Smart Concrete Extruder Design and Prototyping

Author

Muhammad Umais Qamar

Registration Number

320707

Supervisor Name

Dr. Jawad Aslam

DEPARTMENT OF MECHANICAL ENGINEERING SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY, ISLAMABAD

May 2023

Smart Concrete Extruder Design and Prototyping

Author

Muhammad Umais Qamar

Reg. # 320707

A thesis submitted in partial fulfillment of the requirements for the degree of

MS Mechanical Engineering

Thesis Supervisor:

Dr. Jawad Aslam

Thesis Supervisor's Signature: ______________________

DEPARTMENT OF MECHANICAL ENGINEERNG

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,

ISLAMABAD

MAY 2023

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by Mr. Muhammad Umais Qamar, Registration No.320707 of SMME has been vetted by undersigned, found complete in all aspects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature with stamp: DR. JAWAD ASLAM Associate Professor School of Mechanical & Manufacturing Engineering (SMME) NUST, Islamabad

Name of Supervisor: Dr. Jawad Aslam

Date: 17-7-2023

Signature of HoD with stamp: ______________

Date: 17-7-2023

Signature (Dean/Principal): ______________

Date: 17. 7. 2023

FORM TH-4

National University of Sciences & Technology

MASTER THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: (Student Name & Regn No.) Muhammad Umais Qamar (Reg no. 320707) Titled: Smart Concrete Extruder Design and Prototyping be accepted in partial fulfillment of the requirements for the award of MS-ME degree.

Examination Committee Members

1. Name: Dr. Riaz Ahmad Mufti Signature: ______

2. Name: Dr. Mian Ashfaq Ali Signature: ______

3. Name: Dr. M. Usman Bhutta Signature: ______

Supervisor's name: Dr. Jawad Aslam Signature: ______

Date: 17-7-23

Head of Department

17-7-2023
Date

COUNTERSINGED

Date: 17-7-2023

Dean/Principal

Declaration

I certify that this research work titled "*Smart Concrete 3D printer Extruder Design and Prototyping*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

MUHAMMAD UMAIS QAMAR

2019-NUST-MS-Mech-320707

Proposed Certificate for Plagiarism

It is certified that PhD/M.Phil/MS Thesis Titled Smart Concrete Extruder Design and Prototyping by Muhammad Umais Qamar has been examined by us. We undertake the follows:

a. Thesis has significant new work/knowledge as compared already published or are under consideration to be published elsewhere. No sentence, equation, diagram, table, paragraph or section has been copied verbatim from previous work unless it is placed under quotation marks and duly referenced.

b. The work presented is original and own work of the author (i.e. there is no plagiarism). No ideas, processes, results or words of others have been presented as Author own work.

c. There is no fabrication of data or results which have been compiled/analyzed.

d. There is no falsification by manipulating research materials, equipment or processes, or changing or omitting data or results such that the research is not accurately represented in the research record.

e. The thesis has been checked using TURNITIN (copy of originality report attached) and found within limits as per HEC plagiarism Policy and instructions issued from time to time.

Name & Signature of Supervisor

Dr. Jawad Aslam

Signature : DR. JAWAD ASLAM
Associate Professor
School of Mechanical &
Manufacturing Engineering
(SMME) NUST, Islamabad

Copyright Statement

Acknowledgements

I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor Dr Jawad for his help throughout my thesis. Each time I got stuck in something, he came up with the solution. I appreciate his patience and guidance throughout the whole thesis.

I would also like to pay special thanks to my friends for their tremendous support and cooperation. Without their help I wouldn't have been able to complete my thesis.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents and adored sibling whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

3D printer is a form of additive manufacturing technology. In 3D printer, a 3D object can be formed by laying down successive layers of material. 3D printers are easier to use than other manufacturing technologies, they are also faster and more affordable than other manufacturing technologies. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. One of the world's first 3D printer was based on Fused Deposition Method (FDM). It was developed by Scott crump in 1980's.

3D printers revolutionized the prototyping industry by enabling more rapid, more efficient, and cost-effective prototyping. According to the manufacturers 3D printers are 5 times cheaper and at least 10 times faster than the ordinary methods. Not only that, but when it comes to prototype production, no other technology comes close to 3D printers. 3D printer is capable of making complex geometries with ease and provide you with a realistic prototype at exact dimensions and all of it without needing any expert machinists. This technology has found applications in many fields because of the number of materials that can be used for printing.

The objective of this study was to design a smart concrete 3D extruder and prototyping. The extruder is the most significant component of a 3D printer because it is responsible for drawing in the material, melting it (in 3D printers that need fused material, such as FFD), and pushing out the material. The essential aspects that were kept in mind while designing the extruder were speed, precision, and long-term reliability. The first stage was to develop the extruder based on a concrete mixture specifically designed for 3D printers employing locally accessible resources and materials. Investigating structural stability and long-term usage in Pakistan's environment. Investigating the impact of printing factors such as layer thickness, nozzle size, printing speed, and flow rate. The extruder design is crucial, because the printer will not function properly until it is done correctly. In our case, the extruder is enclosed in an aluminum casing, and the material is pushed in through pneumatic pressure pushing from above. A stepper motor-powered leadscrew is transporting the material to the nozzle, which is effectively pushing out the material based on the numeric feed input.

TABLE OF CONTENT

List of Figures

CHAPTER 1: INTRODUCTION

3D printer is a form of additive manufacturing technology. In 3D printer, a 3D object can be formed by laying down successive layers of material. 3D printers are easier to use than other manufacturing technologies, they are also faster and more affordable than other manufacturing technologies. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. Modern 3D printers can print model that can be used as product prototypes [1-3].

Figure 1: 3D printer [4]

1.1 Brief History:

One of the world's first 3D printer was based on Fused Deposition Method (FDM). It was developed by Scott crump in 1980's. In this design, model (colored pink) is printed on a

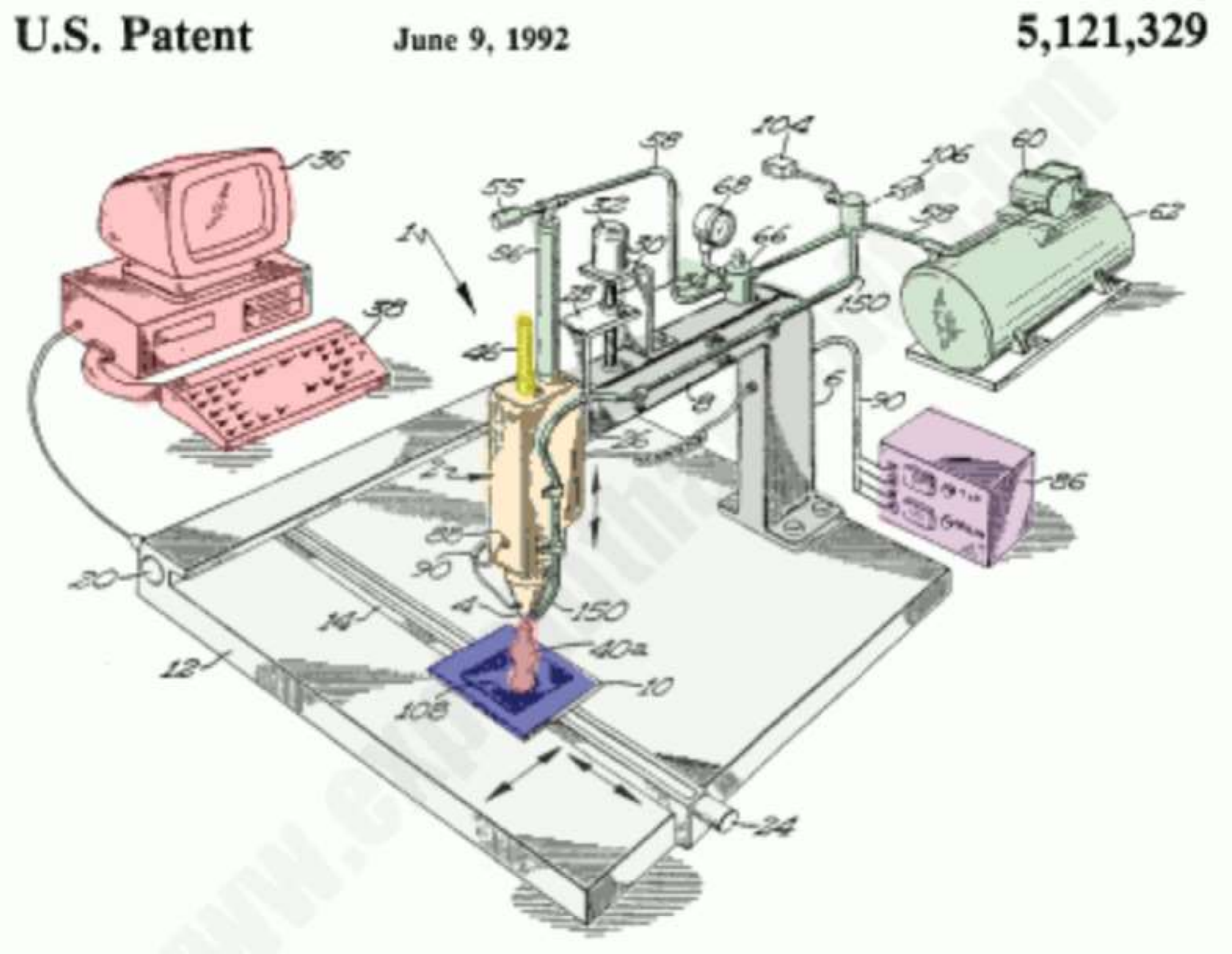

Figure 2: 3D Printer Patent [6]

baseplate (which can move horizontally in X-Y directions), while the nozzle (mounted on print head) moves in the vertical direction (Z axis). A plastic rod (shown with yellow color) is heated to the molten state inside the print head and is carefully regulated by a thermocouple which is in turn connected to a temperature controller. A compressor is connected (shown in green). Compressed air from the compressor will be used to extrude the rod. Since then, many changes have been made but the basic principle of feeding the material through numeric control and layered structure remained the same. [5]

1.2 Research Gap:

Independence is extremely valuable in technological sectors. We must progress towards self-sufficiency by beginning with the manufacturing of modest machinery and progressing toward more complicated technology. Modern technology has greatly decreased labor work in a variety of businesses throughout the world. Modern technology allows them to work more efficiently and for longer periods of time without getting tired. There are still several sectors in Pakistan that require improvement. Research was conducted to identify the gap that might be filled by this study. Keeping in mind the local construction workers in Pakistan, it was discovered that regular 3D printing technology is present in Pakistan, but 3D concrete printing is still under research, this idea was evaluated for feasibility analysis and future adaption, thus we strive to make this idea a reality and give a solution to our building enterprises and small-scale local workers. Even though this production is on a small scale and can only be used for prototyping, with full access to resources and materials, it can be completely deployed to manufacture entire building structures as well as dam construction.

1.3 Process (step by step)

- Create (or import) a 3D CAD file
- Export the file in STL format
- Select Material
- Select parameters
- Create G-codes
- Print

1.4 Importance:

3D printers revolutionized the prototyping field. 3D printers give you the option of faster manufacturing at cheaper rates. According to the manufacturers 3D printers are 5 times cheaper and at least 10 times faster than the ordinary methods. Not just that, no other technology comes close to 3D printers when we talk about prototypes manufacturing. 3D printer is capable of making complex geometries with ease and provide you with a realistic prototype at exact dimensions and all of it without needing any expert machinists. This technology has found its applications in many fields because of the number of materials that can be used for the printing. The details of which are discussed in the next section.

1.5 Applications:

3D printer found its applications in many fields because of the various different kinds of materials that can be used and the complexity of the model that can be achieved. Some of the applications of 3D printer are briefly mentioned below

1.5.1 Medicine

Doctors were one of the firsts to explore the 3D printer technology as it has a lot of potential in the field of medicine. Human body is fragile and a technology that can promise to replace the body parts and tissues is of great significance. 3D printed arms, legs, ears and muscles have already been seen. 3D printer is also in use to produce artificial cells, tissues and even skin. Experiments are also being conducted to produce 3D printed organic bones (to replace a shattered bone) whose size can be modified according to the person requirement and it can stay inside the body without causing damage to other organs. Even though we have advanced a lot in the field of 3D printing body parts but we are still far from perfection as researchers plan towards a future where we will have complete 3D printed organs (even liver and heart).

Figure 3: 3D Printed heart as displayed by US NIH image gallery [7]

Apart from replacements, 3D printed parts are also being used for educational purpose. US NIH image Gallery displayed a 3D printed heart which is shown in figure above. Surgeons perform heart surgery on 3D printed hearts At Nicklaus Children's Hospital in Miami, Florida. Elsewhere similar approach is used for brain surgery.

1.5.2 Aerospace and defense

Although, most parts of an aircraft are tested on a computer-based models but still we need to develop a physical model for testing over a wind tunnel and such. Parts production of an aircraft is a very expensive considering most of these parts are custom made and cannot be produced in bulk quantity. A Boeing Dreamliner has approx. 2.3 million parts in it. It is true that commercial planes are mostly built-in quantity but military planes cannot be made likewise and are more likely to be highly customized. 3D printer makes it possible to design, test and manufacture low volume parts cost effectively.

Spacecrafts are even more complex than an aircraft. Parts are more customized and have increased complexity. To produce tools and methods to make each part separately is very costly. 3D printer helps in this regard and is producing many of the parts for the spacecrafts. On board 3D printers are also being used in space which can be used to make parts according to requirement in space when needed instead of estimating requires parts and shipping them over, they can make the required parts as they see fit. The latest, human-supporting NASA Rover uses 3D-printed parts produced with help from Stratasys.

Even marines take advantage of 3D printer. It makes more sense to board a 3D printer on the ship and make and replace parts that need replacing instead of carrying bundles of spare parts with them on voyage or docking the ship for each repair. Most of the ships are having onboard 3D printers now a days. Thanks to US NAVY pictures of a few parts that 3D printed and are being used in ships are made public. They are displayed below. [5]

Figure 4: 3D printed undersea wireless charger

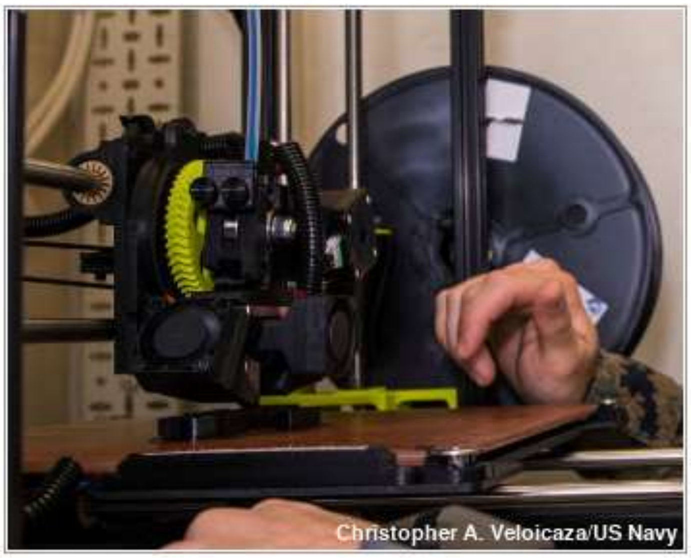

Figure 5: Lulzbot Taz 6 3D printer being used to make spare parts onboard a US naval ship

1.5.3 Visualization

Using 3D printer for custom making aerospace or aircrafts parts is a much broader use of the 3D printer. Most people use 3D printer for 3D visualization of their products and to get a good view what their product will look like. Virtual reality can also be used for this purpose but people prefer something they can see and touch. More commonly, 3D printer is a must have for new entrepreneurs. You can talk about a product; you can even model it in CAD software but until and unless you have the product in your hand you will always feel lack of some level of satisfaction. 3D printer relieves that itch in a very satisfying way.

1.5.4 Personalized products

People want to look different than everyone else. Everyone wants one-of-a-kind product. This is the reason that the ‘designer labels’ are so expensive. No one wants off the rack stuff. 3D printer makes this possible for the artisan product to be made public. Take the design of an artist, or sketch an idea of your own using CAD software and 3D print it at your home and you will have something that no one possess hence making it invaluable. The need of uniqueness is growing steadily and 3D printer makes it possible to achieve this farfetched dream.

Researchers have always been curious natured creatures. It is because of this peculiar nature that we enjoy a variety of different products every day. 3D printer is a dream come true for them as they can make custom made tools and things according to their need without having to explain it to anyone. Even the material used in this is limited to our imagination only. Anything that can be squeezed through a nozzle can be used for 3D printing. A group of scientists playfully attempted to 3D print using granulated sugar as their material. Picture of their experiment is shown below.

Figure 6: 3D printing using granulated sugar as material [8]

3D printer has the advantage of custom making any product based on our needs. How often a person wanders the street looking for something to buy but returns joyless because not everyone has the same taste and the products in the market are mostly produced in bulk quantities. 3D printer has changed the trend somewhat now. People has started 3D printing jewelry and much more. Some stores like shape ways and staples have started services where anyone can 3D print their own design. Just make a model and send it to them and they will 3D print it for you.

CHAPTER 2: LITERATURE REVIEW

3D printers were first developed in 1980s and over the years many new technologies have been introduced is addition to the improvements made in the already developed printers to minimalize or remove faults. A study was published in 2020 on Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing. Among the technologies used for 3D printing, Fused film fabrication stands out the most and this study explains the optimization of the process by proposing analytical methods, establishing numerical techniques or experimental techniques. This review discusses the future perspective of 3D printing technology and the most relevant work from recent years [9-10].

2.1 FFF Extruder

This printer uses a direct extruder type technology where the cold end and the hot end are connected together. This kind of printer offers clear prints and also the responsiveness to extrusion and retraction.

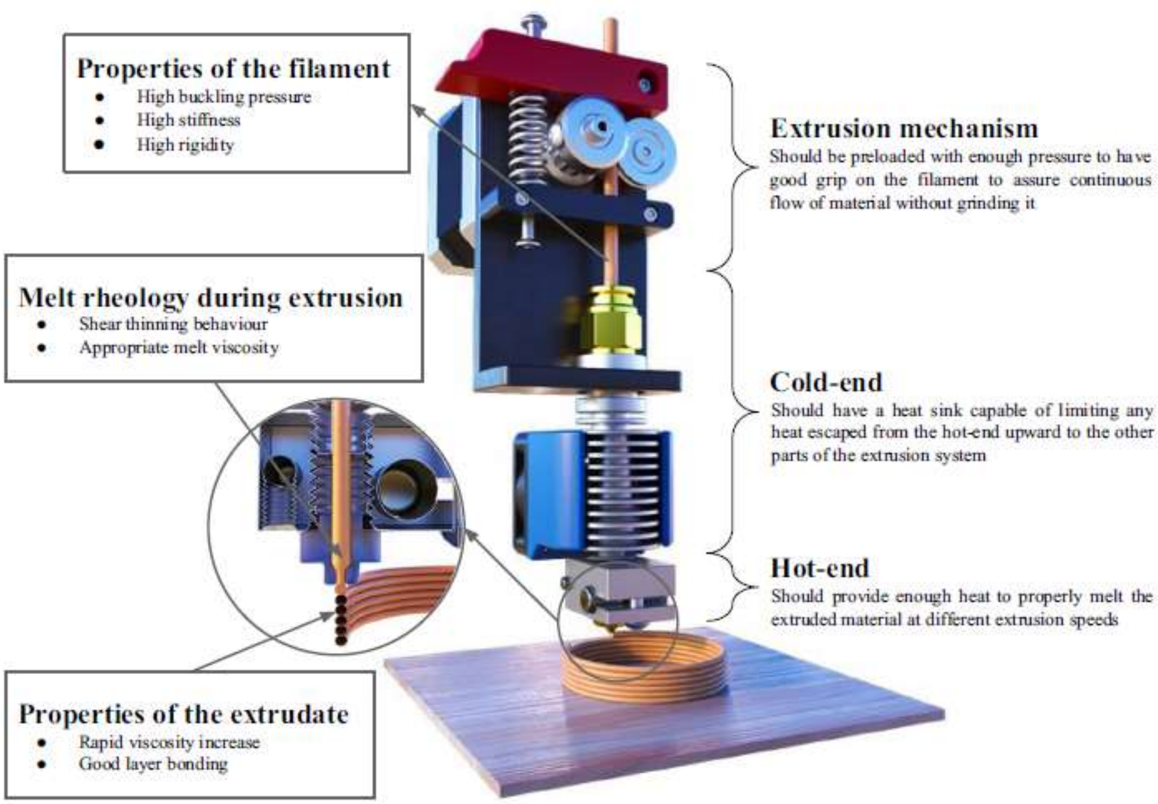

Figure 7: Detailed construction of the extrusion system in an FFF 3D printer highlighting the main features required for proper material extrusion [10]

2.2 Syringe type Extruder

FFF gets its important because of variety of fields it can be used in but some require some unique kind of printing or some unusual materials which can be printed using FFF. That's where we have to rely on other 3D printer technologies to get our results. One of these technologies is 3D printing using syringe pump extruder. This is a type of 3D printer that is used mostly in the bioprinting, embedded printing and food printing.

A key challenge faced in this type of printer is the volume of the syringe that is in use. You cannot increase the volume without compromising on the printing speed or printing Resolution. In 2018, a study was published for the syringe type 3D printer that has a large volume syringe pump extruder. Other advantage of this 3D printer is its compatibility with low cost, open-source 3D printer making it invaluable and affordable at the same time [11-12].

Extruder can effectively store 60ml of ink in the syringe for printing. Minimum diameter of the nozzle is 100μm which enables it to print complex shapes with ease. In detailed picture of printer parts and the complete assembly are shown below. The extruder technology is Bowden type. Detail about Bowden type extruder is mentioned is section 4.2.

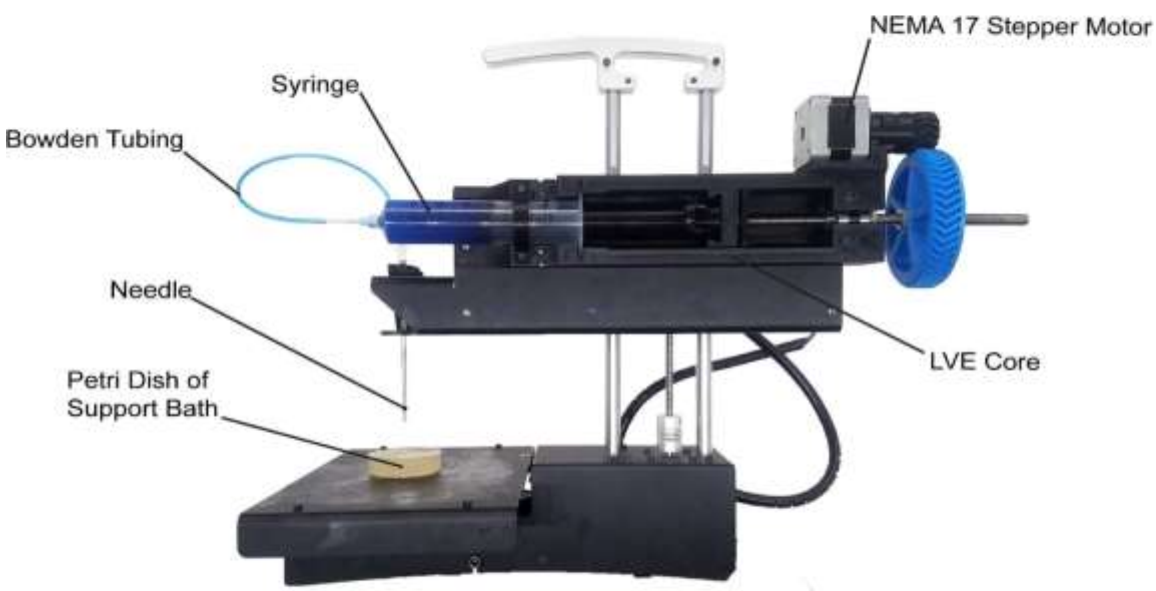

Figure 8: Large volume syringe pump extruder for desktop 3D printers [12]

Figure 9: Printer parts [12]

2.3 Screw type extruder

The extruder we used for this project is a screw type extruder instead of a syringe type extruder because the syringe type extruder requires a gap in the production in order to fill the syringe meanwhile the screw type extruders can have the advantage because the material can be constantly supplied. It's not a direct extruder neither does it have the hot end because there is no material to melt. Instead, a mixture is inserted into the extruder from the top through a large external container from where the material flows towards the extruder and from there it is transported by screw to the nozzle opening. The screw type extruder also has the advantage of high pressure built which allows the use of small nozzle hence increasing resolution of print. [13] used this screw type extruder for instead of conventional FDM extruder. They placed a heater and a thermostat right before nozzle in order to provide control heating which is enough to melt the filament before reaching nozzle. [13] [15]

A picture demonstrating the screw type extruder used in [13] is attached below.

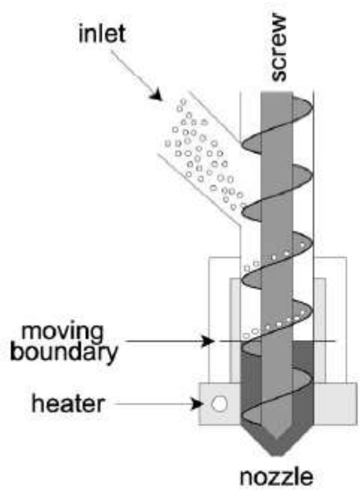

Figure 10: Depiction of the Screw extrusion Process

The printable material is entering through the inlet from where the screw drives it towards the nozzle. A heater is placed just before nozzle to melt the residue which is then extruded out from the nozzle. Another design for 3D printer using screw type extruder was proposed in [14] for the production of 3D ABS objects. In this extruder, compression of the printing material was also performed by the extruder. This main design perimeters selected by then were its channel (C), diameter (D), Flight land (E), Flight (F), Root (G), Channel depth (H), Tip (I), Key (J), Hub (K), Length (L), Pitch or lead (P), Shank (S), Helix angle (φ) and are shown in the figure below.

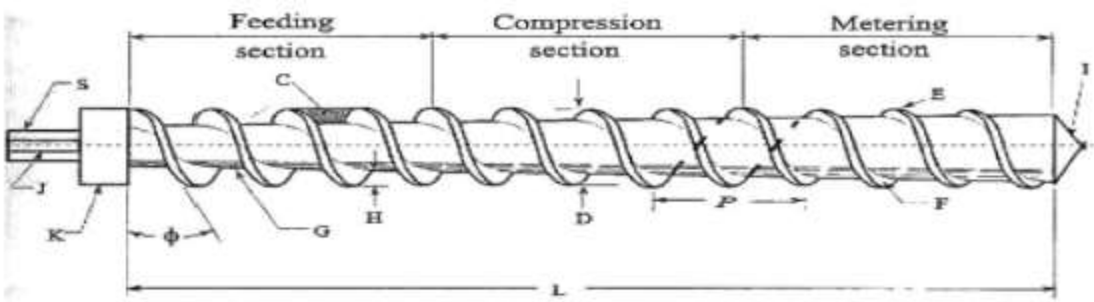

Figure 11: Extruder screw [14]

CHAPTER 3: 3D PRINTER TECHNOLOGIES

3D printer uses many different technologies to develop 3D structures and objects. Many of these methods are still in use while some have fallen by the wayside. This chapter will focus on different technologies of 3D printer or in simple terms, different types of 3D printers.

3.1 Fused deposition modeling

FDM is the most common type of 3D printer used now a days. It was developed in 1980s by Scott Crump from Stratasys. Many other companies use similar technology but under different names. Using fused deposition modeling you can not only make operational prototypes but also ready to use products as plastic gears or Legos. FDM uses engineering-grade thermoplastic so the printed items have excellent mechanical, chemical and thermal attributes which is quite beneficial for engineers and manufacturers. [16]

Figure 12: 3D printed prototype Fused deposition method [17]

Printers that use FDM technology construct the model from the bottom-up, layer by layer by heating and extruding the thermoplastic filament. Specialized programs break the whole model into thin layers (thickness of a layer is equal to extruded layer of 3D printer) and then 3D printer forms these layers. The process is fairly similar to stereolithography. The filament is heated to the melting point and then extruded through nozzle. Extruder moves according to predetermined pattern determined by the slicer software or CAD model. The slicer software is connected to the 3D printer through a computer which translates the measurements of the object into X, Y and Z coordinates. Extruder and the base platform are controlled and also controlled by the slicer and follow controlled route as guided by the software. The extruder ejects plastic as it moves, this thin layer when come into contact with the layer beneath it, it melts and hardens and as the extruder completes a layer the base and the extruder return to the origin awaiting command for the next layer. A simple layout of FDM printer is shown below in which the extruder moves in X, Y axis and the table or base moves in Z axis.

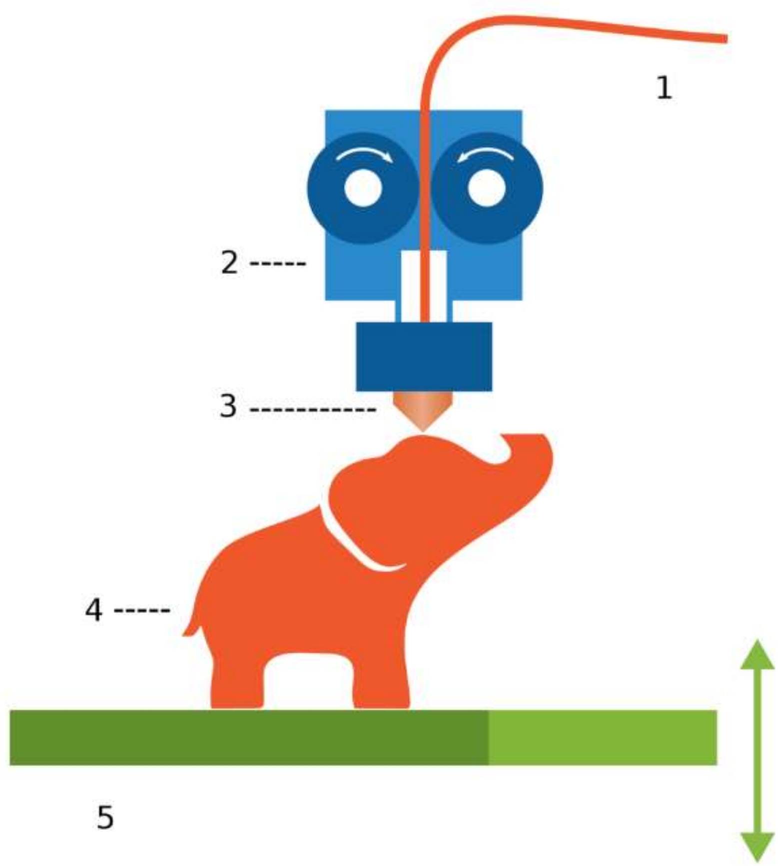

Figure 13: FDM process explained

In terms of speed, fused deposition method is slower than stereolithography. The overall speed is depending on the size of the product and the complexity of the design. There are some design constraints using FDM (e.g., you cannot start printing a layer that has no base in the middle of air, the material will drop to the base), in some cases you can use some supporting material to help you get over these constraints. Nylon is generally used for supporting material meanwhile water-soluble wax or polyphenylsulfone (PPSF) is also common. When printing is complete you can simply remove these supporting materials and the design will hold.

FDM technology is widely spread and it is in use for prototype development, product development and even end manufacturing. Its widely spread in automobile and toy manufacturers. By using FDM it is possible to construct complex geometries and cavities.

We can use many different types of thermoplastics with FDM printers. The most common of these are ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) plastic.

3.2 Stereolithography (SLA)

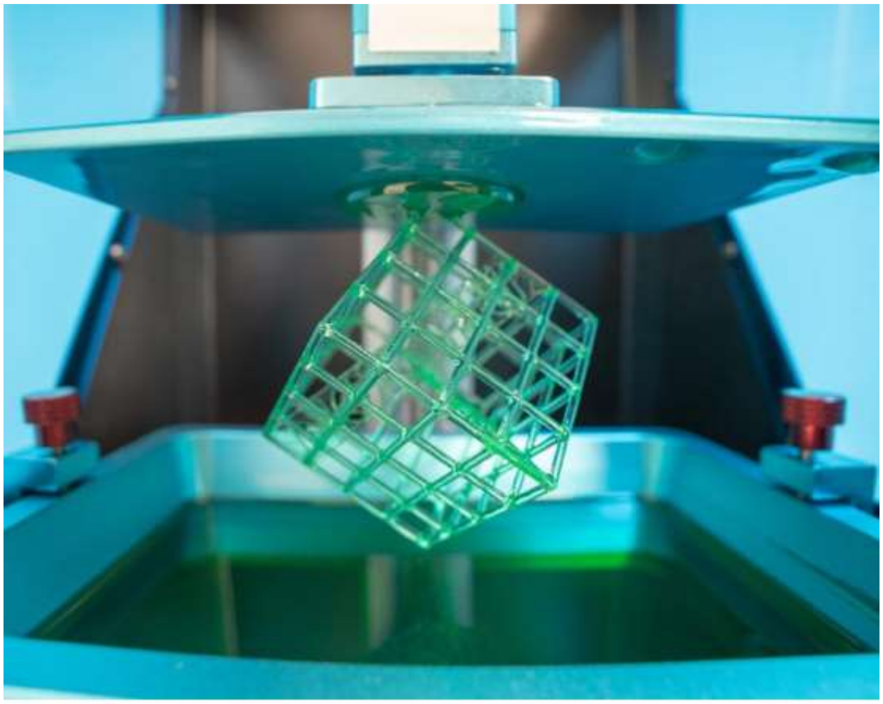

Figure 14: Stereolithography [18]

SLA is one of the earliest methods used in 3D printer and it is still very much in use. SLA printer brings your model to life, whether it is a prototype or an actual mechanical part. The working of SLA is different from other printers in the sense that the liquid is not dropped in form of some ink from top. In Stereolithography, Liquid is present at the base of the container and a laser beam is shot from the top. This laser beam when comes in contact with the liquid, solidifies it. Hence, forming a solid layer at the bottom. The bottom platform is moved down by fraction of a millimeter, by a piston (generally) which holds the base. The laser beam is shot again at the liquid and another layer is formed. The path of the laser beam is controlled using a slicer software which breaks the model into layers. Bottom layer is formed first when the piston is at its topmost position at as it moves down middle layers are formed. The maximum height of the model is determined by the stroke of the piston. The working principle is described perfectly by the following figure.

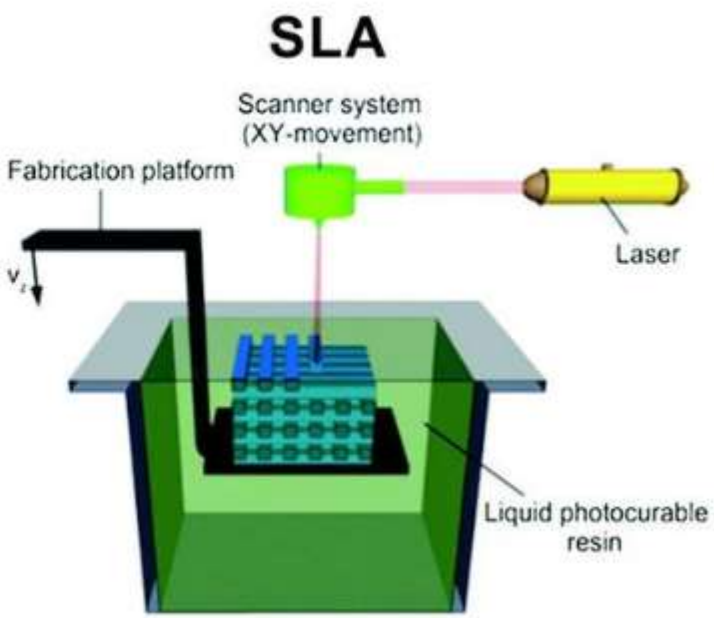

Figure 15: SLA Printing explained [19]

Laser is shot at a scanner which directs it to the liquid photocurable resin below (according to the slicer model). The liquid solidifies as it comes into contact with the laser forming a solid layer. As a layer is completed the fabrication platform is moved downward by the width of a layer (usually fraction of a millimeter) so that next layer can be formed on top of the previous.

The SLA approach not only allows more intricate features to be incorporated into the design but also it gives the designer freedom to produce precise and accurate parts with high quality surface finish, consistently.

3.3 Digital Light Processing (DLP)

Figure 16: Digital Light Processing 3D printer [20]

The DLP printer works similar to that of an SLA printer. In Digital Light Processing printer light is reflected using micromirrors. The photosensitive liquid is placed in the fabrication platform below meanwhile UV light is reflected on to it using micro mirrors and as the liquid is exposed to photons of light it hardens, forming a solid layer. The platform is lowered by the fraction of a millimeter and the liquid is exposed to light again forming another layer. The process is continued until the model is completed.

The main difference between SLA and DLP is the light source, stereolithography uses a laser light and Digital Light Processing uses an Ultraviolent light. Also, In Digital Light Processing the light source remains stationery as it cures the complete layer of resin at one time meanwhile in Stereolithography Laser beam moves from point to point tracking the geometry. Difference between Stereolithography and Digital Light Processing is explained with the help of a picture below.

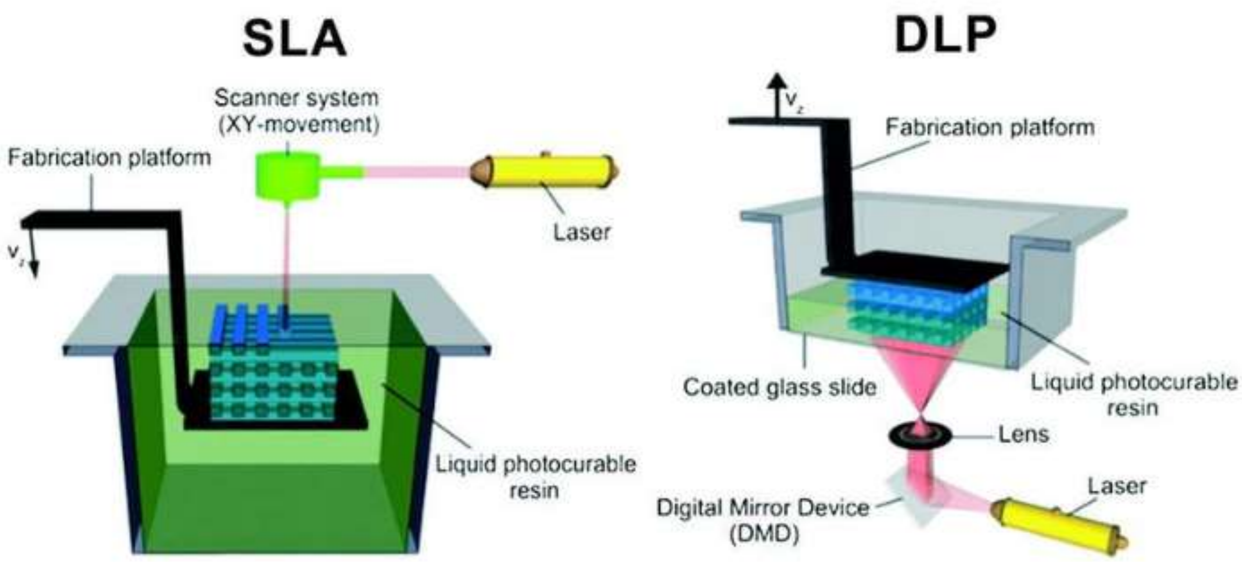

Figure 17: Difference between SLA and DLP [19]

Digital Light Processing printers are very accurate as the minimum thickness for a layer can be set at 10 µm. Other than the accuracy the key advantage of DLP is the speed of printing. SLA printer is considered fastest generally but when you need to form a full layer DLP is much faster as it can form a full layer in matter of a few seconds. Another advantage is the cheap price of printers, DLP printers are very cheap when compared to other printers.

DLP printers are widely used for prototyping usually by engineers. Other common application of DLP is in production of jewelry, healthcare and souvenirs. An example of DLP is shown below depicting how intricate parts can be made.

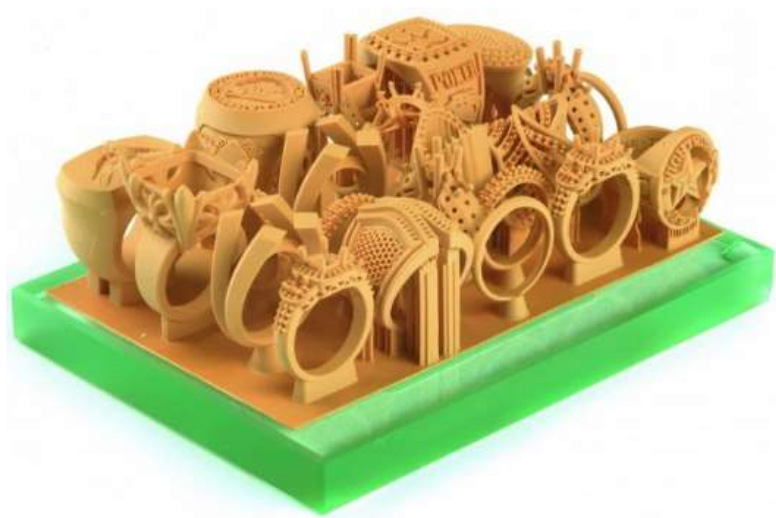

Figure 18: DLP Printed part

3.4 Selective Laser Sintering (SLS)

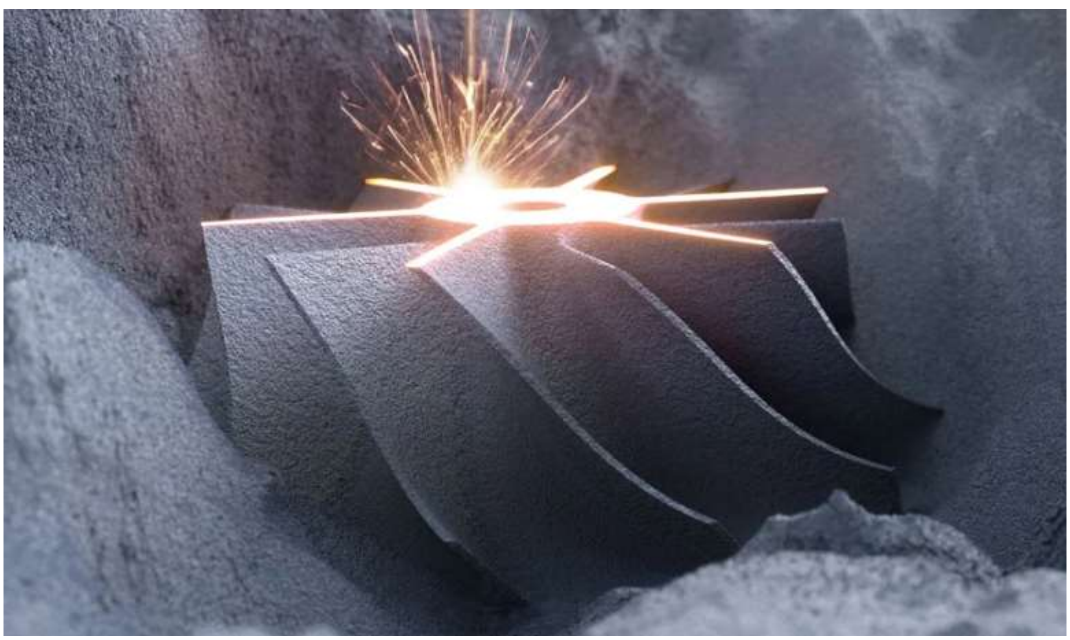

Figure 19: Selective Laser Sintering (SLS) [21]

Selective Laser Sintering (SLS) printer basic working principle is very much similar to Stereolithography (SLA). Unlike SLA and DLP that uses liquid in the container and then solidify it by using light wither laser or UV, SLS uses powdered material in the base and solidify this material using some strong laser beam. Once a layer a formed the base platform moves down and another layer of powder is laid which is solidified using laser. The process continues until the model is complete. The basic working principle is explained with a figure below.

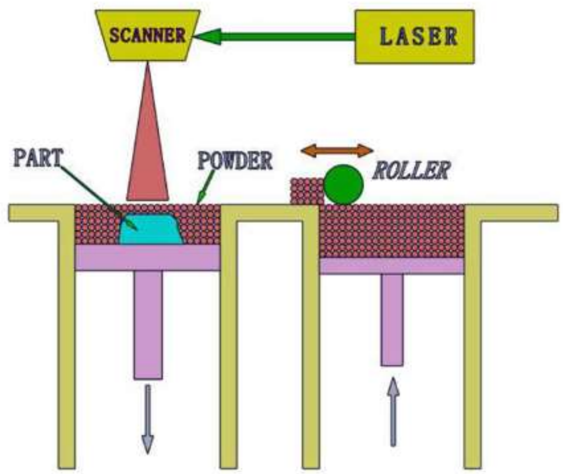

Figure 20: SLS working principle

As I mentioned earlier, SLA and SLS technique are almost exactly the same but SLS has the advantage over the type of materials that can be used. Material used in SLS can range from Nylon, glass and ceramics to even metals such as aluminum, silver or steel.

SLS printers uses high powered beam and hence they are quite expensive which is why they are used mostly in industries rather than by private entities. Nonetheless SLS printers are very accurate and material variety available make them even more handy.

3.5 Concrete 3D printer

Concrete 3D printing is most commonly known as concrete printing. It refers to 3D printing cementitious material using a CNC program and 3D printer technology. Construction industry has taken most advantage from this kind of printer for printing building elements, blocks, street furniture or civil infrastructure.

Construction industry is one the biggest industry in the world. It consumes a very large chunk of manpower, time and money. Automating this field has been the focus of engineers since the beginning of 20th century and the concrete 3D printer is the way about it. Two main methods for concrete 3D printing were established in late 90's. First one is based on concrete layer extrusion and was developed at the University of Southern California's Information Sciences Institute, in the Viterbi School of Engineering.

Figure 21: Concrete 3D printer [22]

Meanwhile the second was demonstrated by Joseph Pegna which included binder jetting of cementitious materials. A simple 3D concrete printer is demonstrated below.

3.5.1 Layered extrusion 3D printing

Layered extrusion 3D printing or fused filament fabrication is a wide spread and accessible 3D printer technology. It is called Fused filament fabrication only when we use polymers as feedstock. Other than polymer, concrete, clay and foams can also be used in layered 3D printing. This technology was first developed in 1990s by Behrohk Khoshnevis for concrete crafting.

Working of the concrete 3D printer is much like other 3D printer technologies where it involves a numerically controlled nozzle. This nozzle can precisely extrude a cementitious material layer by layer. This nozzle is sometimes joined with a towering tool which flattens the 3D printed layer and cover the groove at interlayer grooves. Extruded layer varies in dimensions by printer to printer and is generally 5mm and few centimeters in thickness.

The main advantage of layered extrusion 3D printer is that it doesn't require a form work unlike concrete casting and spraying. It is significant because formwork takes a lot of time and resourced and according to a general estimate formwork takes about 50–80% of the resources which is more than raw material, labor and reinforcement combined.

The main challenge in the layered 3D concrete printer is the formation of cold joints at the interface between consecutive layers and the integration of reinforcement. The working of the layered 3D printer and ac actual printed is shown below.

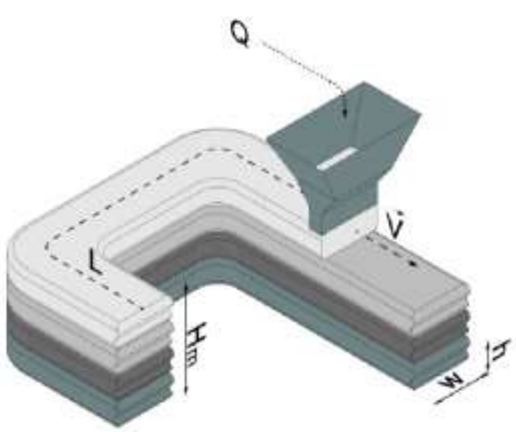

Figure 22: layered 3D printer working

Figure 23: Actual layered extrusion 3D printer [23]

3.5.2 Binder jet 3D printing

Binder jet technology was developed in 1993 for activating gypsum or starch powder or with water as binder and is also called binder 3D printing. Technique was successful and soon other materials such as sand and epoxy resin, acrylic powder and cyanoacrylate, aluminosilicate, sugar and water, metakaolin powder and sodium silicate etc. were also used as new powder and binder combination. A couple years later an idea to use this technology in 3D printer was proposed and that's how we got ourselves binder 3D printer.

Working principle of the binder jet 3D printer is different than that of layered 3d printer. This technology works by depositing a liquid binder on a powder substrate, selectively. Layer by layer repeating this process gives us the finished product. The typical thickness varies between 0.2 and 2mm depending upon the shape and level of detail in the finished part.

Two approaches used in binder jet concrete printing involve, Portland cement with water or water-based binder and injecting liquid cement paste into a bed of fine aggregates. Sorel cements and geopolymers can also be used instead of Portland cement in first case.

Binder jet printer has the advantage over other concrete extruders in terms of geometrical independence. Complex shapes can be easily constructed using binder jet printing and also overhangs or hollow parts or even unsupported cantilever type structure can be easily made without requiring any auxiliary supports because it relies on bed of unbounded powder for support.

The challenges faced while using binder jet printing is the recyclability of the unbounded powder. Typically, it is reusable but when cement or aggregate powder is used it cannot be reused because exposure to humidity can trigger the binding process. Another factor is post processing. Binder jet printing requires post processing to remove the unconsolidated powder mechanically. Brushes and vacuum tubes are used for it. Other than this heat treatment in controlled environment may also be needed using oven or microwave and to improve the surface quality of the part polyester or epoxy resin coating may also be needed.

Figure 24: Binder jet 3D printing [24]

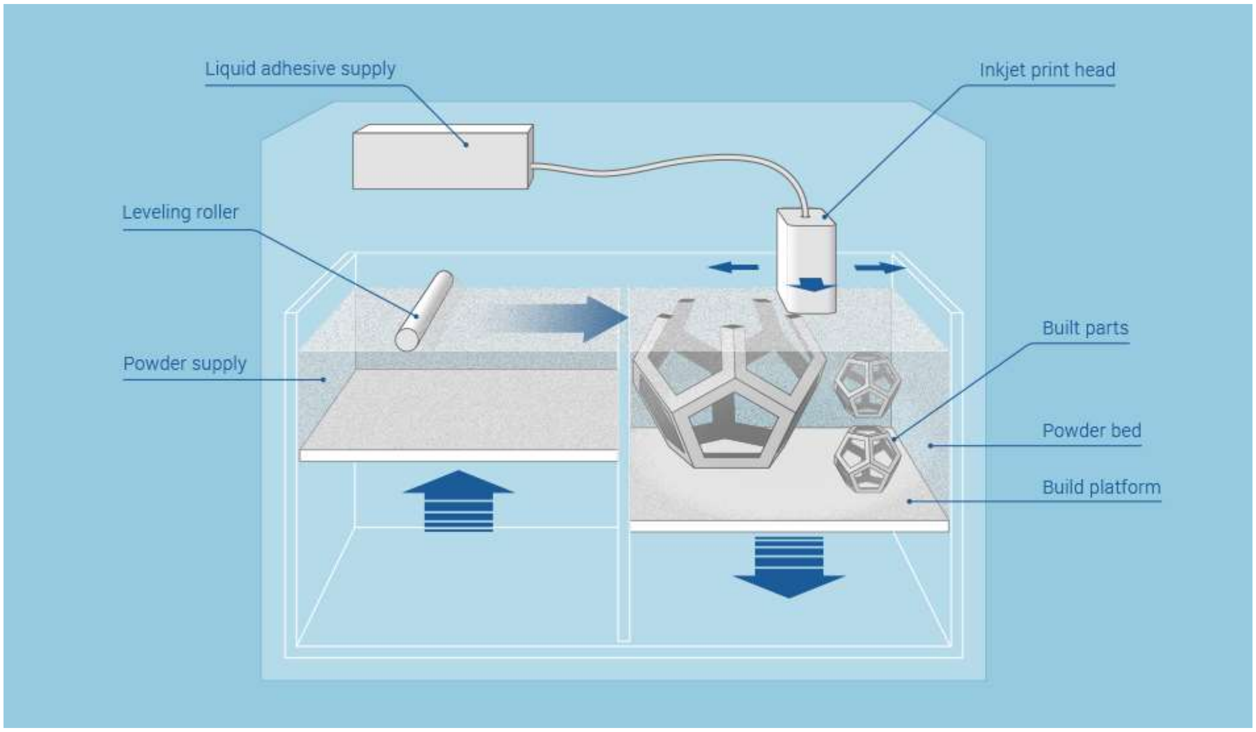

Figure 25 : Binder Jet 3D printer working

CHAPTER 4: EXTRUDER DESIGN

The objective of this study was to design a smart concrete 3D extruder and prototyping. Extruder can be considered as most important part of a 3D printer as it is responsible was drawing in the material, melting it (in 3D printers that require fused material e.g., FFD), and pushing out the material. The design of the extruder is very crucial and unless done accurately our printer cannot function properly. In our case we are using an aluminum housing for the extruder and the material from the container above will be drawn in using pneumatic pressure pushing from above. A leadscrew driven by a stepper motor will move the material towards the nozzle at the end which will push out the material precisely according to the numeric feed supplied.

4.1 Extruder main elements

An extruder has basically two main elements. First is the cold end which generally refers to the upper portion of the extruder where the filament is fed. The second is the hot end where filament is melted and squirted out.

4.2 Extruder types

Basically, there are two types of extruders depending upon the drive of the extruders. First is the direct extruder. In this the hot end and the cold end are attached together. Advantage of this type of extruder is clear prints and also the responsiveness to extrusion and retraction. The second type is the Bowden type extruders in which there is a tube that extends from extruder to its hot end. This type of extruder prints faster with more precision and accuracy [25]. The working principle of each of these extruders and how they actually look are show below.

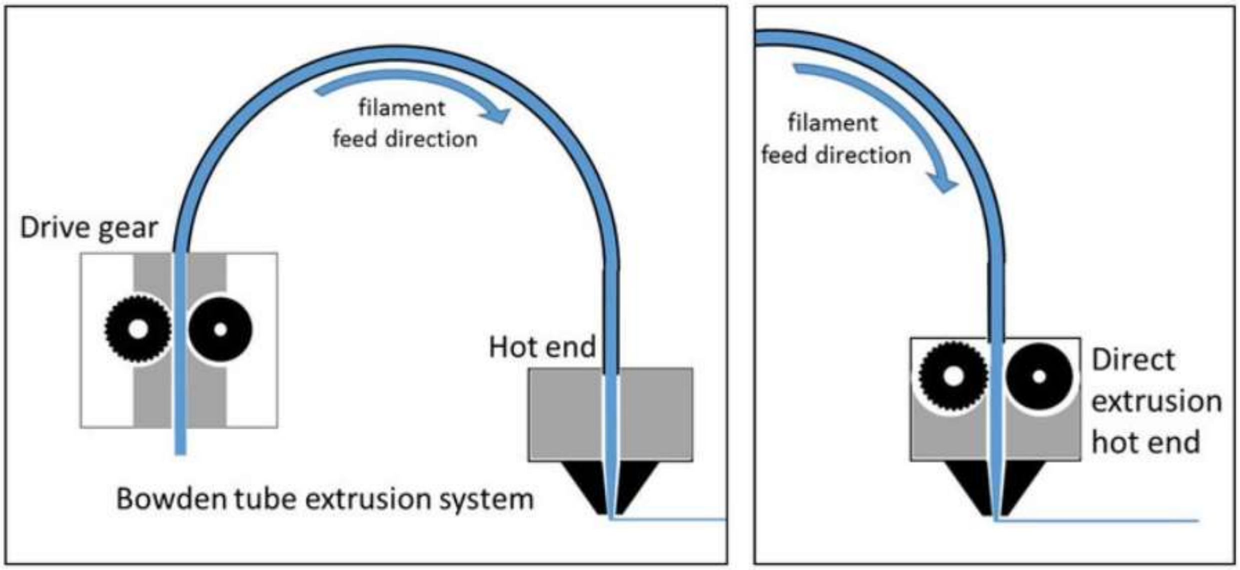

Figure 26: Direct and Bowden type extruders [26]

As demonstrated in the figure above, the main difference between the two extruder types is where the drive gear is placed with respect to the hot end. In Bowden type extruder drive gear is placed far from hot end hence making the extruder light weight and capable to move at high speeds easily. Meanwhile in direct extruder, the hot and cold ends are joined together. Real life picture highlighting this difference are shown below.

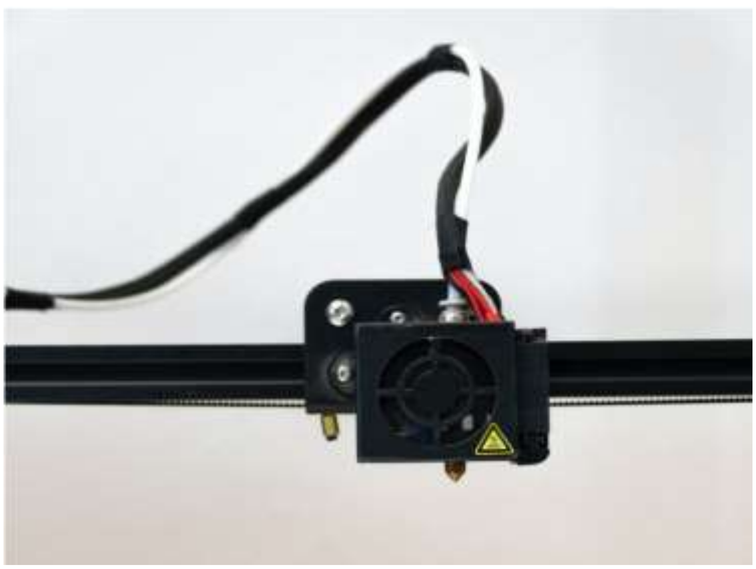

Figure 27: Real life Bowden type extruder

Figure 28: Real life direct extruder

4.3 Stepper motor

Selection of this motor is an important task as we need to make sure it has enough torque to push out the cementitious mixture as the leadscrew feeding the material to the nozzle needs to be powered by this motor. So basically, what we are looking for is a stepper motor/lead screw combination which can exert enough linear force to move the clay through the nozzle. 4 bars of pressure will be required for it. The rate at which the material is extruded would be determined by the stepping rate of motor.

Pressure = 4 bar = 0.4 N/mm^2

Force exerted = Pressure (N/mm^2) * Area (mm^2)

$= 0.4 * \pi * r^2$

$=0.4 * \pi * 32.5^2$

= 1320 N

For the sake of safety and to make sure the system functions smoothly, I am rounding this up to 1400 N

F = load on the screw = 1400N

d_m = mean diameter = 0.01m

μ = coefficient of friction = 0.2

l = lead = 0.002m

$$\text{Torque} = \frac{Fd_m}{2}\left(\frac{1+\pi\mu d_m}{\pi d_m - \mu l}\right)$$

I also used another formula which incorporated the angle of friction and lead angle just to be sure of my results.

Φ = angle of friction = 11.3°

λ = lead angle = 3.6433°

$$\text{Torque} = \frac{Fd_m}{2}\tan(\Phi + \lambda)$$

In both cases the torque came out to be 1.86 Nm and considering the torque we used Nema 23 stepper motor, it with 1.8 deg. step angle (200 steps/revolution). Each phase draws 4.2A, allowing for a holding torque of 3.0Nm(425oz.in)

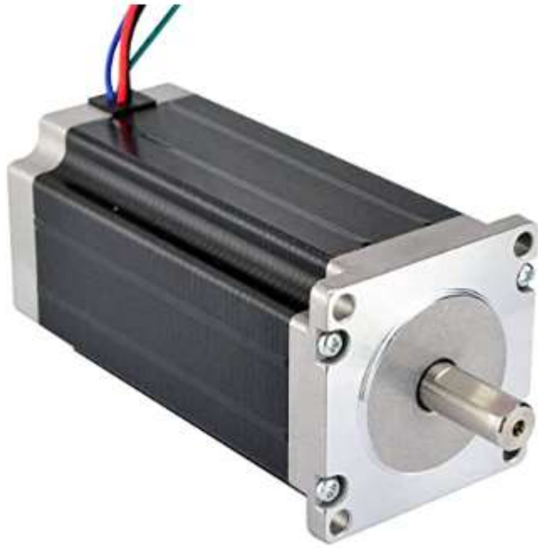

Figure 29: Nema 23 stepper motor

Stepper motor selection is very important because if we select a motor that cannot deliver the required torque it will have the most effect on printing quality. Motor has to drive the screw which is responsible for feeding the material to the nozzle opening. So, careful selection is ensured in case of motor.

4.4 Extruder Screw

The extruder design was finalized and the following screw was selected based on the availability of the market and the design finalized.

Figure 30: Extruder Screw

The detailed design and the geometry are shown below

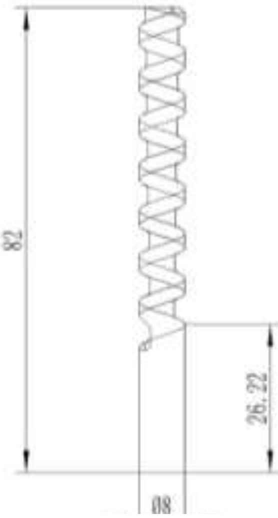

Figure 31: Geometry 1

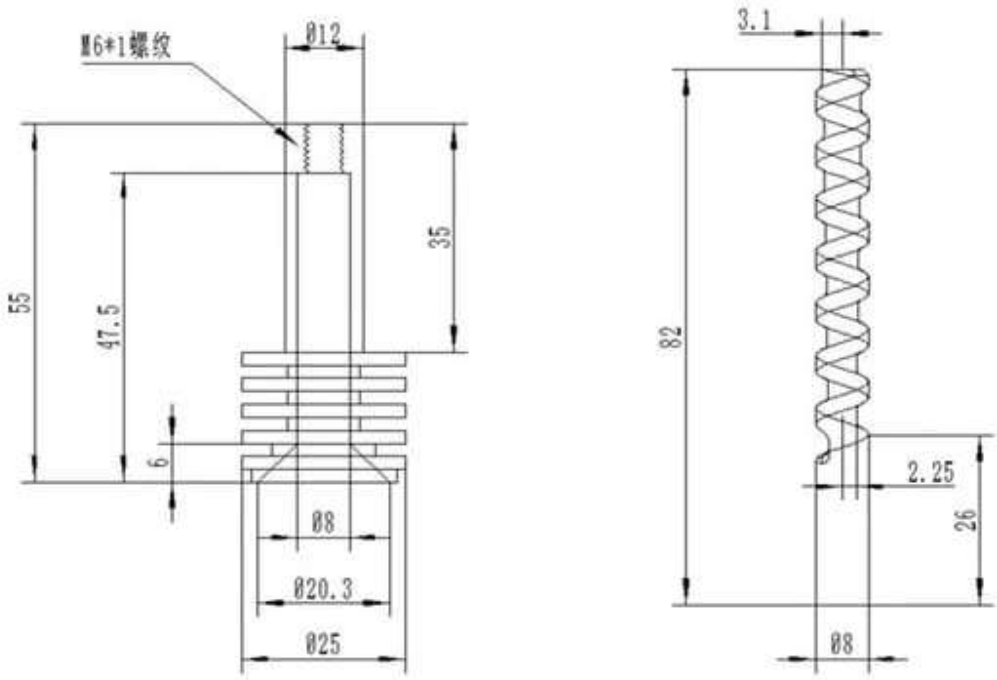

Figure 32: Geometry 2

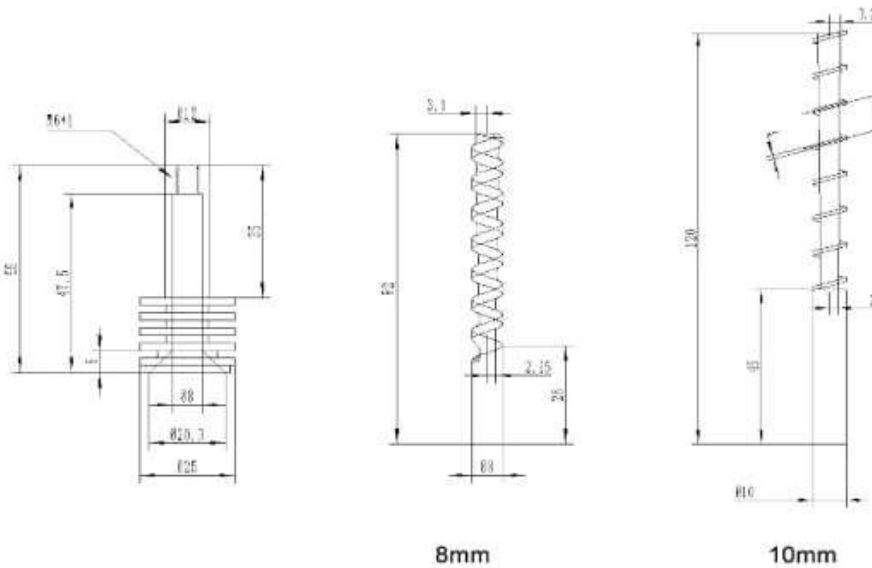

Figure 34: Geometry 3

Figure 33: Finalized Screw 8mm and 10mm

CHAPTER 5: RESULTS AND CONCLUSION

5.1 Prototype Development

The fabrication process consisted of two stages. In 1st stage we finalized the extruder, motor and the motor hub. Assembly was designed in such a way that it can house two different kinds of motor and extruder of 8mm or 10mm can be used depending upon varying input and output conditions. The 1st assembly and the parts used are shown below.

Figure 35: Motor and Extruder Assembly

Motor coupled with Screw extruder is displayed where the nozzle above is for concrete input which is the material for printing. The coupling is covered by an aluminum block and holes are drilled in to reduce the weight of the assembly. Moreover, extruder is force fitted through a bearing in the hub which also works as a seal to stop backflow. MS (mild steel) plate joins the extruder hub (which is screwed to the plate) and the coupling housing (bolted in). Nozzle is attached at the end of the extruder to deliver a smooth and precise output. Another picture with a side view is shown below.

Figure 36: Motor and Extruder Assembly (side view)

This tank holds the concrete mixture which is supplied to the extruder for printing. The hole below is for feeding the concrete in. The concrete primarily flows in due to gravity but there is also an option to provide pneumatic pressure on the top. The tank and the extruder together are shown below.

Figure 37: Storage tank (Front View)

Figure 38: Extruder and Tank assembly (isometric view)

These are the individual parts; all parts of the assembly are shown below.

Figure 39: Stage 1 all parts (a)

Figure 40: Stage 1 all parts (b)

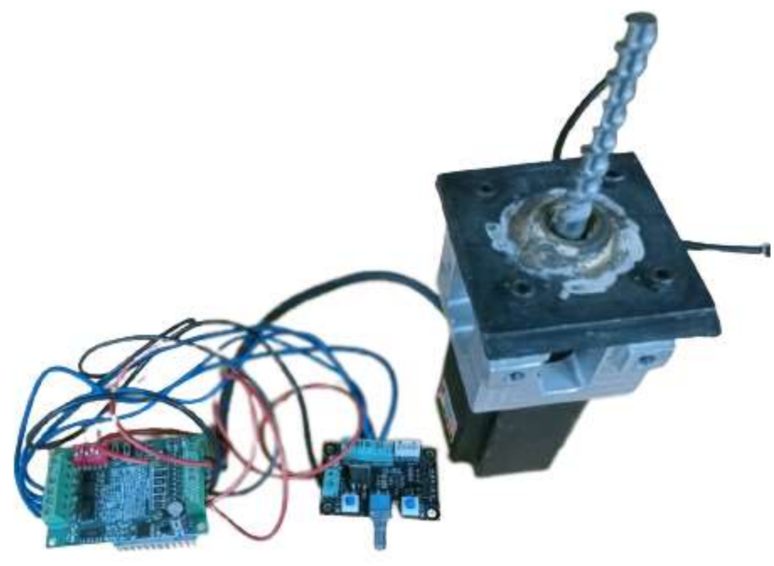

Figure 41:Motor Assembly

This is the 1st phase of the fabrication process. In this phase the constant supply of the concrete was a problem. Concrete was too thick to be pulled by the gravity alone and even when we introduced pneumatic pressure the results were not satisfactory. To solve these problems, we decided to introduce a new type of container which will offer less resistance and a smooth flow can be ensured.

Figure 42: Modified tank and Extruder assembly

Figure 43: Pneumatic cylinder connected to tank

Figure 44: Pneumatic cylinder and valves attached

In this stage, we installed Teflon tank for concrete storage and introduced pneumatic pressure. At the end we were able to get a uniform flow of concrete for 3d Printing.

In terms of further improvements, we reduced the weight of the extruder to minimize the cost of operation. Instead of aluminum and cast iron we used plastic where possible. This helped us reduce the weight significantly thus allowing us to use smaller motor to move extruder in x-y direction. Final image of the extruder is as below.

Figure 45: Final Shape of the extruder

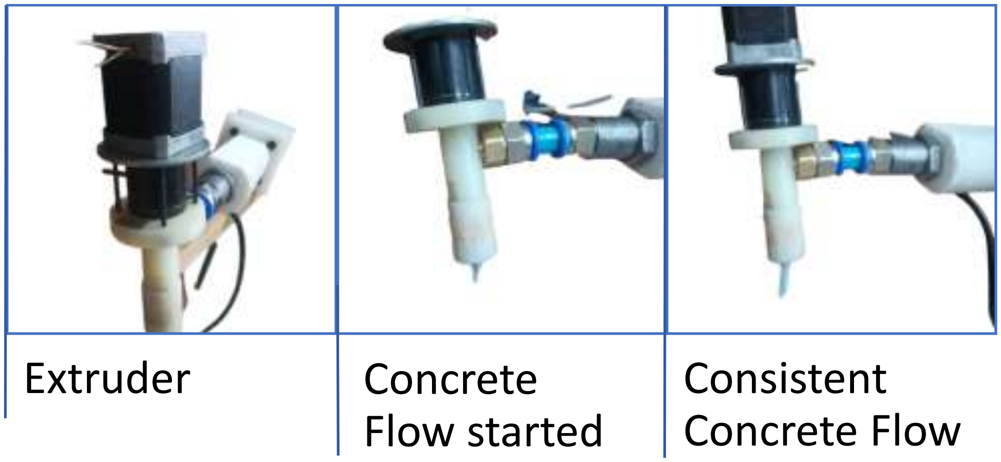

Figure 46: Extruder and the Extruded Concrete Flow

5.2 Results:

Our system has a capacity to operate at a minimum of 140rpm and a maximum of 400rpm. The nozzle used has a diameter of 7mm. We calculated the flow rate of the concrete flowing out of the extruder using different concentration of water and grout and the results are as follows:

Case 1:

Water = 60g (33.33%)

Grout = 120g (66.66%)

Filling

Cylinder Length = 70mm

Pressure = 2 bar

Time taken (t) = 2 min 50 sec

⇨ Flow rate = 60g/min

Solution is flowing out of the extruder at a rate of 60 g/min or 3.6 Kg/hr.

Case 2:

Water = 27g

Grout = 70g

Filling

Cylinder Length = 50mm

Pressure = 2 bar

Time taken (t) = 1 min 40 sec

⇨ Flow rate = 58.9 g/min

Solution is flowing out of the extruder at a rate of 58.9 g/min or 3.534 Kg/hr.

Case 3:

Water = 20g

Grout = 65g

Filling

Cylinder Length = 70mm

Pressure = 2 bar

Time taken (t) = 1 min 50 sec

⇨ Flow rate = 46.36 g/min

Solution is flowing out of the extruder at a rate of 46.36 g/min or 2.7816 Kg/hr.

Case 4:

Water = 30g

Grout = 60g

Filling

Cylinder Length = 70mm

Pressure = 2 bar

Time taken (t) = 1 min 10 sec

⇨ Flow rate = 77 g/min

Solution is flowing out of the extruder at a rate of 77g/min or 4.62 Kg/hr.

The extruder length is 80mm but since the mixture is not inserted at the starting point of the screw so effective length of the screw is about 55-60mm in this case.

5.3 Conclusion:

3D printing has the potential and ability to radically change the construction industry as we see it now by enabling the creation of customized structures with reduced labor, material waste, and construction time. Screw type extruders is generally used. These extruders were developed to be used in the processes where constant feed is required or thick paste is to be used. Screw type extruders are used not only with concrete printer but also other type of printer like FDM. [13]

There are several challenges associated with concrete 3D printing, including the need for specialized equipment, the limited range of printable materials, the potential for structural defects, and the lack of standardized design guidelines and building codes. Research on concrete 3D printing is still in its early stages, and there is a need for further investigation into areas such as material properties, structural design, printing process optimization, and environmental impact.

Another factor to consider while dealing with a 3D printer, 3D printer can create many various shapes and patterns, but it cannot totally replace a creative competent worker with original design ideas. A printer is only as good as the person using it, but an excellent craftsman is well-stocked with innovative thoughts to work with. So, while 3D printers might minimize worker stress, they cannot totally replace a skilled worker.

The goal of this research was to create a screw-type extruder for a 3D concrete printer. Different water-to-grout ratios were created and allowed to flow through an extruder at a constant pressure and cylinder length. It was discovered that when the grout proportion in the mixture increased, the flow rate began to drop. When the grout was 66.66%, the flow rate measured was 60g/min. When the grout was raised to 76%, the flow rate measured was 46.36g/min. Increasing pressure and motor speed can both raise the flow rate. The weight of the extruder is kept as light as possible, aluminum and plastics rather than heavy metals are utilized to connect it to the printing system so that it can conserve energy while moving the extruder, resulting in better output.

REFERENCES

1. Whitaker, M. (2014). The history of 3D printing in healthcare. The Bulletin of the Royal College of Surgeons of England, 96(7), 228-229.
2. Horvath, J. (2014). A brief history of 3D printing. In Mastering 3D Printing (pp. 3-10). Apress, Berkeley, CA.
3. [Online]. Available: https://edutechwiki.unige.ch/en/3D_printer
4. [Online]. Available: https://www.bhphotovideo.com/c/product/1296081-REG/makerbot_mp07825_replicator_3d_printer.html
5. [Online]. Available: https://www.explainthatstuff.com/how-3d-printers-work.html
6. Crump, S. S. (1992). U.S. Patent No. 5,121,329. Washington, DC: U.S. Patent and Trademark Office.
7. [Online]. Available: https://www.flickr.com/photos/nihgov/20690695698/
8. [Online]. Available: https://www.flickr.com/photos/oskay/490968325/
9. Krishnanand & Taufik, Mohammad. (2021). Fused Filament Fabrication (FFF) based 3D Printer and its Design: a review. 10.1007/978-981-15-9853-1_41.
10. Shaqour, Bahaa & Abuabiah, Mohammad & Abdel-fattah, Salameh & Juaidi, Adel & Abdallah, Ramez & Abuzaina, Waleed & Alqarout, Mohammad & Verleije, Bart & Cos, Paul. (2021). Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review. The International Journal of Advanced Manufacturing Technology. 114. 10.1007/s00170-021-06918-6.
11. Darling, C., & Smith, D. A. (2021). Syringe pump extruder and curing system for 3D printing of photopolymers. HardwareX, 9, e00175.
12. Pusch, K., Hinton, T. J., & Feinberg, A. W. (2018). Large volume syringe pump extruder for desktop 3D printers. HardwareX, 3, 49-61.
13. Drotman, D. T. (2015). Design of a screw extruder for additive manufacturing (Doctoral dissertation, UC San Diego).
14. Nassar, A., Nassar, E., & Younis, M. (2021). A novel design to external filament extruder for 3D printer. Australian Journal of Mechanical Engineering, 19(3), 268-275.
15. Kim, N. P., Cho, D., & Zielewski, M. (2019). Optimization of 3D printing parameters of Screw Type Extrusion (STE) for ceramics using the Taguchi method. Ceramics International, 45(2), 2351-2360.
16. Dudek, P. F. D. M. (2013). FDM 3D printing technology in manufacturing composite elements. Archives of metallurgy and materials, 58(4), 1415-1418.
17. [Online]. Available: https://penandplastic.com/3d-printer-types/
18. [Online]. Available: https://www.fastradius.com/resources/prototyping-sla-fdm/
19. Yu, Xiaoling & Zhang, Tian & Li, Yuan. (2020). 3D Printing and Bioprinting Nerve Conduits for Neural Tissue Engineering. Polymers. 12. 1637. 10.3390/polym12081637.
20. [Online]. Available: https://3d-expo.ru/en/article/chto-takoe-tsifrovaya-svetodiodnaya-proektsiya-dlp-80503
21. [Online]. Available: https://www.3dnatives.com/en/direct-metal-laser-sintering100420174-2/#!
22. [Online]. Available: https://www.designboom.com/technology/tu-eindhoven-concrete-3d-printer-06-28-2016/

23. 3D Printing in Concrete: General Considerations and Technologies - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Deposition-of-layers-of-mortar-during-printing-via-extrusion-deposition-of-cement-based_fig5_332282851 [accessed 27 Jul, 2022]
24. Concrete 3D printing - Progress worldwide and in India - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Binder-Jetting-using-D-Shape-printer-adapted-from-Jakupovic-2016_fig2_344100265 [accessed 27 Jul, 2022]
25. [Online].Available: https://www.cmac.com.au/blog/5-things-about-extruder-core-part-3d-printer#:~:text=Extruder%20is%20considered%20as%20one,that%20is%20in%20powder%20form.
26. Ahlers, Daniel. (2018). 3D Printing of Nonplanar Layers for Smooth Surface Generation.
27. Online]. Available: https://jiga.io/resource-center/3d-printing/3d-printer-extruder-hot-end-guide/
28. Analysis and Design of Control System for Desktop Size Concrete 3D Printer - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/SKR-PRO-12_fig2_363377702 [accessed 17 Jun, 2023]
29. Pham, Loan & Nguyen, Thu & Trinh, Thanh & Nguyen, Anh & Do, Quang & Bui, Bien & Xiao, Jianzhuang. (2022). Development of 3D printers for concrete structures: mix proportion design approach and laboratory testing. Smart and Sustainable Built Environment. 10.1108/SASBE-07-2022-0137.
30. Hoffmann, Marcin & Żarkiewicz, Krzysztof & Zielinski, Adam & Skibicki, Szymon & Marchewka, Łukasz. (2021). Foundation Piles—A New Feature for Concrete 3D Printers. Materials. 14. 2545. 10.3390/ma14102545.
31. es-sebyty, Hanane & Abbi, Bouchra & Ferretti, Elena & Mohammed, Igouzal. (2022). Development of a mini 3D printer for concrete custom structures.
32. Jo, Junho & Jo, Byung & Cho, Woohyun & Kim, Jung-Hoon. (2020). Development of a 3D Printer for Concrete Structures: Laboratory Testing of Cementitious Materials. International Journal of Concrete Structures and Materials. 14. 13. 10.1186/s40069-019-0388-2.
33. Zhairvaeva, Gulnaz & Aubakirova, Zulfiya & Ivashina, Yana & Soldun, Alexandr & Makienko, Alina. (2023). Exploring the capabilities of 3D Printer S-6045 for additive manufacturing of street furniture. Technobius. 3. 0033. 10.54355/tbus/3.1.2023.0033.
34. Strohle, Max & Sadique, Monower & Dulaimi, Anmar & Kadhim, Mustafa. (2023). Prospect and barrier of 3D concrete: a systematic review. Innovative Infrastructure Solutions. 8. 21. 10.1007/s41062-022-00975-w.
35. Ramos-Grez, Jorge & Sen, Mihir & Ramos-Cahis, Matías. (2023). Theoretical study of the interactions between vibrations of large numbers of FDM 3D printers. Progress in Additive Manufacturing. 1-15. 10.1007/s40964-023-00438-3.
36. Ali, Ammar & Riaz, Raja & Malik, Umair & Abbas, Syed & Usman, Muhammad & Shah, Mati Ullah & Kim, In-Ho & Hanif, Asad & Faizan, Muhammad. (2023). Machine Learning-Based Predictive Model for Tensile and Flexural Strength of 3D-Printed Concrete. Materials. 16. 4149. 10.3390/ma16114149.
37. Katsiotis, Marios & Michalis, Vasileios & Papargyriou, Despoina & Mavratzotis, Emmanouil & Savvidou, Martha & Mavrelos, Theodoros & Almpani, Despoina & Tsilikas, Ioannis & Kalligeros, Christos & Vasileiou, Georgios & Papageorgiou,

Dimitrios & Stavridou, Athina & Spitas, Vasilios. (2023). 3BUILD – First 3D Printed Structure in Greece. 10.1007/978-3-031-33187-9_62.
38. Pettalolo, Andy & Rosid, Ibnu & Tontowi, Alva. (2022). PENGEMBANGAN MESIN 3D PRINTING BANGUNAN UNTUK MATERIAL SISA RERUNTUHAN BANGUNAN. RADIAL : Jurnal Peradaban Sains, Rekayasa dan Teknologi. 10. 122-133. 10.37971/radial.v10i1.226.
39. Cao, Chenyu & Sun, Dongsheng & Xian, Zhijun & Zhang, Hengyu. (2022). A brief review of 3D printed concrete. Highlights in Science, Engineering and Technology. 28. 374-380. 10.54097/hset.v28i.4204.
40. Adji, Riyanto & Sen, Tjong & Sutisna, Nanang. (2021). Pengembangan Material Campuran Beton untuk Perencanaan Protipe Mesin 3D Printer Rumah Sebagai Alternatif Pembangunan Rumah yang Lebih Efisien. 19. 105-115. 10.22219/jmts.v19i2.17451.
41. Verma, Ankit. (2022). 3D Concrete Printing Technology.
42. Ushakov, Andrej & Minaeva, Anna & Matorin, Andrey. (2023). Additive manufacturing technology of concrete products. E3S Web of Conferences. 389. 10.1051/e3sconf/202338906021.

3D Printer

by Muhammad Umais Qamar

Submission date: 13-Jul-2023 12:06PM (UTC+0500)

Submission ID: 2130473294

File name: Thesis_draft_Plagiarism_Check-_Copy_1.pdf (1,004.79K)

Word count: 7422

Character count: 45501

DR. JAWAD ASLAM
Associate Professor
School of Mechanical &
Manufacturing Engineering
(SMME) NUST, Islamabad

3D Printer

ORIGINALITY REPORT

11%	9%	5%	4%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	penandplastic.com Internet Source	2%
2	en.wikipedia.org Internet Source	2%
3	www.studymode.com Internet Source	1%
4	www.explainthatstuff.com Internet Source	1%
5	link.springer.com Internet Source	1%
6	John Ryan C. Dizon, Alejandro H. Espera, Qiyi Chen, Rigoberto C. Advincula. "Mechanical characterization of 3D-printed polymers", Additive Manufacturing, 2018 Publication	<1%
7	www.amazon.com Internet Source	<1%
8	crackedinnotime.wordpress.com Internet Source	<1%

DR. JAWAD ASLAM
Associate Professor
School of Mechanical &
Manufacturing Engineering
(SMME) NUST, Islamabad

9	www.wetfeet.eu Internet Source	<1%
10	Simon Scott, Zulfiqur Ali. "Fabrication Methods for Microfluidic Devices: An Overview", Micromachines, 2021 Publication	<1%
11	Submitted to Charotar University of Science And Technology Student Paper	<1%
12	worldwidescience.org Internet Source	<1%
13	Upender Punia, Ashish Kaushik, Ramesh Kumar Garg, Deepak Chhabra, Anmol Sharma. "3D printable biomaterials for dental restoration: A systematic review", Materials Today: Proceedings, 2022 Publication	<1%
14	Patricia Ares-Elejoste, Ruben Seoane-Rivero, Iñaki Gandarias, Aitziber Iturmendi, Koldo Gondra. "Sustainable Alternatives for the Development of Thermoset Composites with Low Environmental Impact", Polymers, 2023 Publication	<1%
15	repositories.lib.utexas.edu Internet Source	<1%
16	www.coursehero.com Internet Source	<1%

17	Submitted to Higher Education Commission Pakistan Student Paper	<1%
18	Submitted to Ibra College of Technology Student Paper	<1%
19	dspace.uiu.ac.bd:8080 Internet Source	<1%
20	R. R. A. K. N. Raiapaksha, B. L. S. Thilakarathne, Yashodha G. Kondarage, Rajitha De Silva. "Design and development of pump based chocolate 3D printer", 2021 International Research Conference on Smart Computing and Systems Engineering (SCSE), 2021 Publication	<1%
21	sahris.sahra.org.za Internet Source	<1%
22	www.niagararegion.ca Internet Source	<1%
23	Submitted to University of Teesside Student Paper	<1%
24	archive.org Internet Source	<1%
25	Xuejun Chen, Shanshan Wang, Jie Wu, Shuwei Duan et al. "The Application and Challenge of	<1%

DR. JAWAD ASLAM
Associate Professor
School of Mechanical &
Manufacturing Engineering
(SMME) NUST, Islamabad

Binder Jet 3D Printing Technology in Pharmaceutical Manufacturing", Pharmaceutics, 2022
Publication

---

26 Bahaa Shaqour, Mohammad Abuabiah, Salameh Abdel-Fattah, Adel Juaidi et al. "Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review", The International Journal of Advanced Manufacturing Technology, 2021 <1%
Publication

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		