Automation of robotic concrete printing using feedback control system

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Abstract –

In recent years, digital fabrication is termed as "third industrial revolution" and its interaction with extrusion based cementitious material has been well known as concrete printing. In concrete printing, a gantry/robotic system deposits concrete layer by layer following G-codes generated from slicing of the 3D component. However, the robotic system does not consider the material (concrete) properties and component geometry which sometimes cause failure in the printing process. Concrete properties are usually attributed with time and therefore the system parameters such as extruder velocity and layer height are necessarily to be controlled accordingly to obtain an uninterrupted smooth flow. In line with this, our current research aims to automate the printing process by collecting material's fresh properties through a feedforward control system. A six-axis industrial Denso® robot was used for 3D printing of geopolymer concrete with the help of screw pump and ten-millimeter circular extruder. The obtained experimental results confirmed the validity and robustness of this automated set up.

Keywords –

Digital construction; Process control; Concrete printing; Autonomous robot

1 Introduction

It has been proposed that 5.3 billion houses are needed to be built in near future to cope with the impact of the ageing population, immigration and the singleton lifestyle [1]. In this regard, it is too much cumbersome for the government as well as civil builders to raise shelters in short span of time due to low productivity and labour intensive nature of conventional way of making buildings. Unlike other industries our current construction process lacks automation that can reduce the supply chain while making the building process faster, economic and accurate. This compels lot of researchers and industries to enter the new ear of automated building construction system to save time, labor and cost as well as improve safety.

Recent years have seen several automated construction technologies such as slip forming, mesh molding while simultaneously combining the benefits of both robotic system and digital modelling [2-5]. Concrete printing is one of such advanced technology that apply fused deposition modeling (FDM) principle of rapid prototyping for large scale construction. The first published evidence of 3D concrete printing was in 1997 with an innovative approach suggested by Pegna [6]. However, the actual development started in the mid-1990s in California, USA, when Khoshnevis introduced a technique termed Counter Crafting [7]. Contour crafting (CC) is a gantry based robotic system that extrudes material in a layer by layer manner to construct on-site structures [8]. Soon after, researchers at Loughborough University printed high strength fiber reinforcement concrete to construct various complex civil structures. For the first time, four key parameters such as extrudabilty, buildability, workability and open time were introduced with respect to printing of cementitious material [9,10]. Figure 1 shows some of these recent pioneering works done by (a) Apis-Cor, Russia, (b)Tu/e Eindhoven and (c)Xtree, France [11].

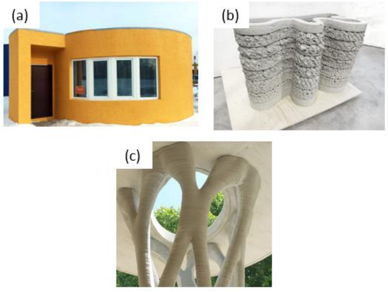

Figure 1. Examples of 3D concrete printing [11]

It is much clear from the above literature survey that concrete printing has the capability of building large scale freeform structures directly from the 3D model without any tools and human intervention. However, few challenges are still remained with respect to machine (system) and material development that are possibly impeding its wide spread application in various industrial domains. A right balance between material and machine (printer and pump) properties is highly necessary to achieve smooth extrusion during the printing process. Therefore, this paper aims to incorporate material behavior and machine automation through a feedforward control system. In the system, control variables were tuned based on off knowledge thixotropic behavior of the material. Few important parameters of concrete printing were highlighted in the next section following the full experimental set up developed here, to synchronize material and machine parameters such as print speed, layer height, pump flow rate etc. Finally, the last section, i.e section 4 concludes with results and discussions for future directions.

2 Research on control parameters

Concrete printing begins with 3D modelling of the component and subsequently generating G-codes by slicing it with respect to required layer height. A robotic arm (6-Axis Denso industrial robot) or gantry system controlled by the G-codes can be used with a screw pump and extruder for concrete printing application as shown in below figure.

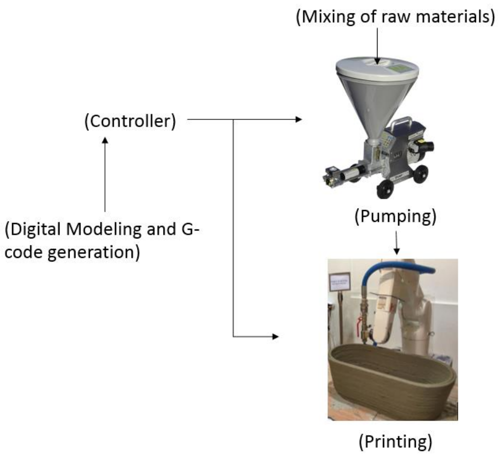

Figure 2. Flow of concrete printing process

Using the abovementioned setup, some preliminary investigations have been carried out at building and construction laboratory, Nanyang Technological University (NTU) Singapore and it was found that concrete printing is an interdisciplinary research between printable material, machine (printer and pump) and geometry of the part (figure 3). Material viscosity, machine speed, pump flow rate and geometric complexity are highly related to each other and a mismatch among these parameters can cause the printed part to collapse due to non-uniformity of the material deposition [12]. Unlike FDM, a constant flow rate in this process is not viable because the fresh properties of the material such as viscosity, yield stress changes with time. Inconsistent print paths, poor surface finish, pores, intermittent flows are some common defects that were observed (figure 4) when using constant flow rate in the printing process. This is because of lack of high flow rate necessary to overcome the resistance offered by slowly changing material. Therefore, in this research a feedforward system was developed to adjust the material flow with printer speed while accounting for material fresh properties. The complete test set up and experimental procedure were described in the following section.

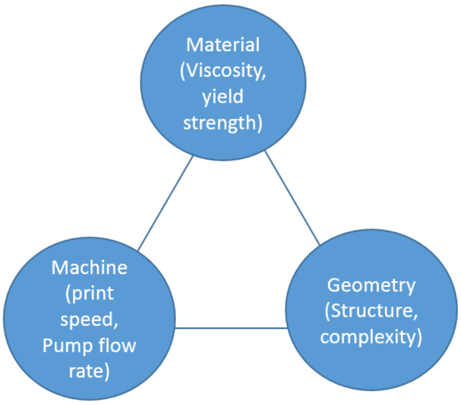

Figure 3. Concrete printing components

Figure 4. Failures in concrete printing

3 Experimental setup and Equipment

Since the flow rate plays an important role in concrete printing, there is a necessity to control it accurately with respect to the changing material behavior. Literature reveals several methods of monitoring material behavior by using calorie meter, ultrasonic wave generator, vicat setting time apparatus etc. [13]. However, for concrete printing measurement of shear stress is more favorable since the material needs to be extrudable and zero slump at the same time to build more layers one over another [8]. In order to measure instant change in material fresh property, a shear vane apparatus can be directly mounted in the hopper of the screw pump as shown in figure 5 or alternatively, data from rheometer can be taken as reference to mimic the process as offline routine.

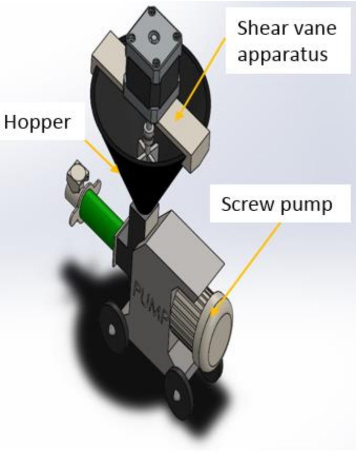

Figure 5. Shear strength measurement of geopolymer mortar

All the raw materials of geopolymer i.e fly ash (class F), slag (GGBS), river sand (below 1.18 mm) and potassium silicate (molar ratio=1.8) were mixed in the fixed ratio as per mix design shown in Table 1 and instantly placed in the hopper of the screw pump.

Table 1: Mix design for geopolymer 3D printing

Materials	**Weight percentage**
Fly ash	22.42
Slag	3.27
Silica Fume	6.54
Sand	49.0
K- Silicate	13.25
Thixotropic additives	0.50

Initially, some geopolymer mix was extruded out to avoid any air bubble present in the hose pipe and then the printing was continued by using the automated flow set up. The complete process of flow automation can be described in four stages [14]:

(i) Data preparation (Modelling and G-codes),
(ii) Concrete mixing and shear stress measurement,
(iii) Flow parameter tuning, and
(iv) 3D concrete printing

In data preparation, the 3D CAD model was converted into an STL file, and sliced with the desired printing parameters; nozzle diameter, layer thickness, etc, to generate a G-code file for the robotic printer (figure 6). To control the flow rate and print speed, pump was integrated to the robotic printer via robotic operating system (ROS) in a feedback loop. ROS, is generally used as the communication middleware between its different modules [15]. This allows different modules to send and receive information from other nodes. The robot motion server interprets the G-code file, and pass the cartesian coordinates and speed information over to the path planner module. Using CAD models of the robotic arm and nozzle, a database of its static information was precomputed. This database can take up to half a day to generate, depending on the complexity of the nozzle end effector. However, this simplify the inverse kinematic problem during motion planning and only needed to be generated once. The motion planner uses BiRRT to generate a collision free, geometric path with no timestamp, followed by a Parabolic Smoother, which simultaneously shortcuts and times the trajectory, subjected to velocity and acceleration constraints. The robot pose throughout the printing process was given by the Cartesian coordinates in the G-code file, and orientation restricted by requiring the end effector print nozzle to be pointing downwards during printing. The inverse kinematic solution was solved through OpenRAVE’s IKFast TranslationDirection5D.

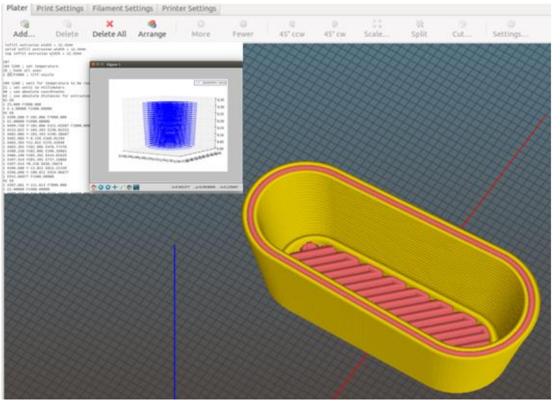

Figure 6. G-Code generation for concrete printing

The screw pump flow rate control was achieved by setting a potentiometer through Arduino microcontroller and digital to analog converter circuit. The microcontroller receives ROS messages containing desired flow rate from the robot motion server. Initially for the prepared geopolymer mortar, flow rates were varied from 0-10V with respect to material shear strength. The change of shear strength (with time) is shown in figure 7.

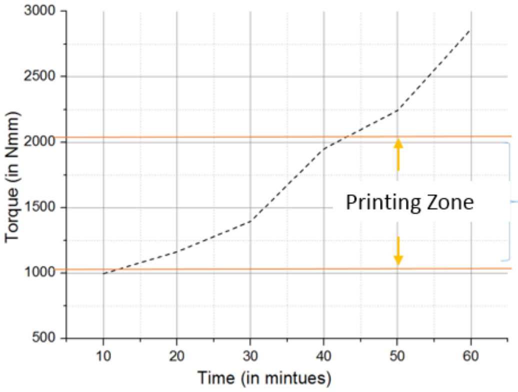

Figure 7. Variations of shear strength with time

The shear strength was achieved from a rotational rheometer by varying the rotational velocity from zero to sixty rpm and it is clear from figure 7 that the shear strength geopolymer mortar increases with time which causes to increase the flowrate of the pump to achieve smooth flow without any interruption. Simultaneously, to match the flow rate, printer speed was adjusted based on our machine limitation and complexity of the designed component. A flow chart of the complete process is shown in figure 8.

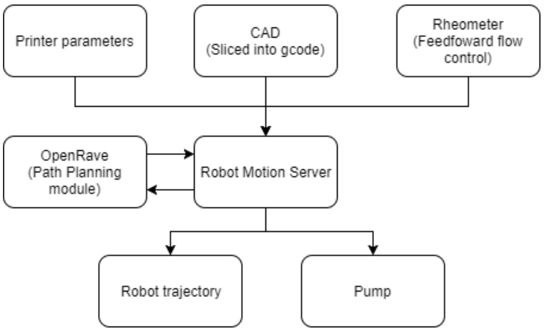

Figure 8. Printer and material integration using feed forward control

4 Discussions and concluding remarks

Our current practices for controlling flow during concrete printing is purely manual and involves lot of trial and error approaches. This sometimes causes disruption in the extrusion and leads to part failure. Therefore, in this research a feedforward flow control method was adopted considering material hardening behavior with progress of time. Path planning of robotic motion system was improved by accounting the limitation of flow rate and pump pressure. Figure 9 (a) shows geopolymer printed part using the proposed flow control system. It is concluded from these images that controlling the flow with proper material knowledge results uniform, continuous deposition of material as per the designed 3D model.

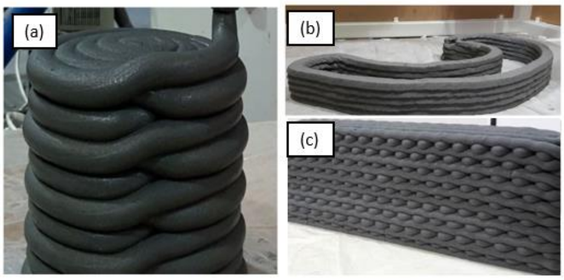

Figure 9. Examples of freeform concrete printing

It is worth to mention that, apart from concrete flow rate and print speed, nozzle height above the printed surface has also the influence in print quality and part stability [16,17]. Sometimes due to material sagging, height between printed surface and nozzle increases dramatically which results in strange (zig zag) flow pattern for the material coming out of the nozzle. In this regard, authors are currently working on integrating an optical feedback system to the nozzle that can detect the slump of final layer and will adjust the nozzle position accordingly. It has been found that during printing of some complex geometry material over-deposition occurs in corners and sharp turning edges which can be reduced by controlling the concrete flow and print speed simultaneously. It is believed that our flow control approach will be useful to the upcoming concrete printing users to tune the flow according with their fresh concrete aging behavior.

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