Extrudate formation modelling and variable geometry nozzle system design for extrudate geometry control in 3D concrete printing

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**EXTRUDATE FORMATION MODELLING AND VARIABLE
GEOMETRY NOZZLE SYSTEM DESIGN FOR EXTRUDATE
GEOMETRY CONTROL IN 3D CONCRETE PRINTING**

Ph.D. Thesis

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School of Mechanical and Aerospace Engineering

January 2020

**EXTRUDATE FORMATION MODELLING AND VARIABLE
GEOMETRY NOZZLE SYSTEM DESIGN FOR EXTRUDATE
GEOMETRY CONTROL IN 3D CONCRETE PRINTING**

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submitted to

The Nanyang Technological University

in partial fulfilment of the requirement for the degree of

Doctor of Philosophy

January 2020

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

23, January, 2020

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

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Authorship Attribution Statement

*(B) This thesis contains material from 2 accepted or submitted papers in the following peer-reviewed journals / from 2 papers accepted at conferences in which I am listed as an author.

Section 3.4 is published as Lao, W., M. Li, L. Masia, and M.J. Tan. *Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design*. in *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium (SFF 2017)*. 2017. Austin, TX. doi: 10.32656/sff.2017.208

The contributions of the co-authors are as follows:

- Assistant Prof L. Masia provided the initial project direction, scientific review and editing of the manuscript drafts.
- Wenxin Lao prepared the manuscript drafts. The manuscript was revised by Dr M. Li.
- Wenxin Lao co-designed the study with Dr M. Li. I also performed all the 3D printing experiments, data collection and data analysis.
- Prof M. J. Tan advised on the project direction.

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- L. He advised on the project; and provided the design of an active trapezoid nozzle.
- Prof M. J. Tan advised on the interpretation of the material distribution problem.

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- Wenxin Lao co-designed the experiment with Associate Prof Tegoeh Tjahjowidodo and Dr M. Li.
- Wenxin Lao performed all the 3D printing experiments, sample processing and data analysis. I also performed the ANN model training; ANN structure optimization and the model validation experiments.

- Wenxin Lao measured all cross-sectional extrudate data and surface roughness data was measured in Singapore Center of 3D Printing.
- Associate Prof T.N. Wong provided guidance in analysis of material rheological properties.
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- Wenxin Lao developed the control strategy for the nozzle. Wenxin Lao also developed the slicing algorithm to acquire target extrudate geometries.
- Wenxin Lao measured the surface roughness data of the printed structure in the Singapore Center of 3D Printing.

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Abstract

3D printing is a fast-developing technology which allows for solid part fabrication in layer-by-layer manner. This technology has been introduced to construction industries and it draws a lot of attention due to its potential for higher customization, reduced human intervention and shorter construction time for complex structure. Recently, large-scale house and structures can be fabricated using this technology with fresh concrete material. However, the lack of control on extrudate formation has become a major drawback for this technology. Without the control of extrudate formation, the design freedom is restricted, and printing quality is limited.

This research focuses on the computational and experimental studies to control the extrudate formation process to improve the output quality of 3DCP. In order to allow for a controllable process, the relationship between the printing parameters to the resulting extrudate shape needs to be established. Preliminary studies show that an appropriate strategy to adjust nozzle outlet shape can be utilized to control the extrudate formation to improve the printing quality. Moving forward, the nozzle-adjustment strategy suitable for on-site printing applications needs to be developed.

A machine learning method is used to analyze the relationship. A data-driven predictive modelling methodology based on Artificial Neural Network (ANN) is adopted to develop the relationship between the nozzle shape and the extrudate cross-sectional geometry. This approach allows for establishing a nonlinear relationship

between nozzle shape, which is represented by the finite geometrical points, to the extrudate shape. The results show that the ANN method successfully maps a nonlinear relationship between the nozzle shape and the extrudate formation with encouraging results. The accuracy of the predictive ANN model is experimentally validated, and surface finish quality is improved in several case studies.

Based on the developed model, an active mechatronic nozzle, which can adapt its shape during printing, is designed to control the extrudate formation during the printing. This nozzle is featured for its capability to control extrudate cross-sectional by adjusting the nozzle outlet shape. With this nozzle, the extrudate geometry can be controlled to comply to the designed outer surface shape of the structure, and hence improve the surface finish quality. A slicer program is also developed to analyze the CAD file of the designated printed structure and to extract the desired geometries for every extrudate layer for printing. The controller of the variable-geometry nozzle is developed to regulate the nozzle shape to achieve the desired extrudate geometries. Finally, an arch structure was printed with the active nozzle and exhibited obvious improvement in surface finish quality.

The current study could be further enhanced in three directions. The monitoring system could be integrated on printing system to allow for close-loop control of printing quality. The predictive ANN model could be improved to predict the extrudate geometry for different materials. The variable-geometry nozzle could be applied to solve other quality problem in 3DCP, such as material distribution problem in curved-path printing.

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Abbreviations

3DCP	3D Concrete Printing
AM	Additive Manufacturing
ANN	Artificial Neural Network
CAD	Computer Aided Design
CC	Contour Crafting
CNC	Computer Numeric Control
DOF	Degree of Freedom
FDM	Fused Deposition Modeling
MSE	Mean Square Error
NTU	Nanyang Technological University
R_a	Arithmetic Average Roughness
Re	Reynolds number
stl	Standard Tessellation Language
TU/e	Eindhoven University of Technology
USC	University of Southern California

Chapter 1. Introduction

1.1. Background

3D printing technology has experienced rapid development in many disciplines [1]. The technology covers broad aspects that include many techniques that could create into a physical prototype in a layer-by-layer manner. In most of 3D printing technologies, the input CAD model is sliced into many horizontal layers and the 3D printer sequentially deposits the material in a layer-by-layer manner to build the product [2]. This method has a lot of advantages such as high level of automation, high complexity, customization and relatively low cost for building small quantity of products. However, the working principle of the printer is largely dependent on the usage of the final product and the material to be used in printing. The 3D printing was first applied in the area of prototyping and tooling. The technology is being extensively studied in industries such as aerospace, medical sector and radio-frequency field. [3].

Application of 3D printing technology in construction industry has become an extensive study recently. Owing to the practicality of directly creating specific shapes of concrete elements without the need of underlying formwork, the 3D printing technology potentially improve the automation level in construction industry [4]. This can reduce human intervention, reduce construction time for complex structures and improve the freedom in the architecture design [5, 6]. This can also cut the cost in construction by reducing the labor cost [7].

3D printing technology was introduced into construction industry when Khoshnevis and Dutton [8] developed the first 3D Concrete Printing (3DCP) technology in the mid-1990s. In the past few years, a rapid development in 3DCP was observed and many studies have shown large-scale printed structures. For example, the 3-meter high bath room unit printed by NTU, the bridge printed by Eindhoven University of Technology (TU/e) [9] and the five-storey building created by Winsun [10] , as shown in Fig. 1.1. The growth of automation approaches and the decrease in labor cost have also been documented [11, 12].

Fig. 1.1: Large-scale structures created with the 3DCP solutions

Most of the existing 3DCP technologies have adopted the extrusion-based “line forming” 3D printing process. The Contour Crafting (CC) method, as well as

most of other 3DCP technologies, has adopted the extrusion-based printing manner which is similar to the Fused Deposition Modeling (FDM). In the extrusion-based 3DCP process, the nozzle which is installed on 3DCP printer is moved along a pre-designed printing trajectory. During the motion, the nozzle extrudes the material and forms several extrudate layers. These layers accumulate to form the final structure. This manner is widely adopted because the direct-extrusion printing process is easy to utilize, and it has low material waste in the printing. Other printing process like the powder-binding method as in the D-Shape Printing [13] could also create large-scale structures, but with significant larger material waste as its price [5].

As for the printing material, fresh-mixed concrete is widely accepted in existing 3DCP technologies. The concrete material is adopted in 3DCP mostly because it is affordable (S\$ 96 per cubic meter [14]) for the building & construction purpose, which may utilize a large amount of printing material. Moreover, concrete material gains high mechanical strength after the curing process and could support the weight of large-scale structures. Concrete material stands for a mixture which may consist of many ingredients including cement binder, stabilizer, aggregates, fiber and water. Within a short span of time after the mixing (normally within 30 minutes), the fresh concrete mixture is flowable and can be deposited by the 3DCP printer. As time pass by, the deposited concrete material gradually gains mechanical strength and solidifies due to its hydration reaction between cement and water.

1.2. Motivation

In the current stage of 3DCP technology, the main challenge is attributed to the surface finish of the results due to the absence of the controllability in the extrudate cross-sectional geometry. Obvious lines or marks are typically observed in between layers in the 3DCP-created structures, even in a simple vertical wall as shown in Fig. 1.2a. In addition, as shown in Fig. 1.2, a staircase effect is clearly seen on 3DCP-created structures with curvy shape.

Fig. 1.2: Existing surface finish problem in 3DCP (a) jagged surface (b) staircase effect

Surface finish quality is an important aspect in 3D printing processes [15]. The surface finish problem becomes more severe in large scale 3DCP printing [16]. A rough surface might cause a secondary problem as the structure tends to wear faster than those with smooth surfaces [17-20]. In addition, stress concentration that might manifested itself at layer interfaces in a rough surface structure might reduce the bonding strength between layers [21]. Therefore, it is very important to control the surface roughness of the 3DCP-printed structure.

The ability to control the extrudate cross-sectional geometry during printing might lessen, if it does not totally mitigate, the surface finish problems. Without a proper extrudate deployment control, a jagged surface problem will occur as the extrudate freely deform during the process as illustrated in Fig. 1.3. In 3DCP process, the extrudate geometry does not necessarily follow the shape of the nozzle outlet due to the gravitational effect and material flowability properties. It is hence important to characterize and control the extrudate deformation process.

Fig. 1.3: A brief schematic for the jagged surface problem in 3DCP where (a) stands for nozzle shape (b) represents the ideal extrudate cross-sectional geometry, (c) represents the actual extrudate geometry in 3DCP process caused by extrudate deformation (d) stands for the ideal surface finish and (e) stands for actual surface finish problem – the jagged surface

The staircase effect is caused by a fixed-geometry nozzle that is typically used in the existing 3DCP process for printing complex curvy structures. Using a fixed-geometry nozzle, the extrudate geometry cannot be adjusted to comply to the designed geometry of the printed structure. Hence, the resulting output is a discrete-

geometric approximation the designated geometry consisting many ‘staircases’ [16, 22, 23] as illustrated in Fig. 1.4. The method to precisely control the extrudate needs to be developed to overcome the staircase effect in 3DCP.

Fig. 1.4: Reason for staircase to take place in extrusion-based 3D printing

Some work has aimed to improve the surface finish of 3DCP-created structures. Khoshnevis et al. [24] have implemented trowels on the nozzle to mechanically comb any excessive materials with trowels attached along the side of the nozzle. Roussel [11] concluded that changing the rheological property of the deposited material can noticeably decrease the deviation of the extrudate geometry. Kwon et al. [23] found that modifying the nozzle outlet shapes might affect surface finish quality. More commonly, rectangular-shaped nozzle outlet has been applied in the 3DCP process to create extrudate with closer-to-rectangular shape, which improves the surface finish quality in vertical-wall printing.

However, no existing methods have covered the gap to directly predict and control the final extrudate geometry. Methods including the utilization of rectangular

nozzle and the changeable-size square nozzles are simple, but with limited quality improvement and limited usable scenarios. Methods including the CC and post-processing are limited to the mechanically (passive trowel-shaving, active turning or milling) improving the printed wall structures during or after printing. This method has limited understanding on the extrudate formation process cannot be used if there is not enough space for the tools (trowels, drillings) near the object surface. The proposed method of adjusting the material's rheological parameters to limit the extrudate deformation is an interesting perspective, but there have not been many studies in this direction yet. It is important to control each line of extrudate because any problem on the individual extrudate lines would accumulatively affect the final quality of the structure.

Hence, it is necessary to cover the current gap in the 3DCP research and develop a methodology to control the extrudate formation during the printing process. The cause of the extrudate deformation during the deposition process must be studied scientifically, and the appropriate methodology to control this deformation must be developed. This would help to resolve the surface finish problem in 3DCP and improve the quality control in the current processes.

1.3. Objective

This study aims to understand the influential parameters in the extrudate formation process of 3DCP and to develop a novel method to control the shape of the extrudate. The parameters affecting the extrudate formation process are studied

by computational and experimental approaches. Based on the parametric study, the methodology to control the extrudate formation process is developed. A printing system that includes a dedicated printing kit with proper slicing algorithm and extrudate shape controller is developed to deliver controllable extrudate geometry for on-site 3DCP process.

1.4. Scope

To aim for the objectives of this research, a few scopes are targeted. In the first place, some 3DCP experiments are conducted under various printing parameters to characterize the process, which include nozzle designs, flow rates and printing paths. Extrudate geometries from different parameters are measured as the targeted parameters.

In the second place, a data-driven predictive model based on Artificial Neural Network (ANN) is adopted to develop the relationship between the nozzle shape and the extrudate cross-sectional geometry. The model will subsequently be used to design and fabricate a series of appropriate nozzles to print a non-straight wall. The structure printed using the designed nozzles will successively be benchmarked and compared to that printed with a static fixed nozzle that typically used in 3DCP to validate the approach.

Upon a successful completion of the validation, a mechatronic variable-geometry nozzle will be designed and developed to control extrudate geometry based

on the developed predictive model. This nozzle will be equipped with actuators to actively alter its outlet shape to comply for the designated extrudate shape that follow the printed surface structure.

Prior to the printing process using the developed active nozzle, an appropriate algorithm to extract the extrudate formation geometries from the designated structure is required. A dedicated *slicer* program will be developed that translates the 3D geometry of the structure to be printed and extract the desired extrudate formation for the entire printing path. In addition, a dedicated controller for the variable-geometry nozzle will also be developed to adjust the nozzle-outlet shape according to the extrudate geometry in real-time. To quantify the surface finish improvement achieved by the proposed nozzle, a surface roughness quantifier will be proposed and used.

It needs to be highlighted here, however, that this research will not cover an active feedback system to monitor the surface finish quality in real-time and control the variable-geometry nozzle accordingly. The data-driven ANN model will only be targeted for geometric quantities and overflow ratio as one of the printing parameters. The model will be less concentrated on other parameters, e.g. material rheological properties.

1.5. Thesis structure

This thesis is written in systematic order and consists of six chapters. Following the introductory chapter, in Chapter 2 the literature relevant to the research objective are covered in four perspectives. Firstly, the process and the material used in the existing 3DCP technologies will be explained and discussed. Secondly, the existing problems in the quality control of the 3DCP-created structures will be reviewed and the state-of-art in improving the surface finish quality in 3DCP field will be discussed. Thirdly, the surface finish improvement methodologies in other relevant research areas will be covered. Lastly, the literature review chapter is summarized, and the existing research gap is discussed.

Chapter 3 presents the analysis of the behavior of fresh concrete under different process parameters in computational and experimental methods. The behavior of concrete material is simulated under the non-Newtonian fluid condition. The reasons that have led to the extrudate deformation in line-forming 3DCP technologies are studied. The effect of the process parameters which affect the extrudate formation are analyzed using computational method and experiment method.

Chapter 4 presents the strategy to control the extrudate shape formation based on a predictive Artificial Neural Network (ANN) model. The ANN model aims to predict the extrudate geometry based on the impactful process parameters. Extensive amount of experiment has been conducted to gather information between the printing parameters and extrudate formation. The predictive model is then developed by a

carefully tuned ANN training process. The validity predictive modelling is verified by experiment.

Chapter 5 introduces the variable geometry nozzle outlet which can extend the previous extrudate control study into on-site 3DCP. The design and development of the printing setup is introduced. The control strategy and the slicing algorithm is also covered. One case study of an arch structure is printed to validate the approach.

Chapter 6 gives a conclusion on this thesis and comments on the potential impact to the development of 3DCP technologies. The deficiency in the current stage of the study and the possible future works will also be discussed.

Chapter 2. Literature review

2.1 The rise of 3DCP

The idea of 3D printing in construction was first introduced by researchers from the University of South California (USC) [8]. This technology combines the 3D printing process with printable concrete material to apply 3D printing for construction industry.

The development of 3DCP technology has become a heated topic in the past few years. In 2010s, researchers from the Loughborough University, TU/e and NTU have started some 3DCP research. After that, many other research institutes and companies have joined in the 3DCP area and since then the technology is being rapidly slung.

Existing 3DCP technologies rely on some fundamental printing processes. Contour Crafting technology, for example, is based on the extrusion-based cementitious material deposition technique. The combined powder-binding and printing-casting method is also utilized for large-scale printing purpose.

Regardless the underlying technologies of the 3DCP process, the surface finish quality is a common problem that can be observed in 3DCP-created structure. One typical surface problem is the jagged surface that can be observed in vertical wall printed structures. The less common but more serious problem is referred to the staircase effect, which typically occurs in curved-surface printing.

2.1.1. Extrusion-based methodology

In the extrusion-based 3DCP, the cementitious material is first mixed to the flowable condition and then forced through a hose to the nozzle by a pumping device. After the nozzle has reached its position on the printing trajectory and has started to move along the print path, the material inside the hose is pressurized by the pump and deposited on the printing board. Many extrudate lines on the same height forms a layer of printed pattern. Subsequently, the deposition of extrudate lines is repeated on top of previous layers until the whole structure is finished [25]. In this manner, the material is deposited one layer after another, and the nozzle automatically raises the height according to the layer height in the printing path. If high yield-stress and high-viscosity cementitious material have enough strength to support the weight of layers built above it, this layer-by-layer building method could continue until the entire printing path is finished.

Majority of the existing 3DCP technologies have utilized the extrusion-based process. The Contour Crafting (CC) used the gantry type 3D printed to create concrete structures [8, 22-24, 26-31] as shown in Fig. 2.1a. Researchers from the University of Loughborough have built giant gantry printers to perform 3DCP and achieved better mechanical strength thank to the application of high-performance extrudable concrete [5, 16, 21, 32-34] as shown in Fig. 2.1b. The Eindhoven University of Technology (TU/e) used another type of giant gantry printer and implemented precise process control of various experimental parameters in the process [9, 25, 35-40], where the result is illustrated in Fig. 2.1c. Researchers from Nanyang Technological University have adopted both robotic and gantry printer

solutions for the 3DCP [41-44]. A 1-meter long robotic printer with moving platform [45] and a giant industrial robotic arm were used for the printing as shown in Fig. 2.1e and f. Many companies in the construction industry have also adopted the extrusion-based process, including the Cybe, Sika (Fig. 2.1h), Winsun (Fig. 2.1g), Singapore HDB, etc. The U.S. military research department has also adopted the extrusion-based process, as illustrated in Fig. 2.1d.

Fig. 2.1: Extrusion-based 3DCP printers with different features (a) USC, (b) Loughborough University (c) TU/e (d) US Army (e) NTU large-scale printer (f) NTU cooperative printers (g) Winsun (h) Sika

Many large-scale structures have been created with the extrusion-based 3DCP concept. The direct-extrusion based 3DCP has created structures with large size and complex shape, like the curved-shape wall printed by Loughborough depicted in Fig. 2.2a and hollow wall with complex surface texture printed by Sika shown in Fig. 2.2b. The technology has also been utilized in the on-site creation of functional building elements, like the outer-wall of barracks printed by the US army (Fig. 2.2c), and the water-proof bathroom units for apartment printed by NTU shown in Fig. 2.2d. Modular concrete elements which could be assembled, like the bridge printed by TU/e shown in Fig. 2.2e and the five-story building assembled with many concrete walls printed by Winsun shown in Fig. 2.2f were also printed using the direct-extrusion technique.

Fig. 2.2: Large-scale structures created by 3DCP solutions (a) complex shaped vertical wall created by Loughborough University (b) vertical wall with complex shape texture created by Sika (c) barracks wall created by US Army (d) functional bathroom unit created by NTU (e) bridge created by TU/e (f) five-stories building assembled by 3DCP-created walls by Winsun

2.1.2. Other forming methodology

D-Shape printing is a selective powder-binding based 3D printing process that utilizes a gantry printer. This printer does not deposit flowable concrete like in the direct-extrusion method, instead, it deposits binder for the concrete powder. In a

layer-by-layer manner, the binder for the concrete is deposited on a selected part on every layer and this process is repeated until the printing finishes. When the printing finishes, the printed structure can be dug out from the powder bed [13], as shown in Fig. 2.3. Compared to extrusion-based methods, the D-Shape printing is the only technique which offers a higher degree freedom in design because the powder-binding technique does not require support structures, in such, there are no limitations on construction features. The binding technique also gives the hardened part a relatively high compressive and flexural strength [5]. Besides, in the selective binding method, one does not have to be concerned about the inhomogeneity of the material property during the process. However, the material waste of this process is significant, and the surface quality is rather unsatisfying.

Fig. 2.3: D-shape printing

Researchers have also studied the methods to combine the casting method with the 3D printing method to create construction-purposed structures. Researchers

from Hebei University of Technology first printed the outer-surface part of concrete element and the flowable concrete material was casted in the printed “concrete mold”. Many parts of concrete elements were created in this manner and the parts were assembled as the bridge structure shown in Fig. 2.4a. In a similar manner, researchers from MIT used plastic 3D printing to create a giant mold and casted concrete in the mold as shown in Fig. 2.4b. The method to combine casting and printing could be the possible solution to allow for reinforcement in 3DCP. However, the mold cracking because of the pressure exerted by the deployed concrete, the demolding method and the filling behavior have not been deeply investigated. The comparative study between the construction using 3D printed mold and that from the conventional-fabricated mold has not been reported either.

Fig. 2.4: Concrete structures created by combined printing and casting method (a) bridge created in Hebei University of Science and Technology (b) plastic mold for concrete casting created in MIT

2.1.3 Summary of the existing 3DCP technologies

The 3DCP technology has emerged fast in the past few years. With the help of numerous research institutes and companies, many large-scale structures have been created with 3DCP solutions. The 3DCP technology has demonstrated its capability to create complex-shape and large-scale structures for build and construction purposes.

The majority of the existing 3DCP technologies have utilized the extrusion-based printing process. This process is widely adopted because it is proven to be useful in creating large-scale structures in faster speed with minimum material waste. The extrusion-based process also has a low requirement on the material preparation because it utilizes fresh-mixed concrete material, which is a common material used in construction industry. The extrusion-based process is also flexible for on-site production and factory production purpose.

In literature, 3DCP technology has been reported as a potential construction method considering the fabrication speed, cost, environmental impact and safety. The level of automation is also leveraged by 3DCP as no underlying formwork is needed in the fabrication process, which significantly reduced the waiting time (for concrete to cure). In 3DCP, a drop in the labor cost has been witnessed because the creation of formwork, where in conventional construction method is very labor-intensive and costly, is no longer required. Other reports also show that 3DCP is more environmental-friendly compared to the conventional construction method.

2.2 Concrete material in extrusion-based 3DCP

Concrete material is widely accepted as 3D printing material for construction purpose, especially in the extrusion-based 3DCP. The material selection in the 3D printing targeting for construction industry needs to satisfy several conditions. First, the material has to be 3D printable, which means it is flowable at delivery stage and can be extruded by the nozzle at the corresponding place on the printing trajectory.

This is also named as printability of the material [34]. Second, the material needs to be 3D buildable, so it can sustain the weight of its own and the subsequent deposited layers quickly after deposition. This is named as buildability of the material [34]. Third, the material has to be affordable because the volume of material for building purpose in the construction industry can reach several cubic meters. The 3D printing material in polymers (25 USD per kilogram for raw material) and metals are very costly for this size of printing structures. Lastly, the material needs to have a high final strength after the curing process because safety is important for construction industry.

In construction purposed 3D printing, people have turned to cheaper and more durable material which is more suitable for large-scale construction and much cheaper than the polymer-based 3D printing material. Cementitious material, which is the most commonly used structural material in modern construction industry, draws a lot of attention [46]. Cementitious material is a term stands for the mixture consisting of many ingredients including cement binder, stabilizer, aggregates, reinforcement and water. After mixing, the fresh concrete mixture (which is also called mortar) has good workability and can be pumped and deposited in the 3D printing technology. Then, the mixture undergoes a phase transition from liquid state to subsequently solid state because of the hydration reaction between the cement and water. This property is similar to the material used in 3D printing [47]. This setting time of the concrete can be controlled by adjusting the ratio of different composition in the concrete. The hardened cementitious material has high performance in the

mechanical strength perspective and is quite affordable [36]. Thus, this material draws a lot of attention from the study of construction-purpose 3D printing.

In the 3DCP, because the material have to be extrudable through the nozzle which is around 30×10mm [25], large aggregate needs to be avoided in the material composition. The material is closer to “mortar” which has a limited particle size and is more homogeneous than the concrete. A number of work also assume this kind of material as a homogeneous, single-phased fluid [48]. Under this assumption, the flow of cementitious material can be described by constitutive equations subject to the material’s rheological properties.

The rheological property of the material has significant impact on the printability and buildability of the material. Two viscous fluid model are mostly used in to describe the flow behaviour of fresh cementitious material, namely the Bingham Plastic Model and the Herschel–Bulkley Fluid Model. The Bingham Plastic Model is the most commonly adopted rheological model for cementitious material analysis [48] and Herschel-Bulkley Model is a ‘parent’ of Bingham Model and takes shear thinning and shear thickening behaviour into account. The constitutive equation for Bingham Plastic Model is shown in Eqs. (1):

$$\frac{\partial u}{\partial y} = \begin{cases} 0 & \tau \leq \tau_0 \\ (\tau - \tau_0)/\mu_\infty & \tau > \tau_0 \end{cases} \quad (1)$$

This is commonly written in the form of Eqs. (2):

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (2)$$

Here $\partial u/\partial y$ (or $\dot{\gamma}$), is the shear rate of the fluid, τ is the shear stress and τ_0 is the yield stress property of the fluid. The μ_∞ is the plastic viscosity constant. This models that the shear rate, $\partial u/\partial y$ (or $\dot{\gamma}$), is directly proportional to the amount by which the applied shear stress exceeds the yield stress.

As for the Herschel-Bulkley Model, the constitutive equation of the model is shown in Eqs. (3):

$$\tau = \tau_0 + k\dot{\gamma}^n \quad (3)$$

The shear stress and yield stress are the same with the Bingham Model, the k is the consistency index and n is the flow index. If $n < 1$ the fluid is shear thinning, if $n > 1$, the fluid is shear thickening, if $n = 1$, the fluid is Newtonian, and this model is identical to the Bingham Model.

These rheological properties are crucial factors affecting the behavior of material in 3DCP. The yield stress is the most important parameter because it affects the both the printability and buildability of the material. If the yield stress of the material increase, the buildability of the material increases but extrudability decreases. If yield stress decreases, the material is easier to extrudate but hard to be buildable. The plastic viscosity constant also affects the extrudability of the material. If the viscosity is high, the flow rate of the material is retarded in the hose and the

extrudability of the material decreases. A detailed discussion on the impact of rheological parameters to the final extrudate formation was given by Roussel [11].

In the existing practices of 3DCP, the material will be carefully designed to match the optimized rheological property for the printing. The rheological property of the material is particularly important to the cementitious material because the buildability of fresh concrete does not rely on the quick-hardened material like thermoplastic concrete. Instead, the buildability of the cementitious material relies totally on its thixotropy and yield stress. After hardening, the concrete structure can carry heavy weight, but this hardening takes hours to finish. The hardening property of printing concrete is analyzed by strength correlation with time [33]. This means the material will stay in the state between fluid and solid during the printing process, in such the flowability of material persists. Loading the printed structure under this situation is risky and problematic because the structure may not withstand its own weight before the concrete is getting hardened. As a result, the maximum height of the printing is limited by the buildability of the material and these rheological properties have to be carefully adjusted before the material composition is finalized.

The rheological property of the material also has strong influence on the extrudate formation process in 3DCP. The rheological property determines the material's ability to resist deformation. This kind of deformation is named as the slump property of the material and the extrudate formation under different kinds of printing parameters is highly related to the slump property. These properties are crucial parameters in simulation-based analysis and also in experiment printings.

The final strength of the structure after the hardening process is important for construction industry. The compressive strength of the printed product can be affected by the nozzle geometry because the nozzle geometry potentially affects the size and number of the voids within the structure. It has been found that the structure printed with a rectangular-shaped nozzle has a better compressive strength comparing to the structure printed with a round-shaped nozzle [41]. Interlayer bonding strength is another important aspect of the structure's mechanical performance. In the literature, the analysis of interlayer bonding mostly focuses on the printing time gap between each layer [49] and the material composition [50, 51].

2.3 State-of-art for improving printing quality in 3DCP

2.3.1 Surface finish and compactness problems

Jagged surface problem, which is typically observed in vertical wall structures, and the staircase effect, which occurs at curved-surface printing, are two common surface quality problems in 3DCP process. The problem might cause gaps on the printed structure that could reach up to several millimeters in the large printing scale of 3DCP.

Jagged surface problem can be observed in nearly every product created by 3DCP technologies. Because of the flowable nature of concrete material, the extrudate lines will deform after deposition. Hence, obvious gaps or mark lines will

exist between layers that are referred to as a jagged surface. The gaps between layers is affected by the nozzle size and the level of deformation for the material. These gaps can be observed easily on many printed parts, for example on those shown in Fig. 2.5.

Fig. 2.5: The reason for jagged surface problem to take place in 3DCP where (a) represents nozzle shape (b) shows the deformed extrudate (c) shows formation of gap between layers (d) shows the gaps on a 3DCP-created wall and (e)(f) as two examples of jagged surface in 3DCP

The second surface quality problem that typically appears in curvy structure, the so-called staircase effect, is less observed as not many complex surface structures

are printed with 3DCP. However, this problem would be inevitable when the 3DCP technology is employed for complex-shaped structures [16], as discussed in Section 1.2.

Similar surface finish problem could be observed also in any extrusion-based printing such as FDM. Nevertheless, the magnitude of the roughness in a common FDM process is significantly different. The nozzles of the FDM machine are generally very small (0.3~1mm for a FDM) [52]. In 3DCP method, however, the nozzle size is many orders bigger as the target product is a building-size object, which is a way much larger than the target of typical 3D printing objects. In common applications, a rectangular-shape nozzle used in 3DCP has the size range from 30×10mm to 40×10mm, while the round-shape nozzle has the diameter range from 6-25mm [25]. This feature has made the surface roughness problem becoming more serious in 3DCP.

In addition, the lack of control on extrudate formation affect the compactness and surface finish of the printing structures. Different extrudate in the printing affect the stacking between different print roads, whereas the stack affects the compactness of the printed structure [33] that corresponds to the mechanical strength. In 3DCP with a round nozzle, the compactness of the printed part is relatively low and voids between print paths will appear and obviously observed as shown in Fig. 2.6 [33]. This case will lead to another problem related to its mechanical strength [34].

Fig. 2.6: Compactness issue caused by bad stacking of extrudate lines

2.3.2 Adjusting the nozzle shape

Adjusting the nozzle shape is found to be helpful in creating high-quality printed parts. Since the shape of the nozzle constrains the flow of the extrudate before deposition, the nozzle can easily influence the shape of the extrudate. The extrudate would naturally exhibit a similar shape to the nozzle outlet when it just left the nozzle. Hence, it is intuitive to improve the surface finish quality by adjusting the nozzle shape.

Currently, the two commonly adopted nozzle shapes in 3DCP are round and rectangular shaped nozzles. The round nozzle is easier to be applied in the 3D printing system as the round nozzle is not constrained by its orientation. The 3DCP printer with a round nozzle is easier to build than that with a rectangular nozzle as the latter needs to control its facing direction, thus it requires an additional rotational degree-of-freedom (DOF). However, the compactness of the part created with round nozzles are relatively low and voids between print paths are very obvious in the results which might lead to low mechanical strength.

On the other hand, the rectangular-shaped nozzle generally has a better printing quality than the round nozzle. The extrudate shape which is close to rectangular could reduce the voids generated between layers and, hence, improve the mechanical strength of the structure. The surface finish quality could also be improved with the rectangular-shaped nozzle (this will be shown in the preliminary experiment result in Section 3). As a result, most existing 3DCP solutions used rectangular-shaped nozzle to print with better quality. From the literature and the observation of videos showing printing process, most existing 3DP including USC, NTU, TU/e, Winsun, Sika, etc. have adopted the rectangular nozzle, while only the printer in Loughborough University adopted the round nozzle.

Experiment on testing the surface finish for part printed with different nozzle shapes was performed by Kwon et al. [23]. The test is based on the Contour Crafting experimental setup and, instead of using concrete, a non-slump extrudable material is used. Two different nozzles are used, i.e. rectangular and elliptical ones. However, the paper did not present supporting evidences on the result from different shapes of nozzle. The authors focused mainly on the visual behavior of the product and the difference in the visual behavior of different printed parts were not clearly observed. Moreover, different nozzle shapes were combined in the used of attached trowels, which made the effect of nozzle shape even harder to be distinguished.

Xu et al. [53] has proposed the concept to build an assembly that can change the size of a square-shaped nozzle during the printing as shown in Fig. 2.7. The study aims to increase the printing flexibility of the conventional fixed-shaped rectangular

nozzles. The quality improvement of the parts created with the “size-changeable square nozzle” still needs to be evaluated.

Fig. 2.7: Schematic drawing of square nozzle with adjustable size

2.3.3 In-process and post-process surface finishing

Researchers from USC have developed a method to perform “in-printing process surface finishing” that is referred to as the Contour Crafting (CC) with obvious surface finish quality improvement. Instead of performing a post-surface-finishing-process, a few trowels are attached on the side of the nozzles to comb the surface during the printing.

In CC, trowels are applied on the vertical and horizontal directions and the trowel constrains the extruded flow by cutting off excessive extruded material from the printed body [28]. The length of the trowel is longer than the height of one-layer

printing path. During the printing, the trowel can move with the nozzle and remove the material which expand over the pre-designed printing path because of the overflow. The material cut by the trowels lost the binding with the surface and can be easily removed from the printed part after it is hardened. This technology, which is defined as “using the mold as part of the moving component” [5], constrains the material flow during the printing so that the surface finish of the printing is significantly improved [23].

Mechatronic assembly and part dynamic control can be applied in the CC technology to make the mold flexible to more external shapes. This technology can be used to smoothen the surface which is more complex than orthogonal wall by dynamically controlling the trowels. With the aid of sensors and controllers, the trowels can change its orientation and accommodate to different printing path and improve surface during for different shapes in printing as shown in Fig. 2.8 [27].

Fig. 2.8: Nozzle with trowel attachment used in CC

However, despite the improvement of the surface finish structures offered in CC method, this technology is limited to straight walls. Only straight walls have been tested with the CC because the trowels have limited freedom for geometric variation. The length of the trowel cannot change, and the shape of the trowel cannot vary during the printing. These limitations prevent the CC to accommodate to complex outer-surface curvature. CC attempted to print a dome shape structure as shown in Fig. 2.9 [22], however, the surface finish quality of the printed structure is not improved because of the trowels limitations . In the process, the trowels have to be lifted to avoid scratching the deposited layers and that limits the CC's usage in curved-outer shape curvature. Besides that, the use of trowels could only be applied to limited conditions and is mostly applied to the outer-surface improvement of a

vertical-wall. The trowels need to be extended lower than the printing level to improve the surface finish and this could cause collision to the printed structure. Without a proper control, the trowels could easily cut into the printed structure and damage the printing. Even with proper controlling, the use of trowels is still mostly applicable to simple outer-surface improvement, which further limits the use of CC.

Fig. 2.9: Staircase effect on the dome shape created by CC

Besides the in-process printing method like in CC, the post-processing method like turning or milling on the printed concrete structure can also improve the surface finish quality of the printed part. The post-processing method has the best performance against the surface finish problems. However, this method is extremely time and energy consuming because the hardened concrete has high mechanical strength. Only the company Cybe has tried the post-processing solution on 3DCP-created part as shown in Fig. 2.10.

Fig. 2.10: Post-processing of 3DCP-created structure

2.3.4 Modify printing parameters which affects final extrudate formation

A detailed discussion on the rheological requirements to control the extrudate final geometrical dimensions and surface quality was presented by Roussel [11]. Roussel analyzed the standard direct-extrusion deposition process, in which the material prior to deposition is sheared. It spreads on the printing support or on the

previous layer. As it slows down, it builds up a structure and a yield stress until it reaches its final shape.

The study from Roussel [11] has concluded that the final extrudate dimension depends on the rheology of the printable material, on flow rate and on the nozzle geometry. This question is, up to the author knowledge, a very opened research field but also an unavoidable one for the design of printing heads and nozzles along with the precise control of the layer shape as a function of the ability of the printable material to flocculate upon deposition.

2.3.5 Summary of the state-of-art in printing quality improvement

Surface finish problem and compactness issue are major problems in the further development of 3DCP. Surface quality problems such as jagged surface or staircase effect commonly occurs on the 3DCP-created product because the extruded geometry does not necessarily follow the shape of the nozzle outlet due to the effects of gravity and material rheological properties. Although the quality of many extrusion-based 3D printing processes are limited by extrudate deformation or staircase effect [15], the surface roughness problem becomes more apparent in 3DCP due to the large printing scale [16]. Surface roughness is important for the printing quality because a rough surface tends to wear more quickly than a smooth surface

[17-20]. In addition, the compactness of the structure might be affected. Therefore, it is very important to control the surface roughness of the 3DCP-printed structure.

No existing methods for improving the surface quality by applying a directly control the extrudate formation process. Some methods are available, for instance by utilizing a variable-size square nozzle, but with the quality improvement is rather limited while the usable scenarios are also limited. CC method and other post-processing methods are limited to the mechanical improvement through shaving, turning or milling. Despite the simplicity, these methods have no knowledge on the extrudate formation process and cannot be used on a case with limited the tool enough space (trowel or drilling space) in the vicinity of the object. The proposed method of adjusting the material rheological parameters to limit the extrudate deformation is an interesting perspective, but there have not been thoroughly studied in this direction.

Hence, it is necessary to develop a method that can predict the final geometrical dimension of the extrudate as a function of the influential parameters in the printing [11]. Many printing parameters, including the nozzle outlet shape, material flow rate, nozzle travel speed, nozzle standoff distance, and rheological performance of material could significantly influence the extrudate formation. The predictive method should be developed to control extrudate formation based on these influential parameters, and each extrudate lines should be improved with the model and achieve the detailed quality control in the 3DCP.

2.4 Methodology to control extrudate dimension in relevant research fields

2.4.1 Simulation approach in molten ceramics extrusion

Computational analysis has been utilized to understand the extrudate formation process in 3DCP and also in other field of extrusion-based 3D printing technologies. The simulation is consisting of two stages: one extrusion stage and one deposition stage. In the extrusion stage, the cementitious material inside the nozzle is pushed by the pressurized inlet and extrude from the nozzle orifice. In the deposition stage, the extruded material is deposited on the substrate because of gravity. The simulation is a moving-boundary problem because the nozzle is supposed to move along the printing trajectory during the printing and extrude material to the correct location. There are many factors to be considered for the simulation problem. These parameters include the shape of the nozzle outlet, rheological property and the viscosity model for the material flow, the movement speed of the nozzle, the pressure at the nozzle inlet, the standoff distance of the nozzle, etc. Different simulation method can be used to analyze the behavior of fresh concrete.

Theoretically, the final geometry of the extrudate can be calculated analytically from the material flow during the deposition. The printed cementitious material can be assumed as a single-phase non-Newtonian fluid and the flow

behavior of material follows the Navier-Stokes equations (Eqs. (4) and (5)) because the flow channel has a much larger dimension than the particles [48].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \times \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} \quad (5)$$

In the literature, simulation has been carried out to study the influence between the nozzle orifice shape and the quality of the surface finish in 3DCP [23]. This research used the Computational Fluid Dynamics to calculate the behavior of clay material during the 3D printing. In the study, the simulation is simplified by modeling the clay material as a homogeneous material which can be considered as a single-phase laminar fluid. The simulation utilized a commercialized CFD package “Flo++” to solve the problem. The mesh and the simulation result for the extrusion in the rectangular nozzle are shown in Fig. 2.11. From the simulation, the extrusion flow at the outlet does not have homogeneous speed because the wall and the side trowel retard the flow. In the 3DCP, the computational analysis of the printing process is not adequate because the number of studies is limited. However, the extrudate formation problem in fused-direct-extrusion 3D printing area is extensively studied. Also, the behavior of cementitious material flow at fresh stage has also been studied in different scenarios. These studies can be referenced to solve the problem in 3DCP.

Fig. 2.11: Simulation of nozzle orifice effect in printing process [23]

Except for 3DCP analysis, the extrudate formation problem has been computationally studied in fused deposition of ceramics and polymers. This study attempts to analyze the extrudate formation and use the reverse prediction to optimize the shape extrudate by changing the shape of nozzle. In this kind of extrudate formation problem, the die swelling effect which stands of the expansion of viscoelastic fluid after extruded from an extrusion die [54], is commonly observed. Similar material behavior can also be observed in 3DCP. As a result, the shape of the extrudate will deform and deviate from the nozzle shape after extrusion, even though it will persist some features of the nozzle outlet. The cross section of the extrudate tends to slump due to the combined effect of many factors, including the die swelling effect and gravity.

This kind of phenomenon has been recorded in simulation of 3D printing with molten ceramic [55]. In his experiment, the non-Newtonian flow of molten ceramic

was extruded from a rectangular shape nozzle. The flow of the viscous material follows the Navier-Stoke equation. The rheology of the molten ceramic is considered as thermoplastic shear-thinning material and a power law viscosity model is used to analyze this material. From the simulation, die swelling effect is obvious in the extrudate formation in the viscoelastic material printing. Optimized nozzle design might be able to counter a die swelling effect and produce extrudate with the designated shape. Based on viscoelastic behavior of the material and the simulation methodology, a ‘reverse engineering approach’ is used to find the optimized shape of the nozzle based on the desired extrudate shape [55]. The study was carried out based on a model with appropriate flow parameters in “PolyFlow”. This simulation software is also recognized for its function of reversely simulate the shape of extrusion die to produce the desired extrudate shape. The author named this method as reverse engineering. The simulation result shows that the size of the extrusion from the square nozzle is larger than the nozzle size itself as shown in Fig. 2.12a. To print a square extrudate, the nozzle predicted by reverse engineering method is close to a star-shape as shown in Fig. 2.12b. [55]

Fig. 2.12: Die-swelling phenomenon in fused deposition of ceramic [55]

The die swelling effect plays an important role to the quality of 3D printing with viscoelastic material [56]. In the research of simulation on a large-scale FPM process, a large industrial robot was utilized together with a fused pellet extrusion system to deposit fused pellet along the printing path. The gap and overlap between the path cause inevitable void density problem in the deposition process as the extrudate has an elliptical cross-section. The study of FPM also proposed the use of star-shaped nozzle to produce an optimized rectangular-shaped extrudate and to minimize the void inside the printed structure as shown in Fig. 2.13. However, the effect of using star-shaped nozzle to improve printing quality has not been confirmed experimentally. A numerical modeling of extrusion in FDM to study the parameters influencing the shape of the extrudate was also presented in [57].

Fig. 2.13: The nozzle shape required to created ideal filament shape in FPM

In the 3DCP, the nozzle can be tested experimentally because the nozzle outlet can be designed and fabricated for experiment. The study of material deformation occurred during printing could be very helpful in obtaining a desired extrudate shape. If this method could be validated experimentally, the rough surface finish issue in 3DCP can be solved.

2.4.2 Machine learning approach

Machine learning technique is seen to be an alternative to the predictive model of the concrete extrudate geometry. The basic idea of a machine learning approach is to train a model to recognize the pattern from the training dataset that correlates the input parameters and the output state, which subsequently, the model can be used to predict the output for given input entities. The artificial neural network (ANN) is a computational implementation of the machine learning technique, which is capable of developing a predictive model directly by feeding a proper training data. This machine learning method has been proven to be useful in many areas, including hand-writing classification, speech recognition, image classification [58-60].

A typical structure of ANN consisting of an input layer, an output layer and several hidden layers is shown in Fig. 2.14. Controllable variables, in this case are the printing parameters, are fed to the input layer and subsequently, process the information through the hidden layers and finally represent the output, where in this case is the predicted extrudate geometry, in the output layer. Each layer might be represented by many neurons, where each neuron comprises a weightage and a

specific bias. The information is transmitted from one neuron to another neuron in the subsequent layer by edges, which means that each neuron can affect all the neurons in the next layer [61], iteratively until it reaches the output layer. By properly tuning the weightage and bias in all neurons, the overall network will represent the model that correlate the input and output entities. After being properly trained with data, the ANN model could instantly predict the output based on a given set of input entities.

Fig. 2.14: Schematic of a typical ANN model

There are several studies in 3D printing area which used the machine learning method to predict surface roughness, like in the FDM printing [19, 20]. Machine learning method has been proven useful also in predicting flowability and

mechanical strength of concrete [62-66]. From literature, there is an evident of a new trend to introduce machine learning in 3DCP-related areas [67].

Wu et al. [19] and Li et al. [20] have summarized that only a few researches has been reported on predicting the surface roughness of additively manufactured parts using multiple sensors and machine learning algorithms. This research gap was found from a system review focused on surface roughness of FDM conducted by Turner et al. [68] which include the discussion on existing approaches to surface roughness prediction [15, 69, 70]. Hence, a data-driven machine learning method was developed to predict the surface roughness of an additively created structure in this study.

Machine learning has also been adopted to predict the concrete behavior in the fresh state and hardened state. The method has been utilized to model the flow performance of self-compacting concrete [71-73]. It has been used in the prediction of concrete slump flow test as shown in Fig. 2.15. It has also been utilized to predict final compressive strength of the concrete mixture based on the composition of material [65].

Fig. 2.15: ANN method to predict the slump of self-compacting concrete

As a summary, machine learning method has been widely applied in the prediction of the flowability of the self-compacting concrete material and the overall predicting performance is satisfying. This has proven that machine learning method could be used on analyzing the concrete flowability. The 3DCP process is by its process nature related to the concrete flow problem. Although the 3D printing involves a lot more parameters than only concrete composition, it is possible to apply machine learning method to achieve prediction on the extrudate formation process.

2.5 Summary of literature review

The extrusion-based printing method is the most adopted method in existing 3DCP technologies. However, this method suffers from serious limitations in the quality control. In the existing surface finish improvement methodologies, the study of the relationship between the extrudate formation process and the influential process parameters is inadequate. The current improvement technologies used mechanical method, such as trowels to mechanically improve the surface finish, but this approach can only be useful in limited scenarios.

Finding the relationship between the final extrudate geometry and the process parameters is a pre-requisite to resolve the quality control problem in 3DCP. Several previous studies have discussed the possible relationship between the final extrudate geometry and the influential process parameters, but the relationship still needs to be proven by experiment or calculations.

In other research field, the extrudate formation process has been studied by computational method, including the CFD simulation and the machine learning method. The CFD simulation is mainly utilized to analyze the printing parameters and understand their physical effect on extrudate geometry. The machine learning method, on the other hand, is used as a black box model to directly predict the final surface roughness of the printed product.

As a conclusion, two obvious research gaps exist in the current 3DCP fields. First, the effect of different process parameters on the extrudate geometry has not been fully explored. Second, the method which can control the final extrudate

geometry needs to be discovered. By covering these two research gaps, the final geometry in each line of the extrudate can be controlled, and the surface finish problem could be resolved. Hence, it is necessary to study the formation process and the influential process parameters in 3DCP using computational and experimental approaches. As a complementary, a CFD simulation is utilized to analyze the printing parameters that affect the extrudate formation process. The influence of different process parameters is studied by conducting 3DCP experiments on a controlled-parameter basis. Then, the approach to control the extrudate geometry is developed considering the effect of surface finish improvement and the practicability in the on-situ 3DCP process. A data-driven predictive modelling methodology for extrudate geometry based on Artificial Neural Network (ANN) will be adopted to develop the relationship between nozzle shape and extrudate cross-sectional geometry in extrusion based 3DCP.

Chapter 3. Understanding 3DCP and the influential process parameters

3.1. Introduction

As explained in the first and second chapters, the surface finish quality of the extrusion-based 3DCP is affected by the extrudate formation process. However, a systematic discussion between the printing parameters and the extrudate formation is still missing in the area.

In this chapter, the experiment setup of a typical extrusion-based 3DCP system will be introduced. The printing system is located in the Singapore Center of 3D Printing (SC3DP). The parameters involved in the 3DCP process would be discussed and their influence on the extrudate formation process will be analyzed using experimental and computation methods. This chapter aims to provide the reader with a background of the extrudate formation process in 3DCP.

3.2. Brief explanation on 3DCP printer setup

A typical extrusion-based 3DCP system consists of three parts. The first part is the material feeding system that pressurizes the concrete material and forces it through the nozzle. Another part is the nozzle-motion system, which can move the nozzle along the designated printing trajectory with the desired printing speed and

deposits the material along the trajectory. The last part is the nozzle, where the material is extruded during printing. In this chapter, the setup used in this research as one of the facilities in the Singapore Center of 3D Printing (SC3DP) will be presented.

The pumping device in the setup is shown in Fig. 3.1. The concrete material at flowable state after the mixing is fed to the pump through the material inlet. The motor pump rotational speed is controlled by an attached control box, while the roller stator as the feeding screw is driven by the motor. During the operation, the motor drives the roller stator to push the material out of the material outlet. The pressurized material is then delivered to the nozzle by a delivering hose. The pumping device directly controls the feeding of material and the volume flow rate of the material extrusion in the 3DCP process.

Fig. 3.1: A pumping device using auger screw mechanism

The nozzle-motion system is used to move the nozzle along the pre-designed printing trajectory, as shown in Fig. 3.2. Both gantry and robotic arm systems are utilized in SC3DP. The kinematic of the two moving systems are different, but the result of the two systems are similar. The nozzle-motion system determines the printing speed and the nozzle standoff distance, which play an important role on the extrudate formation process in 3DCP.

Fig. 3.2: A robot-based nozzle-motion system

The nozzle is the place where the material is extruded out and get deposited. The shape and dimension of the nozzle outlet and even the design of the nozzle flow channel could vary for different printing purposes. Fig. 3.3 depicts different types of nozzles. The nozzle plays an important role in the extrudate formation process, the nozzle shape constrains the material before extrusion and affects the final extrudate shape, as discussed in Section 2.3.2, where the nozzle dimension affects extrudate dimension and the flow channel design affects the material flow homogeneity.

Fig. 3.3: Nozzle outlets with different sizes, different shapes and different delivery channels

Except for these aforementioned printing parameters, the extrudate formation process is affected by the material rheological properties, as mentioned in Section 2.2. The material is a mixture of different kinds of powder before mixing. However, the material exhibits flowability property after mixing, so it can be extruded and deposited (see Fig. 3.4). The material viscosity will define the actual volume flow rate, while the deformation of extrudate under gravity is affected by the material yield stress.

Fig. 3.4: Material in different printing stages (a) powder form before mixing (b) mortar form after extrusion

3.3. Discussion on the relationship between extrudate formation and printing parameters

The extrusion-based 3D printing process consists of two steps. First, the material is pumped through the pipe until the printing head or nozzle. Second, the printing head is moved to the designated positions to deposit the extruded material layer by layer. Roussel [11] discussed the requirement of printable materials. The material should be flowable enough to be pumped through the pipe, while it should also be strong and stiff enough to keep the shape and also to sustain the weight. After deposition, the material in one layer is cured for a period of time before another layer of material is deposited beyond. Since the fresh state material is pumpable and flowable, the filament in one layer tends to have slump and deformation will occur after being printed and deposited. It could further deform after layers of material are deposited on top.

The final geometrical dimension of the extrudate can be calculated by analyzing the material flow during the deposition. Because the flow channel has a much larger dimension than the particles, the printed cementitious material can be assumed as a single-phase non-Newtonian fluid in the computational analysis. Given a specific boundary condition, the final state of material flow can be solved by the Navier-Stokes equations [48]. As a result, there exists a functional relationship f which can model the final geometrical dimension of the extrudate, namely the final state of flow $\mathbf{E}$ given a set of boundary conditions $\mathbf{C}$, as indicated in Eqs. (6). This means the geometrical dimension of the extrudate ($\mathbf{E}$) can be calculated with a specific set of flow boundary conditions ($\mathbf{C}$), which represent the printing parameters in the 3DCP experiments.

$$\mathbf{E} = f(\mathbf{C}) \quad (6)$$

Before modeling the functional relationship f , the experiment parameters affecting the boundary condition $\mathbf{C}$ needs to be determined. These parameters could include the shape of the nozzle, the shape of the nozzle channel, the nozzle traveling speed, the material flow rate and other rheological properties of the material, etc.

The shape of the nozzle outlet has an important effect on the geometry of extrudate. The shape of the nozzle outlet ($\mathbf{D}$) constrains the shape of material before extrusion and that shape is the initial shape of the extrudate before further deformation. The material used in the printing is a viscous fluid with Reynold number smaller than 1, so the deformation of the material after leaving the nozzle will not be too large. The shape of the nozzle can be modified to control the geometry

of extrudate, like the use of rectangular nozzles in many institutes to produce extrudate geometry closer to rectangular.

Among the process parameters, including the pump feeding rate, the printing speed of the nozzle and the size of the nozzle outlet, can be combined in a new term named “flow ratio”. This “flow ratio” of the material, ε , is defined as a ratio between the material volume flow rate (Q) to the ideal material deposition rate as shown in Eqs. (7):

$$\varepsilon = \frac{Q}{v_t * A} \quad (7)$$

An ideal material deposition rate is the product of the nozzle feed rate (v_t) and the nozzle outlet area (A). Obviously, this deposition rate is the volume of material that should be deposited in the printing, and the (Q) stands for the material feeding rate from the pump. When the flow ratio is less than 1, the material flow rate cannot match the deposition rate, which might result in an underflow condition. On the contrary, when the flow ratio is greater than 1, the material feeding rate is higher than the deposition rate, and overflow might happen [42]. Theoretically, any variations in flow ratio will lead to different extrudate geometry. If severe overflow or underflow happens, the final extrudate geometry is significantly affected.

The rheological properties of the material have a significant effect on the final geometry of extrudate. The dynamic yield stress corresponds to the deflocculated microstructure. It could affect the pumpability and flow rate. The dynamic yield stress also affects the process for the deposited material to stop flowing and build up

strength [74]. The static yield stress is another rheological parameter that affects the geometry stability of extrudate in the individual strength-based layer and collective strength-based layer [11]. The concrete material exhibits different yield stress at the static state because of particle flocculation and CSH bridges [75, 76]. The deposited material at the static state is subjected to gravity shear force caused by its own weight and the weight of subsequently deposited layers. If the shear force exceeds the static yield stress, the extrudate will slump and expand in width. If the shear force does not exceed the static yield stress, the material may still exhibit elastic deformation and this deformation is affected by elastic modulus (G). Thus, in the perspective of the rheology of cementitious materials, the 3D printable materials should have low dynamic yield stress and high static yield stress and modulus. Qian and Kawashima [77] found that the discrepancy between dynamic and static yield stress is related to thixotropy. Thus, high thixotropic materials are preferred [78].

The printing parameters which have an impact on extrudate formation can be summarized in Fig. 3.5. It can be observed that the “nozzle geometry” factor is different from other factors as it appears as a direct factor. The geometry of extrudate is directly affected by the nozzle geometry. The other influential parameters are less significant to the extrudate formation but more to the deformation factors. Hence, the rest of this chapter mainly focuses on exploring the feasibility of controlling extrudate geometry by adjusting nozzle geometry.

Fig. 3.5: The printing parameters affecting the extrudate formation process in 3DCP

3.4. Parameter: nozzle shape in straight-line printing

3.4.1. Methodology

As discussed in Section 2.2, an implicit function, f , can be used to represent the relationship between the nozzle shape to the extrudate shape as $f(D) = E$, when only the nozzle shape D is considered in all the boundary conditions C . Here, D stands for the geometry of the nozzle and E stands for the geometry of extrudate.

In the experiment, the shape information of the nozzle and extrudate can be measured from the printed samples. Mathematical tool was utilized to find the relationship between the shape of nozzle and extrudate. To analyze the relationship, an assumption is made that for every point on the nozzle there is a specific implicit function linking it to the corresponding point on the extrudate because the impact of all other factors varies for different points. For example, the falling impact factor would mostly influence the points near the bottom of the extrudate, in such, for each point there exists a dedicated function, f , to be considered. In addition, this relationship is made based on an assumption that each point on the side of nozzle only affects the corresponding point on the cross section of extrudate. This assumption is accepted only when the target shape at its side is smooth, where other points on the nozzle would also affect the studied point. However, when an abrupt change occurs between the position of two close points on the nozzle, these two different points would affect each other and the existence of f is affected.

The implicit function f is hard to be analytically calculated, so iterative parametrical method is used to find the target extrudate shape based on the experimental data of the shape of nozzle and extrudate. In the iterative method, the shape of target extrudate is represented by a set of sample points as $T_1, T_2, \dots, T_{12}$, similar to the sample points for nozzle and extrudate. The shape of extrudate can approach the target shape by solving the Eqs. (8) and (9).

$$F_n = 0 \quad n = 1, 2, \dots, 12 \quad \text{where} \quad (8)$$

$$F_n(D_n) = f(D_n) - T_n = E_n - T_n \quad n = 1, 2, \dots, 12 \quad (9)$$

Parametrical methods can be utilized to iteratively solve equations (1) and (2). In each iteration, the shape information of nozzle and extrudate are D_n and E_n and the number of iterations is represented as i . In the i^{th} experiment, $f_n(D_{i,n}) = E_{i,n}$. In the $(i - 1)^{th}$ experiment, $f_n(D_{i-1,n}) = E_{i-1,n}$. The implicit function f_n is the same for different iterations because the nozzle shape and experiment parameters remains constant. Based on these, parametric methods can obtain the nozzle design for the next iteration by solving $D_{n,i+1}$ where $f_n(D_{n,i+1}) = T_n$.

Two parametric methods are used to approach target shape T_n , namely the Newton's method and the Bisection method. In every iteration, the two different methods are applied to obtain the nozzle design for the next iteration. For Newton's method, the set of points for the new nozzle design is calculated by solving the Eqs. (10):

$$\begin{aligned}
 D_{i+1,n} &= D_{i,n} - \frac{F_n(D_{i,n})}{F'_n(D_{i,n})} \\
 &= D_{i,n} - \frac{F(D_{i,n})}{\frac{F(D_{i,n}) - F(D_{i-1,n})}{D_{i,n} - D_{i-1,n}}} \\
 &= D_{i,n} - \frac{E_{i,n} - T_{i,n}}{\frac{E_{i,n} - E_{i-1,n}}{D_{i,n} - D_{i-1,n}}}
 \end{aligned} \tag{10}$$

where $n = 1, 2, \dots, 12$ and $i = 2, 3, 4, \dots$

From those acquired data and the nozzle shape data $D_1, D_2 \dots D_{12}$, Then, the CAD model of the nozzle can be designed and the nozzle with the desired shape can be fabricated and then tested in the experiment and a new iteration started. This continued until the obtained extrudate shape was close to the target shape $T_1, T_2, \dots T_{12}$.

During the continuous iteration, all the points $E_1, E_2, \dots$ and E_{12} on the printed extrudate would be closer to the target points $T_1, T_2, \dots T_{12}$. After each iteration, the error for each point could be calculated and the printed extrudate was compared with the target extrudate geometry. This iteration process would be continued until all the points are close enough to the target.

In this way, the extrudate geometry can be approached closer to the target extrudate geometry by iteratively adjusting the nozzle shape.

3.4.2. The experimental setup

This section aims to estimate the feasibility of improving surface finish quality in straight-line printing by optimizing the nozzle shape. The nozzle shape has a significant influence on the final extrudate geometry and the surface finish quality, as discussed in Section 2.3.2 and Section 2.4.1. However, only limited literature can be found on a thorough investigation of the relationship between the nozzle shape and the final extrudate shape. In this section, the relationship between the extrudate geometry and the shape of nozzle will be discussed.

In this approach, the shape of the nozzle is considered as an input and the shape of the printed extrudate is the output. It is assumed that there exists a numerical relation between the input and output if all the other factors affecting the shape of extrudate are kept the same during the experiment. With sufficient experimental data, a mathematical method can be applied to analyze the relationship between the input and the output. When the relationship is determined, the shape of the nozzle that will produce the desired shape of extrudate can be analyzed.

In the experiment, the nozzle is mounted on the 3DCP printer to perform the printing process with constant printing parameters. Similar to the preliminary experiments, the nozzles are designed in CAD software, fabricated by an Ultimaker 2 and mounted on the 3D printer by four screws, as illustrated in Fig. 3.6.

Fig. 3.6: (a) The CAD model for the plastic nozzle (b) the fabricated nozzle

The material used in the experiment is mortar mixed by cement, fly ash, aggregate and water. This compound exhibits relatively high viscous fluid. The composition of the cementitious mixture is also kept the same for all experiments (Table 1).

TABLE 1: MIXTURE PROPORTIONS FOR 6L PRINTING MATERIAL

PORTLAND CEMENT (G)	3152
FLY ASH (G)	3152
SILICA FUME (G)	630.6
WATER (G)	2980
SAND (G)	3468
SUPERPLASTICIZER (G)	9

The pump is utilized to pressurize the material through the hose and extruded through the nozzle, while the rotational speed is set to be constant in the experiment.

In the experiment, the printing path is designed to provide sufficient samples for later analysis of the surface finish. The path has two long straight lines and two small turnings to form a close loop, as shown in Fig. 3.7. Three layers of this printing path are printed additively and only the middle layer is chosen for analysis because the bottom layer has close contact to the substrate during printing and the top layer is compressed by the nozzle.

Fig. 3.7: The printing trajectory in the experiment

During the experiment, it is observed that the flow rate is relatively fluctuating while using the pump. This requires an on-site flow rate adjustment to be conducted in every experiment. A sample nozzle of a fixed size (30×15 mm or 34×20 mm) was used for one printing and the printed part is measured to ensure that the layer width corresponds to the nozzle size (within the range of 29-31 mm or 33-35 mm).

The printed path is then split into pieces and the straight-line part in the printed path is cut into smaller samples by using a Struers Secotom-15 diamond cutter, as shown in Fig. 3.8. The cutting direction is perpendicular to the printing direction and each sample are cut for 4 cm long. The diamond cutter allows for a very high quality of the cutting surface and parallel cutting surfaces. Only the samples on the straight-line part will be used because when the nozzle is turning, the movement of the nozzle is slow and results in heavy overflow at the turnings. To reduce the error in the experiment, 6 samples are analyzed for each print and an average value is used in the calculation of the next-generation nozzle to minimize the influence from the flowrate fluctuations.

Fig. 3.8: Process of acquiring specimen from printed structure (a) diamond cutter (b) acquired samples (c) cross-sectional view of the sample

3.4.3. Result

Several different nozzle outlets with different shapes were tested to examine their effect on the final extrudate geometry.

The first nozzle is a simple rectangular nozzle (nozzle shape in Table 2), which is commonly used in the 3DCP printing. An obvious extrudate slump problem is observed and the surface gap between printing layers is obvious, as shown in Fig. 3.9. The extrudate shape printed with rectangular is presented in Table 3.

Fig. 3.9: (a) The rectangular nozzle and (b) the extrudate printed by the rectangular nozzle

TABLE 2: COORDINATE OF THE SAMPLE POINTS FOR THE RECTANGULAR NOZZLE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
D1	-15	D7	15
D2	-15	D8	15
D3	-15	D9	15
D4	-15	D10	15
D5	-15	D11	15
D6	-15	D12	15

TABLE 3: COORDINATE OF THE SAMPLE POINTS FOR THE RECTANGULAR NOZZLE EXTRUDATE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
E1	-15.67	E7	15.15
E2	-16.67	E8	16.47
E3	-17.00	E9	17.26
E4	-17.86	E10	17.80
E5	-18.25	E11	18.19
E6	-17.66	E12	17.80

The second nozzle is a trapezoid nozzle and the nozzle shape is shown in Table 4. Note that the shorter side (the 29 mm side) of the nozzle is at the front during the printing. The extrudate slump problem and the surface gap between printing layers are still observable, as shown in Fig. 3.10. However, judging from the extrudate shape presented in Table 5, the extrudate slump is obviously reduced.

Fig. 3.10: (a) The trapezoid nozzle shape and (b) the extrudate printed by the trapezoid nozzle. Note that the short side of the trapezoid nozzle is at the front in the printing

TABLE 4: COORDINATE OF THE SAMPLE POINTS FOR THE TRAPEZOID NOZZLE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
D1	-15.48	D7	15.48
D2	-15.28	D8	15.28
D3	-15.08	D9	15.08
D4	-14.88	D10	14.88
D5	-14.68	D11	14.68
D6	-14.48	D12	14.48

TABLE 5: COORDINATE OF THE SAMPLE POINTS FOR THE TRAPEZOID NOZZLE'S EXTRUDATE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
E1	-15.34	E7	15.54
E2	-16.34	E8	16.07
E3	-16.27	E9	16.34
E4	-16.53	E10	16.67
E5	-16.80	E11	16.80
E6	-17.00	E12	17.00

Subsequently, the third nozzle was generated by the iterative experimental method. The dimensions of nozzles and extrudates are shown in Table 6 and Table 7. Note that the shorter side (the 26.11 mm side) is at the front during the printing. The surface finish quality has been significantly improved because the extrudate geometry was much closer to rectangular shape, as shown in Fig. 3.11. The maximum angle between the wall and the vertical direction is only approximately 5 degrees. In this way, the extrudate could stack up and form the structure with a better surface finish quality.

Fig. 3.11: (a) The calculated nozzle shape and (b) the extrudate printed by the calculated nozzle shape

TABLE 6: COORDINATE OF THE SAMPLE POINTS FOR THE THIRD NOZZLE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
D1	-15.97	D7	14.83
D2	-16.40	D8	16.03
D3	-15.22	D9	15.19
D4	-14.74	D10	14.70
D5	-14.29	D11	14.27
D6	-12.92	D12	13.19

TABLE 7: COORDINATE OF THE SAMPLE POINTS FOR THE THIRD NOZZLE'S EXTRUDATE

POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)	POINT NUMBER	DISTANCE WITH THE MIDDLE LINE (MM)
E1	-16.07	E7	15.94
E2	-16.20	E8	16.07
E3	-16.05	E9	16.18
E4	-16.07	E10	16.20
E5	-16.01	E11	16.33
E6	-16.27	E12	16.14

The jagged surface problem is caused by the extrudate deformation in the printing process, as discussed in Section 1.2. In the literature, the extrudate deformation was measured by a factor Φ . Defined in Eqs. (11). The factor Φ measures the difference between the deformed extrudate geometry and the ideal rectangular geometry [79].

$$\Phi = \frac{L_t}{L_b} \quad (11)$$

Where Φ is the extrudate deformation factor, L_t is the width of the shortest line of the extrudate's cross-section; L_b is the width of the longest line of the extrudate's cross-section, as shown in Fig. 3.12.

Fig. 3.12: L_t and L_b measured on the cross-section of a deformed extrudate line

Factor Φ is measured for the benchmarking rectangular-shaped nozzle and the iterative-generated nozzle shapes. The L_t and L_b are acquired by reading the photo of the extrudate cross-sectional geometry, as shown in Fig. 3.13.

For the extrudate printed by the rectangular nozzle, Φ is equal to 1.18. As for the extrudate printed by the iterative-generated nozzle, Φ is equal to 1.01. It can be observed that the extrudate geometry become obviously closer to the ideal rectangular geometry when the iterative-generated nozzle is used. As a result, the jagged surface problem can be reduced if the nozzle shape adjustment methodology is used in the printing.

Fig. 3.13: (a) rectangular nozzle (b) iterative-generated nozzle (c) L_t and L_b measured on extrudate printed by rectangular nozzle (d) L_t and L_b measured on extrudate printed by iterative-generated nozzle

3.5. Parameter: nozzle shape combined with printing path

3.5.1. Simulation

Besides the straight-line printing, the extrudate formation needs special attention in the curved printing paths. Because the curved printing paths have longer outer side than the inner side, material printed by the rectangular nozzle in curved printing trajectories become unevenly distributed, causing the deposited filament to be offset from the expected position. This section presents the analysis of this problem and the proposal of the solution using a trapezoid nozzle shape.

The simulation schematic is shown in Fig. 3.14. The nozzle was 20 mm in height with a 30 mm × 15 mm inlet at the top. The bottom of the nozzle was covered

by a 2 mm thick trapezoid plane and thus, leaving a trapezoid opening with different sizes. The standoff distance was 15 mm from a static no-slip substrate. The outlet was divided into multiple sections averagely in width, and the volume flow rates of these outlets were simulated under different flow conditions. The ratios of volume flow rates between smaller and larger sides were considered as the material distribution ratios of the corresponding trapezoid nozzle shapes.

Fig. 3.14: Simulation schematic of trapezoid nozzles

The viscosity of material used in these simulations was described by the Bingham Plastic model, where the yield stress was 256.0 Pa, and the plastic viscosity was 33.37 Pa·s. The material density was 1800 kg/m³. The inlet velocity was changed from 0.05 m/s to 0.15 m/s with 0.01 m/s interval.

Simulation of different sized trapezoid nozzles was conducted using open source CFD package OpenFOAM 4.1. A self-developed Python code was used to generate simulation cases with different small and large side openings. The left and

right-side openings were changed from 1 mm to 14 mm with a 1 mm interval. Due to the symmetric condition, only the cases where the left-side opening is larger than the right-side opening was generated. Then these generated cases were sent to different CPU cores to compute the outlet flow rate distribution. Simulation residual and mesh density were changed to make sure the simulation results were independent of them before massive simulation cases were computed.

The simulation result conducted by OpenFOAM is shown below. The streamline of the velocity distribution of the material flow is shown in Fig. 3.15. Based on the magnitude of the flow velocity distribution, the flow rate ratio of the extrudate at the different turning angles can be obtained for different nozzles and the shape information of the nozzle can be therefore obtained.

Fig. 3.15: Simulation of fresh material flow

Thus, the corresponding turning radius can be computed from similar triangles rules once the flow rate ratio is obtained, as shown in Fig. 3.16 and Eqs. (12).

$$R = \frac{aW}{1 - a} \quad (12)$$

where R (mm) is the turning radius, W (mm) is the width of the nozzle, a is the flow rate ratio of smaller and larger sides. Part of computed turning radiuses with different opening sizes under 0.1 m/s inlet velocity are listed in Table 8.

Fig. 3.16: Determining turning radius with similar triangles of flow rate and nozzle width

TABLE 8: PART OF COMPUTED TURNING RADIUS (MM) WITH DIFFERENT OPENING SIZES UNDER 0.1 M/S INLET VELOCITY.

OPENING SIZES (MM)	14	13	12	11	10	9	8	7	6
13	392.5								
12	171.3	327.1							
11	99.3	143.4	276.1						
10	64.6	82.8	120.8	237.9					
9	44.3	53.6	69.7	102.7	204.4				
8	31.3	36.7	44.8	59.3	89.0	179.8			
7	22.7	25.9	30.6	38.0	50.9	77.1	156.3		
6	16.4	18.4	21.2	25.2	31.6	42.6	64.3	129.6	
5	11.8	12.9	14.6	16.9	20.3	25.5	34.1	51.5	105.1

3.5.2. Experiment

Three different trapezoid nozzles, i.e., opening sizes are (7 mm, 12 mm), (8 mm, 12 mm), and (7 mm, 9 mm), were picked from Table 1 as their simulated turning radiuses are close to 30 mm, 45 mm and 75 mm, respectively. These three nozzles were fabricated by a desktop FDM printer Ultimaker 2, as shown in Fig. 3.17, and then installed on the cementitious material printer to conduct the printing test. Each printing tests were composed of 5 different radiuses with the simulated radius of $\pm 20\%$ and $\pm 40\%$ round to 5 mm. Then the printed filaments were cut into pieces. The photos of the cross-sectional area were taken and analyzed to compute the flow rate ratio of inner and outer sides. If the flow rate ratio of inner and outer sides is almost 1:1, then the material can be considered as evenly distributed. The experiment procedure is the same as stated in the previous section in Chapter 3.4.

Fig. 3.17: FDM fabricated trapezoid nozzle used for curved printing path

In order to find the middle line of printed filament, a needle-shaped nozzle was mounted on the printer, and the printing path was repeated to cut a line in the middle of printed material. To calibrate the position of this needle-shaped nozzle, a straight line printed with a rectangular shaped nozzle, which is believed to be symmetric, was also marked by this needle-shaped nozzle as calibration filament. Thus, the actual position of the needle-shaped nozzle can be calibrated by comparing its position with the centerline of the calibration filament.

One example of the printed path is shown in Fig. 3.18, and one example of the cut cross-section is shown in Fig. 3.19.

Fig. 3.18: Printed filaments with 5 different turning radiuses

Fig. 3.19: Filament cross section with the marked line in the middle

3.5.3. Result

For each turning radius, three samples were picked and analyzed to get the average flow rate ratio. The material distribution for the three picked nozzles under different radiuses are listed in Table 9. Generally, as the turning radius increases, the flow rate ratio of smaller and larger sides decreases as expected. In most of the cases, the flow rate ratios at simulation predicted radius are around 1.00, which means the simulation results can be used to predict the turning radius of the trapezoid nozzle. The main error may come from the static substrate boundary condition. In the future, after the initial turning radius is determined, another round of simulation should be

conducted using a turning substrate, and then the simulation results can be used as the prediction.

TABLE 9: EXPERIMENTAL FLOW RATE RATIO OF DIFFERENT SIZED NOZZLES WITH VARIOUS TURNING RADIUS.

NOZZLE 1 (7 MM, 12 MM)	TURNING RADIUS (MM)	45	60	75	90	105
	FLOW RATE RATIO	1.00	1.01	0.95	0.89	0.82
NOZZLE 2 (8 MM, 12 MM)	TURNING RADIUS (MM)	25	35	45	55	65
	FLOW RATE RATIO	1.14	0.99	0.97	0.97	0.96
NOZZLE 3 (7 MM, 9 MM)	TURNING RADIUS (MM)	20	25	30	35	40
	FLOW RATE RATIO	1.04	1.01	1.08	0.94	0.92

In summary, the material distribution for the various trapezoid-shaped nozzles in 3DCP printing were analyzed by computational method, and the material distribution problem for curved printing trajectories can be mitigated. This has again proved the feasibility of improving the printing quality by adjusting nozzle geometry.

3.6. Summary

From the preliminary discussion, the complexity of the 3DCP process is apparent. Many parameters can affect the extrudate formation process during the extrusion of fresh concrete material. When retracting from the nozzle, the extrudate is heavily affected by the nozzle shape, nozzle size and the nozzle channel design. Upon the deposition, the extrudate formation is affected by the landing impact, die

swelling effect and the overflow ratio. After the deposition, the extrudate formation is affected by its own weight and the weight from subsequent-deposited layers. The rheological property of the fresh-mixed concrete material determines the magnitude of extrudate deformation under the aforementioned factors. Among these influential parameters, the nozzle geometry directly constrains the extrudate geometry upon exiting the nozzle, while all other parameters are more towards deformation factors. As a result, this chapter mainly focuses on exploring the feasibility of controlling control extrudate geometry by adjusting nozzle geometry.

An experimental approach was used for different nozzle shapes, ranging from rectangular-shaped, trapezoid, and calculated nozzle. The nozzles were manufactured by a desktop FDM printer and implemented for experimental tests. The printing tests conducted with the different nozzles showed obvious differences on the final extrudate formation. Moreover, it is found that the nozzle could be designed to lead to a good rectangular-shaped extrudate, and hence improve the surface finish quality of straight-line printing.

As for the curved-path printing, where the material printed by rectangular nozzle becomes unevenly distributed, the nozzle shape could also be adjusted to improve material distribution. In order to ensure uniform material distribution for curved printing trajectories, rotational trapezoid nozzle shape is proposed for 3DCP. The material distributions for various trapezoid nozzles were studied by numerical simulations. Validation experiments showed that the material distribution problem for curved printing trajectories could be mitigated with the trapezoid-shaped nozzle.

From these preliminary studies, the extrudate formation can be controlled by adjusting nozzle geometry. The jagged surface problem and material distribution problem can be mitigated. However, the iterative experimental approach and simulation approach are inefficient and cannot be used in practical on-site printing. If the relationship between nozzle shape and extrudate formation can be established and made more applicable to on-site printing, the corresponding algorithm can be applied, and the printer should be able to change nozzle shape to extrude the correct extrudate.

Chapter 4. Control extrudate geometry using machine learning method

4.1. Introduction

As discussed in Chapter 1, the lack of control in the geometrical shape of the extrudate limits the quality of 3DCP products. In the 3DCP process, the extruded geometry does not necessarily follow the shape of the nozzle outlet due to the effects of gravity and material rheological properties. This leads to a surface quality problem such as the jagged surface or staircase effect on the 3DCP product (see Fig. 1). Although the quality of many extrusion-based 3D printing processes are limited by extrudate deformation or staircase effect [15], the surface roughness problem becomes more apparent in 3DCP due to the large printing scale [16]. Surface roughness is important to the printing quality because rough surface tends to wear more quickly than smooth surface [17-20]. In addition, stress concentration at layer interface might reduce the bonding strength between printed layers [21]. Therefore, it is very important to control the surface roughness of the 3DCP-printed structure.

As discussed in Chapter 3, many experiment parameters, including the nozzle outlet shape, material flow rate, nozzle travel speed, nozzle standoff distance, and rheological performance of material could significantly influence the extrudate formation. The nozzle shape can be adjusted to mitigate jagged surface problem.

Hence, a method needs to be developed to control the extrudate formation with fast speed and acceptable accuracy.

Moreover, the staircase effect in 3DCP still remains to be solved. Staircase effect occurs in 3DCP because of the geometric approximation of a complex profile using uniform extrudate. The printed part would exhibit staircase-like wall illustrated in Fig. 4.1, which can reach up to several millimeters width [16]. The width of the ridge in the staircase-like wall is mainly related to the nozzle size which might vary from 10 mm to 40 mm in 3DCP [80]. In small scale printing like FDM, the staircase problem is typically mitigated by using a smaller nozzle size or reducing layer height [15]. However, reducing the nozzle size is not practical in large-scale extrusion printing like 3DCP due to the long printing time for large concrete structures. Therefore, controlling the extrudate geometry seems to be a more promising way to improve surface finish quality without compromising the printing speed. As an illustration, the curved wall in Fig. 4.1 will have a smooth surface finish if the geometry of the extrudate in every layer can be controlled to follow the outer-surface curvature and join up to form a smooth outer-surface.

Fig. 4.1: Staircase effect in 3D printed parts: (a)The design of the object, (b) the sliced layer-by-layer model and (c) the staircase effect [16]

This chapter will discuss the application of a machine learning technique to develop a predictive model for extrudate geometry in 3DCP. This study explores the feasibility of extrudate shape control implementation in 3DCP processes to improve the surface finish quality of the printed product. A data-driven predictive model for extrudate geometry based on ANN is adopted to develop the relationship between nozzle shape and extrudate cross-sectional geometry in extrusion based 3DCP. The

developed model can be used to instantly find the required nozzle shapes for target extrudate geometries and improve surface finish quality. With this approach, an obvious improvement on surface roughness can be observed. In Section 2, the parameters affecting extrudate deformation are discussed and the modelling strategy is explained. In Section 3, the experiment setup for acquiring training dataset is introduced. A discussion on a predictive ANN model that was trained from 3DCP experiment data together with the model architecture are discussed in Section 4. The experimental validation demonstrating the capability of the developed model to accurately predict extrudate geometry is also shown. With the approach, the model that is suitable to instantly predict nozzle shapes can be used to print extrudate with different target geometries and improve printing quality for 3DCP parts with desired surface curvatures. As the ultimate goal, the extrudate geometry can be simply controlled in the 3DCP process and the printing quality can be improved. This will also allow us to print a complex structure with acceptable printing quality.

4.2. Research Methodology

4.2.1. Description of extrudate deformation in printing process

Based on the previous discussion in Chapter Chapter 3, the extrudate geometry is affected by several empirical parameters, including the nozzle shape (D), localized material flow rate (ε), dynamic yield stress (τ_D), static yield stress (τ_s) and elastic modulus (G), as represented mathematically as Eqs. (13):

$$f(D, \varepsilon, \tau_D, \tau_s, G) = E \quad (13)$$

While the dynamic and static yield stresses and elastic modulus are tagged as material properties, this study aims at proving the concept of the predictive model with more focus on the effect of the nozzle design and the localized material flow rate. In short, in this study, only one type of mixture and material is used with an assumption that the rheological change during the deposition process is negligible. With the aforementioned assumptions, the parameters related to material properties are not considered in the developed model and will be studied in successive work. Therefore, the proposed model is simplified to be subjected to nozzle shape and localized flow rate, as shown in Eqs. (14):

$$f(D, \varepsilon) = E \quad (14)$$

In this model, we assume that a slight change in the boundary condition will only lead to a minimum change in the extrudate cross-sectional shape due to the high viscosity and low velocity of the deposited concrete material during the 3DCP process ($Re < 1$). A machine learning technique is chosen to be used to model the relationship due to the capability of capturing complex nonlinear behaviour. It has to be emphasized, however, that the performance of the machine learning model is dependent to the data fed in the training process.

To control the extrudate geometry, a development of a reliable predictive model is needed so that one can estimate the final geometrical dimension of the extrudate as a function of the printing parameters, including the nozzle shape, rheological properties of material and flow rate. An analytical solution of 3D Navier-Stokes equations is still impossible to be derived. Instead, a computational fluid dynamics (CFD) simulation have been used to predict the deformation of extrudate during the extrusion-based deposition of molten ceramics and polymers [23, 55, 57] and analyze the flow problem of concrete [81-83].

However, the target of this study is to control the extrudate geometry. To achieve this in the experiment, the nozzle geometry which can be used to print the desired extrudate geometry needs to be found. The deposition process can be considered as a flow problem, where the extrudate geometry is the final state of the material flow problem and the nozzle geometry belongs to the boundary conditions of the flow problem. Clearly, the target of this study involves an inverse analysis to acquire the boundary conditions (nozzle geometry) based on the desired final flow state (extrudate geometry).

The CFD simulation cannot be used to conduct this inverse analysis of the flow problem. Many studies optimized the inverse-prediction problem by simulating a large number of flow scenarios with different boundary conditions. However, the use of simulation method requires a huge amount of forward-time modeling to build a database and achieve the inverse-prediction. The simulation approach has the problem of being computationally expensive and inefficient, especially for the 3DCP

case where a huge database (millions of cases) is required to control extrudate geometries for many different 3DCP structures.

Considering the limitation of the simulation approaches, the data-driven ANN modeling method is finally utilized in this study. In this study, the training of an ANN model only takes less than one minute because the optimized structure of the ANN model only has one hidden layer and 5 hidden neurons. The average computing time for the trained ANN model to make prediction is less than 0.0001 second.

4.2.2. Machine learning

The Artificial Neural Network method is used to predict the extrudate geometry based on 3DCP parameters. The ANN method has been introduced in Section 2.4.2. After properly trained, the ANN model could instantly predict the extrudate geometry based on give parameters, which makes this method suitable for on-site extrudate control.

In order to tune all the parameters in the ANN, the training dataset comprising the input data and the corresponding output data is needed. In this case, the input data are the printing parameters, while the observed extrudate geometries obtained from printing experiment represent the output. To highlight it again, as have been discussed in Section 2.1, the rheological property of the material is kept fixed in the

experiment, in such, only the shape of the nozzle outlet and material overflow ratio are considered as the input set for the ANN model.

Using all the training dataset, the model is subsequently optimized by tuning all the weight and bias of all the neurons upon the minimization of the errors between the prediction and the target. Often, the mean-square error (MSE) provides an adequate measure of prediction error and can be written as Eqs. (15):

$$\text{MSE} = \sum_{i=1}^N \frac{\text{Average}(Y_i - \hat{Y}_i)^2}{(N)} \quad (15)$$

In Eqs. (15), Y_i is the target for the ANN prediction, which are the extrudate geometries obtained in the experiment. On the other hand, $\hat{Y}_i$ are the extrudate geometries predicted by the ANN model. Both Y_i and $\hat{Y}_i$ are in vector forms which have twelve elements, corresponding to the twelve-points representation of the extrudate geometry, $(E_1, E_2, \dots, E_{12})$. The value N is the number of different extrudate geometries in the group Y_i . By averaging the N sets of prediction errors, the averaged prediction error of the trained ANN model can be obtained.

The parameter optimization in the training step typically utilizes a back-propagation mechanism. At the initial stage, a random set of weightage and bias parameters are assigned to all the neurons, and the error between the computed output and actual output is calculated, where the parameters are adjusted in a backward sequence, from the last layer to the starting layer to reduce the error using an optimization algorithm. The optimum set of parameters, comprising the weight bias for every neuron is recorded once the optimization is finished. Upon a successful

completion of the training process, the model will be ready, and it will be able to predict the extrudate geometry output for any given input parameters.

After the predictive model is obtained, the nozzle shape can be obtained to print the targeted extrudate cross-sectional shape in experiments. While the ANN model can effectively predict the extrudate cross-sectional shape, it cannot be directly reversed because it involves the inversion of a non-square matrix, which cannot be accurately performed numerically. As a result, a nozzle-extrudate database was established to correlate the nozzle shapes and corresponding predicted extrudate cross-sectional shapes for inversely search nozzle shape from targeted extrudate cross-sectional shape. With this method, the extrudate formation can be controlled and the surface finish quality can be improved in 3DCP.

While the non-invertible relationship of the model is a concern, the machine learning approach is more practical for achieving extrudate control in practice. The authors plan to use this model into a controller of in-situ printing, which requires the solutions to be found in hours to minutes, or even in seconds. It has to be highlighted here that the objective of this study is not to develop the most comprehensive machine learning solution, but rather to have an economical engineering solution to the problem. To the author's knowledge, an analytical solution of 3D Navier-Stokes equations are still impossible to develop, and the numerical simulation is very inefficient. A predictive ANN model, which is the one developed in this Chapter, would be more practical for production tasks. The error of an ANN model can be

large, but the authors believe it is still acceptable since the 3D concrete printing process is already widely fluctuated.

A summary of the workflow is illustrated in Fig. 4.2. The training data for the ANN model was gathered in pre-testing step. The predictive ANN model is then trained after topology optimization. With the predictive model, a database is established by connecting randomly generated nozzle shapes with their predicted extrudate cross-sectional shapes. Finally, nozzles for different target extrudate cross-sectional shapes can be obtained from the database and used in the printing.

Fig. 4.2: The workflow to find the corresponding nozzle shape based on the expected extrudate formation

4.3. Experiment

4.3.1. Materials and experiment setup

The detailed composition can be referred from the work of Weng et al. [44]. This material was chosen for this experiment to meet the flowability and buildability requirement for printing. The material composed of Portland cement, fly ash, sand, silica fume, and water. The material composition was fixed for all the printing.

The mixing procedure can also be referred from the work of Weng et al. [44]. A Hobart mixer was used for material mixing. The dry ingredients including cement, fly ash, silica fume and sand were first weight and mixed for 3 minutes under stir speed (59 RPM) [84]. Subsequently, water was then added and mixed for 3 minutes under stir speed followed by 2 minutes in speed I (107 RPM) [84]; and then, superplasticizer was then added to the mixture mixed for 1 minutes in stir speed and 3 minutes in speed I. Each batch of material was 6 liters. The mixing procedures were fixed for the material in this study to ensure the rheological consistency on different batches of material.

The experiment setup used in the printing process is illustrated in Fig. 4.3. The gantry-typed printer used in the experiment has a printing volume of 1.2 m (L) $\times$ 1.2 m (W) $\times$ 0.8 m (H) and it was controlled by a traditional CNC controller. The gantry comprises four degrees-of freedom (DOF), in addition to three displacement DOFs in x , y , and z directions and one rotational DOF R_z -axis. The gantry served as a motion system to move the nozzle along the printing trajectory following the input G-code. A pumping device equipped with a delivery hose was used to deliver the cementitious materials during the printing through an auger screw mechanism.

Nozzles with pre-designed outlet shapes were fabricated by FDM printer Ultimaker 2 and mounted on the gantry to conduct the printing. The printing speed was 4000mm/min, while the pumping speed was set to 2.0 L/min. The nozzle cross-sectional area was set to be 450 mm² for all the different nozzle shapes. The designed layer height was kept 15mm for each laer, which is equal to the width of the nozzle to avoid extrudate squeezing or bad stacking. The above settings were also kept constant for all printing. Note that the notch on the nozzle outlet indicated the nozzle's moving direction during printing.

The overflow ratio is always set slightly larger than 1.1 because the underflow condition should be avoided in the 3DCP experiment. The underflow will immediately lead to cracks on the printed extrudate and may even lead to a discontinuity of printed material [42] which profoundly affect the printing stability. Due to the material inhomogeneity and the instability of rotor-stator pumps, the overflow ratio fluctuates significantly in the printing even if the pump speed, print speed, material composition, and material mixing code are strictly fixed. It has been observed in the author's experiments that the overflow ratio typically fluctuates $\pm 10\%$. Therefore, to avoid overflow ration drops below 1.0, it is necessary to set the average overflow ratio to be slightly larger than 1.1.

Fig. 4.3: Experimental setup for 3DCP, (a) the pump and gantry printer, (b) the material deposition nozzle on gantry printer and (c) the changeable nozzle outlet. Note that the front side of nozzle outlet is marked by a notch on the nozzle

To acquire training dataset to develop the relationship between the nozzle shape and extrudate geometrical dimension, 13 different shapes of nozzle outlet were considered, as depicted in Fig. 4.4. The top and bottom sides of the nozzle outlet were kept parallel and the distance between the top and bottom sides are held at 15 millimeters, as we considered the possible material distribution problem in each layer of extrudate deposition. These shapes were varied on the sides only, taking into account for different slopes with different angles, concavities and convexities, and asymmetries. The cross-sectional area of the outlets, however, was maintained to be 450 square millimeters for all nozzle shapes, implying the same localized volume

flow rate of the material. It is believed that the dimensional variation due to the polymer shrinkage when the nozzle is printed by FDM is negligible compared to the dimensional variation in the 3DCP process itself, where that of the nozzle dimension is about 1% and on the extrudate is around 10%. Besides, it has to be noticed that for some nozzle shapes, the result extrudate geometry is affected by the nozzle's moving direction in the printing. A trapezoid-shaped nozzle, for example, would create different extrudate when the long side or short side is at the front. Thus, the orientation of the nozzle is marked by a notch which indicates the front side of the nozzle.

Fig. 4.4: The 3D CAD model of nozzle, and 13 different shapes of nozzle used in the experiment. The notch indicates the front side of the nozzle in the printing

4.3.2. Photo processing and data analysis

For every nozzle, a 500 mm long oval trajectory were printed with three layers. The two straight sections of the oval shape were parallel and printed along y axis, as illustrated in Fig. 4.5. After 7 days' curing, the straight-line section was cut into 40 mm length samples by a Struers Secotom-15 diamond cutter for further extrude shape analysis. After each printing, the middle line of the printing path was also labeled on each sample by a needle for further analysis of the extrudate formation.

It has to be noted that only the middle layer was used as the sample. The top layer is less relevant to be used in the training as it would not be affected by the landing impact of the subsequent layer. It is obvious that the top layer tends to be less deformed and less expanded than the middle layers. The bottom layer is heavily affected by the geometry and geometrical accuracy of the print bed, which may not be completely flat [39]. Hence, the extrudate on the bottom layer could be created with uncontrolled geometrical deviations or improper deposition [39]. For the middle layers, the influential process parameters are typically consistent, therefore, the extrudate shapes for the middle layers can be evaluated by the same model, which is derived in this paper. If a printed structure has 100 layers, then 98 layers can be classified as middle layers,

The extrudate cross-sectional shape was analyzed by reading the cross-section images with MATLAB image toolbox. Each image was acquired in a controlled illumination environment to minimize any possible shade and by keeping

the camera perpendicular to the sample at a fixed distance, where the result is illustrated as shown in Fig. 4.5. The resolution and image size were kept fixed at 3024×3024 pixels and $200 \text{ mm} \times 200 \text{ mm}$.

Fig. 4.5: (a) The 3-layer printing trajectory and (b) the cross-sectional shape of the printed sample

To quantify the shapes of the extrudate cross-section and the nozzle outlet for modelling purpose, finite sample points on shape contour [41] were used. The nozzle design and extrudate cross-sectional shape were sliced into five sections horizontally, which result in twelve sample points for both sides. The sample points of nozzle design were represented as $D_1, D_2, \dots$, and D_{12} , while the samples of extrudate cross-

sectional area were denoted as E_1 , E_2 , ..., and E_{12} , as illustrated in Fig. 4.6. In this way, the input and target for the ANN model can be represented numerically.

In the testing of different nozzle geometries, the top and bottom sides of the nozzle outlet are kept parallel to avoid the influence in material distribution. As shown in Chapter 3.5, the adjustment of geometries on the top and bottom sides of the nozzle could be used to counter the uneven distribution when the nozzle turns. Clearly, the variation the top and bottom sides could significantly affect the material distribution in the printing.

To avoid this influence on the material distribution which might be undesirable in the printing, the top and bottom sides are kept parallel to each other in this study. Hence, this study firstly focusses on the adjustment on the left and right sides of the nozzle. However, it is important to notice that the influence of the top and bottom side of the nozzle still needs further investigation in the future.

Fig. 4.6: (a) Schematic of sample points in (b) nozzle design and (c) extrudate cross-section

In order to take into account the material flow effect on the model, the ratio of the extrudate cross-sectional area to that of the nozzle is calculated, where the

extrudate area was measured by calculating the number of pixels on the cross-section and the nozzle shape was measured from the CAD software. When this ratio is higher than one, which implies that the material feed rate is high for the print speed and the material is overflowing, is later referred to as the overflow ratio,

The variation of overflow ratio, which may be caused by a small flow rate fluctuation or printer vibration, was observed in the printing. This variation can be observed even when all the process parameters were fixed. As an illustration, 9 samples were cut from an extrudate line which was created with fixed process parameters. Obvious fluctuation on the overflow ratio was still observed on the 9 samples, as can be observed in Fig. 4.7. As such phenomenon is difficult to be eliminated or controlled in the printing process, the samples in the experiment were randomly taken from the printed filament and, thus, the predicted extrudate formation shape was averaged from all samples.

Fig. 4.7: The overflow ratio of 9 samples cut from one straight line in an ascending order

From the experiment, it is noticed that the overflow ratio from the 101 samples inherently varies as presented in Fig. 4.8. This results in the variation of the overflow ratio from 1.02 to 1.35, although the motor pump voltage and the material composition were kept fixed on all 101 samples printed. The variation of the overflow ratio might be pertaining to the pumping mechanism or the non-Newtonian nature of the printed material, as it is known that the viscosity of concrete depends to the shear stress that might fluctuate during the printing process. The fluctuations become larger than that in the single-nozzle printing because of the batch-to-batch different of material's rheological properties.

Fig. 4.8: Overflow ratio for all the tested samples in an ascending order

4.3.3. ANN model training

An ANN model was, subsequently, trained to correlate the resulting extrudate cross-sectional shape and the nozzle shape including the overflow ratio. For the back-propagation, the Levenberg-Marquardt method [85, 86] was used, where the training was carried out under MATLAB environment with Neural Network Toolbox. The input layer of the ANN network consists of 13 neurons that include the 12 sample points of the nozzle shape and the overflow ratio, where the target layer was 12 sample points of the extrudate cross-sectional shape. From the entire training dataset, 70% was used for training purpose, 15% was used for testing, while 15% was used for validation. The data used for these processes were randomly chosen by MATLAB.

The structure of the ANN model was optimized to improve the accuracy of the trained model. To evaluate the performance of different ANN architecture in the model accuracy, various number of hidden layers and neurons were tested in the trial-and-error process. The number of hidden layers in the ANN model was limited to 2 in the optimization process because the ANN model with two hidden layers could theoretically approximate any smooth mapping to any accuracy as stated by Heaton [87].

To minimize the possibility of falling in local minima during back-propagation, 100,000 ANN models were independently trained with random initial seeds assigned by MATLAB. Upon the training of each model, the performance of the training, testing and validation sets were calculated by means of MSE. Finally, the ANN model with the best testing performance (smallest MSE) was found and recorded.

4.3.4. Database generation

From the optimized model, we expect to predict what the extrudate geometry will look like for a specific shape of nozzle outlet. However, in real applications, we need to determine the optimal nozzle shape for a desired extrudate geometry. Unfortunately, it is observed that the trained ANN model exhibits a non-invertible relationship, where the nozzle shapes cannot be directly derived from extrudate geometry.

To overcome the problem, a database was generated to record nozzle shapes which would be relevant to print selective extrudate cross-sectional shapes. Random, yet realistic, nozzle shapes were generated by varying the value of nozzle sample points between 12 to 18 mm while maintaining the nozzle cross-sectional area to 450 mm². However, to avoid unrealistic shape, the randomly generated nozzles were checked in two steps. Nozzles that comprise sharp angle features will be discarded as this shape as those with sharp angles, as illustrated in Fig. 4.9, could lead to severe discontinuities in material flow during printing. To filter such shapes, a MATLAB code to examine the geometry was generated and used.

Fig. 4.9: Sharp angle feature that might cause flow discontinuities on generated nozzle shapes

The second check in preparing the database is by controlling the overflow ratio. Ideally, the ratio between the area of predicted extrudate shape and the area of

nozzle shape should correspond to the input overflow ratio. If the calculated ratio does not match the predetermined overflow ratio, the generated nozzle shape will be rejected. A MATLAB script was also written to filter such cases.

Subsequently, the remaining generated nozzles were fed to the predictive ANN model and a corresponding extrudate cross-sectional shapes were generated. The database was, subsequently, established by iteratively generating random nozzle shapes and recorded all the resulting extrudate shapes.

With the aid of the database, an appropriate nozzle shape can be evaluated for a desired extrudate cross-sectional shape. However, preceding the deployment of the algorithm for wall printing, a CAD model of the wall geometry should be analyzed. The wall model is sliced into layers, after which the target extrudate cross-sectional shape will be analyzed for each layer. Referring to the generated database, the relevant nozzle shape can be evaluated and used for printing of each extrudate layer.

4.3.5. Surface roughness factor

In this study, the surface roughness parameter is used to characterize the surface finish quality of the 3DCP-created structures. The surface metrology has been used to characterize the surface quality for many different 3D printed product [88, 89].

To measure the surface roughness parameter, the 3DCP printed structure is sliced and the photo of the cross-sectional shape of the sliced sample is taken. The profile of the surface is extracted from the photo and represented by a set of data points with 0.1323 mm resolution. Subsequently, the surface form is removed by the least-square methods [90]. After the form removal, the profile passes a gaussian filter defined by ISO 16610-21 [91]. The filtering is conducted by the “open profile gaussian filter program” [92] written in MATLAB which can separate the waviness and roughness profile. Based on the roughness profile of the printed structures, the factor R_t and R_q are measured to analyze the surface texture quantitatively. The factor R_t measures the sum of the height of the largest profile peak height and the largest profile valley depth within the evaluation length [93]. The R_q parameter is defined as the root mean square value of the ordinate values within the sampling length [93].

4.4. Results

4.4.1. Extrudate slump behavior

From the experiment, 101 extrudate cross-sectional samples were generated, where some of them are illustrated in Fig. 4.10. The training dataset was established based on the geometrical samples, the corresponding nozzles shapes and the measured material overflow ratio.

Fig. 4.10: The 101 extrudate cross-section samples

The results show that the nozzle shape significantly affects the extrudate formation as illustrated by some samples shown in Fig. 4.11. Changing the slope on the two sides of the nozzle is shown to be effective in modifying the final extrudate formation.

Fig. 4.11: Different nozzle outlet shapes lead to variation in the slump behavior of corresponding extrudate shapes: (a, c, d) Different nozzle outlet shapes; (b, d, f) corresponding extrudate cross-sectional shapes. Note that scales are different for nozzles and extrudate

4.4.2. ANN model training

The neuron configuration of the ANN model was optimized by trial-and-error. The performance of the ANN topology was tested for many different neuron configurations in two hidden layers configuration. The maximum number of neurons in each hidden layer is limited to 20. For the first and second hidden layers, the neuron number was varied from 1-20. The ANN configurations also include the tests when only one hidden layer is present in the ANN model structure. Each neuron configuration was trained 1,000 times with different initial seed and the most

optimized parameters in terms of the testing performance (MSE) was recorded to be used as the final ANN model. Among all the tested neuron configurations, the ANN structure which had one hidden layer with five neurons had the optimized testing performance. Increasing or decreasing the neuron number would lead to worse testing performance. The final ANN model consists of a single-hidden-layer and 5-neurons topology as shown in Fig. 4.12 with MSE of 0.2816. The final ANN model exhibited fast convergence, while the predicted output and the target in all datasets showed a satisfactory correlation ($R > 0.999$) as indicated in Fig. 4.13.

Fig. 4.12: Optimized ANN structure

Fig. 4.13: The training performance and the regression of the ANN model

4.4.3. Validation of the trained model

The accuracy of the ANN model, subsequently, was revalidated by three test nozzles, which have different shapes than those in the training set. The designated test nozzles were fabricated and subsequently used to print some samples. The geometry of the extrudate samples were, therefore, analyzed and compared with the

predicted extrudate shapes from the trained model. The results were compared and contrasted as shown in Fig. 4.14, where the blue dot lines indicate the experimentally-acquired extrudate geometries, while the red lines represent the predicted extrudate cross-sectional shapes from the trained model.

The mean prediction errors, which represent the average of the absolute difference between the experimental extrudate geometry and the predicted results, are 0.44 mm, 0.54 mm, and 0.58 mm for the three test nozzles a, b, and c, respectively. The error of the ANN prediction is calculated based on its difference from the experimental result, as shown below:

$$Pointwise\ Error = Average(\frac{|E_{pre} - E_{exp}|}{|E_{exp}|})$$

Where E_{pre} stands for the extrudate geometry predicted by the ANN model; E_{exp} stands for the extrudate geometry obtained in the experiment. The average of pointwise difference for the three validation nozzles are 0.44 mm, 0.54 mm, and 0.58 mm for the three validation nozzles a, b, and c. The averaged pointwise errors for the three validations nozzles are 0.0238, 0.0293 and 0.0329. Thus, the prediction error of ANN model is 0.0287 in the validation experiment and the accuracy of the prediction is 97.1%. Therefore, it can be concluded the three validations and the model is considered to be able to predict extrudate formations.

Fig. 4.14: (a, b, c) The shape of the three randomly generated validation nozzles and (d, e, f) the comparison between the extrudate cross-sectional shape measured in the experiment and predicted by the ANN model for validation nozzles. Note that scales are different for nozzles and extrudate

4.4.4. Sensitivity of the input parameter

After validation, in the first place, the influence of the overflow ratio to the extrudate geometry predictions was analyzed. Fig. 4.15 shows the predicted extrudate geometries as results from a fixed rectangular nozzle outlet shape, while the overflow ratio varied from 1.05 to 1.4.

As can be observed from Fig. 4.15, when the overflow ratio increases, the width of the predicted extrudate geometry also increases. This was observed

particularly on the lower part. The extrudate that was printed with higher overflow ratio tends to deform inherently from the nozzle shape as a result of the slump phenomenon as indicated on the lower part.

Fig. 4.15: The predicted extrudate geometry for a fixed rectangular nozzle with the localized overflow ratio ranging from 1.05 to 1.40. Note that scales are different for nozzles and extrudate

Subsequently, different nozzle shapes were analyzed together with varying overflow ratios. Five different nozzle shapes were considered and two overflow ratio values, i.e. at 1.1 and 1.4, were selected to analyze the nozzle shape influence.

Fig. 4.16 shows the results of the extrudate geometry prediction with the varying parameters. The nozzle shape has a more significant influence on the extrudate geometry when the overflow ratio is at 1.1. However, when the overflow ratio is set higher, it can be seen that the overflowing effect becomes more significant. This implies that at high overflow ratios the nozzle shape geometry would be less effective in affect extrudate geometry. In other words, controlling nozzle shape to achieve a designated extrudate geometry is only feasible when the overflow ratio is close to, but not less than, one.

Fig. 4.16: The predicted extrudate geometry for (a) 5 different nozzles with the localized overflow ratio at (b) 1.1 and (c) 1.4. Note that the scale is only for the nozzle

4.4.5. Applying the trained model for improving printing quality

A database containing ten million random nozzle shapes and the corresponding predicted extrudate cross-sectional shapes was generated and used to find nozzle shapes for designated extrudate cross-sectional shapes. As the first case study, we considered printing a 15-degree inclined wall which is 210 mm in height as illustrated in Fig. 4.17(a). The interior part of the structure has infilled extrudate to support the inclined wall. The unique feature of the wall requires a specific extrudate shape as shown in Fig. 4.17(b) that was analyzed from the CAD model of the designated wall. Using the generated database, the nozzle geometry that can produce the approximated extrudate geometry with the smallest mean square error to the target extrudate was obtained, as indicated in Fig. 4.17 (c), and subsequently the analyzed nozzle was fabricated and used for printing the wall.

For benchmarking, a common rectangular-like nozzle shape was used to print such targeted wall and the result is shown in Fig. 4.18 (a). It could be easily observed that the wall printed with the predicted nozzle shape, as shown in the Fig. 4.18 (b), demonstrated better surface quality than the prior one. The surface roughness of the part was measured in a relatively similar manner to 3-layer stacks, in the print-cut-photo sequence. A bandsaw was used to cut the samples from the straight-line part of the full print because the size of the printed part was too large for diamond cutter. Quantitatively, Fig. 4.18 (c) and Fig. 4.18 (d) illustrate the roughness profiles of the printed walls for the latter and prior cases, respectively, where the surface roughness parameter (R_t) of the wall can be calculated. The surface roughness has been reduced

when the predicted nozzle is used in the printing, as shown in Table 1. In terms of R_t , the surface roughness has been reduced by 36.5% with the predict nozzle shape.

Fig. 4.17: (a) The CAD model for a 210mm height inclined wall and the desired extrudate near the outer surface (b) the target extrudate cross-sectional shape (c) the nozzle predicted by the database to print the target extrudate cross-sectional shape, note that the scale is only for the nozzle

Fig. 4.18: The inclined wall printed with (a) rectangular-shaped nozzle (b) predicted shaped nozzle, (c) roughness profile for the wall printed with rectangular nozzle and (d) roughness profile for the wall printed with predicted nozzle

TABLE 10: COMPARISON OF ROUGHNESS FACTOR FOR THE INCLINED WALL

NOZZLE	R_t (mm)		R_q (mm)	
	Mean	Std. Dev.	Mean	Std. Dev.
RECTANGULAR SHAPE	4.6667	0.3109	0.9357	0.0654
PREDICTED SHAPE	2.9627	0.5963	0.5163	0.0624

In the second case, a simple vertical wall of was evaluated to see if the wall property, in terms of the roughness, could be improved using the proposed approach. The same database that was used in the previous study was also employed to determine the most optimal nozzle shape to print such a wall. Similar to the previous test, as a benchmark the same designated wall was also printed using a common rectangular nozzle Fig. 4.19(a). The target extrudate shape for the vertical wall is shown in and the predicted nozzle shape is shown in Fig. 4.19 (b). The roughness profiles shown in Fig. 4.19 (c) and (d) illustrate the results of vertical walls printed using the rectangular nozzle and the predicted nozzle, respectively. The figures show that steps and gaps on the side of the wall are significantly reduced on the wall printed with the predicted nozzle compared to that printed by the rectangular nozzle. The surface roughness has been reduced when the ANN model approach is used to predict nozzle geometry for printing, as shown in Table 11. In terms of R_t , the surface roughness has been reduced by 39.4% with the predict nozzle shape.

The result from the proposed approach exhibits a comparable surface finish quality to that obtained through experimental iteration approach as presented by Lao et al. [41]. However, in the current proposed approach the analysis requires much less processing time and it has been shown from the previous test that the approach also capable of printing a broader range of extrudate formation.

Fig. 4.19: The straight wall printed with (a) rectangular-shaped nozzle (b) predicted shaped nozzle, (c) roughness profile for the wall printed with rectangular nozzle and (d) roughness profile for the wall printed with predicted nozzle

TABLE 11: COMPARISON OF ROUGHNESS FACTOR FOR THE VERTICAL WALL

NOZZLE	R_t (mm)		R_q (mm)	
	Mean	Std. Dev.	Mean	Std. Dev.
RECTANGULAR	2.9288	0.2636	0.5476	0.0927
SHAPE				
PREDICTED	1.776	0.3478	0.3081	0.068
SHAPE				

In the final case, a more complex part of 225 mm height with a dynamic-curvature surface was also considered. The targeted wall comprises a curvy surface,

where consequently the required target extrudate shape is not identical in every layer. For the sake of simplicity, in this validation test, one specific nozzle will be used to print three layers of extrudate. After 3 layers, the printing process would be paused, and the nozzle would be replaced by another predicted nozzle appropriated for the next 3 layers.

As a benchmark, similar to the previous tests, the curvy wall was also printed using a common rectangular nozzle. The parts, subsequently, were sliced and analyzed.

The cross-section of the part printed with rectangular and with the predicted nozzles are shown in Fig. 4.20(a) and (b), respectively, while the five different predicted nozzle shapes correspond to the five 3-layer sections are shown in Fig. 4.20(c). As for quantitative measure, the roughness profiles of the corresponding samples are shown in Fig. 4.20(d) and (e). As can be observed from the roughness profile and the surface roughness parameter in Table 3, the surface finish improvement of the curved wall is insignificant. Both the roughness factor R_t and R_q have only been slightly reduced when the predicted nozzle is used in the printing. In terms of R_t , the surface roughness has only been reduced by 10% with the predict nozzle shape.

There are several reasons which might have caused the deficiency in the surface roughness improvement for the curvy wall case. First, to reduce the nozzle-changing time, the number of nozzle geometries are limited to only 5 nozzle shapes for the 15-layer structure, which has limited the surface improvement. That is

because the nozzle-changing process is time-consuming, but the printing of the structure must be finished within the printable windows time of the material, which is normally 30 minutes. Second, the nozzle-changing process could significantly affect the flow stability in the printing because the process requests a stop and restart of the printing. Third, the time-consuming nozzle-changing process could cause the material rheological property, which is dependent on time, to change significantly and affect the deposition.

Fig. 4.20: The inner-curved wall printed with (a) rectangular-shaped nozzle (b) predicted shaped nozzles; (c) the nozzle shaped predicted by the ANN model, (d) roughness profile for the wall printed with rectangular nozzle and (e) roughness profile for the wall printed with predicted nozzles

TABLE 12: COMPARISON OF ROUGHNESS FACTOR FOR THE INNER-CURVE

NOZZLE	R_t (mm)		R_q (mm)	
	Mean	Std. Dev.	Mean	Std. Dev.
RECTANGULAR	5.7160	0.6331	0.7854	0.0342
SHAPE PREDICTED SHAPES	5.1174	0.6448	0.7737	0.0273

4.5. Summary

This chapter has demonstrated a predictive modeling-based approach to directly control the geometry of 3DCP extrudate with different shapes of nozzle. Thirteen different nozzle shapes were predetermined and fabricated, and subsequently used to produce some extrudates. The cross-sectional shapes of the nozzles together with the corresponding extrudate geometry images were analyzed with the help from MATLAB. A predictive model was then developed to correlate between the nozzle shape and the extrudate shape counterpart using ANN. Upon accomplishment of the model development, a nozzle-extrudate database was formed to allow for analyzing the optimal nozzle shape for a specific target extrude shapes. The results show that the proposed approach offers the improvement of the surface quality on three structures with different curvature by adapting the nozzle geometry according to the corresponding targeted extrudate shape.

Benchmarking to the results of rectangular-shaped nozzles, the output from the analyzed nozzle demonstrates noticeable improvement to the surface finish quality without additional post-finishing effort. More importantly, the proposed approach shows flexibility to facilitate surface finish improvement for several

printing structures which have different outer-surface shapes. This approach has potential to improve the surface finish quality for various kinds of 3D printable structures as it directly controls the extrudate geometry which, in turns, enables the improvement of surface quality. The proposed approach could be an innovative solution to improve surface finish quality without reducing the size of nozzle.

Our primary future plan is to extend the concept into in-situ printing. The major obstacle between the concept and the application is the lack of a nozzle which has a real-time controllable outlet geometry. A variable-geometry nozzle prototype is designed to have a variable-geometry outlet and is being tested in SC3DP. In the meantime, we will continue improving the machine learning model to include more process parameters of 3DCP in the future.

Chapter 5. Extrudate geometry control using a novel variable-geometry nozzle

5.1. Introduction

As mentioned in Chapter 1, a major hurdle in 3DCP is to maintain the surface quality of the result due to the lack of control in the extrudate lines' geometry. Obvious lines or marks are commonly observed in between layer in the 3DCP-created structures, even in a simple vertical wall. Even more, the staircase effect will be apparent on a structure with a curvy profile. Surface finish quality is an important aspect in the quality of 3D printing processes [15] and the surface finish problem needs more attention in a large scale structure [16]. Rough surfaces tend to wear quicker than smooth surfaces [17-20]. In addition, stress concentration that manifested themselves at layer interface of rough surfaces might reduce the bonding strength between printed layers [21]. Therefore, it is very important to control the surface quality of the 3DCP-printed structure.

The staircase effect is almost inevitable in a 3DCP process using fixed-shaped nozzle. This is because the fixed-shaped extrudate, which is created by fixed-shaped nozzles, could not be used to form the complex outer-surface curvature. Instead, the printed part exhibits a geometric discrete approximation of a complex profile using fixed-shaped extrudate, as illustrated in Fig. 5.1. Nevertheless, the staircase effect can be solved if the geometrical shape of each individual extrudate

line can be controlled. This chapter will discuss the approach to directly control extrudate geometry for every extrudate in on-site 3DCP using a variable-geometry nozzle.

Fig. 5.1: Illustration of staircase effect in 3DCP (a) design of the structure, (b) staircase effect caused by fixed-shaped extrudate and (c) ideal surface finish when the extrudate geometry is controlled to fit the outer-surface geometry

Compared to the conventional fixed-shaped nozzle, the variable-geometry nozzle provides a controllable cross-sectional geometry to the extrudate, which could be adjusted to fit the designed outer surface shape of the structure. A variable-geometry nozzle assembly is developed to allow for the deployment of different extrudate geometries following the prescribed structure to be printed. The shape of the nozzle is adjusted with respect to the intended extrudate shape that is determined from the designated structure shape through a dedicated slicer program. The program gets an input from the CAD of the designed structure to be printed and slice the geometry to extrudate geometry in every layer. A dedicated controller is also developed to adjust the shape of the variable-nozzle during the printing process based

on the trained model to achieve the corresponding extrudate geometry. As a case study, an arch-shaped structure is printed to demonstrate the effectiveness of the proposed system. The result is presented in terms of the surface roughness measured on the printed structure and compared with those printed using a conventional fixed-geometry nozzle.

The chapter is organized in the following: in Section 2, the design of the variable geometry nozzle and the experiment setup is introduced, while in Section 3, the detailed workflow of the experiment setup and the background for extrudate-geometry control is explained. In Section 4, The result of the variable-geometry nozzle printed structure is presented. In Section 5, the advantage and limitation of the proposed system is concluded, and future work is sketched.

5.2. The variable geometry nozzle and the experiment setup

5.2.1. Extrudate-control methodology

The proposed method in this study is to explore and to develop a variable-geometry nozzle rather in such the extrudate geometry could be precisely controlled to comply to the designated surface of the printed structure. Compared to the printed results from that of the conventional fixed-geometry nozzle, where the result exhibits cusp heights for different layer as illustrated in Fig. 5.2a, by regulating the nozzle shape, the extrudate geometry can be adjusted to comply to the designated outer-surface geometry as illustrated in Fig. 5.2b. In this way, the structure can be printed

with a better surface finish quality to avoid staircase effect, especially in a complex outer-surface structure.

Fig. 5.2: Comparison of printed structures using (a) conventional fixed-geometry nozzle, and (b) varying nozzle geometries at each layer

Our preliminary work shows that the extrudate geometry in 3DCP could be adjusted by the varying the nozzle geometry [41]. In our subsequent work, it is also shown that the geometry of the deposited extrudate, which is affected by nozzle geometry, material property, flow rate and other parameters, can be predicted using the machine learning method [94]. Based on this principle, an ANN model is developed to correlate the extrudate geometry and the nozzle outlet shape. The

detailed explanation of the methodology in extrudate geometry control is later introduced in Section 5.3.

The accuracy of the ANN model was validated experimentally by three test nozzles, which have different shapes than those in the training set. The mean prediction errors, which represent the average of the absolute difference between the experimental extrudate geometry and the predicted results was around 0.5mm, which was insignificant for 3DCP process. Therefore, the ANN model prediction is considered to fit tightly to the experimental result for all the three validations and can be used for further prediction of extrudate formation.

Subsequently, an active nozzle prototype that is capable of changing its outlet shape is designed and manufactured. Based on the developed ANN model, the outlet shape is, therefore, adjusted according to the desired extrudate geometry output. The design and prototype of the variable geometry nozzle are presented in Section 5.2.2.

5.2.2. Design of variable geometry nozzle assembly

A variable geometry nozzle prototype was developed to perform the extrudate geometry control in 3DCP. This prototype consists of three functional modules, i.e. one deposition module and two shape-varying modules, as shown in Fig. 5.3.

Fig. 5.3: Variable geometry nozzle prototype

Deposition module contains one stainless steel barrel with two side-openings on each side and a 38×15 mm rectangular-shaped opening at the bottom. The barrel is firmly clamped to the rotational module and is driven by the KUKA A6-axis motor to rotate the facing direction of the rectangular nozzle outlet according to the print path. During the printing, the concrete material which is pressurized by the pump flow in the barrel's main channel and get deposited from the nozzle outlet. The barrel has two side-openings on each side, and each side-opening let 5 sliding plates extend into the barrel's main channel. To avoid leakage from the barrel, the side-opening on the deposition module is created by EBM and the gap between the wall and the

sliding plates is minimized. Seal rings are also embedded in the slot carved along the side-opening to prevent material leakage.

Shape-varying module contains 5 sets of actuators which varies the extending length of the sliding plates into the flow channel. The actuators are arranged tightly in the shape-varying module to minimize the size of the module and avoid leakage, as illustrated in Fig. 5.4. Slots are cut on the bottom and top plate of the actuation module to ensure the linear movement of the actuator. Each set of actuator includes a stepper motor with a reducer, a motor controller, a disk with a locating pin, a groove plate, two hardened steel rods threaded on both sides, and one sliding plate, as shown in Fig. 5.5. Each actuator is driven by a reduced motor. The locating pin transfers the rotating motion of the motor into a reciprocating straight-line motion of the groove plate. The two hardened steel rods transfer the linear motion of the driving pin to the sliding plate. Each actuator works independently from each other.

Fig. 5.4: The arrangement of 5 actuations sets in one shape-varying module

Fig. 5.5: Actuation mechanism of the sliding plates

The variable-geometry feature of this nozzle results from the control of the sliding plates. On each side-opening of the deposition module, the 5 sliding plates of the shape-varying module can tightly join up with each other side by side, resulting in a specific shape on each side of the main flow channel in the deposition module..

Comparing to the “sample point” approximation in ANN model, the physical variable-geometry nozzle changes nozzle geometry by using sliding plates which have certain thickness. In the sample points approximation, six sample points are used to represent the geometry of one side. These sample points are only representation of the geometry and the sample points do not have physical thickness. In the fabrication of the physical variable-geometry nozzle, sliding plates with certain thickness are used. For example, the sample point approximation of one nozzle side can be represented by D_1 to D_6 , where D_1 and D_6 are the two points on the top and bottom ends, as shown in Fig. 5.6a. If the 6-points approximation needs to be represented by discrete sliding plates, 5 sliding plates can be used. As an example, the placement of the sliding plate at section “ D_1 to D_2 ” is equal to the average of the two sample points, $(D_1 + D_2)/2$, as shown in Fig. 5.6b.

Fig. 5.6: Nozzle geometry approximation using (a) sample points and (b) physical sliding plates

Each sliding plate is rigidly connected with a linear-driving pin that links with an eccentric pin via a pin-slot connection. When controller sends command to the 10 motors, all the motors will independently drive their corresponding eccentric pin to a certain angle, causing the groove plates to simultaneously slither along with their linear slot and reach the target position. Then, the 10 sliding plates are forced to move linearly inside the main flow channel and reach their corresponding target position, which works with the fixed inner wall and form a flow channel which has an adjustable cross-sectional shape. The two long edges of the shape-changeable flow channel are always parallel to each other, but the sliding plates can be moved to change the nozzle geometry. Each sliding plate is able to change its position from 0 mm to 8 mm, so the maximum achievable nozzle size is 38*15 mm rectangular while the minimum possible nozzle size is 22×15 mm. Notably, the control and actuation of each sliding plates are independent to each other, and the smallest adjustable step of the sliding plate is 0.1mm.

The nozzle is carefully designed and fabricated to prevent any form of material leakage during long concrete printing run. The developed variable-geometry prototype contains multiple electronics and aluminum mechanical element which will be damaged if it is in touch with concrete. To avoid this, all the parts which directly get in touch with the concrete, including the entire deposition module, and all the 10 sliding plates are fabricated with stainless steel. The side-openings on the deposition module are fabricated by EBM with tight tolerance, and seal-rings are

embedded along the side opening to prevent leakage. All the sliding plates are designed so they can join side-by-side and allow no gap to exist between the plates. Sealing rings are embedded in the moving track of the hardened connecting rod. With these efforts, no leakage was observed after 1 hour of continuous printing, and only slight amount of concrete remains on the inner wall of deposition module and on the side of the sliding plate which can be easily cleaned with water. However, the sliding plates should be disassembled from the shape-varying module after each printing and apply lubrication oil on the side for fear that a slight amount of material might remain on the part and cause corrosion.

5.3. Workflow

5.3.1. General workflow of the experiment setup

The printing workflow using variable geometry nozzle is presented in Fig. 5.7. In the first place, a given 3D CAD model of the designated structure in binary *stl* format, is processed by a designated MATLAB program to slice the geometry into extrudate layers. The ‘slicer’ program serves two purposes:

1. The program slices the 3D CAD model into thin, layer-by-layer print path on a set of z-plane generated based on printing layer height. The coordinates and the normal of the generated trajectory are eventually sent to the KUKA robot controller (KRC) as the trajectory paths.

2. The program determines the extrudate geometry which complies the outer-surface shape for every point on the print path. The target extrudate geometries are calculated by slicing the 3D CAD model with denser horizontal planes and this process extract the detailed outer-surface shape information of the structure. Finally, the program calculated the target extrudate geometry for each point on the print path. The extrudate geometries are then sent to the nozzle controller.

Using the generated trajectory and the [21]optimized extrudate geometry analyzed by the slicer code, the surface finish issue could be mitigated by prescribing a “correct” nozzle outlet shape along the printing path obtained using the trained ANN model. The algorithm for the slicing program will be illustrated in Section 5.3.2.

In determining the optimized nozzle outlet shapes for the entire printing path, a MATLAB code that we referred to as “controller” is used. In this phase, a database that consists of ten million different nozzle geometries and their corresponding extrudate geometries is utilized. The trained ANN model is used on various nozzle shapes to generate a database that stores realistic nozzle geometries and the corresponding extrudate geometries. A single nozzle geometry or extrudate geometry is stored in vector form. All the nozzle geometry vectors are grouped together to form one matrix, and the extrudate geometries are grouped in another matrix. When a target extrudate geometry needs to be printed, the “controller” looks up in the generated database and compares all the stored extrudate geometries with the target extrudate. The difference between the stored extrudate geometry vector (E) and the

target extrudate geometry vector (T) is estimated by the mean squared deviation (MSD), as shown in Eqs. (16). Based on the calculation, the “controller” locates the stored extrudate geometry which is closest (have smallest MSD) to the target extrudate geometry and the corresponding nozzle geometry is located. This nozzle geometry is later referred to as the “optimized nozzle geometry” and used to adjust the shape of the variable-geometry nozzle. This process is repeated during the entire printing process. The algorithm for developing the database will be discussed in Section 5.3.3.

$$\text{MSD} = \sum_{i=1}^{12} \frac{(E_i - T_i)^2}{12} \quad (16)$$

Finally, with the printing path and the optimized nozzle geometries ready, the printing process will begin. The experiment setup includes the variable geometry nozzle, a KUKA robotic arm, a concrete delivery pump and concrete mixer, as illustrated in Section 5.3.4. The KUKA robotic arm follows the printing path and moves the nozzle along the printing trajectory. In the meantime, the sensors report the positioning of KUKA robotic arm to the KRC. A server program on KRC publishes the position of KUKA to the remote computer where the MATLAB program looks up the optimized nozzle geometry for that specific positioning. Then, the MATLAB program publishes the optimized nozzle geometry to the Siemens S7-200 PLC controller, which calculate the motor positioning and send commands to the motor. The nozzle shape is then adjusted to the optimized nozzle geometry for the

current printing point. This process repeats automatically during the whole printing process.

Fig. 5.7:Workflow of the variable geometry nozzle in the 3DCP process

5.3.2. Slicing algorithm to find target extrudate geometry

Conventional slicing algorithm for direct extrusion-based 3D printing typically slices a 3D CAD model into many horizontal layers, which can be later additively joined together in the 3D printing process. However, the target geometry of the extrudate cannot be found using conventional slicing algorithm. A slicing program was developed to calculate the target extrudate geometry, the methodology is illustrated in Fig. 5.8.

A target 3D geometry is shown in Fig. 5.8 (a). As shown in Fig. 5.8 (c), printing paths are generated by slicing the 3D geometry with a number of horizontal planes in Fig. 5.8 (b). The space between two horizontal planes represents a single printing layer, so the distance between each plane is equal to the printing layer height, which is 15 mm based on the above exemplary nozzle. During the slicing, a number of intersecting points were found from the intersection between outer-surface geometry of the 3D geometry and the horizontal planes. From these intersection points, a number of trajectory points which need to be passed by the 3D printer's nozzle during the printing could be found. Hence, the printing path could be generated. The slicing algorithm to generate printing paths for 3DCP was already discussed in several previous studies [35, 45].

To acquire the outer-surface geometry of the 3D geometry, each single printing layers in the structure are individually analyzed. A cross-sectional geometry of the extrudate is calculated for each trajectory point on this single printing layer. This extrudate geometry would be created by the nozzle in the printing and hence is

dependent to the moving direction of the nozzle. A cross-section plane, which is always perpendicular to the nozzle's moving direction, is generated for each trajectory point on this single printing layer. This extrudate cross-section plane is defined with the coordinate of the trajectory point and a normal vector pointing to the printing direction. The intersection between this cross-section plane and the outer-surface geometry of the 3D geometry is the exact cross-sectional extrudate geometry at this exact trajectory point.

However, the “exact cross-sectional extrudate geometry” is a curvature and is hard to be directly utilized in further calculation. Therefore, an approximation of this exact geometry is obtained by slicing this single printing layer with dense horizontal planes. A set of dense horizontal planes are placed between a base plane and top plane of this single printing layer, and the density of horizontal planes depends on the desired resolution on acquiring surface geometry. The outer-surface geometry of the single printing layer is approximated by recording the intersection points between the outer-surface geometry and the dense horizontal planes. For all the outer-surface geometry sliced between the base plane and top plane, the intersection points between the extrudate cross-section plane and the sliced outer surface are calculated. The intersection points of each slicing plane are connected and form the target extrudate geometry for this printing layer, as illustrated in Fig. 5.9. This approximation of the extrudate geometry is called the “target extrudate geometry” at this trajectory point.

Fig. 5.8: Slicing algorithm to get target geometry (a) original 3D geometry (b-c) 3D model sliced by the printing height (d-e) one-layer structure is separated from the 3D model and sliced by a number of horizontal layers to extract approximate outer-surface geometry (f-g) acquiring the cross-section plane for a trajectory point on print path

Fig. 5.9: The extracted target extrudate geometry for a trajectory point on the print path

This process is repeated for all the trajectory points on the entire print path, and the target extrudate geometry is calculated for every trajectory point. Then, the target extrudate geometry is exported to the nozzle controller together with the printing trajectory. In the experiment, the variable geometry nozzle aims to print extrudate with calculated target geometry for all the trajectory points on all the printing layers, so the surface finish problem can be eliminated.

5.3.3. Nozzle geometry – extrudate geometry correlation database

A database containing ten million different nozzle geometries and corresponding extrudate configurations was generated. Realistic nozzle shapes were generated for all the possible nozzle geometry within the shape-adjustable range of

the variable geometry nozzle by varying the value on each of the 12 nozzle sample points between 12 to 18 mm from the nozzle midline. The final nozzle shape was adjusted so that the final area of the nozzle is maintained to be 450 square millimeters, so the final flow ratio was not affected by the nozzle geometry change.

After the nozzle shapes are generated, two filters are applied to improve the quality of the nozzle shape selection by filtering out the nozzles that cannot be used in real printing. First, nozzles that comprise sharp angle features will be discarded. This criterion is based on the phenomena that no sharp angles can be observed on the nozzles used for printing experiment because the concrete cannot be extruded from the sharp angle feature of the nozzle and hence cause severe discontinuities on the surface. For the angle features on the side, the angle should be larger than 90 degrees. For angle features on the corner, the angle should be larger than 45 degrees. If there exists angle different from this criterion, the generated nozzle was filtered out. Also, ideally, the ratio between the area of predicted extrudate shape and the area of nozzle shape should correspond to the input overflow ratio. This criterion is based on the definition of the flow ratio which is defined by the cross-sectional area of extrudate over the area of the nozzle. Based on a given input of a nozzle geometry and flow ratio, the predicted extrudate geometry should always have the same area as (nozzle area * flow ratio). If the equality is not true, this means that the prediction result of the ANN model is not acceptable for this nozzle geometry. Hence, the nozzle geometry is filtered out. The remaining generated nozzles were fed to the predictive ANN model and the corresponding extrudate geometries were generated. Each

generated extrudate geometry is also recorded in vector form, by listing the value of its 12 extrudate sample points.

The database was, subsequently, established by recording all the generated nozzle geometries and predicted extrudate geometries. The database stores all nozzle geometry vectors in one matrix and their corresponding extrudate geometry vectors in another matrix.

5.3.4. Experiment setup

The experiment setup used in the printing process is different with those in the previous chapters because the on-site large-scale 3DCP printer is used, as shown in Fig. 5.10. The variable geometry nozzle is clamped on a “KR 120 R3900 ultra K” 6-axis KUKA robotic arm. The nozzle outlet is kept pointing downwards (-z of KUKA coordinate system) and the center of the nozzle deposition module share the same center with the KUKA’s end-effector. The robot arm has a 3.9m maximum reach and a rated payload of 120 kg. The KUKA robotic arm serves as a motion system to move the nozzle along the printing trajectory following the pre-designed track. The KUKA robotic arm also provides the nozzle with one rotational DOF around the z-axis, which ensure the facing direction of the nozzle outlet to be always following the pre-designed track. A pumping device equipped with a delivery hose is responsible for delivering concrete material to the variable geometry nozzle for selectively concrete deposition to build up the final structure.

The material used in the experiments was composed of Portland cement, fly ash, sand, and water. This material is flowable and has moderate static yield stress, which allows itself to be printable and buildable in multi-layers 3D printing. The composition of the cementitious mixture was fixed for each printing.

Two SoRoTo Forced Action Mixers were used for mixing. Each mixer has a maximum mixing capacity of 80 L. In the mixing, the powder of all solid ingredients was mixed 5 minutes in the mixer, then water was added and mixed for 5 mins. Upon completion of mixing, the material is loaded into the pump.

A rotor/stator pump was used to pressurize the flowable concrete material through the 10-meter-long hose and deliver to the nozzle. The material was extruded through the variable-geometry nozzle and deposited on subsequent layers. The deposited extrudate additively build up the designed structure in a layer-by-layer manner. The variable-geometry nozzle constantly adjusts its geometry according to command, and the geometry of extrudate was optimized to fit the outer-surface curvature of the designed structure.

Fig. 5.10: The variable geometry nozzle mounted on the KUKA robot and connected to the material delivery hose

5.4. Case study: Arch

5.4.1. Design and printing of an arch

An arch is an architectural element that has been systematically used in the construction industry ever since the Roman empire. The curve-shaped outer surface on arch structure is high on visual impact and in most cases, is strong and durable. Creating an arch by 3DCP process is more appealing. Still, all the previous attempts targeting for curved outer surface have limited finish quality because of the serious

staircase effect left on the surface [22]. In the following, an arch structure was designed and appropriately achieved by the variable-geometry nozzle via 3DCP process. The arch structure was also easier to measure surface roughness. After the printing, the arch structure was sliced into several samples by a bandsaw, and the surface roughness of the structure was measured by reading the photo of the arch's cross-section.

The CAD model of the arch is shown in Fig. 5.11. The structure is 1 meter long and 225 mm high. The side surface of the structure is curved. The inner part of the arch is filled with many lines of extrudate to support the overhanging curved surface. When printing the infill lines of the arch structure, the variable-geometry change its shape to 30*15mm rectangular geometry. The slicer program analyzes the CAD model of the arch and plans the printing path and target extrudate geometries.

Fig. 5.11: The infilled arch structure of (a) overall design (b) cross-section view (c) printing trajectory lines

The designed arch structure was fabricated using the developed variable-geometry nozzle with the standard 3DCP process, as shown in Fig. 5.12(a,b). Also, another structure with the exact design was fabricated using the conventional fixed-shaped rectangular nozzle, as shown in Fig. 5.12(c,d). Overall, the fabricated structure using the variable-geometry nozzle looks better on the surface finish quality comparing to the structure fabricated by the fixed-shaped nozzle. Comparing to the structure printed with fixed-shaped nozzle, the staircase effect is reduced on the structure fabricated with variable-geometry nozzle, and the structure is closer to a continuous curvature.

Fig. 5.12: Comparison on (a-b) conventional fixed-geometry nozzle in the printing and (c-d) variable geometry nozzle which can accommodate to changing curvature (The vertical lines on the part was manually cut immediately after printing, to separate the printed part for later bandsaw-cutting)

5.4.2. Results

Compared to the ideal surface geometry in Fig. 5.13a, the structure printed by fixed-geometry nozzle shown in Fig. 5.13b exhibits obvious staircase effect, while

the structure printed with the variable geometry nozzle shows visible improvement on surface finish quality, as shown in Fig. 5.13c.

Fig. 5.13: Comparison on (a) designed outer-surface curve, (b) structure printed by fixed-geometry nozzle and (c) structure printed by variable-geometry nozzle

After 7 days of curing, the printed structure was cut with the bandsaw, and the cross-section of the part printed with rectangular-shaped and with the varying-geometry nozzles are shown in Fig. 5.14(a, b). Comparing to the surface roughness profile of wall printed with rectangular extrudate shown in Fig. 5.14c, the roughness profile of the part printed with predicted nozzle shown in Fig. 5.14d had significantly smaller fluctuations. The surface roughness has been reduced when the varying geometry nozzle is used to predict nozzle geometry for printing, as shown in Table 13. In terms of R_t , the surface roughness has been reduced by 34.3% with varying geometry nozzle.

Fig. 5.14: cross-sectional view of the arch (a) printed with rectangular-shaped nozzle and (b) printed with variable-geometry nozzle (c) roughness profile for the arch printed with rectangular-shaped nozzle (d) roughness profile for the arch printed with variable-geometry nozzle

TABLE 13: COMPARISON OF ROUGHNESS FACTOR FOR THE ARCH

NOZZLE	R_t (mm)		R_q (mm)	
	Mean	Std. Dev.	Mean	Std. Dev.
RECTANGULAR	6.2482	0.9637	1.1493	0.0414
VARIABLE GEOMETRY	4.1027	0.6792	0.6319	0.0826

5.5. Summary

This chapter aims to demonstrate the surface finish improvement in extrusion-based 3DCP using a variable-geometry nozzle. This new approach allows 3DCP process to create structures with a better surface finish for outer-surface curvature, which is much complex than mere vertical-walls. A variable-geometry nozzle was developed, and the nozzle prototype was used in 3DCP process. The workflow, including the slicing algorithm and the extrudate shape control method, was explained. Finally, a one-meter long, arch-shaped structure was printed to illustrate the surface finish quality improvement made by the variable-geometry nozzle.

The design and prototype of a novel variable-geometry nozzle assembly was presented in this study to control the extrudate geometry during the process and improve the surface finish quality of 3DCP product. The variable outlet geometry is achieved by using 10 independently controlled sliding plates extending into the flow channel to change the geometry of the nozzle outlet during the process. The deposition module of the flow channel is carefully sealed to avoid any leakage out of the flow channel and ease the cleaning process.

The workflow of controlling the variable geometry nozzle in 3DCP process is also presented. An innovative slicing algorithm was developed to calculate the target extrudate geometry for every point on the print path. A nozzle-extrudate geometry correlation database based on predictive ANN model was developed to find optimized nozzle geometry for all the target extrudate geometry along the print

path. During the onsite 3DCP process, the program looks up in the database to find optimal nozzle geometry based on nozzle position and send commands to the nozzle, which eventually print extrudate with desired geometry at all the position on the print path.

As a case study, an infilled arch structure of 1 meter long and 225 mm high was designed and printed with both fixed-shaped nozzle and variable geometry nozzle. The surface roughness for both fabricated structures were measured to characterize the surface quality improvement. Case study result suggests that the proposed system could lead to visible improvement in the surface finish quality when printing curved outer surface. Comparing with conventional fixed-geometry nozzle, the variable geometry nozzle can reduce the 38% of mean arithmetic roughness (R_a) on the printed part. These advantages make the variable geometry nozzle capable of controlling extrudate geometry during the printing process to achieve the desired outer-curvature, which is not anymore limited to straight-wall printing, but open to structures with larger variety and complexity of outer-surface curvatures. This will make the 3DCP technology more flexible and feasible for the future industry.

Furthermore, the approach presented in this study is an inspiring new approach to improve the 3DCP process in engineering applications. By introducing geometry control on nozzle outlet, control is directly applied to the extrudate lines, which is the smallest engineering component of any extrusion-based 3D printing technology. Although the variable-geometry nozzle proposed in this study is particularly useful to 3DCP because of the large macroscopic printing volume, the

approach to apply micro-control in extrudate formation can also be useful to other extrusion-based 3D printing processes.

Chapter 6. Conclusions

This study focuses on the development of “extrudate formation control” which is a critical research gap in 3DCP field attributed on the low quality of the printed structure surface. The author believes that the research outcomes of this project will offer major contributions in the field of concrete 3DP/Additive Construction. Under the current circumstance where the lack of extrudate control is a serious problem to the quality assurance of 3DCP, the work done in this thesis might offer a new paradigm to shorten the process chain in printing a structure with 3DCP technology by improving the output quality in the first place.

The preliminary study concentrates on sensitivity parameter evaluation to figure out the most critical parameters in the extrudate formation process. The extrudate process is explained for a setup presented in the chapter and the determining factors were discussed. Among the factors, the nozzle geometry potentially controls the extrudate geometry and improve printing quality. The subsequent CFD approach and iterative experimental approach have shown that the nozzle geometry can be adjusted to mitigate existing printing problem, such as jagged surface and material distribution at corners. However, the CFD approach and iterative experimental approach are very inefficient for on-site printing applications, which makes it unfeasible to be used for extrudate formation control.

As an alternative, a machine learning approach is used to estimate the deployed extrudate from specific nozzle outlet shape, which can allow us to use it for directly control the geometry of 3DCP extrudate during the process. An ANN

structure is used to develop the model and for the training purpose, thirteen different nozzle shapes were designed and fabricated, and subsequently used to print extrudate samples. A predictive model was then developed using the training samples to correlate the nozzle shape to the extrudate shape. The trained model was validated experimentally and used to design nozzle for test walls with improved surface quality. Benchmarking the results to the walls printed with a conventional rectangular-shaped nozzle, the output from the optimized nozzle demonstrates noticeable surface quality improvement. More importantly, the proposed approach shows its potential to facilitate surface finish improvement for printing structures with varying surface shapes as it directly controls the extrudate geometry.

Moving further, the developed predictive-model was used as a basis for a novel variable-geometry nozzle development, where the outlet shape can be adjusted to comply to complex form structures. Upon the completion of the nozzle development, together with a developed slicing algorithm and a dedicated control method, the system was tested for printing applications. The results suggested that the positive functionality of the nozzle and the predictive model on a case study of one-meter long arch-shaped structure. The results also suggest that the proposed system is offering visible improvement on the surface finish quality of printed curvy surface structures.

In general, the outcomes of this research have proven that the proposed approach is capable of controlling extrudate geometry in real-time printing process of curvy structures and 3DCP is not anymore limited to straight-wall printing. This

opens new horizon of 3DCP technology for more flexibility structures to be printed with acceptable surface finish quality.

6.1. Contribution of this thesis

The effect of nozzle geometry on the extrudate formation process was evaluated using experimental approach and CFD approach. The nozzle geometry could be adjusted to improve printing quality, like the surface finish quality and the material distribution at turning.

A data-driven predictive modeling approach based in Artificial Neural Network (ANN) was adapted to develop the relationship between the printing parameters and the extrudate formation in 3DCP. A training database containing 101 groups of original experimental extrudate geometrical dimension was collected under 52 different sets of experimental process parameters. The predictive model could be used to predict a 30 mm wide extrudate formation with an error of less than 0.5 mm in validation experiments. The nozzle-extrudate shape correlation database containing ten million sets of nozzles and their corresponding predicted extrudate was generated. This ANN-model approach has been proved useful to improve surface finish quality for printed structures.

A novel mechatronic nozzle assembly which has a controllable outlet geometry was designed and developed. The controller of the variable-geometry nozzle which read the information of the slicing result, the real-time position and the nozzle-extrudate

correlation database. The controller dynamically adjusts the nozzle shape to print desired extrudate at desired location. The surface roughness could be significantly reduced with the predictive-modelling approach and the variable-geometry nozzle.

6.2. Future work

Feed-back control is a necessary implementation to the current variable-geometry nozzle system, where the sensors and nozzle controller could monitor and control the surface finish quality on a close-loop basis. The sensors or cameras can be used to monitor the surface roughness during the printing. Until now, the only feedback systems observed in the literature are the standoff distance monitoring system and the flow rate tracking system, developed in TU/e [39] and USC [95]. The close-loop control system is necessary to the 3DCP to monitor and to improve the surface finish quality, especially because the unstable flow fluctuation of the pump is a major limitation of the quality assurance of 3DCP.

The accuracy ANN model could be further improved with more experimental data. The current training data has only covered several aspects in the experiment parameters, i.e. the nozzle shape and flow ratio. However, there are more parameters such as the nozzle standoff distance, material thixotropy and nozzle channel design that could have significant influence on the extrudate formation. Hence, it is necessary to improve the current ANN model and implement these parameters.

The variable-geometry nozzle system could be applied to improve the printing quality in different perspectives. For example, the variable-geometry nozzle could be used to solve the inhomogeneous material distribution problem in the curved-path printing that is mentioned in Section 3.5. Simulation or machine learning method may be applied to predict desired nozzle shape and different printing path to make the material distribution more homogeneous. Subsequently, the nozzle controller could be upgraded to adjust the nozzle shape before the printing of curved-path, and the printing quality could be improved. Moreover, the extrudate width could also be adjusted by the variable-geometry nozzle during the printing, which may largely promote the complexity of the printable pattern in existing 3DCP technology.

The mechanical strength of the product is a very important property of the 3DCP-created structure. The relationship between the nozzle geometry and the mechanical strength of the fabricated structure needs further investigation because the nozzle geometry has the potential to affect the mechanical strength of the printed product. In the future study, a more detailed study on the relationship between the nozzle geometry and the compressive strength of the printed structure remains to be conducted. Also, the relationship between the nozzle geometry and the interlayer-bonding strength should be studied. The adjustment of extrudate geometry may lead to the shape change at the corners of the layer-interface, which are the potential crack-initiation points that affect the interlayer-bonding strength.

The top and bottom sides of the nozzle outlet are influential parameters to the final extrudate geometry. However, the current study has only considered the geometry variations on the left and right side of the nozzle to avoid the influence on the material distribution. The variation of top and bottom side geometries could also affect the final flow state of the extrudate deposition. In the future study, the simulation or experimental method can be utilized to analyze the effect of varying the top and bottom sides of the nozzle geometry.

Hypothetically, this method might be useful for other material-extrusion 3D printing because the deposition process takes a similar principle. Although changing the nozzle shape in a different process conditions can be challenging, the findings in this study offers a solution to improve the printing quality by controlling the extrudate formation in other extrusion-based 3D printings.

Publication list

Journal Papers:

- Lao, W., M. Li, T.N. Wong, M.J. Tan, and T. Tjahjowidodo, *Improving surface finish quality in extrusion-based 3D concrete printing using machine learning-based extrudate geometry control*. Accepted in Virtual and Physical Prototyping (2020). doi: 10.1080/17452759.2020.1713580.
- Lao, W., M. Li, and T. Tjahjowidodo, *Improving surface finish quality in 3D concrete printing with curved outer-surface geometry using a variable-geometry nozzle*. Submitted in Automation in Construction (2020).

Conference Proceedings:

- Lao, W., M. Li, L. Masia, and M.J. Tan. *Approaching Rectangular Extrudate in 3D Printing for Building and Construction by Experimental Iteration of Nozzle Design*. in *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium (SFF 2017)*. 2017. Austin, TX. doi: 10.32656/sff.2017.208
- Lao, W., Tay, D. Y. W., Quirin, D., & Tan, M. J. (2018). *The effect of nozzle shapes on the compactness and strength of structures printed by additive manufacturing of concrete*. in *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018)*, 80-86. doi:10.25341/D4V01X
- Li, M., Lao, W., He, L., & Tan, M. J. (2018). *Effect of rotational trapezoid shaped nozzle on material distribution in 3D cementitious material printing process*. in *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018)*, 56-61. doi:10.25341/D4ZP4W

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