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SCALABLE ADDITIVE MANUFACTURING SOLUTION FOR CONSTRUCTION

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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 have 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 proposes a scalable additive manufacturing system for the construction sector which pursues an eco-innovative approach to reduce cost and time while increasing quality and versatility in building a 3D structure. The proposed solution involves designing and developing two subsystems that form a robotic AM platform. These two systems consist of a positioning system where a robotic arm is implemented in addition to a nozzle system for extrusion the concrete with precision, which enables the achievement of complex geometries.

Keywords: Additive Manufacturing, 3D Printing, Robotics, Nozzle, Concrete 3D Printing, Industry 4.0, automation in construction, mega printing.

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1. Introduction

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. It truly makes an AM scalable system that can print from objects in the range of Nano to Mega size. 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.

In the early stages of the AM’s deployment, the technology was primarily focused toward prototyping and tooling applications; however, in recent years, AM has found success in end-part production, driven by improved manufacturability and reduced lead time compared to traditional manufacturing methods [4]. Additive manufacturing of all types and sizes generally follow a set of processes in order to get to the final manufactured part. Fig 1. illustrates a generic AM process chain. The process begins with a 3D model designed in a CAD software, the CAD file is exported as an STL (Stereolithography) file. The STL file is then sliced into layers using a slicer and then converted to a set of GCode to instruct the AM system to print the desired model. The layer’s resolution can vary anywhere between 10 and 300+ microns depending on the user choice and the hardware capability.

Fig 1. Block diagram of a generic AM process chain [4]

1.1. *Additive manufacturing processes*

The five main AM processes are classified into liquid base and powder based. The processes included in this paper are considered the most relevant now and to this project. Fig 2. shows an overview of the main AM processes.

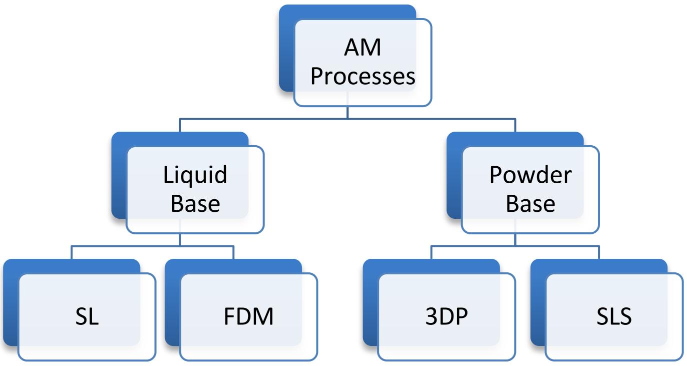


Fig 2. Overview of the common AM processes

1.1.1. *Stereolithography (SL)*

The first type is the stereolithography, which usually includes a perforated platform, a container of a liquid UV-curable polymer, and a UV laser [5]. Based on the layers extracted from the CAD model, a beam of the laser is used to trace the bottom layer of the model on the surface of the liquid UV-curable polymer, which will cause the polymer to solidify. The perforated platform will then be lowered, and the second layer will be traced and hardened by another beam of the laser. The process will be repeated until the 3D model is completed [6].

1.1.2. *Fuse Deposition Modelling (FDM)*

A fused deposition modelling machine melts a thin filament of plastic (typically 1.75 or 3.0 mm in dimeter) and extrudes it through a nozzle. The melted material is laid down on the build platform, where it cools and solidifies [7]. By laying down layer on layer the part is built. The most common materials used in this process are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and an expanding selection of different composites such as wood, metal, conductive, magnetic materials infused with PLA or ABS [8].

1.1.3. Three Dimensional Printing (3DP)

3DP process is a MIT-licensed process where water-based liquid binder supplied in a jet and onto a starch-based powder to print the model from a CAD file. The powder particles are placed in a bed and they are glued together when the binder is jetted. This process is known as 3DP because of the similarity with the inkjet printing process that is used for two-dimensional printing on paper, also called Binder Jetting (BJ). Some of the advantages of using this process are; it can handle a high variety of polymers, it is fast and relatively cheap [9, 10, 11].

1.1.4. Selective Laser Sintering (SLS)

A selective laser sintering is a process where a thin layer of plastic powder in a build platform is selectively melted by a laser. The build platform is then lowered, and the next layer of plastic powder will be laid out on top using a roller, by repeating the process of laying out the powder and melting where needed, based on the CAD file the final parts will be built up in the powder bed [12]. The advantages of using SLS is that the parts manufactured have excellent mechanical properties. Also, the process can handle a range of materials such as plastic, metal, and ceramic.

1.2. Related work: AM Technology Demonstration

Existing additive manufacturing technologies were originally developed 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 depositing materials solutions are investigated. The technological solutions are divided into two types: gantry systems, and multi-purpose robotic systems.

1.2.1. Gantry System

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” [13, 14]. Fig 3.a illustrates the counter crafting gantry system concept.

The research group at Loughborough University in the UK developed the “Freeform Construction” process in 2007 [15]. 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 [16]. 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 as shown in Fig 3b. A material hopper was mounted on top of the printing head and was connected to a pump that carried the material to the printing nozzle [14]. Other solutions that do not relay on extrusion-based system were also made such as the Dini’s D-shape printer that deploys slimier technology to the 3DP in large scale, as shown Fig 3.c.

a) Counter Crafting gantry system concept [17]

b) Freeform Construction Gantry System [18]

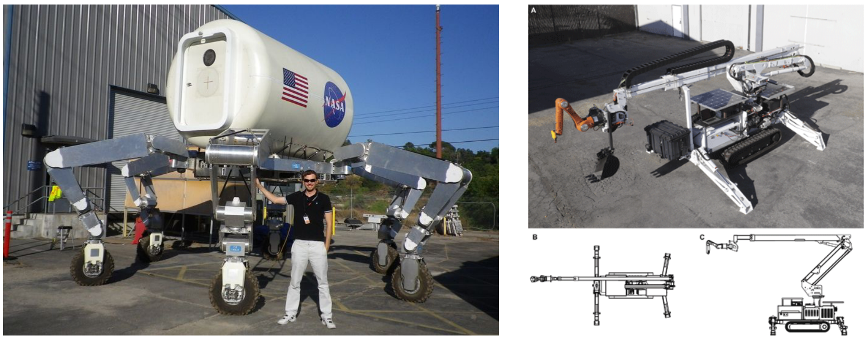
c) D-shape Printer [19]

Fig 3. Examples of gantry systems

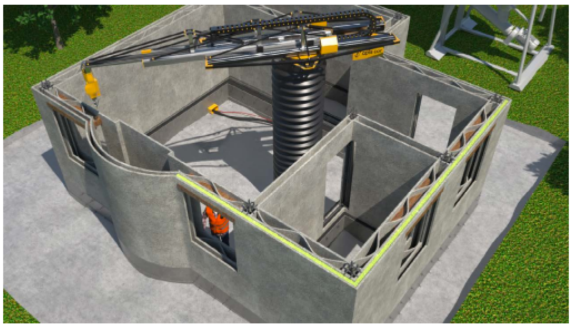
1.2.2. Robotics Arms

Several solutions involve the use of robotic arms. In contrast to the typical gantry-based solutions, robotic arm systems offer the promise of wider task flexibility, dynamically expandable workspaces, rapid setup times, and easier implementation with existing construction techniques [20]. These can either extrude materials by themselves [21–23], or perform subsidiary construction-related tasks [24], such as the spreading of tile adhesives or painting. These robots are particularly well suited for extra-terrestrial environments, such example is the fully conceptualised mobile robotic platform named "ATHLETE" which was proposed by Scott Howe [25]. The ATHLETE (Fig 4.a) is a six-limbed wheel on a mobile robotic platform that can operate without human involvement. Each limb is a six or seven degrees-of-freedom robotic arm that can perform various tasks, including additive construction, digging and drilling.

The Digital Construction Platform (DCP) is another experimental technology for large-scale additive construction. The DCP (Fig 4.b) consists of 5-axis Altec AT40GW mobile hydraulic arm with a 6-axis KUKA robotic arm mounted at its endpoint. A slightly different system that is neither a gantry nor a robotic arm is the Apis Cor 3D printer (Fig 4.c) which is a complete redesigned AM system that is mobile.



a) ATHLETE [26]   b) The DCP [20]



c) APIS COR 3D printer [27]

Fig 4. Robotics arm solutions

2. Proposed Scalable AM system

This paper proposes a scalable additive manufacturing system for the construction industry which takes a holistic approach in addressing the processing challenges such as improved customisation for realisation of complex architectural design and facilitating the optimised extrusion and delivery of cementitious based material through smart/engineered nozzle system. The proposed AM platform is made up of sub-systems. Each system is introduced separately with the proposed designs. These designs are integrated together at the end to form the complete platform. The sub-systems consist (1) Positioning Platform and (2) Nozzle System.

2.1. Proposed Positioning Platform design

A robotic arm positioning platform is chosen to oppose to a gantry system as it is more scalable due its longer reachability and mobility which overcome the fixed printing area of a gantry system. The arm requires less hardware customisations beside the attachment of the nozzle and programming the arm to 3D print an object. Fig 5. illustrates the concept of using a Kuka robotic arm as an AM positioning platform with the attached nozzle system.

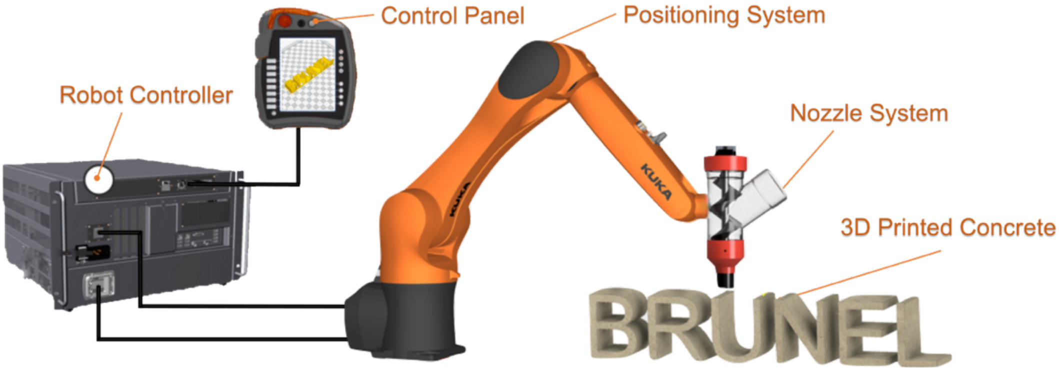


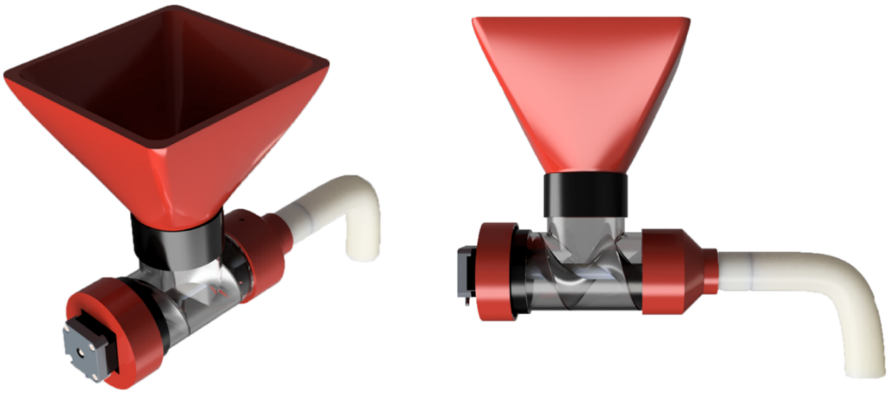
Fig 5. Kuka Robotic arm used as an AM concept design

2.2. Proposed Delivery System Design

The concrete delivery system is the second system to be designed and developed. The delivery system plays a critical role in implementing a successful concrete AM platform. One of the most important aspects of the delivery system is that it must be able to deliver concrete at a continues flow rate to ensure smooth printing. To achieve the continues flow rate multiple designs were prototyped, tested then modified. Below is the main workable design that was used in the lab to test the printability of the materials. Moving away from the lab an industrial screw grout pump is used.

2.2.1. Screw Controlled Delivery System

The pump is prototyped based on a screw pump system. The design has an open hopper which allows for continuous feeding of martials, thus an uninterrupted large-scale print is possible. The design is relatively compact and is lab friendly. Please note the motor is there for illustration, a much larger and stronger motor will be used. Fig 6. illustrates the design concept with a top and side view.



a) Screw Pump Top View b) Screw Pump Side View

Fig 6. Screw controlled delivery system (pump) with different screw designs

2.3. Proposed Nozzle Designs

The final sub-system is the nozzle, where the delivery system will deliver the concrete into. The nozzles job is to layout the concrete in a shape that would allow for layers to be built on the top of each other. There are two common types of concrete extrusion/nozzles in the market and under research right now [28];

1) A passive nozzle, where the extrusion is controlled solely by the delivery system (pump) and the nozzle attached to the end of a hose for example works as a dispenser that defines the shape of the printed layer.

2) An active nozzle, where the extrusion is controlled at the nozzle by a rotating screw. This allow for greater precision and enables the addition of other martials such as admixtures which accelerates the drying of concrete.

Both types are investigated in this project to find which one works best. To try minimising the cost of the nozzles, PVC junction pipes were used as the main body to attach the nozzle. This allows the cost of printing to be cut and makes the designs more flexible and expandable, since the pipes come in various shapes and sizes.

2.3.1. Passive Extrusion Nozzle Designs

The following nozzles are all considered to be passive. The designs are made for various pipe sizes so that it can be used in different scales of AM platforms. Fig 7. shows the nozzle designs with a description of where each nozzle will be attached. A dimeter range of 9-20 mm is found to give sufficient 3D printing result for various different material based on published research papers [29].

a) 20 mm dimeter nozzle, attaches to the hose directly

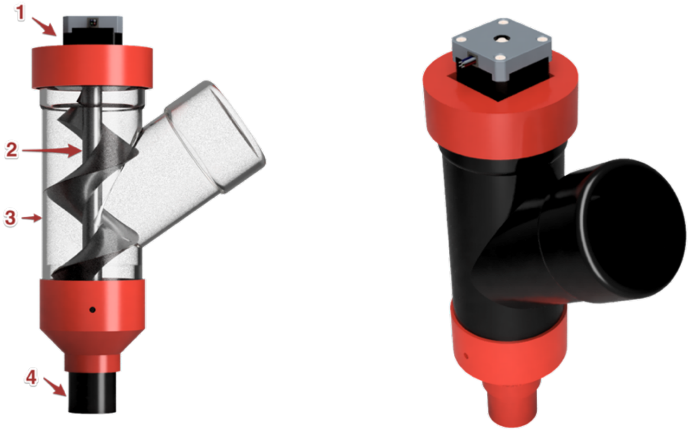
b) 20 mm dimeter nozzle, attaches to a 40 mm PVC pipe

c) Various shapes and sizes (10 – 25 mm), attaches to a 100 mm PVC pipe

Fig 7. The proposed passive extrusion nozzle designs

2.3.2. Active Extrusion Nozzle Designs

An active nozzle is active since the extrusion of the materials is controlled at the nozzle by a rotating screw. This allow for greater precision and enables the addition of other materials such as admixtures which accelerates the drying of concrete. Fig 8. shows the final design of the nozzle. The active nozzle consists of 4 main parts; 1) A motor with a control circuit, 2) screw 3) PVC pipe and a 4) detachable nozzle.



a) Active nozzle side view

b) Active nozzle top view

Fig 8. The proposed active extrusion nozzle designs

2.4. Software Algorithm

The proposed AM system pursues the same architecture of other AM platform or 3D printing system in the industry with a rather larger scale and uses a custom printing head. Therefore, existing software can be adapted to this platform. Fig 9. shows a high-level block diagram describing the steps taken in an overall software process of AM system.

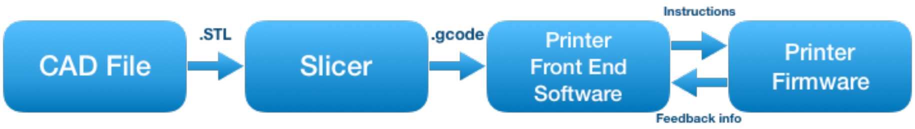
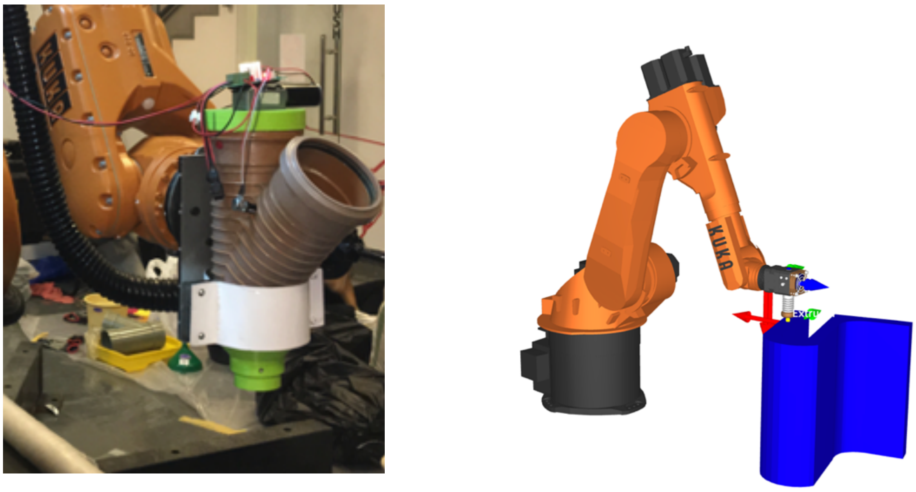


Fig 9. Software High-Level Block Diagram

1. CAD File - A 3D model made in CAD software (Such as Fusion 360) and exported as an STL file.
2. Slicer - Takes an STL file and outputs a GCode, instructions for the printer to understand.
3. Printer Front End Software - Controls the printer and displays status, position, temperature, etc.
4. Printer Firmware – Installs on the printer's microprocessor (In this case Arduino with a RAMP 1.4 shield with Marlin Firmware [30]), and it is responsible for handling the GCode instructions from the PC.

2.5. Positioning Platform Implementation

With Robotic Arm, not much of a physical implementation is required since the robot was already set up and comes readily from Kuka as shown in Fig 10.a. However, a software setup is needed to use the arm as an AM platform. The software chosen for this project is the RoboDK due to its advanced features and ease of use. RoboDK is a simulator for industrial robots and offline programming [31]. RoboDK has an advantage over its competitors as it has built-in 3D printing features such as a slicer and most importantly it can convert the GCode into the Kuka robotic language (Kuka KRC). Fig 10.b shows the setup of the robot as an AM in the simulation environment of RoboDK and the futuristic chair design from Fig 10.b.



a) Proposed Nozzle implementation b) Proposed AM platform in RoboDK simulation

Fig 10. Robotic Arm Implementation

2.6. Preliminary Results

Small test samples have been printed using the ready-mix mortar to evaluate the outcome of the whole platform. The result shows a promising start to an AM platform for construction that can be used to further improve the materials and the nozzle system. The use of small samples rather than large ones is due to the limitation of workspace of the used robotics arm.

a) Chair sample print b) Complex Shape Printing

Fig 11. Sample Prints using the proposed AM platform

3. Conclusion

To conclude, this paper proposed a working solution for a scalable AM platform for the construction industry that purses an approach that could profoundly impact the way construction is done. It uses a zero-waste method and supports the circular economy movement. The solution compromises of two systems, the positioning platform and the nozzle system. The design and implementations of both systems are introduced with some sample prints that were printed using ready-mix mortar by the proposed AM system. This AM system shows promising results to carry on further research on improving the nozzle and developing printable materials.

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