DEVELOPMENT OF A MATERIAL DELIVERY SYSTEM OF 3D PRINTING USED FOR BUILDING CONSTRUCTION

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DECLARATION

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LIST OF ABBREVIATIONS

AM	Additive manufacturing
CAD	Computer-aided design
CC	Contour Crafting
FDM	Fused deposition modeling
STL	Standard Tessellation Language

ABSTRAK

Percetakan 3D merupakan teknologi pembuatan yang moden. Teknologi ini membina model 3D daripada lapisan 2D. Penggunaan percetakan 3D dalam sektor pembinaan bangunan adalah teknologi yang baru muncul. Berbanding dengan kaedah pembinaan tradisional, teknologi ini mempunyai kelebihan dari segi masa, kos, mengurangkan pembaziran dan kebebasan reka bentuk bangunan. Penggunaan percetakan 3D dalam pembinaan memerlukan integrasi teknologi pelbagai sistem. Salah satu sistem penting yang terlibat ialah sistem penghantaran bahan. Kini, kajian tentang sistem penghantaran bahan amat terhad. Projek ini bertujuan untuk mereka sistem penghantaran bahan yang digunakan untuk percetakan 3D dalam pembinaan bangunan. Sistem penghantaran bahan ini direka secara skematik. Kemudian, model bahagian nozel direka dan dihasilkan. Hubungan antara kelajuan nozel, kadar aliran dan saiz tangki penyimpanan juga ditentukan. Ujian yang dijalankan dengan model fabrikasi menunjukkan bahawa fungsi sistem penghantaran bahan sangat bergantung kepada sifat bahan. Sistem ini boleh menghasilkan penyemperitan yang wajar dengan bahan yang sesuai. Ia berpotensi untuk berfungsi sebagai panduan bagi kajian atau projek pembinaan yang mempunyai bahan yang sesuai dan memerlukan sistem penghantaran bahan.

ABSTRACT

3D printing is a modern manufacturing technology. This technology builds 3D models from stacking of 2D layers. The application of 3D printing in the sector of building construction is an emerging technology. It provides advantages over the traditional construction method in terms of time, cost, waste reduction and architectural freedom. Application of 3D printing in construction requires technological integration of various systems. One of the important systems involved is material delivery system. Currently, there is limited research that focused on the material delivery system. This project aims to develop a material delivery system of 3D printing used for building construction. The material delivery system is designed schematically. Then, a model of the nozzle assembly is designed and fabricated. The relationship between the nozzle speed, flow rate and storage tank size are derived. Test carried out using the fabricated model shows that the working of the material delivery system depends greatly on material properties. The material delivery system can produce desirable extrusion with suitable material. It has the potential to serve as a blueprint for 3D printing construction projects or research that require a material delivery system for extruding an available suitable material.

CHAPTER 1 INTRODUCTION

1.1 Research background

3D printing is also known as additive manufacturing. Additive manufacturing (AM) is defined by the American Society for Testing and Materials (ASTM) as a process joining materials to make objects from 3D model data, usually layer upon layer [1]. There are various types of additive manufacturing technology such as stereolithography (SLA), fused deposition modelling (FDM), selective laser sintering (SLS), digital light processing (DLP), material jetting, binder jetting and powder bed fusion. The main advantages of additive manufacturing is minimal material wastage and the ability to fabricate complex geometry due to its layer-adding approach as opposed to subtractive manufacturing technologies.

The typical workflow of 3D printing starts from a 3D model created by using a CAD software. The model is then saved in a common 3D data exchange format, of which the most popular is Standard Tessellation Language (STL) file format. A slicer software then slices the 3D model into 2D layers. Control commands are generated to position printing head or laser beams to build the 2D layers in sequence to form the 3D model [2].

3D printing is a growing technology and has increasing applications in various industries such as manufacturing, medical and aerospace. In recent years, the interest in 3D printing for building construction is increasing [3]. Traditional construction method has many limitations. Reported problems faced by the construction industry are low labour effieciency, high accident rates at construction sites, low work quality, difficult control of the construction site and vanishing skilled workforce [4]. The use of formwork in traditional construction generates large amount of waste. The construction industry is responsible for generating approximately 80% of the total waste in the world [5].

The application of 3D printing technology in construction has a number of advantages. One major advantage is the lower construction cost. 3D printing eliminates the traditional manual brick-layering process for wall construction which is labour-intensive. 3D printing technology can save up to 60% of building materials and 50% to 80% of manpower, allowing houses to be built for lower cost which is especially helpful in third world countries [6]. 3D printing technology can reduce the construction time by 50 to70% [6]. Human construction workers need to rest and it is also harmful to work under extreme weather. 3D printing construction is carried out by automated machines hence does not have these human limitations. At the same time, the risk of accidents on human at the construction site will be reduced. With the reduction in cost and time, affordable homes can be built in short time for the homeless people due to poverty or for natural disaster victims whose houses had been devastated. In Malaysia, this advantage is applicable to building new homes for flood victims. Besides, 3D printing construction can help to reduce our country's dependency on foreign construction labours.

Furthermore, 3D printing provides design flexibility. This technology enables architects to have more freedom in their designs of shapes of the buildings as 3D printers can build complex forms with non-linear shapes and curved walls which cannot be built by traditional construction methods. The tool path in 3D printing is controlled by computer program, hence the designs are not limited by construction workers' skills. Besides, 3D printing generates less construction waste as formworks are not required and the precise amount of material is used to print the desired shape of building. Therefore, it is more environmental friendly.

Although there is an increasing number of research groups and companies involved in 3D printing construction, this technology is still in its infancy [7]. The 3D printing technology used for building construction can be extrusion-based or powder-based. For extrusion-based method, construction material in the form of a thick paste is extruded out of a nozzle and harden to form the structure layer by layer. For powder-based mehod, liquid binder is selectively dispensed onto a bed of powder to solidify the powder layer by layer.

Most of the existing research and 3D-printed buildings are using the extrusion-based method. The extrusion-based method is similar in concept to fused deposition modeling (FDM). FDM is the most common type of 3D printing method and is popular among hobbyists due to its lower cost of machine and material compared to other 3D printing methods. In a common FDM process, plastics filaments are feeded into the 3D printer and heated to melt. Then, the plastics is extruded in a liquid form which solidifies at room temperature after leaving the nozzle. For 3D printing construction, the solidification of the concrete used is governed by its composition and chemical reactions between its constituents. A major challenge in this technology is to extrude the right type of material with the right rheological properties in the right amount at a right speed. Therefore, a suitable material delivery system is crucial to the success of this technology.

1.2 Problem statement

The application of 3D printing in building construction is an emerging technology. Currently, there are only a handful of 3D-printed buildings exist around the world which are mainly built by research teams or construction companies with the aim of exploring this new technology. Despite the many advantages of 3D printing in construction, there is very limited literature focusing on the material delivery system required to support the realization of this technology.

1.3 Objectives

1. To develop a material delivery system of 3D printing used for building construction from the storage until the nozzle.
2. To fabricate a model of the nozzle assembly of the material delivery system.

1.4 Scope of research

This project focuses on developing the material delivery system of extrusion-based 3D printing used for construction of concrete walls. A material delivery system from the storage until the nozzle is conceptualized and designed schematically. A model of the nozzle assembly is designed and fabricated. The relationship between the nozzle speed, flow rate and storage tank size are determined. The control system for the material delivery system is represented using a schematic relationship. The programming for positioning control of the printing nozzle is not included in this project since the material delivery system can be attached to a computer-controlled positioning system which will be responsible for moving the nozzle along the printing path. The strength and rheological properties of the printing material is assumed to be properly controlled by the concrete composition. The formulation of the concrete material is not included in this research.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview

Literature review is done by studying about research in the academic field and buildings in the construction industry in terms of the printing methods, materials and equipment used.

2.2 Methods of 3D printing for construction

The methods of 3D printing used for building construction can be divided into two types which are the extrusion-based method and the powder-based method. Contour Crafting, Concrete Printing and D-Shape are the most notable pioneering works in the field of 3D printing for construction.

The Contour Crafting technology introduced by Khoshnevis et al. at the University of Southern California is the pioneer in this field. Contour Crafting (CC) is a mega scale layered fabrication process which builds large scale three-dimensional parts by depositing paste materials layer by layer at unprecedented speed and with superior surface quality [8]. It is suitable for rapid fabrication of large-scale complex shaped objects. The CC process is based on an extrusion and filling process [9]. Smooth surface of the object is formed by constraining the extruded material using a top trowel and a side trowel. The orientation of the side trowel is dynamically controlled to conform to the slope of surface features [8]. A schematic view of the CC nozzle is shown in Figure 2.1.

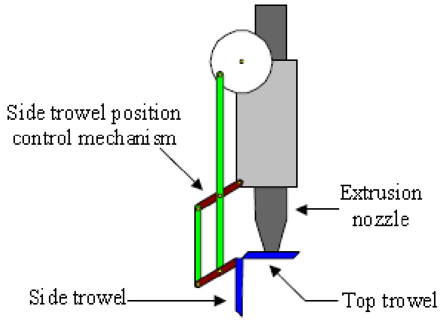

Figure 2.1: Schematic view of the CC nozzle [9]

The nozzle is mounted on a x-y-z gantry robot. In order to study the feasibility of CC construction, the research team used the CC technology to build ceramic parts and a vertical concrete formwork. The formwork was built by extrusion of concrete mortar. Once a batch of the mortar mixture inside the material carrying tank is consumed, the CC system is paused until another batch is loaded before extrusion can be continued to build the remaining structure. A batch of mortar is consumed in approximately 10 minutes and yields a concrete form approximately 2.5 inch (64 mm) high. After the concrete formwork is completed, concrete is poured manually into the formwork to form the core of the wall. The formwork then became an integral part of the wall [8]. With more experimentation, the concrete pouring process can be synchronized with the extrusion process [9]. Another type of wall built by using CC is hollow wall with reinforcement structures [10]. Figure 2.2 shows the two types of concrete walls fabricated by using CC technology.

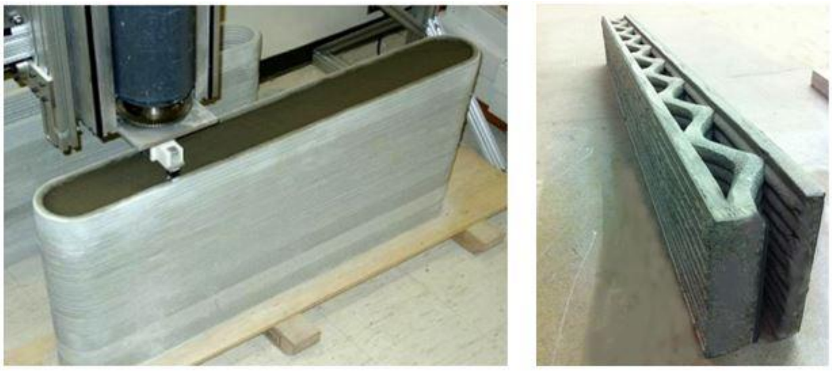

Figure 2.2: Concrete walls fabricated by using CC technology with manually poured core (left) and with reinforcement structure (right) [9, 10]

Concrete Printing is developed by Lim et al. at Loughborough University in the United Kingdom. Concrete Printing also uses the extrusion-based method to deposit the building material [11]. It is similar to the Contour Crafting technology to a certain extent but has a smaller resolution of deposition resulting in a better control of complex geometry and uses a material with better properties which is high performance fiber-reinforced fine aggregate concrete [12]. In order to demonstrate the scale of the process, a wall-like structure named "Wonder Bench" has been designed and printed. The bench is 2.0 m by 0.9 m with a 0.8m height, and the weight is approximately 1 tonne. It is comprised of 128 layers of 6 mm thickness. The bench includes 12 voids that minimize weight, and could be utilized as acoustic structure, thermal insulation, and/or path for other building services. The bench also demonstrates a reinforcement strategy where carefully designed voids form conduits for post placement of reinforcement [12].

Figure 2.3: Bench printed by Concrete Printing [12]

The D-shape technology is developed by Enrico Dini. It is a powder-based 3D printing technique that selectively hardens a large sand-bed by deposition of a binding agent. The schematic view of powder-based technique is shown in Fgure 2.4.

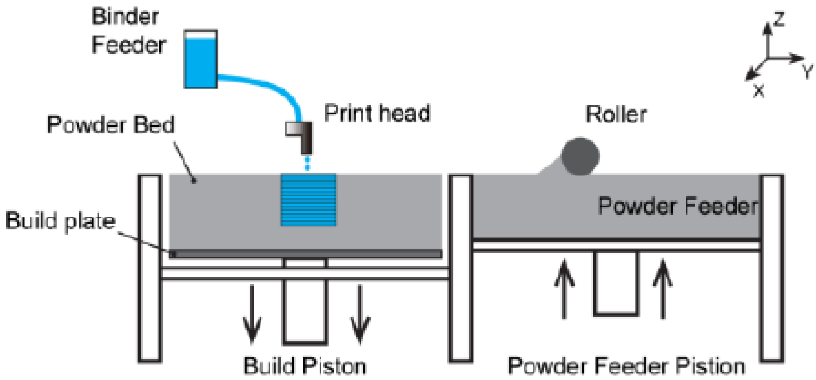

Figure 2.4: Schematic view of powder-based technique [5]

D-shape uses sand as the build material and magnesium oxychloride cement (also known as Sorel cement) is used as the binding agent. It uses a gantry with multiple nozzles mounted in series that requires a single traverse per layer. For each layer, a layer of sand needs to be added and flattened evenly over the entire build area before the binding agent is dispensed [12]. The unbinded sand act as a support. In 2008, Shiro Studio collaborated with D-shape to produce the Radiolaria pavilion (as shown in Figure 2.5) measuring $3 \times 3 \times 3$ meters to demonstrate the capabilities of D-shape technology through complex geometry [5].

Figure 2.5: The Radiolaria pavilion printed by using D-shape technology

Most of the ensuing research and projects in this field are carried out on the basis of the countour crafting technology. With the exception of D-shape, all additive manufacturing of concrete adopt the Contour Crafting approach of stacking layers of extruded materials. Gantry robots and articulated robots are most commonly used [7]. Besides, the buildings can either be 3D printed directly on-site or assembled from prefabricated 3D-printed components.

Some examples of existing 3D printed buildings around the world are the Apis Cor printed house in Russia, the buildings by WinSun, a two-storey house by Huashang Tengda in Beijing, the castle of Andrey Rudenko's garden in Minnesota and the Canal House in Amsterdam. The Apis Cor house was printed totally on-site in Moscow in December 2016 by the Apis Cor company. The house measuring 38 m^2 was built within 24 hours with a cost of US$10134 using a mobile 3D printer [13, 14].

Figure 2.6: Apis Cor printed house (left) and its countour crafting process (right) [13]

WinSun Decoration Design Engineering Co had accomplished several 3D printing construction projects. In 2014, WinSun had built ten 3D printed houses each measuring 200 m^2 in Shanghai, China by using prefabricated components printed by a gigantic 3D printer in a factory and then assembled on the construction site [2, 15]. In 2015, WinSun used similar technique to build a five-storey residential building and a 1100 m^2 villa [2, 15]. In 2016, WinSun partnered with Gensler and built 3D printed office for the Dubai Future Foundation. The parts for the office building were printed in China and shipped to Dubai where the office was assembled within a couple of weeks [16, 17].

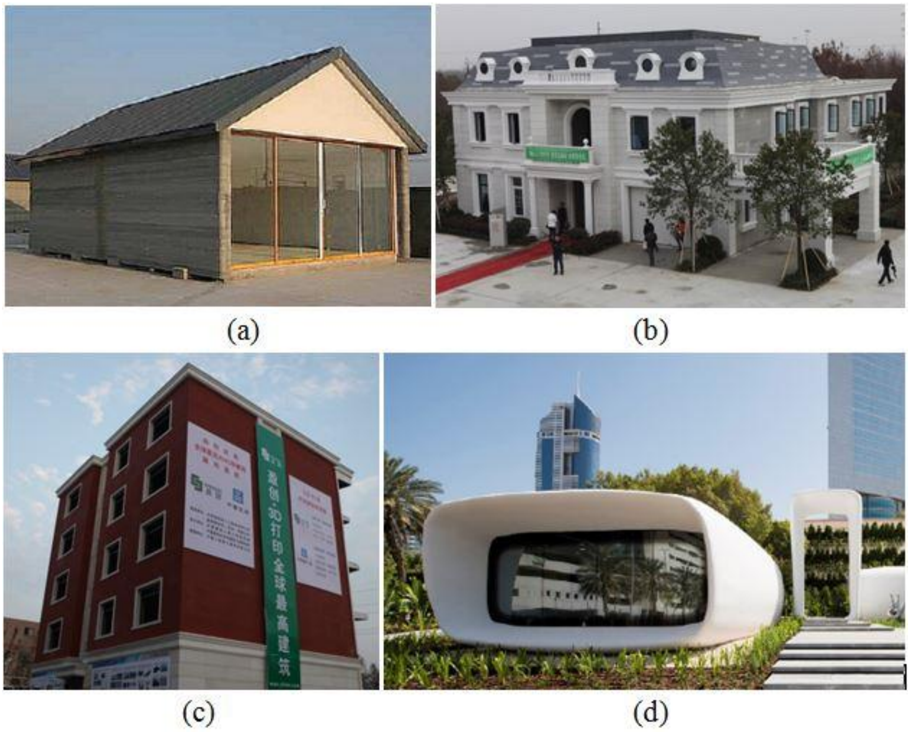

Figure 2.7: WinSun’s 3D printed buildings: (a) house [2], (b) villa [15], (c) five-storey building [15], and (d) office in Dubai [17]

Beijing-based construction company, Huashang Tengda had built a two-storey house using a technique different from WinSun. The 400 m^2 house was printed entirely on-site in 45 days by using a gigantic 3D printer claimed to be developed entirely in-house by the company which is controlled by custom-designed software [18].

Figure 2.8: two-storey house built by Huashang Tengda [18]

Another notable example of 3D printed building is Andrey Rudenko's 3D printed castle in Minnesota where the whole building was printed in one piece except for the turrets [19].

Figure 2.9: Andrey Rudenko's 3D printed castle

The 3D Print Canal House in Amsterdam is a three-year 'Research and Design by Doing' project initiated by Dutch company DUS Architects in collaboration with international partners from various sectors. The 3D Print Canal House functions as a research and also an exhibition open to public [20]. A 6m tall 3D printer called KamerMaker and bioplastics material are developed and used in this project [20, 21].

2.3 Materials of 3D printing for construction

2.3.1 Concrete in general

Concrete is the most used building material worldwide. The term "concrete" does not represent a single specific type of material. It actually represents a large range of composite compositions, with the common characteristic that they consist of a filler of sand, gravel, or other granulate materials, bound by a matrix that is formed by an exothermal hydration reaction between cementitious materials (cement or cement-replacers such as fly-ash) and water [7]. Additional or alternative additives, admixtures, aggregates, and cementitious materials are used to achieve specific properties.

Concrete can be in different stages. Fresh stage is the period of time during which the mixed concrete can be handled, transported, poured and finished before initial setting takes place. Setting stage is the period of time during which fresh concrete in place starts setting, up to before hardening begins. Setting is a condition defined as occurring at the instant when concrete becomes unsuitable for placement [22]. In the hardening stage, the concrete develops compressive strength by a chemical reaction known as hydration. The compressive strength of concrete are usually measured at 1, 3, 7 and 28 days. The process of hydration, once it had passed the initial stage, slows down and can continue at a very slow rate for many years [23].

The properties and performance of concrete are influenced by its proportion of cement, water and aggregates and also the effect from additives and admixtures. An admixture is defined as a material other than water, aggregate, and hydraulic cement which might be added to concrete before or during its mixing. This is not to be confused with addition which is added to cement to aid the manufacturing or handling or to modify the use properties [24]. Admixtures are used in concrete to obtain effects such as acceleration, retardation, air entrainment, water reduction and plasticity [25].

A set retarding admixture is defined as one that delays the time of setting of portland cement and hence that of its mixtures, such as mortars and concrete [24]. Set-retarders retard the initial rate of reaction between cement and water to increase the time taken by mortars and concrete to pass from the plastic to the solid state [22]. Accelerating admixtures can be divided into set accelerator and hardening accelerator. Set accelerators reduce the time for the mix to change from the plastic to the solid state while hardening accelerators increase the rate of development of early strength in the concrete whether or not they affect the setting time [22, 26]. A superplasticizer is defined as an admixture which procure a considerable increase in the workability of mortars and concretes at constant water-cement ratio [22]. Materials such as fly ash, slag, pozzolanas, or silica fume which can be constituents of cement and concrete, and also products acting as reinforcement, are not classified as admixtures [22].

2.3.2 Concrete for 3D printing

Traditionally, concrete mixtures involve three components which are cement (9–15%), water (15–16%), and fine aggregates (25-35%) and coarse aggregates (30–45%). Concrete for 3D printing uses much finer materials such as sand, clay, fly ash, or silica fume [13].

For application in 3D printing, wet properties of the materials in terms of pumpability and stability of the extrusion are very important. Four key characteristic of the materials can be identified as pumpability, printability, buildability and open time [12]. Lim et al. defined the four characteristics as follows [12]:

a) Pumpability is the ease and reliability with which the material is moved through the delivery system.
b) Printability is the ease and reliability of depositing the material through a deposition device.
c) Buildability is the resistance of the deposited wet material to deformation under load.
d) Open time is the period where the above properties are consistent within acceptable tolerances.

For Concrete Printing, Lim et al. had developed a high-performance cement-based mortar which comprises 54% sand, 36% reactive cementitious compounds and 10% water by mass [12].

The Contour crafting (CC) method uses polymer, ceramic slurry, cement, and a variety of other materials and mixes to build large scale objects with smooth surface finish [27]. According to Hwang and Khoshnevis [27], the success in fabricating a part using the CC method depends largely on the characteristics of the extruded material. Through several trial and error experiments, they found that the concrete mixture suitable for their CC machine consists of 9.5 lb (37%) of Type II hydraulic Plastic Portland cement, 10.5 lb (41%) of sand, 0.8 lb (3%) of plasticizer and 4.8 lb (19%) of water.

In the research by Le et al.[28], five different trial mixtures were designed and the optimum mixture was found to be the one with water-binder ratio of 0.26, sand-binder ratio of 60:40, comprising 70% cement, 20% fly ash and 10% silica fume, plus 1.2 kg/m^3 micro polypropylene fibres. 1% of superplasticizer and 0.5% of retarder are also required to achieve optimum workability and optimum open time of up to 100 minutes.

For the reasearch of Bos et al.[7], a custom concrete mixture was developed by SG Weber Beamix which comprised of Portland cement, siliceous aggregate with an optimized particle size distribution and a maximum particle size of 1 mm, limestone filler and specific additives to ease pumping, rheology modifiers for obtaining thixotropic behavior of the fresh mortar, and a small amount of polypropylene fibres for reducing crack formation due to early drying. Performance of the mortar in terms of strength development and speed of strength development can be modified by adding accelerators and/or by changing the ratio of Portland cement and limestone filler [7].

For the research of Gosselin et al.[29], a custom concrete mixture was developed and supplied by LafargeHolcim which comprised of 30-40% Portland cement, 40-50% crystalline silica, 10% silica fume, 10% limestone filler and water-cement ratio of 0.1. The material also contains polymer-based resin to improve interface quality between printed layers, and an accelerating and thresholding agent to achieve optimum rheology and setting time [29].

From the reviewed literature, it is noted that the concrete mixtures used by the researchers vary from each other. The optimum concrete mixture used in each research is developed specifically for that particular research by using trial and error approach. There is no established standard that specifies a suitable mixture for 3D printed concrete. It is difficult to conduct a comparative analysis of the various material formulations used by different researchers and companies due to trade secret preventing technical details from being publicly shared [21]. WinSun reported that the material used for their 3D printed buildings is a mixture of recycled construction waste, glass fibre, steel, cement and special additives [15]. Materials used for the Apis Cor printed house are claimed to be concrete and innovative materials of TechnoNICOL company [14]. The 3D Print Canal House is reported to be built from sustainable bio-based thermoplastics developed by the project's material partner, Henkel [20]. In these companies' projects, the constituents that made up the printed material and their proportions in the material are not disclosed. Huashang Tengda claimed that the material used to print their two-storey house was ordinary C30 class concrete [18] but Bos et al. claimed that this is improbable considering the slump behavior and particle size in relation to printer geometry [7]. The variations and uncertainties in material composition pose a great challenge to the material delivery system.

2.4 Equipment for 3D printing of concrete

In the concrete wall fabrication by Contour Crafting [27], an extrusion system which is mounted on a frame delivers a mortar mixture from the material reservoir and deposits it in controllable amount to form a desired shape. A piston is attached to and driven by the lead screw which turns at constant rotational speed to extrude the mixture. As the mortar exits the extrusion nozzle, the machine moves the nozzle assembly in the X-direction at pre-specified speed. Once a layer is finished printed, the entire extrusion system moves vertically upwards for a distance equal to the height of the subsequent layer. This process is repeated until the final shape is completed. The system is shown in Figure 2.10.

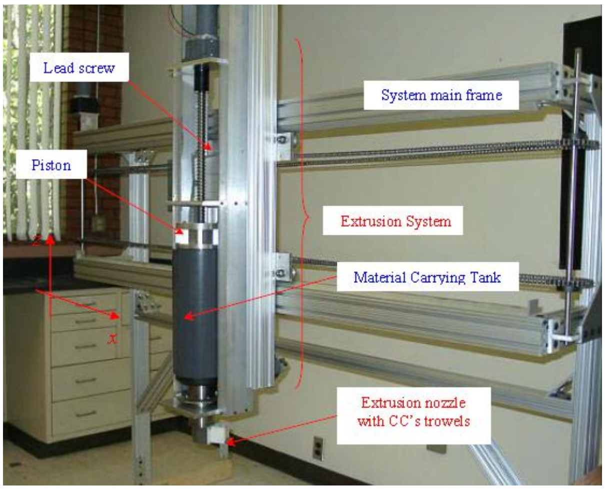

Figure 2.10: Hardware system for fabrication of concrete wall using CC [27]

In the research by Le et al.[28], the prototype concrete printing machine operates within a steel frame with length of 5.4 m, width of 4.4 m and height of 5.4 m. The printing head is digitally controlled by a CNC machine to move in X, Y and Z directions via three chain-driven tubular steel beams. A material container is mounted on top of the printing head and connected to a pump to deliver the material to the printing nozzle. The system is shown in Figure 2.11.

Figure 2.11: Prototype concrete printing machine by Le et al. [28]

In both the Contour Crafting and Concrete Printing [27, 28], the material container is mounted on the gantry system and moved together with the nozzle during the extrusion process. The limitation of this configuration is that the speed of travel of the nozzle may be impeded by the mass of the material in the container. Higher motor power would be required to move the nozzle. Besides, the nozzle would be less maneuverable especially when travelling through curved path or corner due to the inertia of the mass.

The positioning systems applicable for 3D printing in building construction are gantry system and articulated robot. Articulated robots such as a KUKA robotic arm have more degrees of freedom than a gantry system, hence is suitable for printing more complex object. However, articulated robots have some limitations. The reach of the robot is limited by the working envelop of its manipulator. Besides, joint kinematics calculation of the robot can be complicated and the robot may experience singularity on joint velocities. In the research by Shakor et al.[30], the robot in use was limited to a reach of approximately 1100 mm from the base. Printed specimen dimensions are thus limited to be contained within this workspace. The research team also noted that manipulability was significantly reduced at some points of the path. The process was discretized into approximately 130 robot poses in order to complete each layer and the robot approaches singularity between certain joint step intervals [30]. Therefore, gantry system is preferable for the printing of large-scale objects due to its simplicity.

In their research [30], Shakor et al. also found that the flow rate provided by the auger used in the system was inconsistent. Another probem was that the motor used to power the auger struggled to rotate when put under increased loads. Loads from the mixes with higher densities and higher viscosities reduced the augers' practicality [30].

For 3D printed buildings projects in the construction industry, although the components and mechanism involved are not discussed in details, the buildings are generally printed by large-scale 3D printers that are customly developed by the project company or in collaboration with companies from different sectors. Some examples of these printers include Apis Cor's mobile printer, Andrey Rudenko's Total Kustom printer, ICON's Vulcan printer and DUS Architects' KamerMaker printer.

The nozzle shapes used for 3D printing construction are usually round, square or rectangular. There are also various sizes of the nozzle opening. The nozzle diameter for Contour Crafting is 15 mm while Concrete Printing used nozzle diameter between 6 to 20 mm [7, 13]. Le et al. used a nozzle diameter of 9 mm [28]. Shakor et al. used circular nozzles with diameter of 10, 20 and 30 mm and square nozzles of 10, 20 and 30 mm in their experiments [30]. The Apis Cor printed house used an extrusion area of 25mm by 25mm [13]. Andy Rudenko's castle was built using concrete layers of

10mm in height by 30mm in width [19]. Typically, the extruded material from the nozzle has a diameter between 6 to 50 mm [31].

2.5 Review conclusion

Application of 3D printing in building construction is a multidisciplinary new technology. The development of this technology requires good integration between different components including hardware, software, architectural design and material properties. Multidisciplinary effort in robotics, architecture, civil engineering, information technology and material science are fundamental to this new construction method.

Currently, there are no well-established standards to be used as guidelines for a specific component in the system. Existing projects are using material, equipment or algorithms which are developed specifically for the particular project through the collaboration between academic organizations, construction companies, material companies and robotics or 3D printer companies.

The study by Wolfs [32] shows that the different components involved in this new construction technology are clearly connected, but the relationships are generally unknown. According to Wolfs, limited application of concrete printing in the built environment can be explained by lack of knowledge on the components involved in 3D concrete printing. The large quantity of variables results in vast amount of combinations and variations. With every new design or new material, a research team has to start the trial-and-error process all over again to find the proper parameters. Besides, the starting point can be a designed shape, but may also be material properties or a printing strategy [32].

Therefore, the material delivery system to be developed in this project should have a certain degree of flexibility so that it can be adapted to changes in the different variables involved.

CHAPTER 3 METHODOLOGY

3.1 Overview of methodology

This project is started by conducting background research on application of 3D printing technology in the field of building construction. Literature review is done to study about existing techniques and buildings. Then, the steps of developing the material delivery system can be categorized into several stages which are schematic design of the overall material delivery system, design of the nozzle assembly model, derivation of equations, fabrication of the nozzle assembly model, followed by testing of extrusion using the fabricated model.

3.2 Schematic design of the material delivery system

A material delivery system for FDM-based technology is conceptualized based on the consideration of materials preparation, storage, delivery, extrusion and how all of them are interconnected. The properties, constituents, and chemical reactions of concrete are studied. Next, the differences between conventional construction method and 3D printing construction (in terms of methods and hence the requirements on the concrete) are identified. Schematic design is then created by taking into account (i) the sequence that the constituents of the concrete have to be introduced into the system based on the requirement for 3D printing application and (ii) the control required to operate the material delivery system. Figure 3.1, 3.2 and 3.3 show the concept development process of the schematic design.

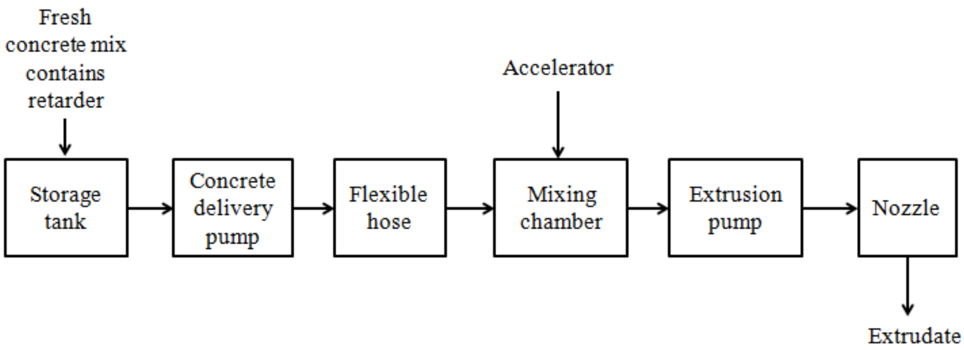

Figure 3.1: Schematic diagram of material flow

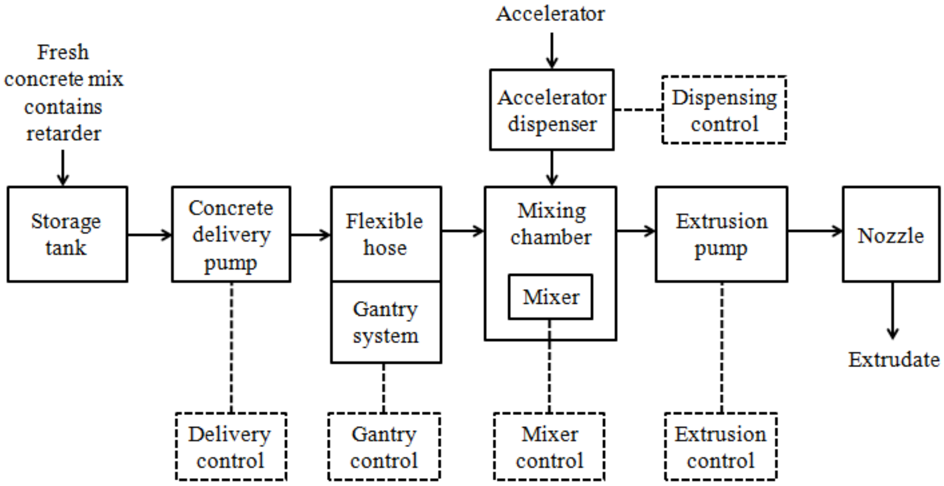

Figure 3.2: Schematic diagram of the material delivery system

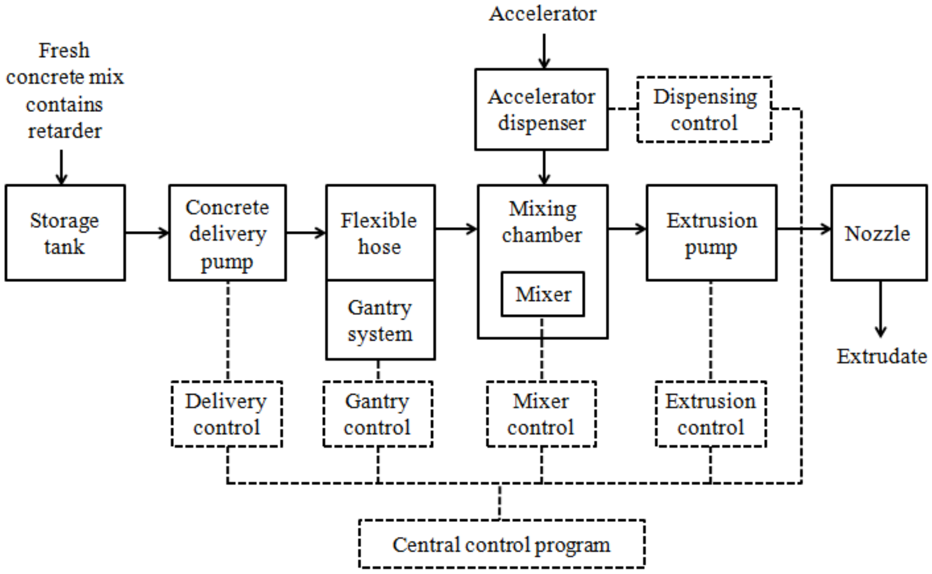

Figure 3.3: Schematic diagram of the material delivery system with central control

After the overall system for material delivery is designed schematically. The focus is then placed on the nozzle assembly.

3.3 Design of the nozzle assembly model

The components of the nozzle assembly are first concepualized and sketched before they are drawn as CAD models by using SolidWorks. Main components of the nozzle assembly are nozzle, pump for concrete extrusion and mixing chamber with mixer.

In order to select a suitable type of pump for concrete extrusion, the following requirements are identified:

- The pump should be able to provide a continuous smooth flow to create a smooth extrusion.
- The pump should be able to function well with viscous fluid.
- The pump should be able to handle solid particles in the fluid since concrete contains aggregates.
- The pump should be able to withstand abrasion because the aggregates may abrade the surfaces they contact with as they passes through the pump.

Then, the working mechanism and characteristics of different types of pumps are studied in order to select a pump type that fulfill the requirements. The type of pump selected is progressive cavity pump. In practice, a pump is usually a purchased part instead of developed by the construction project team. The CAD model of a progressive cavity pump is obtained from an online library [33]. The stator, rotor and drive shaft of the obtained pump model are modified and assembled with the other parts drawn in SolidWorks. Flow simulation is done in SolidWorks to visualize material flow through the components of the nozzle assembly.

3.4 Derivation of equations

An equation that relates flow rate of pump to the nozzle travel speed is derived. This is to enable the control system to regulate the flow rate based on the changing nozzle speed during the extrusion process. After the equation of volume flow rate is derived, the required size of the storage tank can then be determined.

3.4.1 Volume flow rate and nozzle travel speed

In order for the nozzle to deposit a layer of material with uniform thickness, the volume flow rate generated by the extrusion pump must be proportional to the nozzle travel speed. The volume flow rate, Q is derived as

$$Q = whv$$

where w is width of the extrudate,

h is layer thickness,

v is instantaneous travel speed of the nozzle.

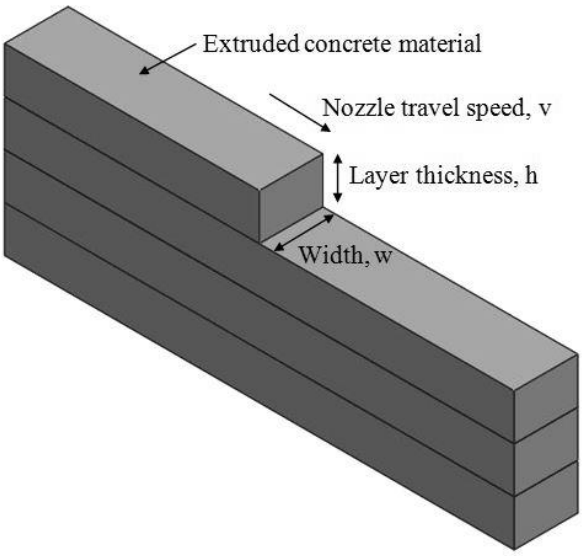

Figure 3.4: Schematic illustration of extruded layers