DEVELOPMENT OF CERAMIC EXTRUDER FOR THREE-DIMENSIONAL PRINTING

LIM CHUN YONG

MASTER OF ENGINEERING (MECHANICAL) (STRUCTURE C)

FACULTY OF ENGINEERING AND SCIENCE
UNIVERSITI TUNKU ABDUL RAHMAN
NOVEMBER 2021

DEVELOPMENT OF CERAMIC EXTRUDER FOR THREE-DIMENSIONAL PRINTING

By

LIM CHUN YONG

A thesis submitted to the Department of Mechanical & Material Engineering,
Faculty of Engineering and Science,
Universiti Tunku Abdul Rahman,
in partial fulfillment of the requirements for the degree of
Master of Mechanical Engineering by Coursework
November 2021

ABSTRACT

DEVELOPMENT OF CERAMIC EXTRUDER FOR THREE-DIMENSIONAL PRINTING

LIM CHUN YONG

Direct ink writing (DIW) 3D printer is one of the additive manufacturing techniques. It is an extrusion based additive manufacturing method, whereby the feedstock is dispensed out of a nozzle under controllable flow rate condition. The feedstock is then deposited on the platform and hence three-dimensional structure is built layer-by-layer (Lewis et al., 2006). Nowadays, the type of 3D printers available in the market are mainly fused deposition modelling (FDM) 3D printers and stereolithography (SLA) 3D printer which uses polymer filament or resin. However, direct ink writing 3D printer are not commonly available in the market. The purpose of this research is to develop a ceramic extruder which can be integrated to existing fused deposition modelling (FDM) 3D printers. Besides that, the extrudability of ceramic feedstock and its printability under the present extruder system are investigated. The development of extruder includes design of extruder geometries, extruder nozzle and materials classification for the design extruder to operate. After the extruder prototype is fabricated, the operation of extruder is analysed. Depending on the quality of printed object, the extruder is fine-tuned so that the best printed quality of product is achieved. The extruder is then attached to existing FDM 3D printer and tested on the synchronization of the extruder with 3D printer movement.

ACKNOWLEDGEMENT

I would like to express deep gratitude to Dr. Yeo Wei Hong, my project supervisor for his supervision, guidance and support, as well as the opportunity to work on this project which is the develop on ceramic extruder for 3D printers. I would also like to thank Dr. Lee Hwang Sheng for providing guideline on thesis writing and encouragement in selecting project in the early stage.

APPROVAL SHEET

This thesis entitled "**DEVELOPMENT OF CERAMIC EXTRUDER FOR THREE-DIMENSIONAL PRINTING"** was prepared by LIM CHUN YONG and submitted as partial fulfillment of the requirements for the degree of Master of Mechanical Engineering at Universiti Tunku Abdul Rahman.

Approved by:

____

(Dr. YEO WEI HONG) Date: 30/11/2021
Supervisor
Department of Mechanical and Material Engineering
Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 30 NOVEMBER 2021

SUBMISSION OF THESIS

It is hereby certified that **LIM CHUN YONG** (ID No: ***21UEM00128***) has completed this final year thesis entitled "**DEVELOPMENT OF CERAMIC EXTRUDER FOR THREE-DIMENSIONAL PRINTING**" under the supervision of **DR. YEO WEI HONG** (Supervisor) from the Department of Mechanical & Material Engineering, Faculty of Engineering and Science

I understand that University will upload softcopy of my thesis in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

_ LIM CHUN YONG _ _
(*LIM CHUN YONG*)

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name ___LIM CHUN YONG____________

Date ____30 Nov 2021________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Recently, additive manufacturing (AM) is getting more popular compared to traditional manufacturing approach in product development. Additive manufacturing is a transformative approach in production. Unlike traditional manufacturing methods which are also known as subtractive manufacturing or compressive manufacturing, additive manufacturing is a layer-based fabrication process. Generally, additive manufacturing requires the product design in detail. Using computer-aided-design (CAD) software, the product design is constructed and imported to additive manufacturing machine. Depending on the material requirements and additive manufacturing technologies, the suitable machine configuration is set for operation. Product is fabricated by printing the structure layer-by-layer and these layers are fused together (Prakash, Nancharaih and Rao, 2018). For some complex geometry such as overhanging structures, it is fairly difficult to be construct without any support structures (Tay, Li and Tan, 2019). Hence, support structures are fabricated simultaneously during the fabrication process. These structures are then removed from the finish product after the completion of fabrication process. The fabricated parts require to undergoes post processing process to permanently fuse all layer of the product. Meanwhile, the material properties of the products are also enhanced during the post processing process. Final product is produced from additive manufacturing process. From this process, it shows that the wastage material is further reduced compared to traditional manufacturing methods as only adequate material is used to fabricate the product (Pereira, Kennedy and Potgieter, 2019). Moreover, for complex geometry product, using additive manufacturing method significantly reduces the lead time as the product is fabricated in one process. Hence, there is a high interest in integrating additive manufacturing to current stage of production sector.

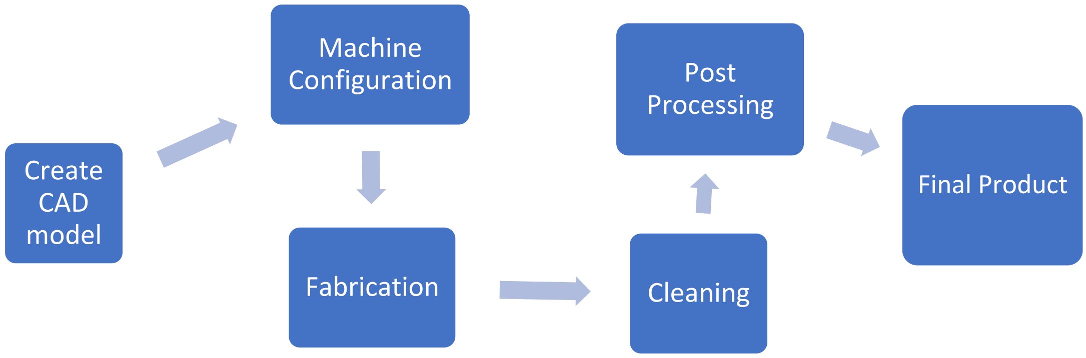


Figure 1.1: Additive Manufacturing Workflow

3D printing technique is categorized in one of the additive manufacturing technologies. At current stage, there are various kind of 3D printer used in manufacturing process such as selective laser sintering (SLS), selective laser melting (SLM), stereolithography (SLA), inkjet printing, binder jetting, direct ink writing (DIW) and fused deposition modelling (FDM) (Zhang, Wu and Shi, 2020). These technologies generally follow the additive manufacturing workflow. The differences are the appropriateness of fabrication process depending on the material used for product design and the mechanical properties requirements of the final products. Most of the 3D printers currently available in the market are used to fabricate product with metal or polymer materials by extrusion process. Whereby the feedstocks are heated close to the melting point of the material at the nozzle area and printed as a final product. Another method of product fabrication in 3D printing technologies is by sintering resin or powder. Same as other 3D printing technologies, the desired design of product is imported using CAD software. Then, feedstock in powder form or resin form are ready in a volume of container depending on the size of 3D printer and heated or sintered layer-by-layer to fabricate product. The common post processing process of this technique is curing process, whereby the printed product is cured under UV light for a period of time and hence enhancing the material properties of the product. The least common 3D printing technique is the direct ink writing (DIW). The main advantage and also the disadvantage of this technique is feedstock does not required heat during the fabrication process, which means that the operation only depends on simple extrusion process. However, this technique required material to have an appropriate viscosity property in natural stage when undergoes fabrication process. Hence, limiting the type of material could be used with this technique.

Even though there are so many 3D printing technologies, the use of ceramics in 3D printer are still in development. Most studies conducted for 3D printing of ceramics are in biomedical applications (Fan et al., 2017; Golcha, Praveen and Belgin Paul, 2020) and piezoceramic production (Smirnov et al., 2021). However, 3D printing technique is not frequently used in manufacturing conventional ceramic product such as clay-based vase due to the capacity of extruder as most of the ceramic 3D printer only holds enough volume to manufacture small product. Besides that, some of the ceramic extruder current available in the market comes in very large system whereby the printing dimension is 400mm width × 440mm length × 1500mm height with 35kg in weight (StoneFlower, 2021).

This proposal aims to develop ceramics extruder for 3D printer focusing on clay-based material and direct ink writing method. The extruder is then attached onto the existing FDM 3D printer.

1.2 Project Objectives

The aim of this research is to design and fabricate a functionable prototype ceramic extruder. The objectives of this research are as below:

I) To design and develop a ceramic extruder system which can directly attached on existing FDM 3D printer.

II) To investigate the extrudability of ceramic feedstock and its printability under the present extruder system.

1.3 Project Deliverables

I) A ceramic extruder system for an existing FDM 3D printer.

II) An extruder system capable of extrude and print clay feedstock

1.4 Project Scope and Limitations

The scope of this project involves in development of ceramic extruder system which could be directly mounted on existing FDM 3D printer. However, due to time and resources constraints, only clay material is tested out to identify its extrudability and printability under the extruder system as a proof of concept. As the proof of concept is established, ceramic materials other than clay can be investigated using the same extruder system to identify the optimum settings for use with an existing 3D printer.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

There are several FDM based 3D printers currently available in the market such as BIQU B1, Ender, Orignical Prusa and Ultimaker S5 (Hoffman, 2021). These 3D printers however only capable of extruder certain materials which exhibits a plastic behaviour such as polylactic acide (PLA), polyethylene terephthalate glycol (PETG) and acrylonitrile butadiene styrene (ABS). There are also 3D printers that could print ceramic material such as clay, for example, WASP Delta 2040 Clay Printer, Cerambot Air and Eazao Zero. Although there are many types of 3D printer in the market, most of the printer does not come with any attachment to change the printing material from plastic like material to ceramic material. Hence, it is essential to develop an extruder that could modify existing FDM 3D printer to work with ceramic.

In the development of ceramic extruder for 3D printers, there are few factors that are required to consider. First of all is the material that will be used with the design extruder. Different material consists of different material properties. Depending on the material properties, wisely choose the type of extruder to work with will further affect the result of the printed object. This is due to different types of extruders has its own configuration and the configuration must be able to cope with the material properties in order for the extruder to operate flawlessly. Therefore, the following factor required to be considered is the type of extruder of the design. This section will be discussed in detail under the type of extruder section. Moreover, the extruder geometry is also an important factor in the development of ceramic extruder.

2.2 Material

Depending on the type of extruder design for 3D printer, selection of material as feed stock is important. Material that selected as feedstock eventually will affect the design parameters of extruder due to different materials have their rheology properties and flow properties (Prem, Sindersberger and Monkman, 2019; Wang, Dommati and Hsieh, 2019). Besides that, the printed structure accuracy is also greatly affected by the viscosity of the material (Darling and Smith, 2021). From their studies, involvement of ceramic material in extrusion process for 3D printing application is highly depending on the mixture composition, water-clay ratio and viscosity of the ceramic material. All these factors are highly important when comes to ceramic working on an extrusion system due different material property requires different printer configuration in order to achieve well-printed structure. The easiest way to observe which material has a better printability is through water-clay. For example, the best fit water-clay ratio for kaolinite clay is between 0.60 to 0.61 (Revelo and Colorado, 2018) whereas for pottery clay the best fit water-clay ratio is 0.68 (Venkatesan, Ks and S, 2019).

2.3 Type of Extruder

For ceramic 3D printing, the technology used will be the direct ink writing method. Whereby the ceramic paste is pre-mixed before the extrusion and extruded on the bed without the need of any heating. There are few types of extruders available with direct ink writing 3D printing method, which are the single-step pneumatic piston, single-step mechanical piston, two-step pneumatic piston with conventional screw and two-step mechanical piston with conventional screw (Ruscitti, Tapia and Rendtorff, 2020).

Table 2.1: Type of Extruder and Comparison

Extruder Classification		Description	Advantage	Disadvantage
Single-Step	Pneumatic Piston (Air extruder)	An extruder with is controlled by compressed air	Simple construction Easy to clean and handle	The extruder is not synchronized to 3D printer movement Requires external compressed air source Poor precision in extrusion flow control Retraction of extruder is not possible Inherent compressibility of clays Issues on bottom of build part to be homogeneous Viscosity of paste must retain within a range during the operation
	Mechanic Piston (Syringe Pump)	An extruder with is controlled by mechanical piston system	Light in weight Powered by commercial motor	Inherent compressibility of clays Delay in extrusion control
Two-Steps	Pneumatic Piston + Conventional Screw	Adding screw extrusion system into pneumatic piston method	Ensure continuous flow of extrusion Removal of paste bubble Possible to achieve good control of the flow in the nozzle under constant paste viscosity System is not restricted to the volume Better quality of printed object due to homogeneous mixing Retraction of extruder is possible	Depending on the material viscosity, air pressure must be calibrated
	Mechanic Piston + Conventional Screw	Adding screw extrusion system into mechanical piston method	Retraction of extruder is possible External compressed air source not required Greater thrust force compared to pneumatic system	Feeding device is bulky and heavy Requires power to operate mechanical system
	Feedstock + Endless Piston	Feedstock is attached to a progressive cavity pump which function as an endless piston	Completely volumetric device Excellent extruder controlling at different speed Outstanding precision in dimension of printed pieces	High cost Size limitation Complex mechanisms

2.3.1 Pneumatic Piston

The mechanism of single-step pneumatic piston is operated by controlling on air pressure at the input. Whereby a clay is first filled up in the cylindrical tank and covered with a piston. The cylindrical tank used in this kind of mechanism is usually a syringe, whereby the diameter of the inlet is larger and requires rubber piston or piston with O-ring seals to ensure inlet is enclosed whereas the outlet diameter is smaller and typical selection of outlet diameter will be based on the details of printing parts. The inlet is then connected to air compressor outlet. When the air compressor release air pressure into the tank, the piston will push the material out from the tank. However, the downside of this mechanism is the difficulty in synchronizing the air pressure with the movement of printers (Ruscitti, Tapia and Rendtorff, 2020). Where the extrusion of material paste could not be paused during the printing process.

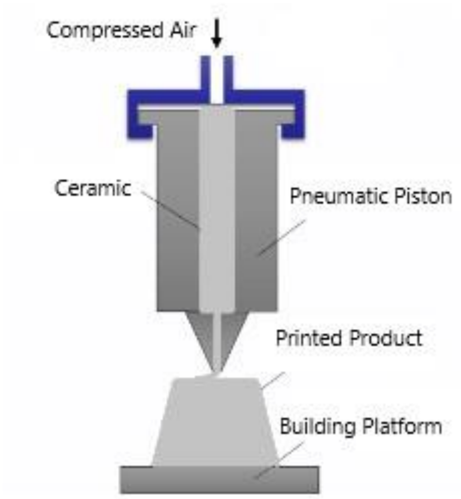


Figure 2.1: Pneumatic Piston (Liu et al., 2018)

2.3.2 Mechanical Piston

The mechanism of mechanical piston is similar to pneumatic piston. However, mechanical piston is fully driven by mechanical device such as motor. After the clay is filled up in the container, it is extruded by the force generated by motor pushing the clay out from nozzle. An example of mechanical piston is syringe-based extruder. Few studies shown the use of syringe-based extruder in bio medical application (Fan et al., 2017; Golcha, Praveen and Belgin Paul, 2020), whereby ceramic and bioceramic materials are used as a feedstock of syringe-based extrusion to print biomedical product such as surgical tool and custom-made prosthetics (Golcha, Praveen and Belgin Paul, 2020). However, the use of mechanical piston in 3D printing has a major issue where during the loading of ceramic material into the container, air gaps are presented. Air gap in mechanical piston results in discontinuity material flow during the printing process. Therefore, an integration of system is required.

Figure 2.2: Mechanical Piston (Fan et al., 2017)

2.3.3 Pneumatic Piston with Conventional Screw

This type of extruder system is an enhanced version of single-step pneumatic piston. Whereby the pneumatic piston pushes the clay into conventional screw. With conventional screw, the flow rate of the clay paste could be controlled and the air gap exist in the pneumatic piston is eliminated when the paste pass through the convectional screw as the clay paste is squeezed before extruded from nozzle. Besides that, the clay paste could be retracted simply changing the rotational direction of the conventional screw. The downside of the system is the air pressure exerted into the system is different depending on the viscosity of the material. Therefore, when clay material is refilled, air pressure must be recalibrated unless the viscosity of the clay material is the same as previous printing.

2.3.4 Mechanical Piston with Conventional Screw

The type of extruder is and enhanced version of single-step mechanical piston. Similar to the pneumatic piston with conventional screw, the air gap exists in the when loading the material paste into the container. The effect of air gap during the printing process is eliminated by conventional screw as the material as squeezed in the conventional screw before extruded. Besides that, mechanical feeding can easily synchronized via electric controller (Ruscitti, Tapia and Rendtorff, 2020) resulting in a better control environment compared to pneumatic piston. However, the weight of this system is higher than all other system as this system requires mechanical parts to operate, typically stepper motor to push the piston and stepper motor to rotate the conventional screw. This system is also commonly used in other type of additive manufacturing system such as Fused Deposition Modeling (FDM) (Koga et al., 2018) by integrating conventional screw with controlled temperature to melt the particle of polymer and further extracted from the extruder to form the product. Since ceramic extruder is under the category of direct ink writing (DIW), the concept is similar to FDM extruder with amendment of removing heating mechanism in the system.

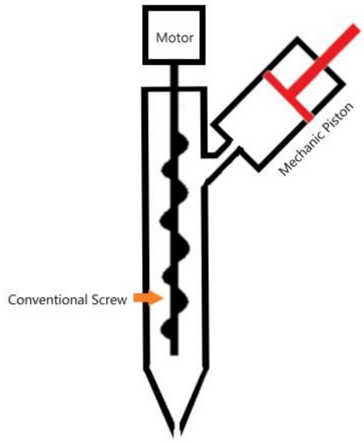


Figure 2.3: Mechanical Piston with Conventional Screw

2.3.5 Feedstock with Endless Piston

This this type of extruder system, the material paste conveyed through an endless piston with an eccentric motion rotor. Endless piston is also known as a progressive cavity pump, which is a positive displacement pump. From figure 2.4(a) (Unfold Fab, 2014), the structure of an endless piston consists of a single-helix rotor with double-helix hole. The double helix hole servers as a conveying chamber with a benefit of constant volume of material conveying as the rotor rotates in eccentric motion. Hence, allowing materials to be delivered. With this technology, material feed into endless piston is allowed to extrude in very small diameter depending on the piston design geometry achieving very detailed printed pieces. However, when comes to integrating this technology to 3D printer, the endless piston required to be mounted on the moving parts of 3D printer. This limits the size and weight of the endless piston. Besides, the structure of the endless piston is complex compared to conventional screw extruder design whereby the cost of building an endless piston extruder is generally higher.

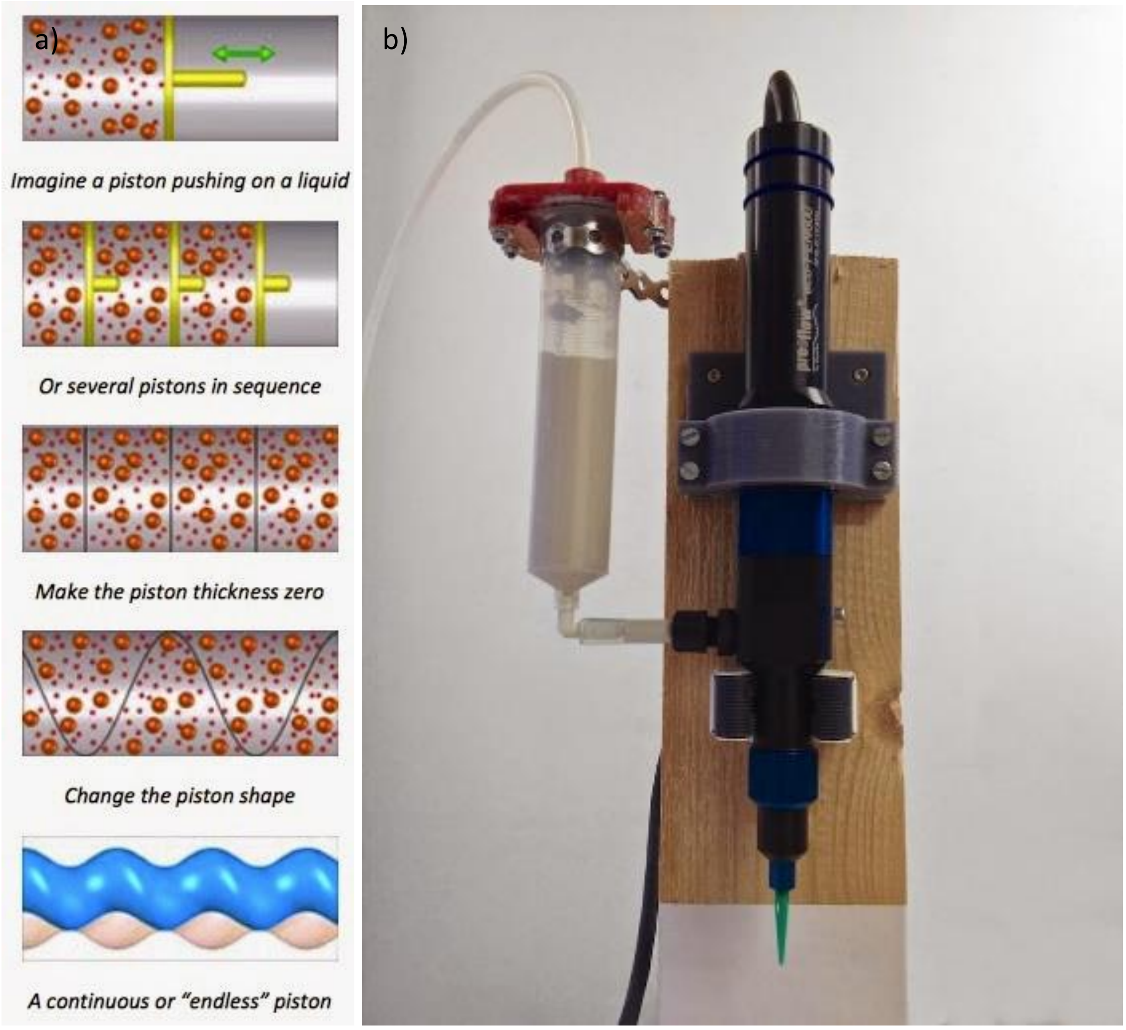


Figure 2.4: (a) Endless-Piston-Principle (Unfold Fab, 2014), and (b) Endless Piston

2.4 Nozzle

Another factor consideration is designing 3D printing extruder is the nozzle. Nozzle geometry will affect the material paste extrusion and the detail of printed parts. Based on study done by (Manikandan et al., 2020), two types of nozzle are investigated which are circular nozzle and rectangular nozzle. From material properties of the printed part perspective, square nozzle exhibits a better result. However, the detail of the printed parts by square nozzle is unacceptable. On the other hand, the circular nozzle provides a better surface finishing of the printed products. Comparing the compression strength of the printed products, the product from circular nozzle is acceptable even though it is lesser than product from square nozzle. Hence, circular nozzle is commonly used in 3D printer as the product is more practical.

There are few studies conducted based on the circular nozzle (Albar et al., 2020; Kontovourkis and Tryfonos, 2020). These studies compare the product structural properties based on different diameter of circular nozzle. Both studies show that a smaller diameter nozzle provides finer details and better material quality of the final product. However, the manufacturing process using smaller nozzle diameter requires longer time as the layer constructed is thinner. In contrast, for larger nozzle diameter, the quality of the final product is lower and the structure is courser and the time required for the 3D printing to complete is lesser than small nozzle diameter as more material is extruded through the nozzle.

Figure 2.5: Nozzle (Albar et. al., 2020)

To improve the usage of 3D printer, the nozzle of the extruder is normally designed as an attachment to the extruder. Hence when constructing different types of material with different requirement, the nozzle can be changed based on the product requirement.

2.5 Capacity of Extrusion

Most of the research done on ceramic extruder only focus on the extruder part. However, the capacity of the raw material is frequently not discussed. Most of the researchers work conducted using syringe based extrusion (Nair et al., 2020; Darling and Smith, 2021; Fan et al., 2017; Venkatesan, Ks and S, 2019). Most of this study used conventional available syringe where the maximum volume is $100cm^3$ (Nair et al., 2020). This means that if a product which requires larger geometry, the 3D printers are either not applicable or required to stop the process time by time to refill the raw material. Hence the product will have some problems in surface finishing and structure construction. To solve this problem, the capacity of the container needs to be increased to reduce or eliminate the need of refilling the material halfway through the printing process. Hence, the capacity of the 3D printer extruder requires more attention in future research.

CHAPTER 3

DEVELOPMENT AND PROTOTYPING

3.1 Design

The first approach is constructing the extruder by drilling holes in metal block and then screw together with stepper motor. However, this approach contains a lot of machining work, the ability of weight of the design to be handle by the structure of 3D printer are not justified and it is hard to ensure the assembly of parts are well matched. The design is then changed to pipe fitting. This allow less machining included in prototyping as most of the parts could be assembled by screw. As this stage, the pipe selected is PVC. This leads to another problem where PVC pipe does not have threads to hold the fitting in both ways where only fitting has treads to screw on the PVC pipe. This design requires changes in pipe material and the frame is not finalized as the frame to hold the extruder must fit to the frame of 3D printer so that the design extruder could be mounted on the 3D printer.

Figure 3.1(c) shows the finalized design, the pipe is change to brass material and the frame is design to fit on 3D printer simply by screwing the frame to the body of 3D printer. Besides that, the selected pipe fitting size is 1/4” as it is easily available in hardware shop. The screw used in this deisgn is a 7.7 mm diameter and 67.3 mm length drillbit where top part of the drillbit is lathed 9 mm length and 5 mm diameter so that it could fit into the coupling. The coupling used in this design is aluminum alloy coupling with 5 mm at both ends. Hence, the drillbit is connected to the stepper motor with the coupling and rotate at the same speed as stepper motor. For the body of the extruder, a 42 mm x 42 mm x 3 mm plate is screw tight fit with a M8 reducing bush where the internal of the reducing bush is lathe to clear surface without threading. The 1/4” brass tee pipe is then screw on the reducing bush and fix on the holder temporary. Then, the stepper motor is mounted on the holder which hold the body of the extruder by using 4 pcs of standoff and screwed with M3 screws. The holder is manufactured using 3D printing PLA and the space for the control board from BIQU B1 3D printer is resevered. The whole extruder is then mounted on the BIQU B1 FDM 3D printer and screwed using M3 screws. The bill of material of the design and assembly could be found in appendix A which is the final extruder design general assembly drawing.

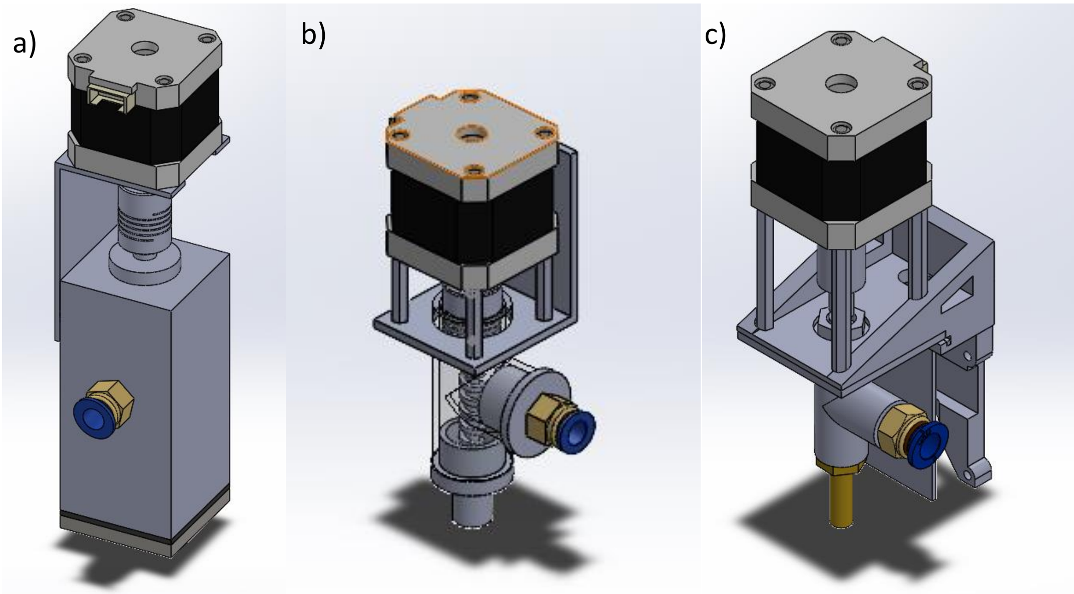


Figure 3.1: (a) First Design, (b) Second Design, and (c) Finalised Design

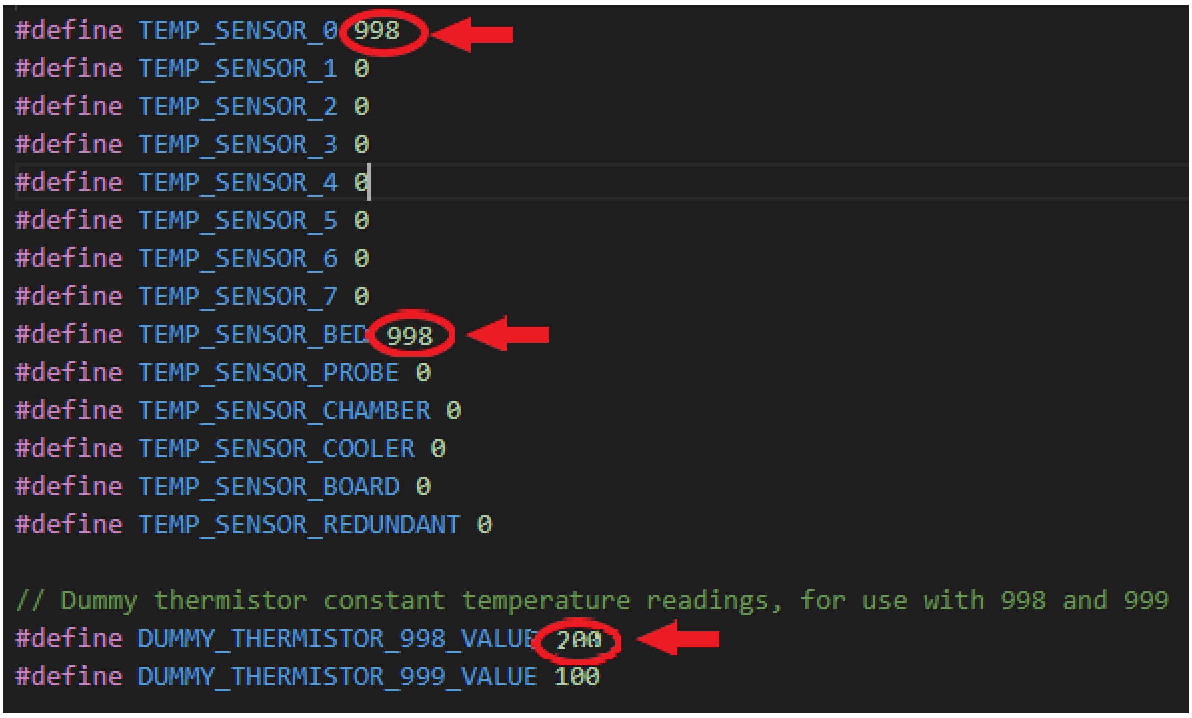
3.2 Material

In this extruder development, the material used to test the functionality of the extruder is HB2 Clay. This clay is purchase online through Shopee (https://shopee.com.my/Multifilla-Handbuilding(HB2)-Clay-For-Handbuilding-and-Sculpting-i.292367726.5948795263). Based on the production description provided by the seller, the material properties are 10% of drying shrinkage and 12% of firing shrinkage. Hence, when this material is used in the extruder, other material properties are required to identify since they are not provided by the seller.

Figure 3.2: HB2 Clay from Multifilla Shopee

3.3 3D Printer Configuration

BIQU B1 is the 3D printer selected to integrate with the designed extruder. Since ceramic printing is direct ink writing (DIW) method while BIQU B1 print material through Fused Deposition Modelling (FDM) method, 3D printer settings are required to reconfigure so that it will works well with direct ink writing method. The main difference between DIW and FDM is the operating temperature requirement during the printing process. In FDM, material such as PLA, PETG and ABS are required to heat up until semi-plastic condition and printed out from the nozzle whereas in DIW, no temperature is required as the temperature may affect the water content in clay material hence affecting the material from extrusion process. These setting is calibrated by coding as the built-in software for BIQU B1 3D printing to work is Marlin. Files and section that are required to recalibrate are shown in figure 3.3 and 3.4. TEMP_SENSOR_0 is the temperature of the thermistor which originally used in FDM method of 3D printing. As mentioned, clay material does not require any heat added into the extruder, the value is set to 998 which is a dummy temperature to ensure the operation of 3D printer does not record the actual temperature value of the thermistor while giving a constant temperature of 200 C. Same goes for TEMP_SENSOR_BED which is the temperature of the printing bed. In testing, the printing bed does not require any heat up. Hence, a constant value if given to the temperature.

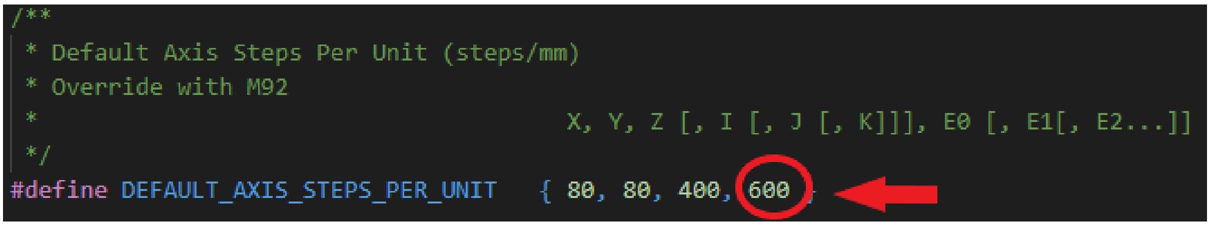


```
#define TEMP_SENSOR_0 998
#define TEMP_SENSOR_1 0
#define TEMP_SENSOR_2 0
#define TEMP_SENSOR_3 0
#define TEMP_SENSOR_4 0
#define TEMP_SENSOR_5 0
#define TEMP_SENSOR_6 0
#define TEMP_SENSOR_7 0
#define TEMP_SENSOR_BED 998
#define TEMP_SENSOR_PROBE 0
#define TEMP_SENSOR_CHAMBER 0
#define TEMP_SENSOR_COOLER 0
#define TEMP_SENSOR_BOARD 0
#define TEMP_SENSOR_REDUNDANT 0

// Dummy thermistor constant temperature readings, for use with 998 and 999
#define DUMMY_THERMISTOR_998_VALUE 200
#define DUMMY_THERMISTOR_999_VALUE 100
```

Figure 3.3: Temperature Configuration

Besides that, the rotational speed of the motor for feedstock extrusion, which is listed as E0 in Marlin configuration file, is also required to reconfigure as originally this motor is used to control the feed rate of filament. Since the 3D printer is now required to work with ceramic paste, the motor speed is set to be higher than the speed at which the filament is fed.



```
/**
 * Default Axis Steps Per Unit (steps/mm)
 * Override with M92
 *                                      X, Y, Z [, I [, J [, K]]], E0 [, E1[, E2...]]
 */
#define DEFAULT_AXIS_STEPS_PER_UNIT   { 80, 80, 400, 600 }
```

Figure 3.4: Stepper motor speed Configuration

On the other hand, the stepper motor used in the present extruder system is the stepper motor originally from 3D printer which extrude filament. However, the orientation of the stepper motor is inverted, this makes the direction of the stepper motor rotating clockwise in the present extruder system. The direction of the stepper motor is required to change to anti-clockwise so that the clay is extruded out from the extruder rather than retracted. To change the direction of the stepper, the wiring of the stepper motor is inverted which is shown in figure 3.5. Whereby the red wire and blue wire is switched in position. This changes the direction of the stepper motor rotation when stepper motor operates.

Figure 3.5: Stepper Motor Wiring

3.4 Slicer Software Configuration

The slicer software used to operate the designed extruder test is Ultimaker Cura. In Ultimake Cura, there are tons of profile that are already available. However, since the extruder design is custom, the profile is required to reconfigure in order to match the operation of 3D printer with the extruder. For the printer settings, since the 3D printer that the design extruder going to be attached to is BIQU B1, the printing bed setting will follow back to BIQU B1 where the X (Width) and Y (Depth) are 235mm, Z(Height) is 270mm and the shape of the printing bed is rectangular. For the extruder settings, the nozzle of the design extruder is 4mm and the compatible material diameter is also set to 4mm.

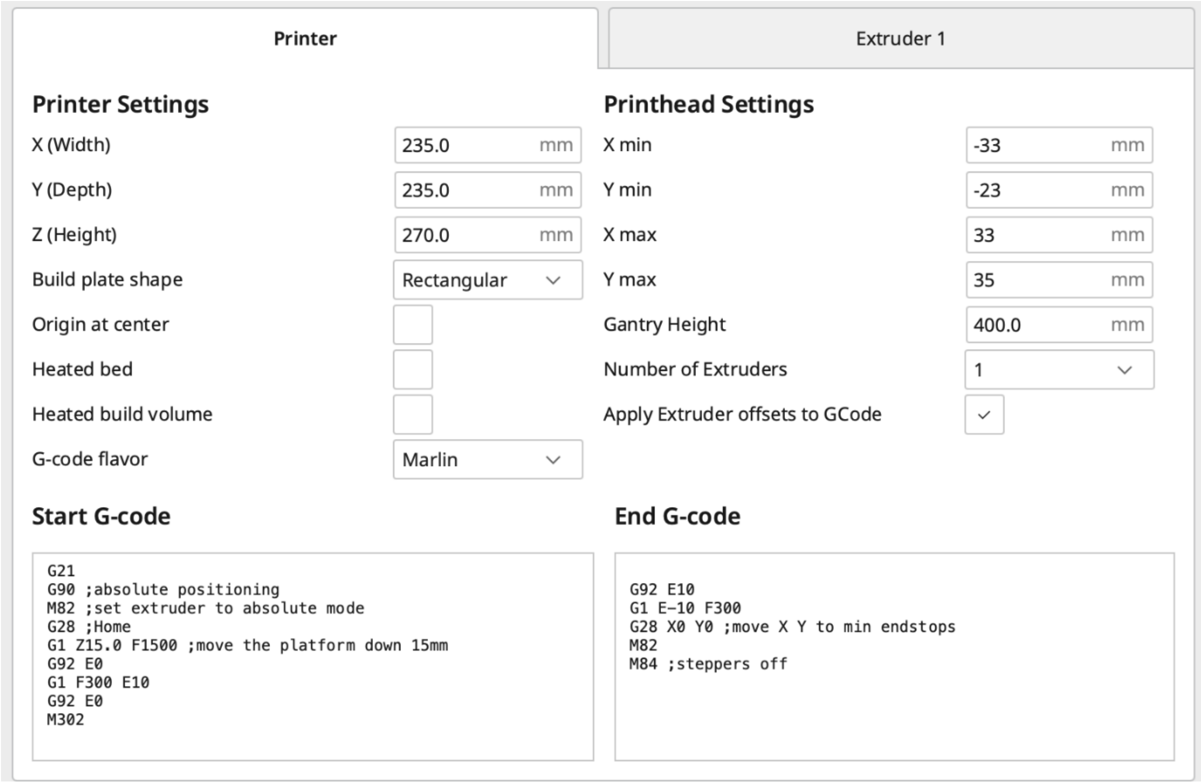


Figure 3.6: Printer Settings in Ultimaker Cura

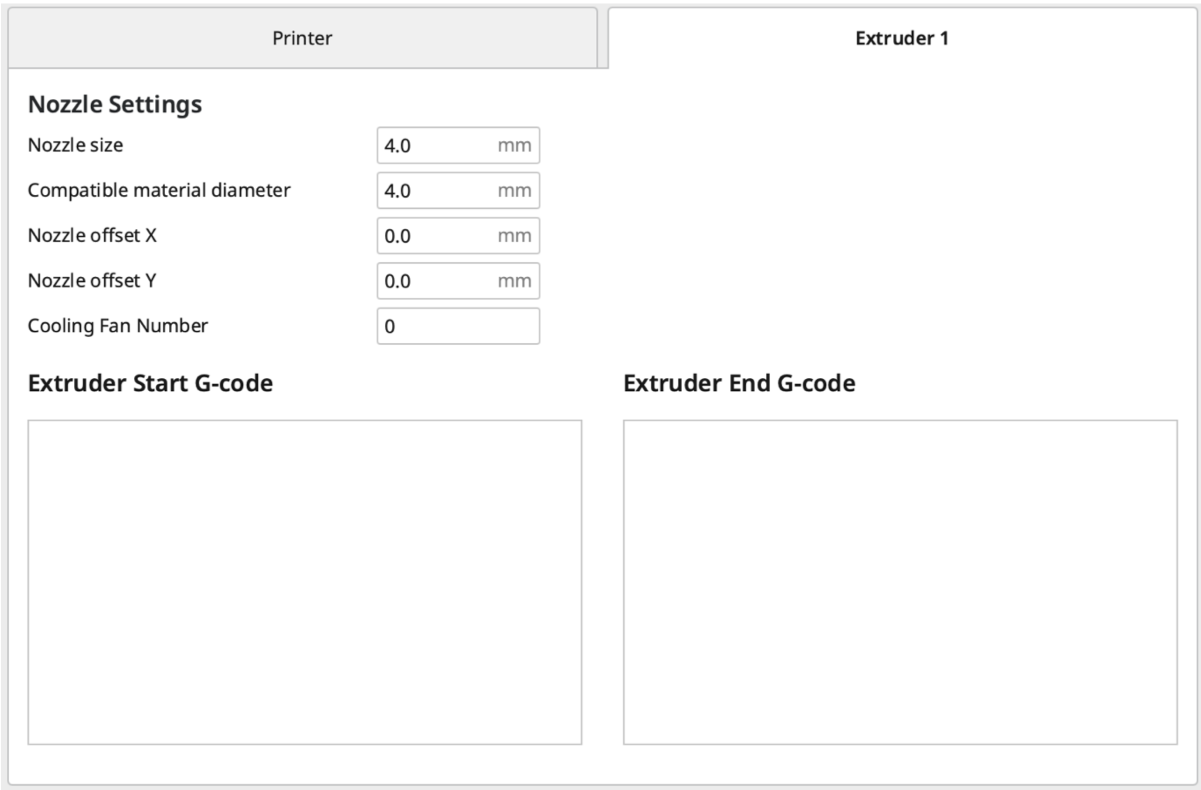


Figure 3.7: Extruder Setting in Ultimaker Cura

CHAPTER 4

METHODOLOGY

4.1 Preparation of Clay Material

HB2 Clay purchased comes with certain hardness. For clay of work with the extruder system, preparation is required. In preparation of HB2 Clay, the clay is first mixed with water until soft condition. The clay is then insert into a disposable syringe with nozzle size of 20 gauge and pressed on an electronic scale. The weight as soon as the clay is out of the syringe is recorded. Based on the testing perform by (Jony, 2021), the suitable clay used is where electronic scale reads about 2.5Kg to 3Kg. Then, part of the clay is used to perform Oven Drying Method based on ASTM D4643 standard to obtain the moisture content of the clay. Another part of clay is filled in extruder feed stock. Clay with electronic scale of 1.3Kg, 1.6Kg and 2.5Kg is used in the extruder testing.

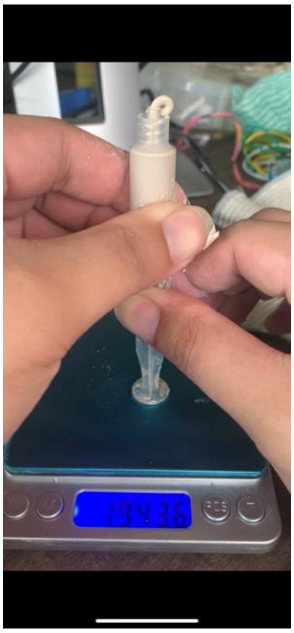


Figure 4.1: Electronic Scale Reading

4.2 Prototype Testing Setup

The clay model printed out from the extruder is a clay disk structure with 60mm diameter and 20mm height. The model is constructed using Solidworks and exported as STL file to Ultimaker Cura for slicing. Where the layer height is set to 1mm with printing speed of 5mm/s. After the printing configuration and the model slicing is done, the model is then exported as G-code and ready to use.

Figure 4.2: Extruder Assembly

In this testing, the designed extruder is attached on BIQU B1 3D printer. The extruder assembly is shown in figure 4.2. Then, 3D printer is then connected of the feed stock with a 7mm outer diameter, 1mm thickness pneumatic tube. The feedstock is then connected to air compressor. The air compressor compressed the air in feed stock pushes the clay from feedstock to the extruder. The value of air pressure used to pressurize the feedstock is adjusted based on the viscosity of the clay. Using 3D printer to control the extruder, the clay is then extruder from the extruder to print out a model.

Figure 4.3: Feed Stock

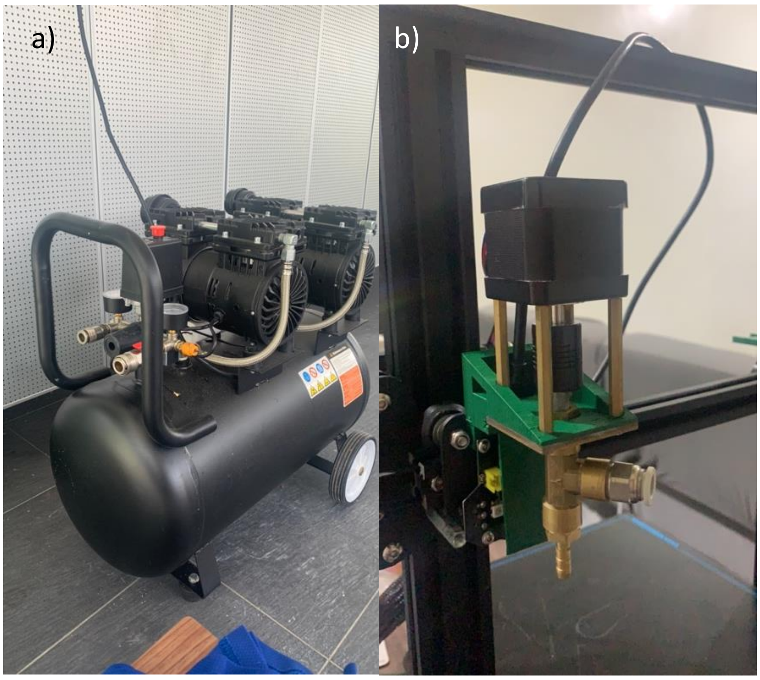


Figure 4.4: (a) Air Compressor, and (b) Extruder attached of 3D printer

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results and Discussions

From testing, it was observed that the developed extruder could print the model at certain range of viscous clay. However, during the printing of the clay model, the air compressor is required to adjust to suitable air pressure to prevent the clay material from over-extruding or under extruding.

Table 5.1: Result of clay printed structure with different viscosity of clay and air pressure.

Clay (Electronic Scale)	Air Pressure	Image	Observation
2.5 Kg	6 bar		Failed to extrude from the extruder due to the viscosity of clay is too high where the clay is unable to extruded from the extruder.

1.6 Kg	4 bar	 	The printed model exhibits a clear structure with fine details. However, as the printing process goes from the bottom layer to top layer, gaps between layer is getting larger and larger. Overall, printing still consider acceptable.
1.3 Kg	3 bar		The printing details is inconsistence as the air pressure is adjust during the print to remove the gap between layers.

Throughout the testing of design extruder, the first setting used is using clay with electronic scale of 2.5 Kg and air pressure at 6 bar. With this setting, the clay model is unable to construct due to the flow rate of clay entering the extruder is insufficient. In order to print this viscosity of clay, higher air pressure is required. However, the specification of the air compressor only allows 6 bar of air pressure release from to application due to safety reason. Hence, with the current setup of 3D printer, it is not possible to achieve good printing quality with this viscosity of clay.

The next testing is the clay with electronic scale of 1.6 Kg. In this testing, the clay is able to print out good finish quality of clay model with only 4 bar of air pressure. Although at the end of printing, it is observed that the top layer of the clay model consists of gaps between layer, this may be due to the inconsistency of air pressure during the extruder. Overall, the printed structure exhibits a good quality of printing.

The clay with electronic scale of 1.3 Kg is then tested to print out the clay model. Since there is a problem found during the printing of clay with electronic scale of 1.6 Kg, when printing this clay model, the attempt done is to increase the air pressure during printing when gaps between layer is found. The printing structure was found in consistency in layer due to the attempt done which resulting the layer at certain height is thicker and certain layer height is thinner.

Another testing is done using clay with electronic scale of 1.6 Kg to print different layer height. From the testing, it further shows the limitation of the system where in printing of 1.5 mm, more clay is required to be extruded from the extruder. In Ulitmake Cura, the flow of printing 1.5mm thickness is set to 150% since the thickness is also increased 50% from the original setting. However, due to the pressure lost in feedstock during the printing, the bottom layer exhibits a good printing structure but when comes to top layer, the gaps between layer is more obvious. This is due to the setup where feedstock is directly connected to the air compressor without any pressure regulator. Hence, the air pressure enters the feedstock to push the clay material to the extruder is fully depending on the air pressure in the air compressor. The pressure lost in the feedstock is due to the volume of air as it pushes the clay is increased while the air pressure supplied from the air compressor remains the same where from the start the air pressure is set to 4 bar. Since there is no additional air pressure supplied to the feedstock, air pressure is lost due to expansion in volume of feedstock.

Table 5.2: Comparison of 1mm thickness print with 1.5mm thickness print

Clay (Electronic Scale)	Thickness	Image	Observation
1.6 Kg	1 mm	 	At the top layer, smaller gap between layer is observed.
1.6 Kg	1.5 mm		Gaps between layer is larger. Some parts of the outer layer are not printed leaving holes.

To determine the water-to-clay ratio, part of the clay used in printing is taken out to perform Over Drying Method based on ASTM standard, where the 100 grams of clay is heated in the oven with 105C up to 24 hours and cool down (ASTM-D-2216-98, 1998). After the clay is cooled down, the weight of the clay is weighted again. The difference between the weight of clay before heating and after heating shows the moisture content in the clay.

Table 5.3: Moisture Content in Clay

Clay (Electronic Scale)	Before Heated (g)	After Heated (g)	Difference (g)	Water Content Percentage (%)
2.5 Kg	100	76.7	23.3	23.3
1.6 Kg	100	74.9	25.1	25.1
1.3 Kg	100	73.2	26.8	26.8

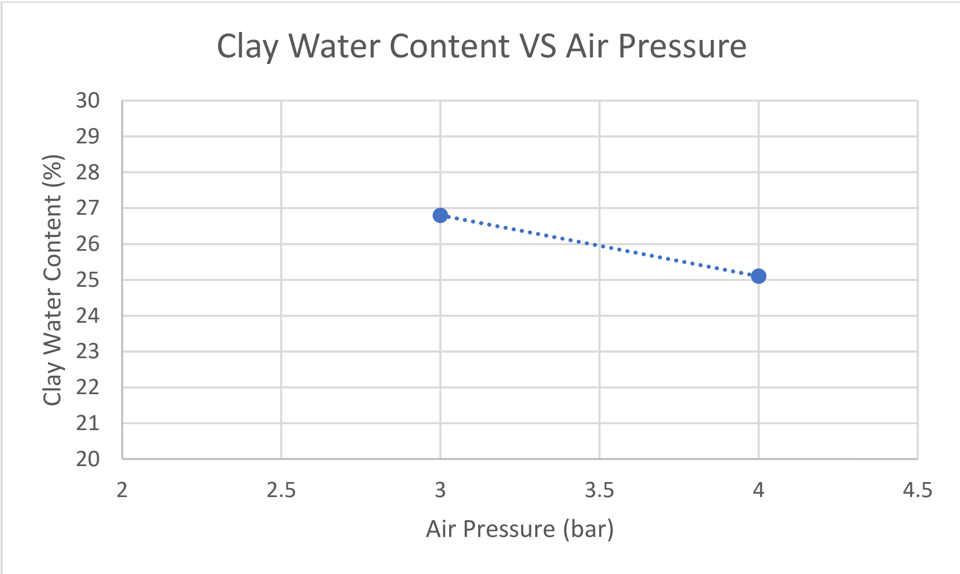


Figure 5.1: Clay Water Content to Air Pressure

The water-content in clay is then plotted to a graph with the operating air pressure where for clay with electronic scale of 1.6 Kg has water content of 25.1% is plotted to its operating air pressure, which is 4 bar, clay with electronic scale of 1.3 Kg has water content of 26.8% is plotted with operating air pressure of 3 bar. The clay with electronic scale of 2.5 Kg is not plotted since its operating air pressure is not justified during the testing. From here, when the clay with different water content is tested in the future, air pressure could be determined from this graph. However, this data is only valid when printing clay for 1mm thickness and 4mm nozzle diameter.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions and Recommendations

The designed extruder is developed and few testing is conducted to identify the suitable clay viscosity to work with. For extruder part, the designed extruder is able to mount directly on existing FDM printer with screws. With the configurations done on the 3D printer settings and slicer settings, the extruder is able to print clay material in acceptable appearance under certain level of moisture content of the clay with air pressure at certain relationship. From data collection, the present extruder system allows the extrusion process with a good print of clay with moisture content of 25.1 % to work at air pressure of 4 bar, printing 1mm layer thickness with its 4mm nozzle diameter and another parameter is the clay with moisture content of 23.3% could be printed out with an air pressure of 3 bar. Hence, by identifying the moisture content of the clay correlated with suitable air pressure, the present extruder system allows the extrudability and printability of clay feedstock at good printing structure.

While ceramic extrudability has been achieved in the scope of this project, keeping the properties of the clay consistent throughout the printing process remains a challenge. This is possibly due to factors such as moisture loss and ambient heat exposure. Hence it is recommended that a better feedstock container design be produced in the future to help mitigate this issue.

From observation, the extrudability of the present extruder system reduces over time during the printing process. This may be due to the flow rate of clay feedstock degrade over time. Currently, to solve this problem, the air pressure is manually increased as soon as the reduction of extrudability of present extruder system is observed. It is suggested that future work be carried out on the pneumatic piston by introducing a closed-loop system which increases air pressure automatically as soon as it detects reduction of flow rate of clay feedstock or replacing it with a mechanical piston which could control the flow rate of the clay feedstock based on the volume displaced in the piston in controllable manner.

REFERENCES

Albar, A., Chougan, M., Al- Kheetan, M.J., Swash, M.R. and Ghaffar, S.H., 2020. Effective extrusion-based 3D printing system design for cementitious-based materials. *Results in Engineering*, [online] 6, p.100135. Available at: <https://www.sciencedirect.com/science/article/pii/S2590123020300414>.

Albu, S.C. and NuȚiu, E., 2019. Study on Designing the Extruder for 3D Printers with Pellets. *Acta Marisiensis. Seria Technologica*, 16(1), pp.19–22.

ASTM-D-2216-98, 1998. Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. *ASTM International*, (January), pp.1–5.

Darling, C. and Smith, D.A., 2021. Syringe pump extruder and curing system for 3D printing of photopolymers. *HardwareX*, [online] 9, p.e00175. Available at: <https://doi.org/10.1016/j.ohx.2021.e00175>.

Fan, T., Liao, G.Y.J., Yeh, C.P. and Chen, J.C.M., 2017. Direct ink writing extruders for biomedical applications. *ASEE Annual Conference and Exposition, Conference Proceedings*, 2017-June.

Golcha, U., Praveen, A.S. and Belgin Paul, D.L., 2020. Direct ink writing of ceramics for bio medical applications - A Review. In: *IOP Conference Series: Materials Science and Engineering*.

Hoffman, T., 2021. *The Best 3D Printers for 2021*. [online] PC mag. Available at: <https://sea.pcmag.com/printers/6173/the-best-3d-printers-for-2020> [Accessed 25 Nov. 2021].

Jony, 2021. *Ceramic 3D printing clay preparation tutorial* . [online] Available at: <https://www.eazao.com/blog/ceramic-3d-printing-clay-preparation-tutorial/> [Accessed 30 Nov. 2021].

Koga, S., Straub, D., Diagne, M. and Krstic, M., 2018. Thermodynamic Modeling and

Control of Screw Extruder for 3D Printing. In: *Proceedings of the American Control Conference*. Milwaukee: AACC.pp.2551–2556.

Kontovourkis, O. and Tryfonos, G., 2020. Robotic 3D clay printing of prefabricated non-conventional wall components based on a parametric-integrated design. *Automation in Construction*, [online] 110, p.103005. Available at: <https://doi.org/10.1016/j.autcon.2019.103005>.

Lewis, J.A., Smay, J.E., Stuecker, J. and Cesarano, J., 2006. Direct ink writing of three-dimensional ceramic structures. *Journal of the American Ceramic Society*, 89(12), pp.3599–3609.

Liu, C., Huang, N., Xu, F., Tong, J., Chen, Z., Gui, X., Fu, Y. and Lao, C., 2018. 3D Printing Technologies for Flexible Tactile Sensors toward Wearable Electronics and Electronic Skin. *Polymers*, 10(6), pp.1–31.

Manikandan, K., Jiang, X., Singh, A.A., Li, B. and Qin, H., 2020. Effects of nozzle geometries on 3D printing of clay constructs: Quantifying contour deviation and mechanical properties. *Procedia Manufacturing*, [online] 48(2019), pp.678–683. Available at: <https://doi.org/10.1016/j.promfg.2020.05.160>.

Nair, S.A.O., Panda, S., Santhanam, M., Sant, G. and Neithalath, N., 2020. *A critical examination of the influence of material characteristics and extruder geometry on 3D printing of cementitious binders*. *Cement and Concrete Composites*, .

Pereira, T., Kennedy, J. V. and Potgieter, J., 2019. A comparison of traditional manufacturing vs additive manufacturing, the best method for the job. *Procedia Manufacturing*, [online] 30, pp.11–18. Available at: <https://doi.org/10.1016/j.promfg.2019.02.003>.

Pollák, M., Jakub, K., Telišková, M. and Jozef, T., 2019. Design of the 3D Printhead with Extruder for the Implementation of 3D Printing from Plastic and Recycling by Industrial Robot. *TEM Journal*, 8(3), pp.709–713.

Prakash, K.S., Nancharaih, T. and Rao, V.V.S., 2018. Additive Manufacturing Techniques in Manufacturing -An Overview. *Materials Today: Proceedings*, [online] 5(2), pp.3873–3882. Available at: <https://doi.org/10.1016/j.matpr.2017.11.642>.

Prem, N., Sindersberger, D. and Monkman, G.J., 2019. Mini-Extruder for 3D Magnetoactive Polymer Printing. *Advances in Materials Science and Engineering*, 2019.

Revelo, C.F. and Colorado, H.A., 2018. 3D printing of kaolinite clay ceramics using the Direct Ink Writing (DIW) technique. *Ceramics International*, [online] 44(5), pp.5673–5682. Available at: <https://doi.org/10.1016/j.ceramint.2017.12.219>.

Ruscitti, A., Tapia, C. and Rendtorff, N.M., 2020. *A review on additive manufacturing of ceramic materials based on extrusion processes of clay pastes*. *Ceramica*, .

Smirnov, A., Chugunov, S., Kholodkova, A., Isachenkov, M., Vasin, A. and Shishkovsky, I., 2021. Progress and challenges of 3D-printing technologies in the manufacturing of piezoceramics. *Ceramics International*, [online] (November 2020). Available at: <https://doi.org/10.1016/j.ceramint.2020.12.243>.

StoneFlower, 2021. *3D printers for ceramics, concrete and pastes, extruders and print heads - StoneFlower 3D printer for ceramics*. [online] Available at: <https://www.stoneflower3d.com/> [Accessed 2 Apr. 2021].

Tay, Y.W.D., Li, M.Y. and Tan, M.J., 2019. Effect of printing parameters in 3D concrete printing: Printing region and support structures. *Journal of Materials Processing Technology*, 271(February), pp.261–270.

Unfold Fab, 2014. *Road to Better Paste Extrusion, episode 3: Industrial quality 3D printing of paste materials with ViscoTec Moineau Pump*. [online] Available at: <https://unfoldfab.blogspot.com/2014/12/Unfold-Viscotec-Professional-Paste-3D-Printing.html> [Accessed 2 Apr. 2021].

Venkatesan, M., Ks, D. and S, S.K., 2019. *Extruder Development for a Clay 3D Printer a*

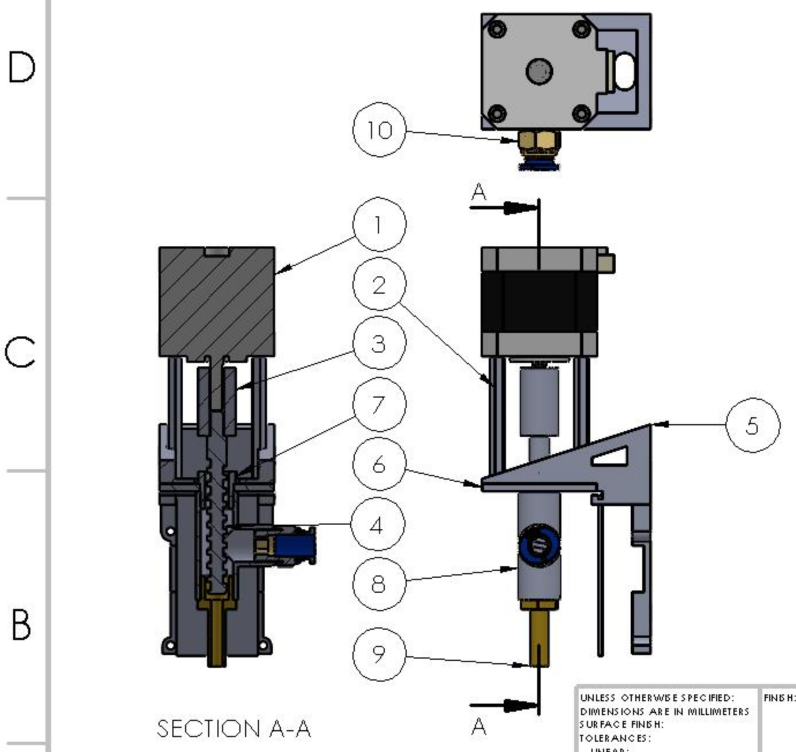
Mini-Project Report. [online] SASTRA Deemed to be University. Available at: <https://www.researchgate.net/publication/333487153>.

Wang, J.C., Dommati, H. and Hsieh, S.J., 2019. *Review of additive manufacturing methods for high-performance ceramic materials*. *International Journal of Advanced Manufacturing Technology*, .

Zhang, X., Wu, X. and Shi, J., 2020. Additive manufacturing of zirconia ceramics: a state-of-the-art review. *Journal of Materials Research and Technology*, [online] 9(4), pp.9029–9048. Available at: <https://doi.org/10.1016/j.jmrt.2020.05.131>.

Appendix A

Finalized Design General Assembly Drawing



11	PLA 3D Printed Sheet	1
10	1/4" Air Hose Pneumatic Connector	1
9	1/4" Bamboo Joint Brass Pipe Fittings	1
8	1/4" Brass Pipe	1
7	M8 Reducing Bush	1
6	Brass Plate	1
5	PLA 3D Printed Holders	1
4	Mild Steel 7.7 mm Drill Bit	1
3	Aluminum Alloy Coupling 5mm	1
2	Brass Standoff M3 45 mm	4
1	Stepper Motor from BIQU B1 FDM Printer	1
ITEM NO.	DESCRIPTION	QTY.

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	LCY	LCY	
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

TITLE: Finalized Extruder Design Assembly

DWG NO.

A4