with a gantry speed of 30 mm/s, a layer height of 15 mm, and an extrusion rate of 50%.

Sliced Model | Printed Model



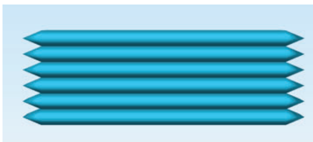
a) Sliced rectangular block measuring 150x150x100 mm

b) Printed model at 30 mm/s and 15 mm Layer Height



c) Sliced rectangular block measuring 150x150x100 mm

d) Printed model at 20 mm/s and 10 mm Layer Height



e) Sliced rectangular block measuring 180x80x60 mm

f) Printed model at 20 mm/s and 10 mm Layer Height. Note the Cyclic effect of the screw.

Fig 11 Initial Printed Parts Using The Proposed Systems

As it can be observed, the initial settings caused a failed print due to the layer height being too high. By tuning the settings and reducing the speed to 20 mm/s, and the layer height to 10 mm while keeping the same extrusion rate, a successful print is achieved. Fig 11d, shows the successful print that observably represents the original model. The extrusion rate, which controls the speed of the extruder's motor, will be varied depending on the consistency of the mixture throughout the testing results. Fig 11e, shows a smaller rectangular block measuring 180x80x60 mm. Fig 11f the printed block, which shows a good buildability and shape stability as far as the material goes. However, a cyclic effect emerges on the middle-printed layers; this effect is quite common with extrusion-based systems due to the rotation of the screw. Better syncing of the gantry speed and the extrusion rate could reduce this effect.

To further test the system output, more complex geometries were designed and printed as presented in Fig 12.

Fig 12 Further Printed object with complex geometries

VI. Conclsuion

To conclude, we have successfully designed and developed a 3D printing system for printing cementitious materials for the construction industry. The system consisted of an active extrusion system that has the advantage of precisely controlling the flow of the materials. Furthermore, the added scraper has dramatically improved the flow of the materials. Also, a positioning platform has been presented to accompany the extrusion system to form the 3D printing platform. The initial results were promising and proved to be visually accurate compared to the computer-aided designs. Further improvements to the extrusion control can be made to achieve higher geometrically accurate structures.

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