RÉPUBLIQUE ALGÉRIENNE DÉMOCRATIQUE ET POPULAIRE

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

École Nationale Polytechnique

المدرسة الوطنية المتعددة التقنيات

Ecole Nationale Polytechnique

DEPARTMENT OF MECHANICAL ENGINEERING

END OF STUDIES PROJECT THESIS

SUBMITTED FOR THE FULFILMENT OF A STATE ENGINEER DEGREE IN MECHANICAL ENGINEERING

SIZING & DESIGN OF
A 5-AXIS 3D FDM BASED PRINTER

Realized By: BOUAB Ouadia

Publicly Presented and Defended on the 07th of July, 2022

In front of the examining committee:

Chairman	BENBRAIKA Mohamed	MAA	ENP
Supervisor	SEDJAL Hamid	MAA	ENP
	BELHABIB Soufiane	MC	NANTES Université
Examiner	TAZI Mohammed	MAA	ENP

ENP 2022

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DÉPARTEMENT DE GÉNIE MÉCANIQUE
MÉMOIRE DE PROJET DE FIN D'ÉTUDE

POUR L'OBTENTION DU DIPLÔME D'INGÉNIEUR D'ÉTAT EN GÉNIE MÉCANIQUE

CONCEPTION ET DIMENSIONNEMENT D'UNE IMPRIMANTE 3D 5-AXES

Réalisé par: BOUAB Ouadia

Présenté et Soutenue Publiquement Le 07 Juillet 2022

Composition de jury

Président	BENBRAIKA Mohamed	MAA	ENP
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	BELHABIB Soufiane	MC	NANTES Université
Examinateur	TAZI Mohammed	MAA	ENP

ENP 2022

ملخص:

في السنوات الأخيرة أصبحت طابعات 3D تحظى بشعبية كبيرة. على الرغم من وجود تكنولوجيا الطباعة 3D منذ عام 1980، إلا أنها تعتبر الآن واحدة من أهم الاختراقات التكنولوجية في القرن الحادي والعشرين. تم اختراع العديد من عمليات الطباعة 3D المختلفة خلال السنوات. كانت نمذجة الترسيب المنصهر (FDM) واحدة من أوائل التقنيات المخترعة وتعتبر الأكثر شعبية اليوم. على الرغم من ذلك، لا تزال عملية FDM تعاني من بعض المشكلات. تبحث هذه الأطروحة في إمكانية التغلب على مشكلة هيكل الدعم باستخدام نظام 5 محاور. يحتوي النظام المكون من 5 محاور على 3 محاور معتادة، X و Y وZ، بالإضافة إلى محورين دورانيين إضافيين. تتكون الدراسة من تحجيم المكونات المختلفة للطابعة ثلاثية الأبعاد ذات الـ 5 محاور، ويتم التصميم باستخدام برنامج SolidWorks. تم تصميم التصميم استجابة للمواصفات المختلفة الواردة في بيان العمل، وكذلك للحفاظ على سعر الطابعة تحت ميزانية معينة.

كلمات مفتاحية: التصنيع بالإضافة، الطباعة ثلاثية الأبعاد، نمذجة الترسيب المنصهر، طباعة الأجزاء، تصميم، طابعة ثلاثية الأبعاد ذات خمس محاور.

Résumé:

Ces dernières années, les imprimantes 3D sont devenues extrêmement populaires. Même si la technologie d'impression 3D existe depuis les années 1980, elle est aujourd'hui considérée comme l'une des percées technologiques les plus importantes du XXIe siècle.

Différents procédés d'impression 3D ont été inventés au fil des années. La modélisation par dépôt fondu (FDM) a été l'une des premières technologies inventées et elle est considérée comme la plus populaire aujourd'hui. Même si, le processus FDM souffre encore de certains problèmes.

Cette thèse examine la possibilité de surmonter le problème de la structure de support en utilisant un système à 5 axes. Le système à 5 axes à les 3 axes habituels, X, Y et Z, plus deux axes de rotation supplémentaires. L’étude consiste à dimensionner les différents composants de l’imprimante 3D 5 axes, et la conception est réalisée à l’aide du logiciel SolidWorks. La conception est faite en réponse aux différentes spécifications données dans l’énoncé de portée, et aussi pour maintenir le prix de l’imprimante en dessous d’un budget donné.

Mots-clés: Fabrication additive, Impression 3D, Fused Deposition Modeling, Impression d’objets, Conception, Imprimante 3D à 5 axes.

Abstract:

In recent years 3D printers has become extremely popular. Even though 3D printing technology have existed since the 1980’s, it is now considered one of the most significant technological breakthroughs of the twenty-first century.

Several different 3D printing processes have been invented during the years. The fused deposition modeling (FDM) was one of the first invented technologies and it is considered the most popular today. Even though, the FDM process still suffers from some issues.

This thesis looks at the possibility of overcoming the support structure problem by using a 5-axes system. The 5-axes system has the usual 3 axes, X, Y, and Z, plus two extra rotational axes. The study consists of sizing the various components of the 5-axes 3D printer, and the design is made by using SolidWorks software. The design is made in response for the different specification given in the scope statement, and also to keep the printer price under a given budget.

Keywords: Additive Manufacturing, 3D Printing, Fused Deposition Modeling, Printing Objects, Design, 5-axes 3D Printer.

Dedications

First of all, I want to dedicate this modest work

To my dear parents, may God guard and protect them for their unconditional, moral and financial support, his encouragement, and for allowing me to carry out my studies in the best conditions.

To my dear brother "SALLAH EDDINE" and my sister "HIBA", those who have given me the desire to learn and know-how, my pride and my symbol of joy, I wish you a life full of happiness and success and may ALLAH protect you.

To my dearest " K. MUSTAPHA, H. MOHAMED", the source of courage.

BOUAB OUADIA

Acknowledgement

My deepest gratefulness goes to the almighty god Allah thank you for helping me pass this very difficult time of my life thank you for giving me the strength and patience to deal with whatever life threw at me lately. I wouldn't have made it if you weren't with me.

My gratitude goes to my parents and my brother and my sister, who was there for me since day one, being my armor and my shield.

I would like to thank my supervisor S. BELHABIB & H. SEDJAL for his valuable instructions and guidance throughout the working period.

I would also like to thank Professor M. BENBRAIKA & M. TAZI who has accepted to chair my jury, and all teachers of the department.

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LIST OF ABBREVIATIONS

AM: Additive Manufacturing.

3DP: 3D Printing.

RP: Rapid Prototyping.

CAD: Computer-Aided Design.

FDM: Fused deposition Modeling.

STL: Standard Triangle Language.

SLA: Stereolithography.

FFF: Fused Filament Fabrication.

REPRAP: Replicating Rapid Prototype.

DLP: Digital Light Processing.

SLS: Selective Laser Sintering.

SLM: Selective Laser Melting.

PLA: Polylactic Acid.

ABS: Acrylonitrile Butadiene Styrene.

PC: Polycarbonate.

HIPS: High Impact Polystyrene.

CNC: Computer Numerical Control.

NEMA: National Electrical Manufacturers Association.

GENERAL INTRODUCTION

General Introduction

Manufacturing is the basis of any industrialized nation, and it has become important in the industrial filed to produce products for the service of different needs. The knowledge of manufacturing practices is highly essential for all engineers, and technocrats for familiarizing themselves with modern concepts of manufacturing technologies. The basic need is to provide theoretical and practical knowledge of manufacturing processes, and workshop technology to all the engineering students. [1]

The word manufacture is derived from two Latin words, manus (hand), and factus (make); the combination of these two words means made by hand, and it describes the manual methods, but in modern context it involves making products from raw material by using different processes, by making use of hand tools, machinery, or even computers. [1]

Manufacturing processes are commonly divided into three categories: formative, subtractive, and additive. While formative and subtractive manufacturing processes are considered more traditional, additive manufacturing (AM) is a group of advancing technologies that are quickly developing with techniques and constraints yet to be explored. [2]

The principle of formative manufacturing is forming material into the desired shape through heat and pressure. The raw material can be melted down and extruded under pressure into a mold (injection molding/die casting), melted and then poured into a mold (casting) or pressed or pulled into the desired shape (stamping/vacuum forming/forging). Formative techniques produce parts from a large range of materials (both metals and plastics). For high volume production of parts, formative manufacturing is many times unparalleled in cost. The main constraint of formative manufacturing is the need to produce a tool (mold or die) to form the part. Tooling is often costly and complicated to produce, increasing lead times and delaying the manufacturing of a part. This large upfront investment is why formative manufacturing is generally only cost effective at high volumes. [3]

Subtractive manufacturing begins with a block of solid material (blank), the material is gradually removed from the bulk of the raw workpiece, using cutting tools until the desired shape is obtained. CNC milling, turning, and machine operations like drilling and cutting are all examples of subtractive techniques. Subtractive manufacturing is capable of producing highly accurate parts with excellent surface finish. Despite the advantages, subtractive manufacturing processes have its restrictions based on the complexity of the part to be produced. [3]

Additive manufacturing (AM) also known as 3D printing (3DP), and rapid prototyping (RP), is a technology that takes information from a digital file (CAD) and prints it on a 3D printer, which creates a solid object by successively depositing layers of material until the desired object is obtained. Those layers that combined one on top of the other is a horizontal cross-section of the product. The quality of the printed parts using a 3d printer relies on many factors, like the material used, the manufacturing process, the printing feeding rate, filament flow rate, the type of 3D printer used, and eventually the dimensions of the printed part of the used printer. [4]

This thesis aims to design a more developed 3D printer with two new degrees of freedom in addition to the three movements the X, Y, and Z axes of conventional printers.

This thesis is divided into four chapters:

Chapter I: gives a concept about 3D printing, what is 3D printing, how it works and the 3D printing process and a background on the history of 3D printing. This chapter also reviews the different 3D printing technologies, a comparison between these technologies and will cover more about one of these technologies Fused Deposition Modeling (FDM).

Chapter II: discuss in detail the fused deposition modeling technique. This chapter includes the types of mechanisms used in fused deposition modeling printers, the different components of an FDM printer, the commonly used filament materials used.

Chapter III: talks about the 5-axes system, how can we achieve a 5-axes 3D printer, and the possible configurations for a 5-axes system. Will also talk about the Softwares used to generate the G-code for the printing process.

Chapter IV: covers the design of the 5-axes 3D FDM based printer using SolidWorks software, sizing and design of the printer components, and the assembling steps. In the end of the chapter we made a price estimation for the designed printer.

1 CHAPTER I: Review on 3D Printing

Introduction

3D printing, also known as additive manufacturing is a set of techniques used for constructing three dimensional objects from a CAD model or a digital 3D model file. The creation of an object using a 3D printer is done by layering down multiple layers of material until the whole object is created. Each one of these layers can be considered as a thinly sliced horizontal cross-section of the final object. Figure 01 show an example of the layering down using the FDM printing technique (see section 2.1). [5]

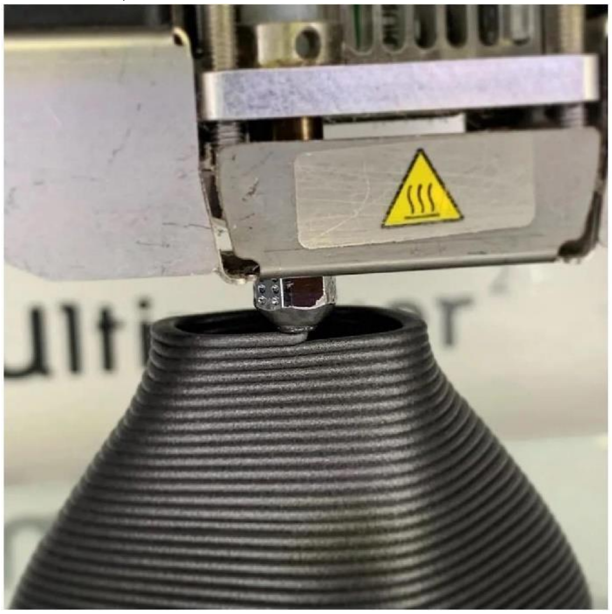


Figure 1.1: Example of an object builds layer by layer using a 3D printer. [6]

The Process of 3D Printing

All 3D printing techniques follow the same basic process to create objects. This 3D printing process consists of the following steps:

1. Create a CAD model of the design.
2. Convert the CAD model to STL file format.
3. Slice the STL file into 2D cross-sectional layers.
4. Build the object.
5. Post-processing and finish the model.

Step 1: CAD

All 3D print parts must start from a software model that fully describes the external geometry. This model is created using any Computer-Aided Design (CAD) software.

Step 2: CAD to STL Format

The CAD file of the designed part must be converted into STL file format. The STL file represents the outer surface of an object as planar triangles. STL file format has been selected as the standard file extension in the additive manufacturing industry.

Step 3: Slicing the STL File of the Part

The STL file is then uploaded to a slicing software called "Slicer". This software slices the object into horizontal cross-section (layers).

Step 4: Building the Object

Once the STL file is processed and saved, the printing process of the part starts. Building the part is mainly an automated process and the printer does not require any supervision.

Step 5: Post-Processing

After the printing process is done. The printed parts require some cleaning and post-processing as removing the support structure, post-curing of photosensitive materials, surface treatment. [3]

History of 3D printing

3D printing has been around since the 1980s. It has exploded in popularity since key patents began to run out in the 2000s. Knowing the historical background of 3D printing is essential to understand the future of manufacturing as this innovation turns out to be more famous and more available to people in general. [7]

The idea of 3D printing has been envisioned back in the 1970's, however the initial trials are dated from 1981, The first documented iterations of 3D printing are granted to Hideo Kodama from Nagoya Municipal Industrial Research Institute for his development of a rapid prototyping technique. He invented and described two first additive manufacturing techniques based on photo-hardening of plastic polymers. His work can be considered as an ancestor and a stepping stone to stereolithography (SLA). Hideo Kodama filed an application for patent, but he did not file the requirements for the patent before the deadline. [8]

In 1984 a French trio-team, Alain Le Mehaute, Olivier de Witte and Jean-Claude Andre filed an application for patent of stereolithography, i.e., an additive manufacturing method which by a laser beam specifically hardens a UV-sensitive liquid resin following a succession of cross-areas of the item to be printed. The patent was abandoned due to a lack of business perspective. [9]

The same year, Charles Hull, filed the first patent for Stereolithography (SLA). In 1986 he submitted his patent application for the technology. The technology was established on UV laser beams that hardens cross-areas by cross-areas of a resin contained in a vat. The .STL file extension Hull adopted is still in use today for most Additive Manufacturing software. He established the 3D Systems Corporation and in 1988, delivered the SLA-1, their first business printer. [9]

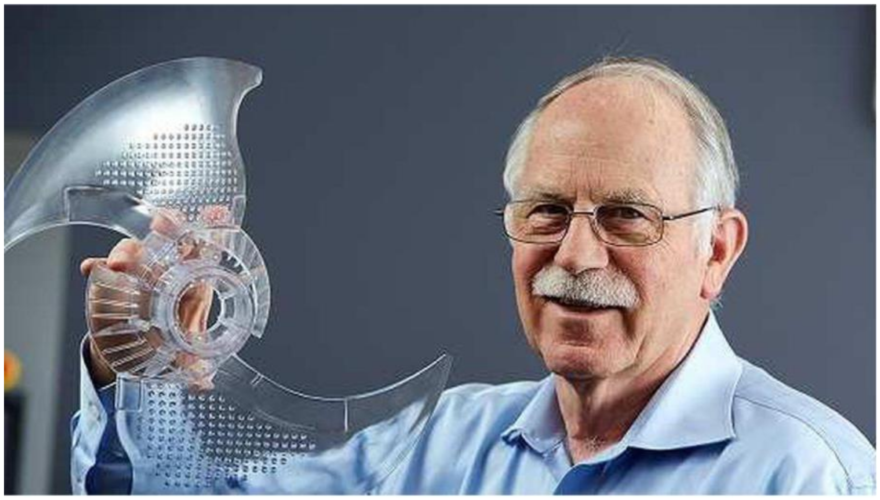


Figure 1.2: Invertor of SLA 3DP technique and the founder of 3D Systems company: Charles Hull. [10]

In 1987, Carl Deckard invented, at the University of Texas, the selective laser sintering technique (SLS), that uses a light of a high-power, as a laser beam that specifically melds powder grains along cross-areas of the wanted shape. The powder can consist in plastic, metal, ceramic or glass, and is typically pre-heated in the bed underneath the fusion point. [8]

In 1989, S. Scott Crump invented and patented the most well-known 3D printing technique, particularly for individuals and low-spending budgets labs. Fused deposition modeling (FDM) known also as Fused Filament Fabrication (FFF). This technique consists in the deposition of fused material (most known plastic) layer by layer. The first machines were commercialized by Scott Crump's company Stratasys beginning from 1992, and a patent was granted (expired in 2009). [8]

In 1993 MIT created what was viewed as 3D printing. The technique consisted in the binding¬ layer by layer-of a bed of powder utilizing an inkjet 3D printer. Same year one more technique was presented by Sanders Prototype (now known by Solidscape), the 'dot-on-dot' technique. It depended on polymer jetting with soluble supports, yielding extremely high-accuracy results. The models were originally printed in wax. [8]

In the year of 1995 in Aachen, Germany at The Fraunhofer Institute the selective laser melting process was invented, the process is similar to the selective laser sintering. The selective laser melting process consists in the melting layer by layer of metal powder through a laser beam. The process yields exact and mechanically solid results, given the utilization of metal alloys and can deal with settled and unpredictable geometries. [8]

In the early 2000s the first 3D printed kidney was presented to the world, but it was not transplanted into a patient, currently 3D printed kidneys are working perfectly and specialists are working on sped up growth to transplant organs quickly. [9]

In 2004 Adrian Bowyer started the RepRap (**rep**licating **rap**id prototype) open-source project in England, the project was in order to develop a low cost and self-replicating 3D printer that can print its own components, this open-source project gave people more access and more popularity to this technology. [11]

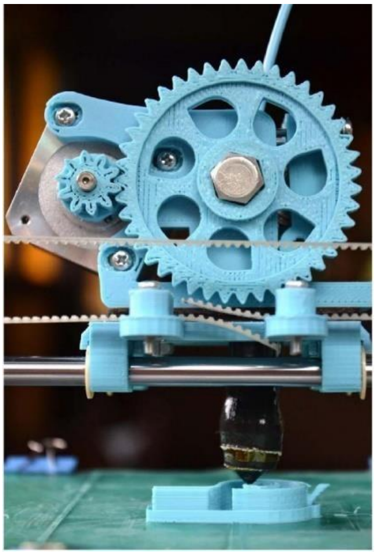


Figure 1.3: 3D printer printed by a 3D printer. [12]

In 2007, a company named Shapeways was established in Netherlands, offering an online 3D printing service for individuals allowing them to send 3D files to have items printed, and sent them back to their address.[8]

In 2009 the Fused Deposition Modeling (FDM) printing process patent expired and the technique fell into the public hands, making it more accessible to companies, which led to a decrease in the 3D printers' prices. [9]

In 2009, the company Sculpteo was created in France, a platform offering the possibility of printing an object from a model created by the user or chosen from a catalog of digital models, it was bought by the German group BASF in 2019. [9]

In September 2013, Voxeljet (Augsburg, Germany) teamed up with NASA and announced its plans for a $100 million IPO (Initial Public Offering), to develop a 3D printer that will be moved to the International Space Station in 2014 for zero gravity part production. [13]

Therefore, 3D printing is not a new technology. What is new is the access of the general public to this technology due to the appearance on the market of printers that are small in size and sold at affordable prices. 3D printing is also experiencing great media coverage of the feats achieved in the medical field thanks to its use. [14]

Overall, 3D printing has changed and improved since its first appearance. SLA, SLS, FDM show the improvements of 3D printing and that it has become an important technique for manufacturing in all fields. [7]

3D Printing Technologies

Additive manufacturing starts with a 3D digital file, created using different 3D software, and the 3D printers starts creating the object layer by layer, The technologies used to build objects one layer at a time are not all the same and quite varied. A few technologies use melting or softening material to produce the layers. The most widely known technologies that utilizes this technique are selective laser sintering (SLS) and fused deposition modeling (FDM). Other technologies use laser beam with UV laser to solidifies and cure resin or powdered materials. Some common technologies use this technique like Stereolithography (SLA) and Digital Light Processing (DLP). [15]

3D Printing Material Types

Conceiving the most suitable classification for additive manufacturing is not a simple task, many methodologies have been taken into consideration for this matter. One choice for classifying the different technologies of additive manufacturing is the type of material printed by the machines, the majority of 3D printing materials can be divided into 3 groups [8]: Liquid, Powder, Solid.

Liquid-based process

Most liquid-based additive manufacturing systems build parts from a liquid resin known as photopolymer, this liquid resin cures and hardens when it is exposed to a laser beam in UV range. Some 3D printers create objects in a vat of liquid resin, the laser hardens the resin on the surface of the vat creating a thin layer, after a layer is created it is lowered by one layer allowing the resin to be coated and another layer is formed over it, this process continuous until the object is formed. Some other 3D printers jet drops of the liquid photopolymer into a build tray via print head, akin to inkjet printing. and curing them with UV light before the next layer is added. This technology is able to mix different photopolymers, allowing the user to create objects made from different materials. [16]

Powder-based process

Powder-based 3D printers primarily use materials powder as the basic for making objects by selectively melting or fusing together continuous layer of the powder. A laser fuses the first layer of the object, after that the platform moves down one layer thickness in height and a recoating blade deposits a new layer of powder on top of the last layer, the laser starts fusing together another layer, and so on until the object is completed. [17]

Solid-based process

Solid-based additive manufacturing systems are very different from the liquid-based photo-curing systems. Solid-based 3D printers makes objects by extruding a molten or in any case semi-fluid material from a print head nozzle. Most regularly this includes extruding a molten thermoplastic that quickly sets after it has left the print head. Other extrusion-based 3D printers manufacture objects by outputting molten metal.[16]

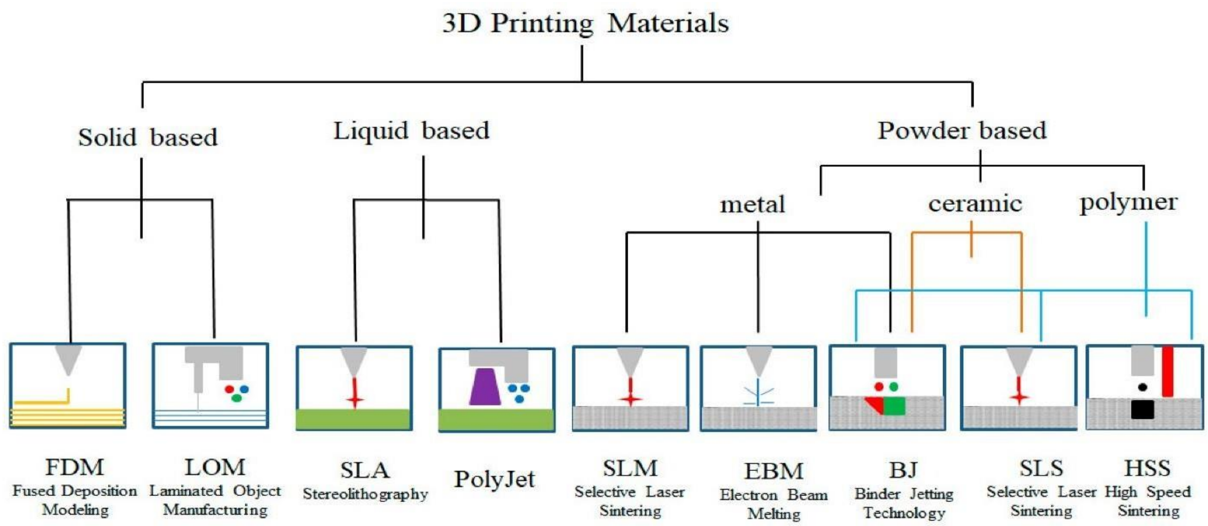


Figure 1.4: 3D printing material types used in different technologies. [18].

Classification of 3D Printing Technologies

In 2010, The American Society for Testing and Materials (ASTM) group "ASTM f42 - additive manufacturing", developed a set of standards that classify the additive manufacturing processes into 7 categories according to standard terminology for additive manufacturing technologies [15]:

- Vat photopolymerization.
- Material jetting.
- Binder jetting.
- Material extrusion.
- Powder bed fusion.
- Sheet lamination.
- Directed energy deposition.

Types of 3D Printing Technologies

Stereolithography (SLA)

Stereolithography was the world's first 3D printing technology, introduced by Chuck Hull in 1986, and it is still one of the most popular technologies for professionals. The main advantage of such a technique is the high resolution achievable, since it is based on a laser beam.

This technique consists of a laser beam selectively solidifies a UV-sensitive liquid resin in a tank. The platform where the object is being built is lowered every layer, until the whole object is printed. During the process, supports are added and removed after the object is completely made. Post-processing after is needed, including using UV-ovens to make the product more grounded and steadier. [19]

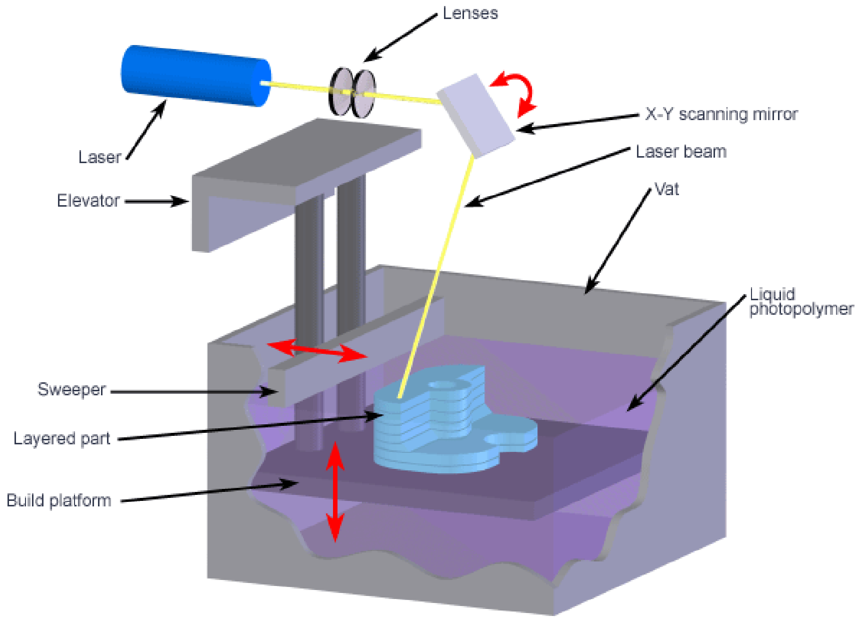


Figure 1.5: Illustration of Stereolithography (SLA) printing process. [20]

Digital Light Processing (DLP)

Digital light processing is similar to SLA in that it cures liquid resin using light. It is based on the same principle of photopolymerization, the primary difference between the two technologies is that DLP uses a digital light projector screen whereas SLA uses a UV laser.

A DLP projector is positioned under a resin vat and the resin is hardened layer by layer (one entire layer at once), the results of DLP are faster and of higher resolutions. [21]

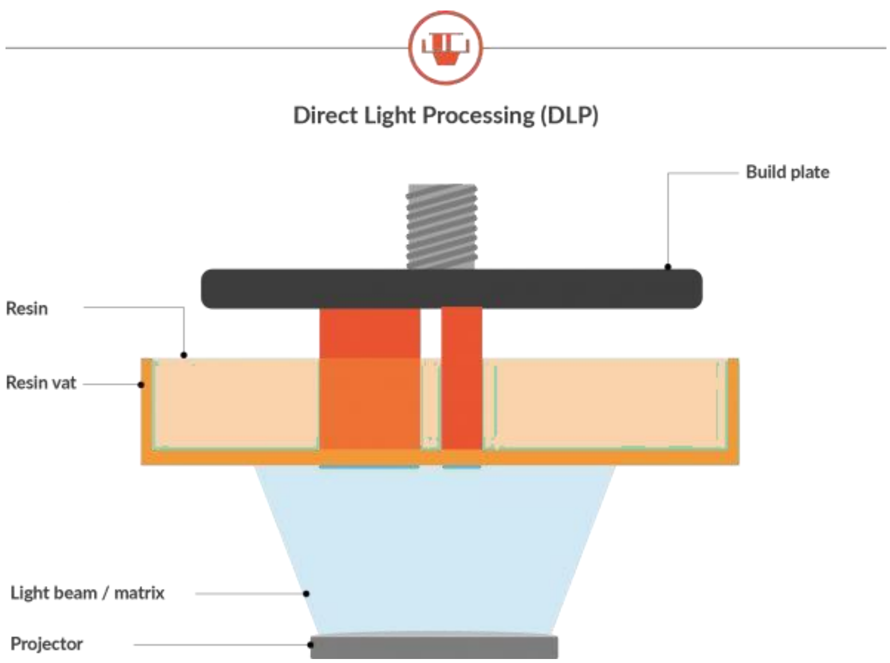


Figure 1.6: Illustration of digital light processing (DLP) printing process. [22]

Fused Deposition Modeling (FDM)

Fused deposition modeling (FDM), also known as fused filament fabrication (FFF), is an additive manufacturing technology used for modeling, prototyping, and production applications, it is the most widely used type of 3D printing at the consumer level, and it was developed by Stratasys.

FDM works on an "additive" principle by laying down material in layers. During the process, a plastic filament or metal wire is unwound from a coil and, the supply material is extruded through a nozzle. The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off.

The nozzle is mounted to an X-Y plotter type mechanism which traces out the part contours, and directly controlled by a computer-aided manufacturing (CAM) software package. On some machines, there is a second extrusion nozzle for the support material. The plastic hardens immediately after being extruded from the nozzle and bonds to the layer below.

The object is built on a mechanical stage which moves vertically downward layer by layer as the part is formed. Stepper motors or servo motors are typically employed to move the extrusion head. [23]

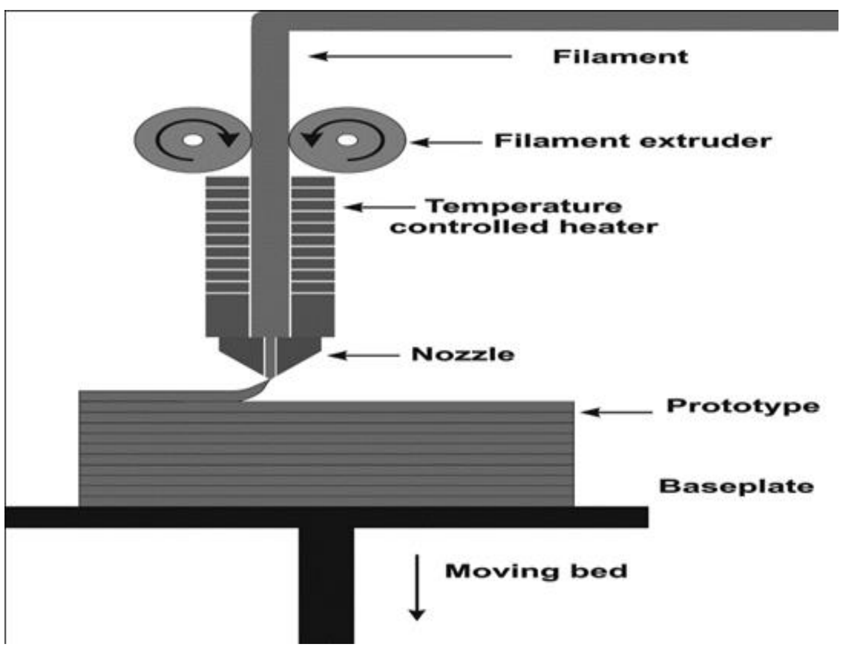


Figure 1.7: Illustration of FDM printing process. [24]

Poly Jet

This technique is a recent development in comparison to previous ones. It is a potentially replacement for stereolithography. In early 2000 it was introduced by Objet Geometries (merged with Stratasys in 2012). it combines a print-head spraying liquid photopolymers into very thin layers, and a UV lamp-positioned under the print-head nozzles- hardening each one of the layers.

Layers are created by lowering the work platform, while the head just moves along the Y axis, since it covers the X axis through a number of nozzles. The support material, which is also a photopolymer, is removed by washing it away with pressurized water in a secondary operation. The advantage of poly-jet systems over SLA systems is that it allows the combination of different materials of different properties. [8]

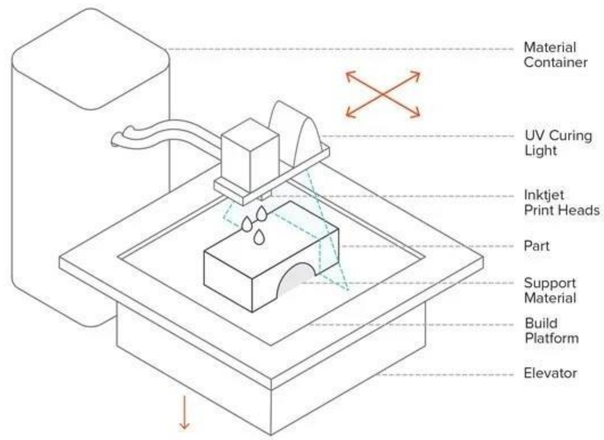


Figure 1.8: Illustration of Poly Jet printing process. [25]

Binder Jetting

Binder jetting is a rapid prototyping, and a 3D printing process in which a liquid binding solution is selectively deposited to join powder particles. The process consists in a multi-nozzle inkjet print head moving, layer by layer, the head uses a chemical binder solution onto the powder spread on the build platform, which solidifies the powder and create the layer according to the section. The bed is then moved down layer after layer until the object is finished. Different materials can be used as powder as metals, sands, polymers, hybrid and ceramics. [26]

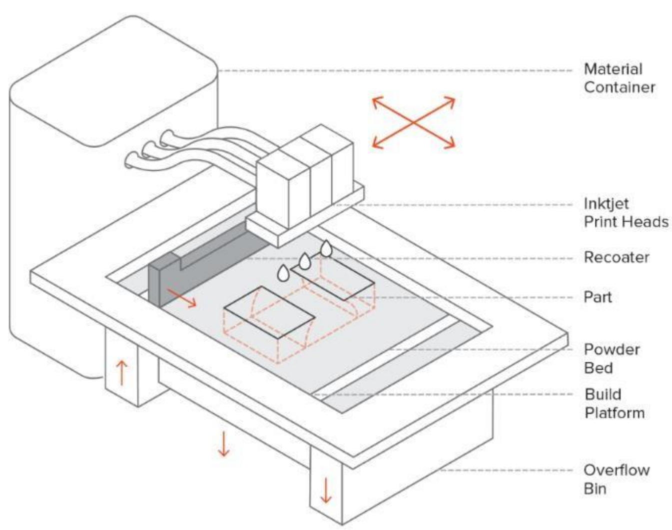


Figure 1.9: Illustration of Binder jetting printing process.[27]

Selective Laser Sintering (SLS)

The process is generally called 'powder bed fusion', It was developed at the University of Texas in Austin, by Carl Deckard and colleagues and it was patented in 1989. This technology uses a high-power source to bond together the particles of powder material. A laser beam is traded over the surface of a powder to selectively melt and fuse the particles together to form a layer of the object. The build platform is lowered down by one layer thickness in height and another layer of Thermoplastic powder is spread by a roller over the previous layer and the process is completed layer by layer.

This technique does not require any supports materials, the powder supports the overhanging parts of the object during the process. During the process the chamber temperature is kept below the melting degree of the powder to speed up the process. [17]

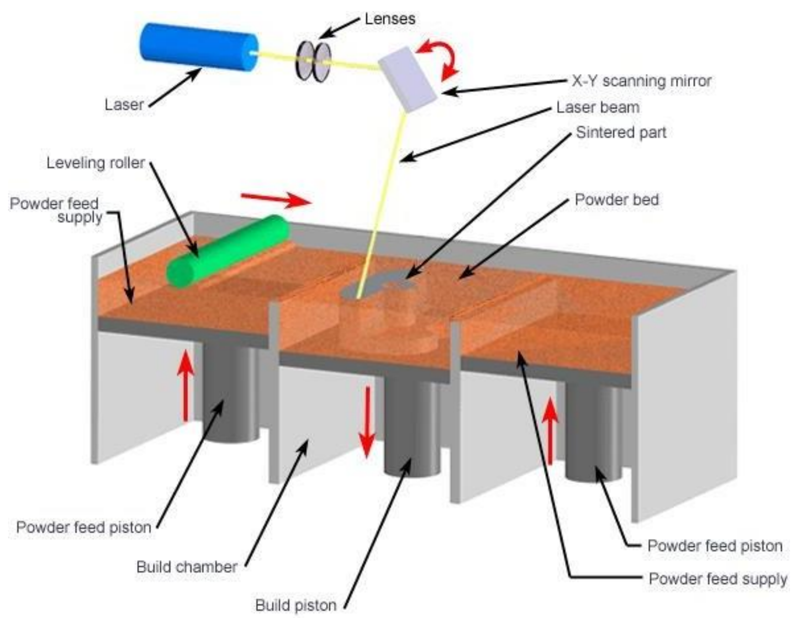


Figure 1.10: Illustration of selective laser sintering (SLS) printing process. [28]

Selective Laser Melting (SLM)

Selective Laser Melting is one of the powder bed fusion processes, Selective Laser Melting uses a high intensity laser beam to produce metal components from metallic powders. The process begins with a thin layer of powder deposited over a building plate and the laser beam melts and fuses the powder particles selectively, as dictated by the CAD data. After the first layer is finished, the second layer of powder is deposited over the first layer. The process is repeated until the final object is completely finished. [29]

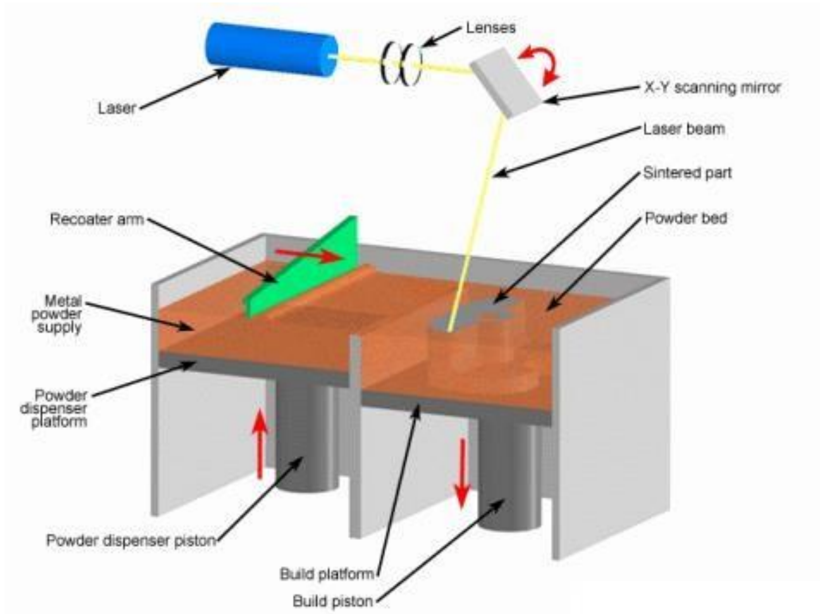


Figure 1.11: Illustration of selective laser melting (SLM) printing process.[30]

Comparison of 3D Printing Technologies

Table 1.1 below shows a comparison between different printing technologies.

Table 1.1: Comparison of 3D printing technologies.[31]

Technologies	SLA	DLP	FDM	Poly Jet	Binder jetting	SLS	SLM
Classification	Vat Polymerization	Vat Polymerization	Material extrusion	Material jetting	Binder jetting	Powder bed fusion	Powder bed fusion
Material used	Liquid photopolymer, Resin	Liquid photopolymer, Resin	Filaments, thermoplastic Metals	Metals, plastic	Ceramic, metal, plastic, sand	Metal, plastic, glass	Gold, silver, metal, steel
Precision	Very accurate	Very accurate	Good	Very accurate	Good	Very good	Good
Volumes (mm)	300*335*200		300*300*600	390*310*190	800*500*400	165*165*300	280*280*360
Surface quality	High	High	Low	High	Average	Average	Average
Domain of utilization	Jewelry Dentistry Modeling	Dentistry Medical Prototyping	Food industry Mechanical industry Aerospace	Prototyping, Medical	Food industry, mechanical industry	Prototyping, aerospace	Aeronautic, Automotive,

Price	Starts at 1200$	Starts at 2500$	Starts at 500$	Starts at 20000$	Starts at 20000$	Starts at 20000$	Starts at 500K$
Advantages	Great value. High accuracy.	Offers a brilliant, colorful, clear image. The final image seems sharper.	Fast. Low-cost consumer machines and materials.	Uses different materials at same time.	No need for support structures. Strong functional parts.	Strong functional parts. Design freedom No need for support structures.	Strong functional parts. Produces large objects.
disadvantages	Sensitive to long exposure to UV light	Sensitive to long exposure to UV light	Low accuracy Low details Limited design compatibility	Sensitive to long exposure to UV light	The material characteristics are not always suitable for structural parts	Post-Processing procedures are difficult.	Very high cost of machine and materials. Needs post-processing

Conclusion

In this chapter we covered the concept of additive manufacturing known as 3D printing and the process of 3D printing parts, we also talked about the background history of 3D printing. This chapter also reviews the different 3D printing technologies, and a comparison between these technologies.

2 CHAPTER II: Fused Deposition Modeling

Introduction

Fused Deposition Modeling, is an additive manufacturing technology, as other 3D printing technologies, FDM builds parts and objects by laying down material in layers. A filament is pulled from the spool into an extrusion nozzle. The flow of material and the movement path of the nozzle are controlled by numerically controlled system. The nozzle is heated to melt the material and the object is built by laying down multiple layers of the heated material that solidifies as soon as it is extruded. [23]

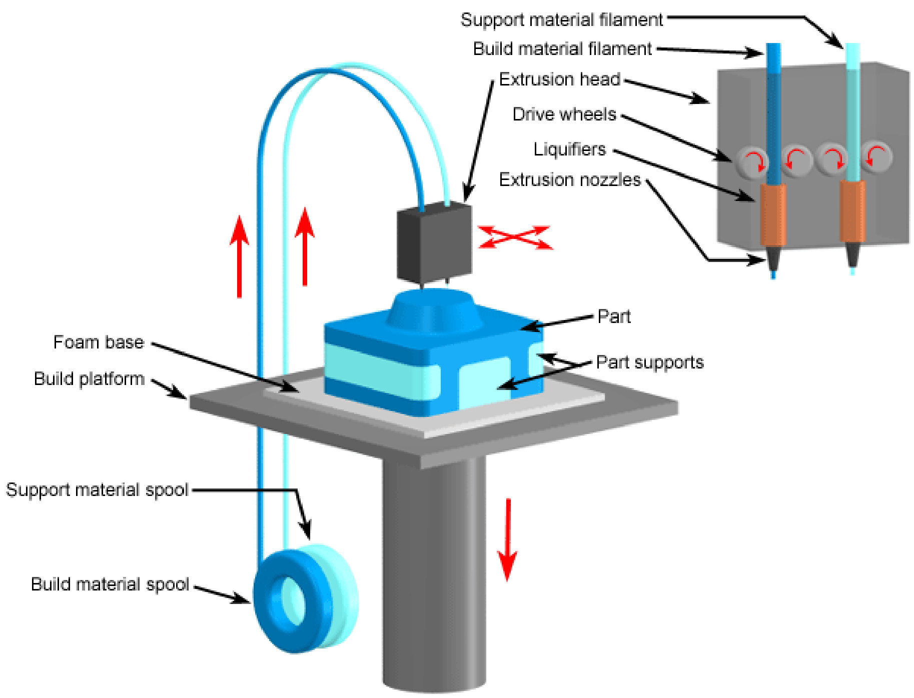


Figure 2.1: Schematic of FDM printing process. [32]

Most know type of mechanism used in 3D printers is: Cartesian.

Cartesian Printers

A regular cartesian 3D printer is based on the cartesian plane method of mapping out three dimensions, defining 3 axes X, Y and Z to coordinate a point. The X axis direction is from left to right, Y axis direction goes back and forth, Z axis is the vertical axis. Cartesian 3D printer has a square build platform and three rails, each rail corresponds to one of the cartesian plane axes. these 3D printers use small stepper motors that can move with great precision and accuracy. [4]

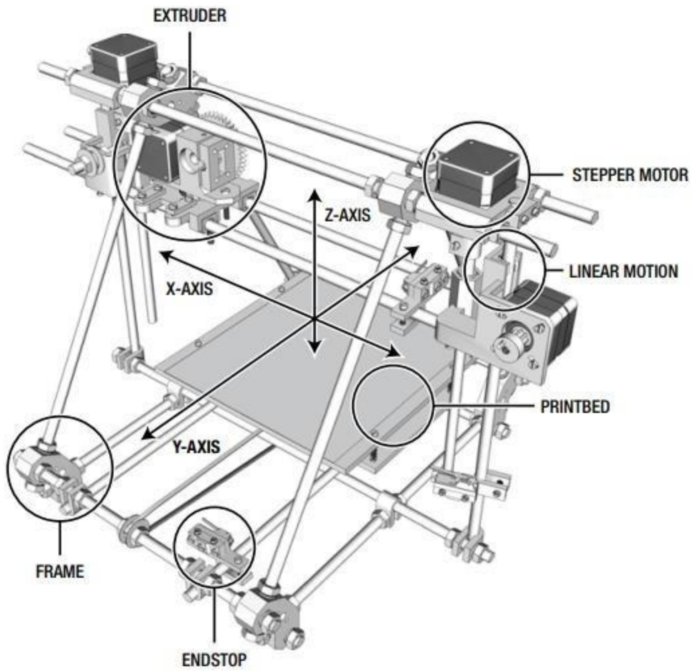


Figure 2.2.: Example of a cartesian 3D printer and its different components. [33]

Printer Components

In the section, we are going to cover the essential components of an FDM 3D printer.

Type of motor

Stepper motors are DC motors that have multiple coils allowing them to move in small increments referred to as steps. These coils are organized in groups called "phases". By empowering each phase in sequence, the motor will rotate, one step at a time. With a computer controlled stepping you can accomplish extremely precise positioning and/or speed control. For this reason, stepper motors are the motor of choice for many precision motion control applications.[34]

Figure 2.3: NEMA 17 3D printer stepper motor. [35]

Types of stepper motors

There are three types of steppers:

- Permanent magnet (PM).
- Variable reluctance (VR).
- Hybrid.

The permanent magnet (PM) stepper is small. So, it is used in applications where size is critical and the weight is small. PM steppers have good torque.

The variable reluctance (VR) stepper has better positioning resolution and precision; however, it has poor or low torque.

Hybrid steppers combine the best highlights of the other two types of steppers. They give good torque as well as the desirable high resolution and accuracy. The most generally used type is the hybrid stepper.[36]

Advantages of stepper motor

- ***Positioning***

Since steppers move in precise repeatable steps, they succeed in applications requiring precise positioning like 3D printers, CNC, Camera stages and X, Y Plotters. Some disk drives likewise use stepper motors to situate the read/compose head.

- ***Speed Control***

Precise increments of movement also allow for excellent control of rotational speed for process automation and robotics.

- ***Low Speed Torque***

Normal DC motors don't have very much torque at low speeds. A Stepper motor has maximum torque at low speeds, so they are a good choice for applications requiring low speed with high precision. [37]

NEMA Standard

NEMA is the abbreviation for “National Electrical Manufacturers Association” and comes from the U.S. association that represents the interests of the electrical engineering industry in the USA. It is responsible for the nationwide and, in cooperation with ISO, also worldwide standardization of electronic and electrical components. The majority of stepper motors suitable for 3D printing are assigned to the NEMA standardization. A description always bears the name “NEMA” followed by a combination of numbers and letters describing specifications about the stepper.[37]

Characteristics of Stepper motors

Stepper motors are available in many different shapes, sizes and styles, and may vary in gearing ratios, wiring setup, step count, and shaft styles. Choosing an appropriate stepper motor for a desired mission depends on these characteristics.

- ***Motor Size***

Stepper motors are available in different sizes, with most usually too powerful when you have a simple 3D printer that doesn't require a lot of force.

The NEMA 17 size, is the most common stepper motor for 3D printers, it is suitable for use in the vast majority of 3D printers. It's highly recommended due to: low noise, long lifetime, high performance and no loose steps.[38]

- ***Step Count***

The precision you might need in terms of positioning resolution or movement is accomplished thanks to stepping count. Step count basically means the number of steps for each revolution, and it usually ranges between 4 to 400 steps. The most step counts are 24, and 200, with the 200 steps for each resolution equivalent to 1.8 degrees per step.

The trade-off for high resolution is speed and torque. High step count motors top-out at lower RPMs than similar size. And the higher step-rates needed to turn these motors results in lower torque than a similar size low-step-count motor at similar speeds.[37]

- ***Torque Rating***

The toque rating on a stepper motor is an indication of the amount of power a motor can generate. larger motors produce extra toque considering they boast an advanced capacity to generate the wished power.

For 3D printing, a torque range of 40 to 55 N.cm is sufficient, being the standard level for stepper motors. These motors provide a compromise between torque and speed, being suitable for both, small 3D printers which does not require a great torque, and large 3D printers which need a great torque.[37]

Types of Transmission

The components that permit to convert the rotational movements of the motor into linear motion are referred to as the transmission. There are two transmission setups commonly used in 3D printers: belt-driven and leadscrew-driven. While these two sorts of transmissions are generally straightforward, little changes can bring significant differences in 3D printer paces and accuracy.

Belt-driven transmission

In belt-driven transmission, an elastic belt with high-tensile fibers is connected to both ends of a carriage in a closed loop. A timing pulley is inserted into this loop. When the motor turns the timing pulley and the belt moves. The timing pulley must have the same tooth profile as the timing belt for the assembly coupling to work properly. The timing pulley and belt arrive in different widths, teeth profiles, and pitches (the distance between consecutive teeth). [39]

Figure 2.4: Belt and pulley.[40]

Leadscrew-driven transmission

Another transmission system used in 3D printers is leadscrews. A leadscrew is a type of mechanical power transmission that converts rotational motion into linear motion. Its operation relies on the sliding of the screw shaft and the nut threads with no ball bearings between them. The screw shaft and the nut are directly moving against each.

The components of a leadscrew are:

- ***Screw Shaft***

The screw shaft is a cylindrical rod that has a single or series of grooves running helically around its length; this is referred to as the external thread.

- ***Thread***

The thread is the structure responsible for converting rotational motion into linear motion as the screw shaft and the nut slide with each other.

- ***Nut***

The lead screw nut is a cylindrical section that has an internal thread that matches the external thread of the screw shaft.

Overall, leadscrew-based transmissions are more accurate than belts, but are slower and more expensive. [41]

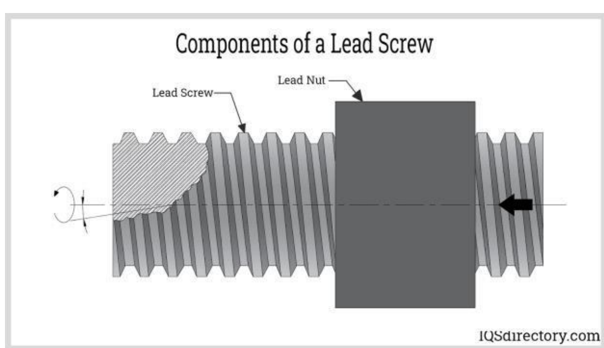


Figure 2.5: Leadscrew components.[41]

Build platform

Build platform, or print bed is the surface that your 3D prints are created on. Some printers have a heated platform to allow you to print with more materials. The platform of some printers can move in one direction or two. For cartesian printers, build platform come in a square shape and for Delta printers in circular or hex shape. [42]

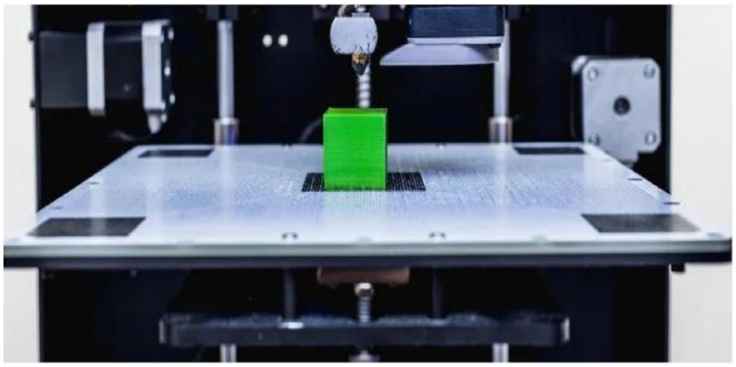


Figure 2.6: Build platform of 3D printer. [43]

Extruder

One of the main components of a fused deposition modeling 3D printer is the extruder.

The extruder is the part of the printer that pulls, melts and moves the filament. The extruder has several parts: extruder drive mechanism (Cold end), which is a motor and a mechanism that pushes the filament into the hot end. The hot end in turn is comprised of a heater, a nozzle, and a sensor. [42]

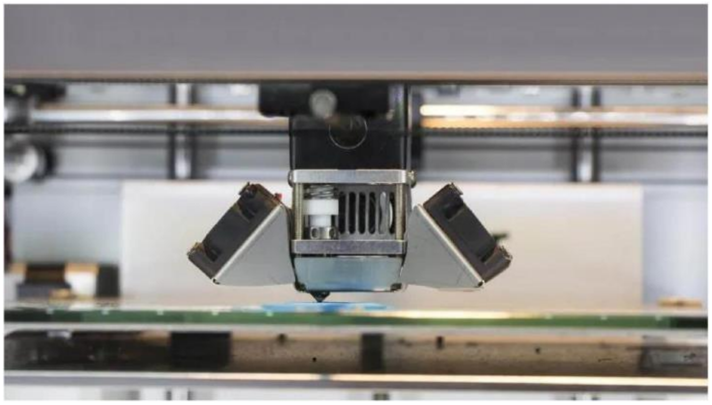


Figure 2.7: Extruder of a 3D printer. [44]

The extruder assembly can be seen as two assemblies: The cold end, and the hot end.

Cold end

The cold end is the cold part in the upper portion of the 3D printer extruder. At this point, there is no heating of the filament. This is just the part with the motor and gearing, pushing the 3D printer filament into the hot end.

Hot end

The hot end is the part where the filament melts from solid to liquid, while extruded on the building plate.

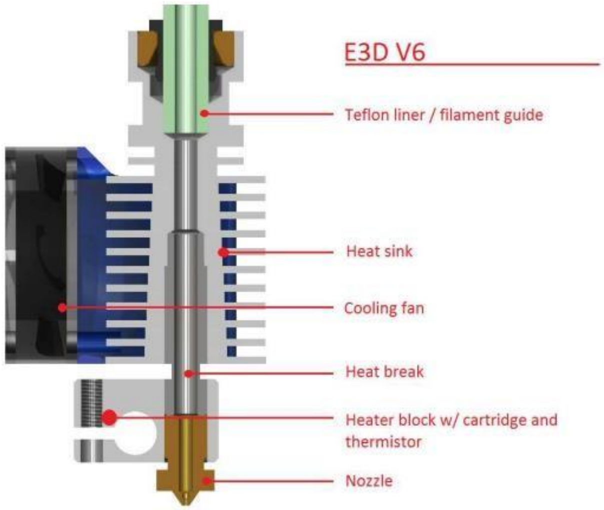


Figure 2.8: Illustration of the E3D V6 extruder.[45]

Types of Extruding Systems

Within extruders there are two types depending on the type of the drive system: Direct and Bowden.

- ***Direct drive extruder***

In a direct drive system, the extruder is mounted on the printhead and so pushes the filament directly into the hot end. This method is helpful for many reasons, but it also has some downsides.

- ***Bowden extruder:***

In a Bowden setup, the extruder is mounted on the printer's frame. It pushes and pulls filament through a long PTFE tube (called a Bowden tube) and into the hot end.[46]

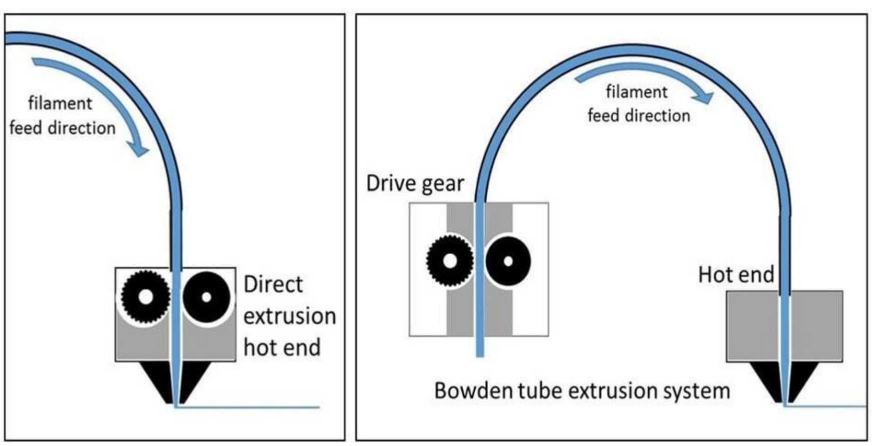


Figure 2.9: Schema of the Direct and Bowden extruder.[46]

Comparison of extruding systems

Table below shows the advantages and disadvantages of each system:

Table 2.1: Comparison between direct drive system and Bowden extruder.[46]

	Advantages	**Disadvantages**
Direct drive system	- Reliable extrusion: In direct drive. The extruder is mounted on the printhead, so the filament is pushed to the nozzle easily, resulting in fewer extrusion-related issues. - Better retraction: Because the extruder is close to the nozzle, it can more easilyretract filament. - Less-powerful motor: Due to the short distance between the extruder and the nozzle, less torque from the motor is required to push the filament. - Wider range of filaments: Direct drive extruder is considered to be more compatible with a wider range of filaments.	- Vibrations: With the extruder mounted to the printhead, the weight is added. This extra weight adds speed constraints, causing more wobble and possibly a loss of accuracy in X and Y movements. - Cumbersome maintenance: In some direct drive setups, the extruder being mounted to the printhead can make accessing certain parts for maintenance more difficult.
Bowden extruder system	- Cleaner movements: In Bowden setup, the extruder is mounted on the printer's frame resulting to less weight on the carriage, leading to faster, quieter, and higher quality prints. - Larger build volume: a Bowden setup can allow for a smaller printhead carriage, which, in turn, allows for increased build volume.	- More powerful motor: Because the extruder must push and pull filament through a long tube, a certain amount of friction exists between the two. This friction calls for more torque to adequately control the filament. - Slower response time: Friction in the Bowden tube results to a delay between extruder and nozzle. These extruders therefore require faster acceleration in extrusion and retraction to deposit properly and avoid stringing. - Material complications: Some flexible and abrasive filaments can easily bind or wear in Bowden tubes.

The Nozzle

The nozzle is a necessary part of the hot end. It is the most important piece in a 3D printer. The nozzle is the mechanical piece of the 3D printer that extrudes the melted filament on the build platform.

One of the great flexibilities in desktop FDM 3D printers is the possibility to change nozzles to suit your printing purpose. There is a lot of choices when purchasing a nozzle for a 3D printer. When selecting a nozzle for a 3D printer 2 characteristics need to be taken into consideration: material, and inner diameter. [46]

Nozzle Material:

All nozzles produced today are made of some kind of metal due to its relatively high thermal conductivity and tight fabrication tolerances. different metals are used in nozzle fabrication. Each has unique properties, which influence the 3D printing process in different ways.

Most known 3D printer nozzle material are: Brass, Stainless steel and hardened steel.

- ***Brass***

Brass is the standard 3D printer nozzle material. This copper-zinc alloy offers great heat transfer at a relatively low cost, making them the first choice for 3D printing beginners. However brass nozzles are the softest, they are highly vulnerable to wear, and can deteriorate externally from every bump or scrape that might happen during the 3D printing process.[47]

Characteristics:

- High thermal conductivity.
- Resistant to corrosion.
- Relatively soft.
- Low abrasion resistance.
- Maximum temperature: 300 °C.
- Best used with: Non-abrasive filaments such as PLA, ABS, PETG, Nylon, and TPE.

- ***Stainless steel***

Stainless steel is another popular material used in nozzles, harder than brass nozzle and they have a higher abrasion resistance. Stainless steel nozzles allow for the long-term printing of filaments enriched with hard particles like carbon fiber and metal without the risk of the 3D printer nozzle eroding and print performance suffering. Unlike brass nozzles, stainless steel nozzles have a poor thermal conductivity.[46]

Characteristics:

- Low thermal conductivity.
- Resistant to corrosion.
- Relatively hard.
- High abrasion resistance.

- Maximum temperature: 500 °C.
- Best used with: Non-abrasive filaments and light use of abrasive materials such as NylonX, carbon fiber, glow-in-the-dark, metal-filled, wood-filled, and ceramic-filled filaments.

- ***Hardened Steel***

Hardened steel nozzles are a major upgrade, as they're tough enough for frequent use of abrasive materials and offer literally years of use without replacement. However, this material has an even lower thermal conductivity than the previous two materials and takes longer to achieve the target temperature. [47]

Characteristics:

- Low thermal conductivity.
- Resistant to corrosion.
- Relatively hard.
- Maximum temperature: 500 °C.
- Best used with: All materials, including heavy use of abrasive materials.

Figure 2.10: Nozzles of different materials and sizes.[47]

Nozzle Inner Diameter

The second and the most delicate nozzle characteristic to consider is the inner bore diameter. The nozzle diameter influences how fine a level of detail you can go for your prints, the widths of the lines, and the layer heights as well.

Nozzle diameters generally range from 0.1 mm to 1.0 mm. This gives the 3D printer user a great degree of flexibility, and many options to choose from. For example, when printing with a 0.15mm 3D printer nozzle versus a standard 0.4mm nozzle, there is the obvious advantage of being able to achieve higher X- and Y-axis resolution, however it comes with a reduction in print speed and an increased possibility of clogging since the inner diameter is so small. [47]

Nozzles with larger diameters will extrude more material through thicker layer heights and widths. In addition, printing with large 3D printer nozzles minimize the printing time, making them suitable for fast prototyping where fine surface detail is a low priority.

Also, the 3D printer nozzle diameter influences the layer height range. The maximum layer height values should not exceed 80% of the nozzle diameter. For example, a 0.4-mm nozzle has a recommended maximum layer height of 0.32 mm.

In the end, it's all about balancing how much filament is extruded and how fast. The absolute standard in 3D printers today is the 0.4-mm nozzle, which is found in almost all popular machines. This diameter provides a great balance between speed and precision. [47]

Figure 2.11: Nozzles of different inner diameters.[47]

Electronics

3D printers are controlled by microcontroller to perform calculations, reading sensors and to translate G-codes into signals to control stepper motors. Stepper motors use a special board called "stepper driver". Some electronics come with the stepper drivers integrated, and others use pluggable daughterboards. [48]

Types of Filaments

The materials used in the FDM process are basically thermoplastic in the form of filament, and they are considered the lowest cost materials used in 3d printing.

Polylactic acid (PLA)

PLA is a common type of filaments materials used in 3d printing, PLA is good for the environment, easy for utilization and it have a good stability when printing large size models. The printing temperature of the nozzle is 180~200°C, and the temperature of the heating plate is 60~70°C. [49]

Acrylonitrile butadiene styrene (ABS)

ABS is another common type of filament materials used in 3d printing, ABS plastic is a polymer composed of: monomers, acrylonitrile, butadiene and styrene. ABS filament is widely used in manufacturing due to having good heat resistance and good mechanical properties. The nozzle printing temperature is 210~240°C and heating plate temperature is above 80°C. [50]

Polycarbonate (PC)

PC material is known for its strong mechanical properties, high glass transition temperature, and transparency. They are also amorphous like ABS. Alternatively; polycarbonates are susceptible to humidity and have high print temperatures. PC can print functional prototypes and has been employed in the automotive and aerospace industries. The extrusion temperature for Polycarbonate is very high 260~310 °C. [51]

Nylon

Nylon is a strong printing material, it has a good flexibility and high physical and chemical resistance, and suitable for making functional part like gears. The nozzle temperature for nylon is around 240~270 °C, and the build platform temperature above 90°C. Drying nylon filament before printing with it gives better results and quality. [52]

High impact polystyrene (HIPS)

HIPS is a biodegradable polymer that is a low strength thermoplastic with good machining characteristics. The advantages of using this FFF filament are its good flow characteristics, impact resistance, and low cost. However, it is prone to wear and it requires a high printing extrusion temperature around 220~ 270 °C, and a heated build platform above 90°C. [52]

The filament material for different applications should be selected based on the properties of materials while considering the purpose or the functionality of the printed parts.

Table 1.2 summarize the sources, advantages, dis-advantages, printing temperature of the discussed filaments.

Table 2.2: Classification of filament materials.[51]

Material	Source	Advantages	Dis-advantages	Printing temperature
PLA	Plant starch	Biodegradable, does not warp, inexpensive	Poor mechanical properties, rough texture, brittle	180~200°C,
ABS	Petroleum	Good impact resistance, toughness, inexpensive	Prone to warp, produce unpleasant gases	210~ 240°C
PC	Bisphenol	Strong and flexible, good optical properties	High print temperature, absorb moisture	260~ 310 °C
Nylon	Crude oil	Good mechanical Properties, in-expensive, wear resistance, heat resistance	Prone to warp, high printing temperature	240~ 270 °C,
HIPS	Petroleum	Dissolvability, high impact resistance, biodegradable	Prone to warp, heated build platform required, emits styrene while printing	220~ 270 °C

The cost is a vital factor for filament material selection due to budget limitations. The price of filament depends on filament preparation steps, the location of plants, labor cost, the grade of materials, and other expenses related to raw materials, productions, and logistics.

Table 1.3 give approximate prices of different filament materials.

Table 2.3: Prices of different filament materials.[51]

Material	PLA	ABS	PC	Nylon	HIPS
Price per Kg	15-25$	17-25$	30-70$	30-70$	20-60$

Printing Parameters (Slicing Parameters)

Layer Height

Layer height is the height of each layer that is extruded by the printer. Layer height plays a few roles within the context of 3d printing. The higher the layer height the quicker it is printed, however, that effects the strength and aesthetics of the print model. One thing to note is layer height is not the same as resolution. Resolution determines the level of detail of an object. However, layer height does affect resolution. Layer height is also determined by the size of the nozzle you are using therefore that needs to be taken into consideration. [52]

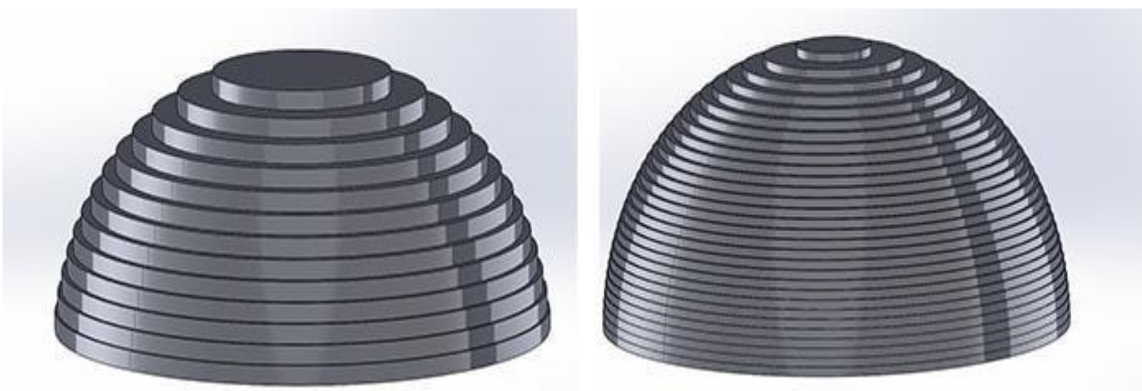


Figure 2.12: Example of an object build with Two different layer heights. [53]

Infill

The word infill refers to the structure printed inside the object. FFF parts usually are not printed completely solid, because that utilizes so much material and takes much longer time to print a solid object. For that, slicing software creates an internal support called infill inside the parts, to minimize filament use and time of manufacturing. Infill percentage is a parameter selected depending on total weight of the piece, used material, resistance to be achieved, printing time and sometimes decorative features (some objects are built transparent). The geometrical pattern of the infill can be also chosen. Some of them are more resistant than others, the Commonly infill geometries used are: triangular, rectangular and honeycomb. Another purpose of infill, is to control shrinkage. Infill patterns are sparse enough to stretch axially as they shrink radially so that they don't pull the perimeters inward as they cool and shrink. This can make 3D-printed parts maintain dimensional accuracy. [3]

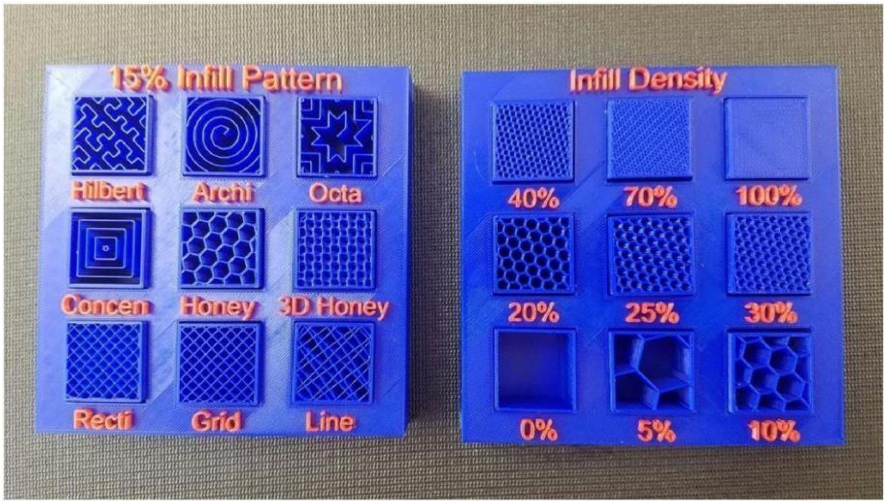


Figure 2.13: Different percentage and patterns of infill. [54]

Perimeter

Each layer of the shell is called a perimeter. The perimeter thickness can be one pass or more depending on the object. For simple geometric shapes a single wall thickness would be good, and for complex geometrics two or more perimeter. Adding more perimeters can improve the rigidity of the outside of the object. [33]

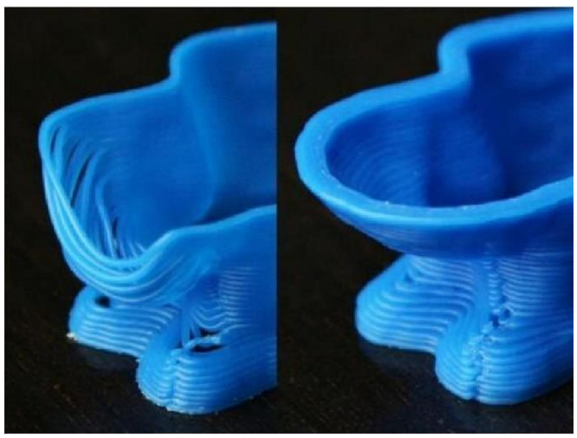


Figure 2.14: The difference of using multiple wall thickness. One wall thickness on the left and 3 on the right. [33]

Support Structures

Support structures are not part of the product built, but they are necessary in the printing process to create the product successfully. Support structures are added for overhanging parts of the product, and zones that are shallower the 45°degree. Usually, Support structures are done using the same material as the product, and for 3D printers that have two extrude nozzles use another material for supports. Slicing software generates support structures automatically, and it is best to avoid or minimize supports if possible because it effects the surface it is in contact with and damages it, it is time consuming to remove them. [3]

Figure 2.15: 3D printed object with support structures. [55]

Raft:

A raft as the name suggests is a flat piece that is printed and the main object rests on. This offers better adhesion but requires more post processing.

Post-Processing

After 3D printing objects, many of them requires some post-processing to remove support structures or marks that are left, or to smooth the surface. Post-processing can be done using different techniques as: Sanding, polishing or coating. [31]

Conclusion

First record of FDM 3D printing technology goes back to the early 90s. However, 2009 was the year when the patent expired, which cause a great spread of the technology in the world making it available for public and individuals, FDM technology is considered the most common technology, due to its low-cost machines and materials, being easy to use, and the ability to produce complex geometries.

FDM 3D printers as other printers have its own limitation in use, the layer-by-layer method used in 3d printers causes the objects printed to likely have visible layer lines, and weak structure if the layer thickness is high. Another obstacle for 3d printer is the build time, building objects layer by layer consume a lot of time, depending on the volume of the object printed, printing small objects take from 6 to 24 hours, and for big products it may take to several days. The time for printing can also increase depending on the infill percentage, most printers create parts with 20% infill. Producing strong products demands high infill percentage which leads to an increase in the build time and the material used.

Most 3d printing technologies requires adding support structure during the printing process. For FDM 3D printer support structure is a must to build overhanging parts. Support structure causes to increase build time, and material used. Building support structure causes another problem: the surface roughness and post processing process. Removing support structure, usually leave marks and impurities on the surface of the product, which requires post-processing, that itself consume more time.

One way to improve FDM 3D printers, and minimize the need for support structure is by adding extra movements axes “Implementation of 5-axis 3D printer”. Having two additional rotational axes on the nozzle or the build platform, allows the creation of more complex geometries and fully eliminate support structure. These axes also enable the possibility to deposit material in more than one direction which give much better surface finish and add more strength to the product.

3 CHAPTER III: 5-Axes System

3D Printing (3-axis) Problems

Additive manufacturing (AM) techniques, and in particular FDM 3D printing, have become very popular for fabricating physical prototypes in various industries owing to the ease of constructing complex geometries on demand, and the affordable prices of the technology. However, FDM technology still has few downsides and limitations, due to depositing material layer-by-layer in a fixed direction. Usually, the finished products often exhibit unfavorable characteristics such as visible layers, rough surface finishes, uneven mechanical properties and the inclusion of support material for overhanging parts. To overcome these limitations and extend the abilities of 3D printing, different strategies of depositing materials in conformal layers have been investigated. [56]

Introduction to 5-axis 3D Printing

If you're familiar with Computer numerical control (CNC) machines, you may have already heard of 5-axes CNC machines. Although 5-axes machines have been used in subtractive manufacturing for quite some time, it is new for additive manufacturing.

Researchers have employed 5 degree of freedom robotic arms to deposit the materials in curved layers, it's something that can be addressed by adding tilt and rotational axes to the printer. Unlike standard 3D printers, which only use the X-, Y-, and Z-axes, 5-axes printers use 2 more:

- B: Rotation in the Y-axis.
- C: Rotation in the Z-axis.
- 6-Axes printers, which take advantage of the "A-axis" rotation in the X-axis – also exist. Though, these are fairly rare because there are actually very few advantages brought by the sixth axes. [57]

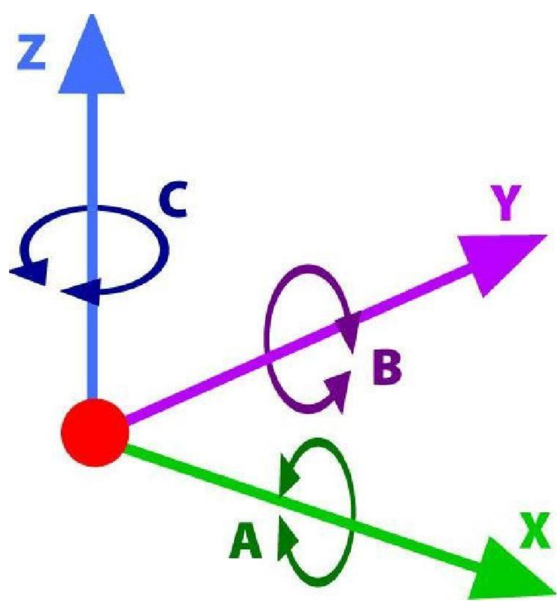


Figure 3.1: Sketch for *6 axes. [57]*

5-axes 3D printing offers a variety of advantages over the traditional 3-axis method, including support-less printing, curved layer deposition that reinforces the mechanical properties of the 3D printed object against multi-directional loads, conformal surface finishes, direct printing of functional materials on conformal surfaces, and less post-processing for the printed objects.

However, 5-axes 3D printing is currently rare in the market and it is inaccessible to many individuals due to high costs and technical complexities, the limited GUI support for conformal slicers creates an additional barrier for users., and the machines take up significant amounts of space and are often not suitable for personal fabrication. [56]

5-axis Configurations:

The 5-axes CNC machine is one of the most used multi axis systems, and the handling of the five axes can vary across machines and manufacturers.

The different types of 5-axes systems vary in where the extra two axes are placed, they can both be placed on the rotating head or on the platform or one in each:

Table/Table:

Table/Table machines are the most well-known configurations used in multi-axis machines. In a table/table configuration all the rotation are done with the building platform (the head does not rotate), meaning that the table is rotating around the X, Y, and Z axes. For this system the machine's rotary devices should be equipped to handle the weight of printed object, while it's attached to the table during the printing process. [58]

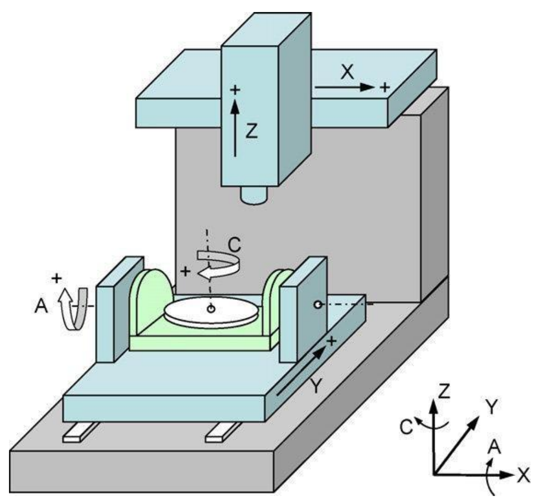


Figure 3.2: Table/Table configuration. [59]

Head/Head:

As the name implies in a Head/Head machine every one of the rotational movements are executed by the head of the machine. These machines can be both vertical and horizontal. When both of the rotational axes are in the head changing the entire head is conceivable. This makes it conceivable to accomplish various ways of behaving in view of the design of the head. [58]

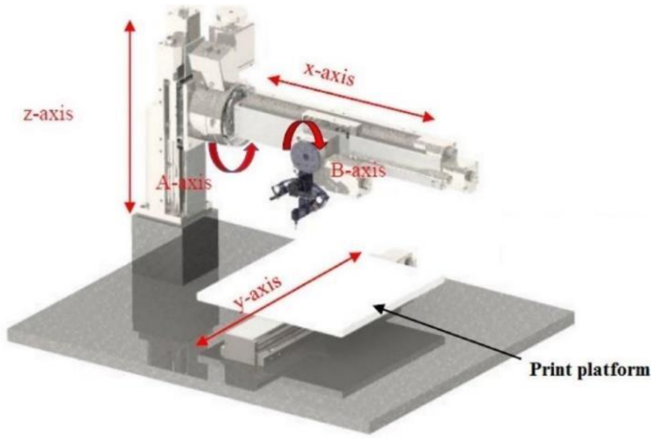


Figure 3.3: Head/Head Configuration. [60]

Head/Table:

Head/Table machines are a blend of the two past designs. Head/Table machines have one rotational axis where the head is appended, and one at the table of the machine. [58]

Classification of 5-axes Configuration:

Each of the listed 5-axes configuration above has its advantages and disadvantages.

Table 04 summarize the advantages and disadvantages of this configuration.

Table 3.1: Classification of 5-axes configuration.

	Advantages	**Disadvantages**
Table/Table	- Have more rotational degrees. - Easy to envision the - table/table system can easily be built larger as long the weight is compensated with stronger motors.	- Less suited for heavy objects.
Head/Head	- Can withstand printing heavy pieces.	- Must take into consideration the length of the head as it tilts back and forth. - System needs to be attached at the head to work properly, making it harder to assemble the design. - The weight of motors is added to X, and Z axis.

Head/Table	- Have more versatile than table/table and head/head systems.	- system needs to be attached at the head to work properly, making it harder to assemble the design. The weight of motors is added to X or Z axis.

3D Printing Softwares:

In order to create a user friendly 5-axes 3D printer, a software package is necessary to allow the user to simply input a 3D object file and generate instruction for the 5-axes printer. There are many software's to help the user in the printing process, the most common and accessible ones are:

Cura:

Cura is an open-source slicing software created by Ultimaker, it could be taken as a general standard since it is compatible with most 3D printers, it has a clear, easy to use interface with most important 3D print settings. It can be easily extended via a plugin system, for which plenty of handy plugins are available. Being the first choice for many beginner users, a quality profile for different 3D printer come along the software, making it easy to get started right away. This slicing program is regularly updated and refined to the last development of 3D printing. [61]

PrusaSlicer:

PrusaSlicer is an open-source slicing software created by Prusa research based on Slic3r software. The first appearance of the software was in 2016 under the name Slic3r PE (Prusa Edition), which was released via GitHub. In May 2019 Prusa renamed to its current name. PrusaSlicer become very common for users due to its constantly develop and evolve, including customizable support structures, multi-material support, and smooth variable layer height functions. PrusaSlicer can be used to slice models for both FDM and resin printers and has various modes that allow you to edit settings based on your skill level, with expert opening up a huge list of things to customize. [62]

Simplify3D:

Simplify3D is very powerful slicing software used in the printing process. This software not only slice your 3D model into layers but also corrects the problems in the model and enhance the quality of 3D prints. It allows you to preview the print process on screen or jump to a particular section, it also can show the travel moves and the toolhead movements. Simplify3D software is compatible with most the 3D printers and it is very fast comparable to other software's. [63]

5 Axis Slicer:

5 Axis Slicer is a slicing software specifically for machines with 5 axis or more. 5 Axis Slicer slicing process works as the other slicing Softwares. The only difference is that this software allows layer generation for curved layers and printing without support. [64]

Conclusion

In this chapter, we presented the possible configuration for a 5-axes system, the advantages and disadvantages of each configuration, and we described the slicing software used to generate the G-code for 3D printers.

4 CHAPTER IV: Sizing and Design of The Printer

Introduction

This chapter will cover the scope statement of the 3D printer, a possible solution to overcome the support structure problem for FDM 3D printers, how to choose the components for your 3D printer, and last is a proposed design for the envisaged FDM 3D printer.

Statement of Work

- **Context and issues:**

3D printing or additive manufacturing is a process of making three-dimensional solid objects from a digital file. A 3D printed object is created by laying down successive layers of material until the object is completed.

Today the FDM printers are the most popular 3D printers. This is most likely because the FDM 3D printers are consumer-friendly, can create rigid parts, and are low-cost. FDM printers still have some weaknesses including accuracy and their inability to print overhanging structures without support. 5-axes 3D printing offers a variety of advantages over the traditional 3-axis method, including support-less printing, and curved layer deposition.

- **The Objective:**

The objective of this thesis is to design and realization of a 5-axes FDM 3D printer capable of creating overhanging parts without support structures under a budget of 150000 DA.

- **Functional Description:**

  - **Main function: Printing 3D objects by FDM process.**
    Description: 3D printing allows you to produce complex objects from a 3D digital file.
  - **Sub-function: Extrusion speed.**
    Description: The speed at which plastic is pushed out is controlled by the combination of this speed and the specified layer height and extrusion width according to a calculation of volume.
    The extrusion speed varies from 0.1 to 120 mm/min.
  - **Sub-function: Print-head.**
    Description: The nozzle is the mechanical part of the 3D printer that extrudes the filament. The three major characteristics to take into consideration when choosing a nozzle are: its size, material, and inner diameter.
    The designed machine will have one nozzle.
  - **Sub-function: Build volume.**
    Description: The build volume is essentially the dimensions of the space into which 3D prints can be produced by a specific machine model. Typically, they are stated in the cartesian form, with values for each of the X, Y, and Z axes.
    The designed machine will print objects of a volume of Ø90*360.

- **Sub-function: Motors**
  Description: For 3D printers, stepper motors are used to provide movements on the X, Y, Z, B, C, and extruder. The X, Y, Z axes and extruder will be using the same stepper motor. For the B, and C axes a different, more accurate stepper motor will be used.
- **Sub-function: Transmission**
  Description: Electrical motors turn electricity into rotational movement. The components that allow rotation of the motor to move the carriage linearly are collectively referred to as the transmission. There are two transmission setups commonly used in 3D printing: Belt-Driven (for X, Y, B, and C axes) and Lead Screw-Driven (For Z-axis).
- **Sub-function: Slicers**
  Description: A 3D model that was created on a Computer-Aided Design (CAD) program, like Fusion 360 or Solidworks, cannot be sent directly to your 3D printer. There are a couple of intermediate steps that are handled by a program known as a Slicer. The three biggest Slicers currently available are Simplify3D, Cura, and Slic3r, with the last two being free.
- **Sub-function: Electronics**
  Description: The motherboard job is to enact the code from the 3D printer software to produce a 3D printed object. Plus, all the electrical components will be connected to the printer motherboard.

Technical Solution

4.3.1 Choosing 5-axis configuration

5-axes systems consist of three main configurations which are: table/table, head/head and table/head (see section 3.3)

In this project it was decided to use a table/table configuration, the reasons for that are:

- Table/Table configuration have more rotational degrees.
- The Table/Table system can easily be built larger as long the weight is compensated with stronger motors.
- The head/head system or a head/table system needs to be compact at the head to work properly. This will make the system harder to assemble and redesign.
- The Table/Table configuration is not suited for printing heavy parts, but since we are printing with plastics, that will not be a problem.

Sizing

Choosing the right stepper motor

For the case of our 5-axes 3D printer we are using 7 stepper motors:

Based on the characteristics of stepper motors mentioned in section 2.4.1, we are using two different stepper motors.

For the X, Y, Z axes and the extruder, the stepper 17HS041801 is used, since the 17HS041801 stepper motor achieve all the needed characteristics of a 3D printer Stepper motor.

Characteristics of the 17HS041801 stepper are:

- Shaft Size: 5mm
- Torque: 54 N.cm
- Step Angle: 1.8°
- Peak Current: 1.68A/phase
- M3 Mounting Holes
- 4 Wire Bi-Polar
- 12-24VDC (Recommended)

For the C and B axes, the used stepper motor is: NEMA 17 "42BYGHM809" which has the following Features:

- Shaft Size: 5mm
- Torque: 48 N.cm
- Step Angle: 0.9°
- Peak Current: 1.7A/phase
- 2 Phase
- Rated Voltage: 3V

For the B and C-axis we used the NEMA 17 "42BYGHM809" because this motor has 400 steps, meaning we can print parts of higher resolution and better surface finish, and we can have more position precession.

Choosing the type of transmission

- **Choosing the belt**

The belt driven transmission system is often used for providing motion to the X and Y-axes in 3D printers.

For 3D printing, the GT tooth profile is optimized to prevent backlash or lost movement when motor reverses the direction of the pulley. The most widely recognized belt width and teeth pitch for 3D printing are 6mm and 2mm, respectively. GT belts with 2mm pitch are called GT2 belts.

The timing pulley comes arrives in a wide range of diameters. The perimeter of a timing pulley is usually reported by the number of teeth. In 3D printing where high carriage speeds are common a 16Tor 20T pulley is used. Using too large of a pulley can be detrimental to the resolution of the 3D printer. [39]

- **Choosing the leadscrew**

For the leadscrew-based transmissions are used to provide the movements for the Z-axis in 3D printers, the reason for that is because that they are unlikely to spin on their own, which means if the printer unexpectedly loses power, the carriage is not going to drop, and they are rarely used for the X- or Y-axis because they are prone to severe backlash leading to position inaccuracy.[62]

While there are different varieties of leadscrews, the most used are trapezoidal (ACME) leadscrews. The most commonly deployed lead screws in 3D printer builds have: 4 starts, 2mm pitch, 8mm Lead (8mm lead means that for every rotation of the screw, the carriage will move 8mm).

Type of extruder:

The designed printer uses a direct drive system for the many advantages of this system over the Bowden extruder system mentioned in section 2.4.4.

Design of the 3D Printer

Introduction

The design of any machine or product is done by using a computer-aided design software (CAD). Computer-aided design software is used to aid in the creation, modification, analysis, or optimization of a design.

CAD software is widely used in the mechanical industries to model and evaluate the behavior of materials, the assembly capacity and the manufacture of parts.

Among the existing computer-aided design software, the design is done using SolidWorks because we have worked with the most during our training at school, so we got used to use it.

Printer design:

In this part, we will detail the components of the 3D printer by presenting models of parts and assemblies using the SolidWorks software.

Frame:

The frame of the 3D printer is designed with aluminum extrusion rails called V-slots. We used extruded aluminum because it possesses a superior strength-to-weight ratio than steel, it is strong enough to handle most structural design applications. Also, it is affordable, and easy to build with. The dimensions of the frame are 400mm*400mm*600mm.

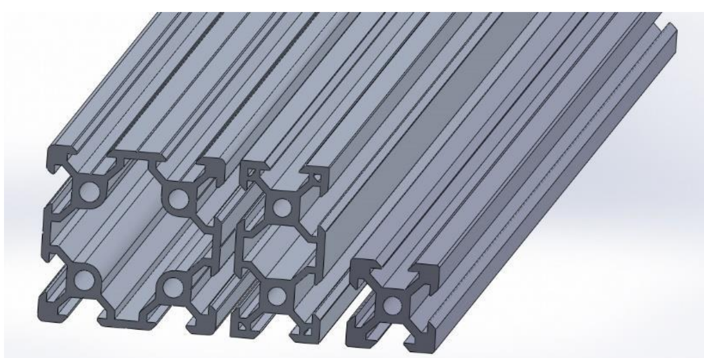


Figure 4.1: V-slots profiles used to build the frame.

To fix the aluminum extrusion rails together we used corner plates and corner brackets with screw and T-nuts

Figure 4.2: Corner plates.

Figure 4.3: Frame of the 3D printer

Y-axis:

The direction of the Y-axis goes backward and forward. The Y-axis uses 2 linear rods to guide of the movements. The rods are supported on the two sides by shaft supports.

The Y-axis is controlled by a belt driven system appended to a stepper motor with pulley.

- ***Linear rod:***

Linear rod is Commonly made from steel and chrome plated for enhanced hardness, they come in a variety of different lengths and diameters. For the design of this printer, we used rods with a diameter of 8mm.

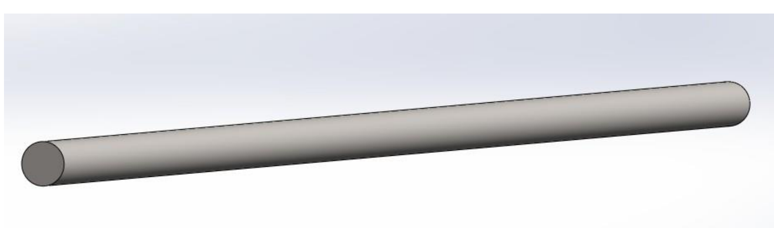


Figure 4.4: 8mm linear rod.

- ***Shaft support:***

They provide an embedding connection and support the linear rods in translation.

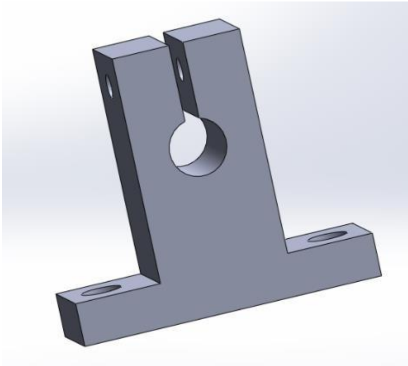


Figure 4.5: Shaft support with 8mm diameter.

- ***Stepper motor:***

To provide movements for the Y-axis, we used the NEMA 17 stepper motor “1704HS168A”.

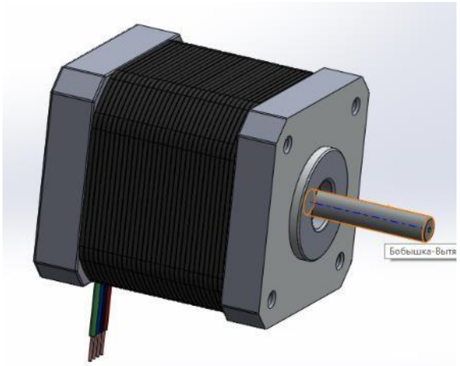


Figure 4.6: 1704HS168A NEMA 17 stepper motor.

- ***Belt & pulley:***

To convert the rotational movement of the motor into linear motion for the Y-axis, we used a GT2 timing belt with a pitch of 2mm and of 6mm width and a GT2 timing pulley with 2mm pitch, 6mm width, 20 tooth and a 5mm bore diameter to match the size of the stepper motor shaft.

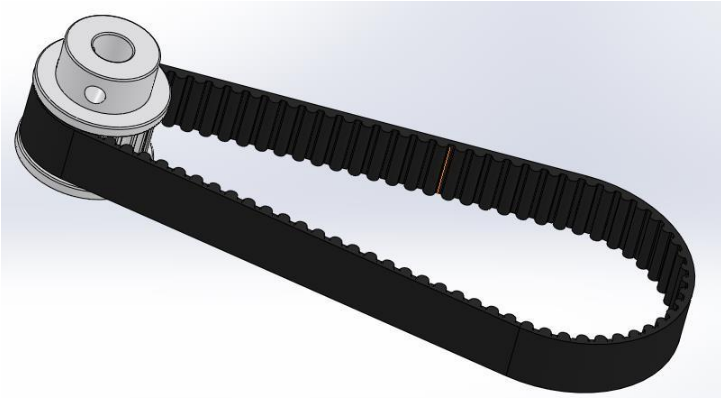


Figure 4.7: GT2 timing Belt and GT2 timing pulley.

- ***Idler pulley:***

To complete any linear actuator that based on a timing belt, an idler pulley is needed. The idler pulley is installed in the opposite side of the pulley.

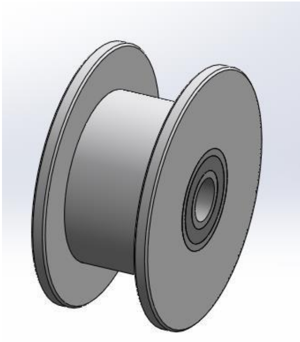


Figure 4.8: Idler pulley.

- ***Printed parts:***

To complete the Y-axis some other parts are needed. These parts can be printed using another 3D printer.

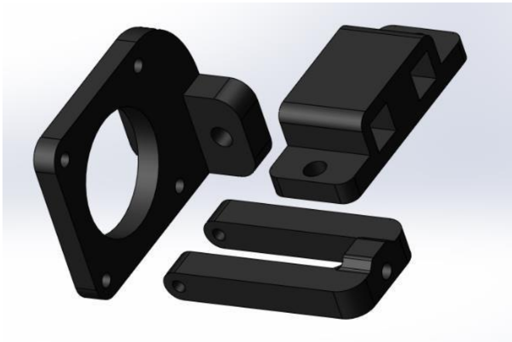


Figure 4.9: Stepper motor bracket & Tensioner.

- ***Y-axis assembly:***

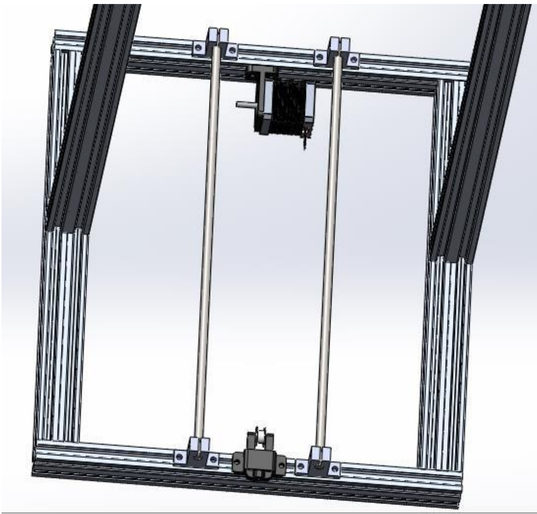


Figure 4.10: Assembly of the Y-axis on the frame.

X-axis

The X-axis direction is from left to right. The X-axis have 2 linear rods to guide the movements. The sides of these 2 rods are inserted in 3D printed parts, which later will be installed on the Z axis.

- ***Printed parts:***

To assemble the X-axis, 2 printed parts are used: X end motor and X end idler.

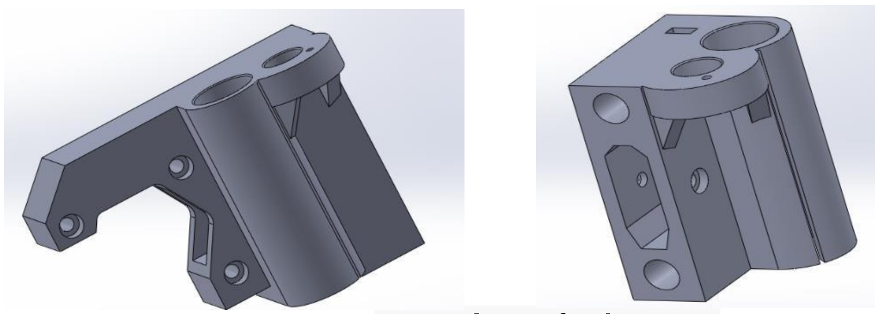


Figure 4.11: Printed parts for the X-axis.

Bearings:

Later, the X-axis will be mounted on the Z-axis, and to slide the X-axis on the Z-axis, we are using Linear ball bearings. Those bearings are inserted inside the two printed parts.

Figure 4.12: Linear ball bearing.

- ***X-axis assembly:***

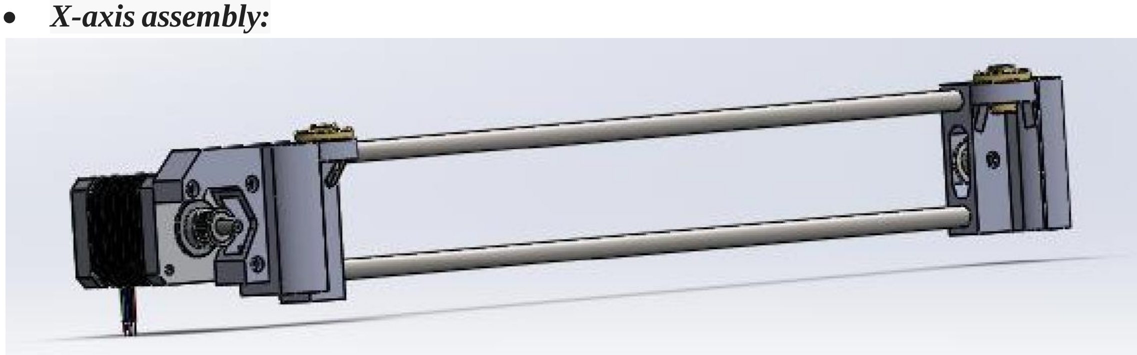


Figure 4.13: Assembly of the X-axis

Z-axis:

The Z-axis is the vertical axis, moving up and down, and moving along with it the X-axis.

The Z-axis have 2 linear rods to guide the movements.

As the X and Y-axes, the Z-axis uses the stepper motor "1704HS168A".

For the motion transmission of the Z-axis, we use a leadscrew.

- ***Lead screw:***

To move the X-axis up and down the Z-axis, a Lead screw is used. The used lead screw diameter is 8mm, a 2mm pitch and 8mm lead.

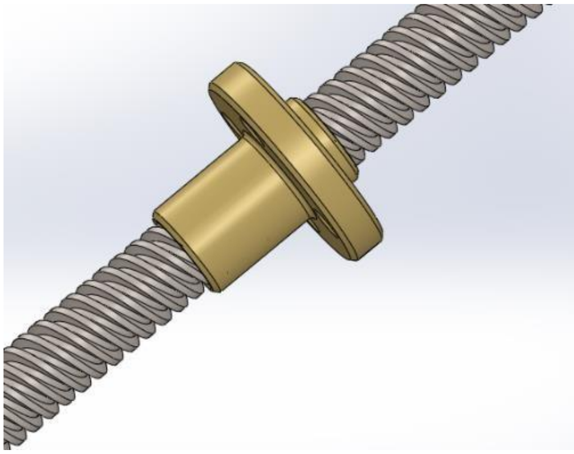


Figure 4.14: 8mm Lead screw and a brass nut.

- ***Coupler:***

Couplings are used to transmit torque from a stepper motor to a lead screw.

The diameter of the motor shaft is 5mm and the lead screw diameter is 8mm, so we chose a 5mm*8mm coupling

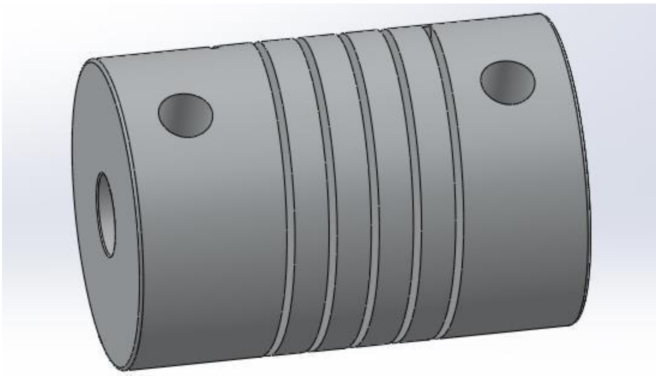


Figure 4.15: 5mm to 8mm flexible coupler.

- ***Z-axis assembly :***

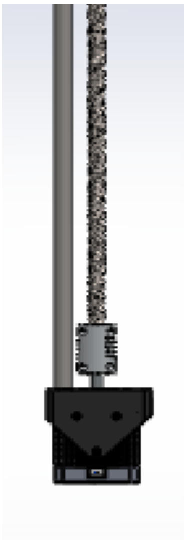


Figure 4.16: Assembly of the Z-axis

Extruder:

The extruder is the component that drives and melts the filament.

To drive the supply filament into the hot end we use the same stepper motor “1704HS168A”.

The extruder rides on the linear rods of the X-axis. To move the extruder, we are using 3 bearings with an 8mm diameter.

- ***Driven gear:***

A driven gear is used to ensure that the filament moves into the hot end correctly.

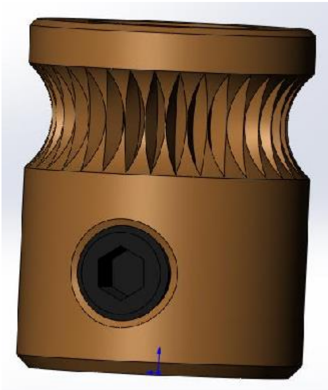


Figure 4.17: Filament driven gear.

- ***Fan:***

The extruder has a fan to cool of the hot end.

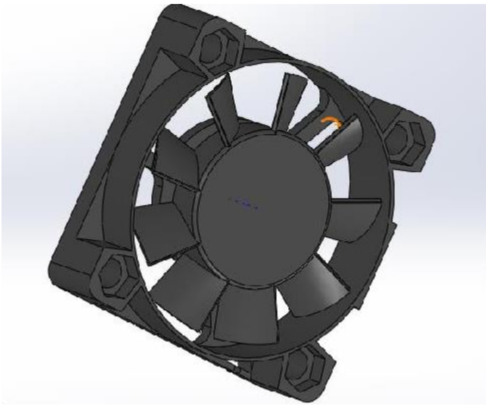


Figure 4.18: Fan

- ***Other parts:***

To assemble the extruder and install it, some parts need to be printed.

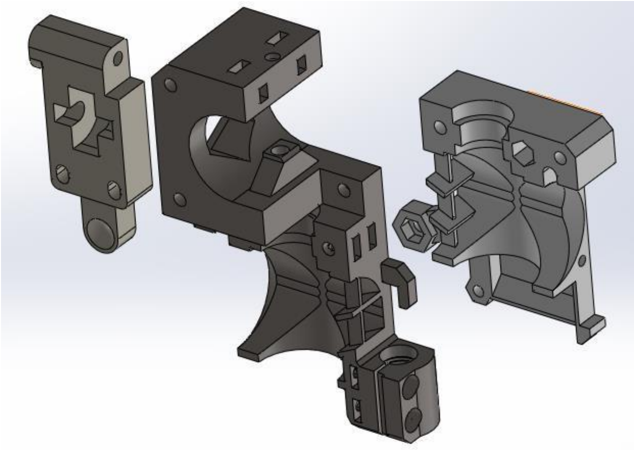


Figure 4.19: Printable parts to assemble the extruder.

- ***Extruder assembly:***

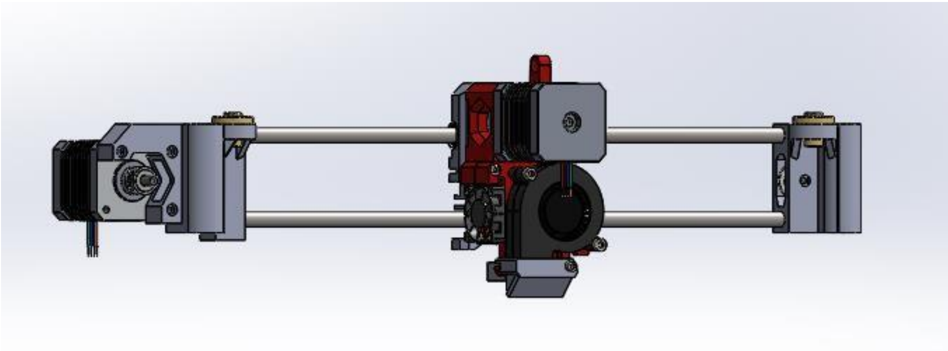


Figure 4.20: Extruder mounted on the X-axis.

Rotary Table:
The primary objective of this work is designing a 5-axes 3D printer.

- ***B & C axes:***

We can achieve that by adding two extra axes to the printing bed (B and C axes).

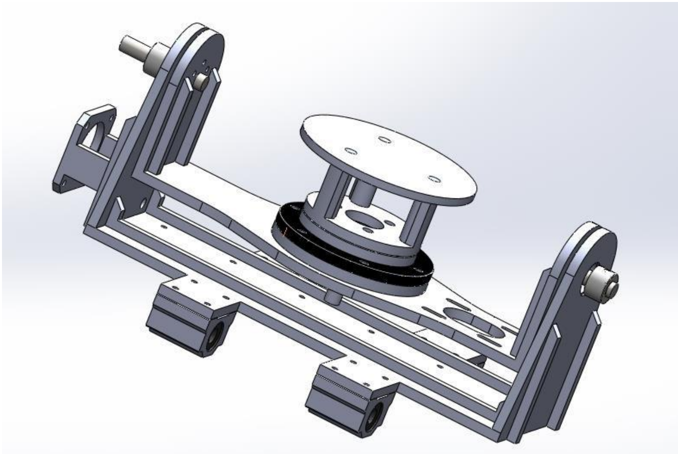


Figure 4.21: Assembly of the rotary table.

- ***Stepper motor:***

For the extra two axes, we are using the stepper motor: NEMA 17 "42BYGHM809".

For the motion transmission we are using the belt driven system.

The rotary table rides on the linear rods of the Y-axis. To move the table, we use block bearings.

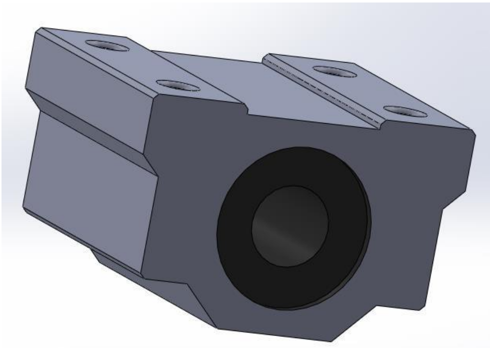
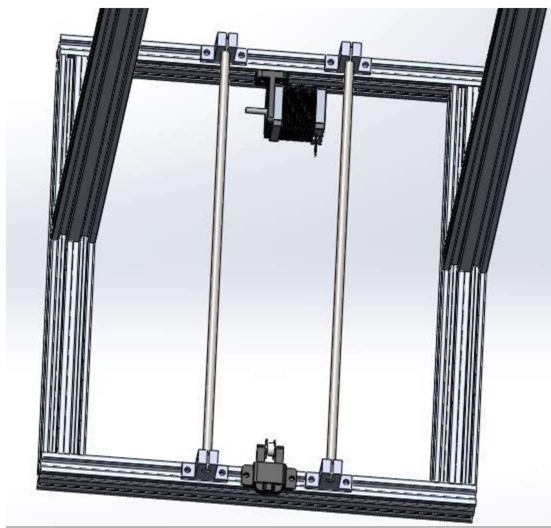


Figure 4.22: Black bearing for the linear motion of the table on the Y-axis.

3D Printer Assembly:

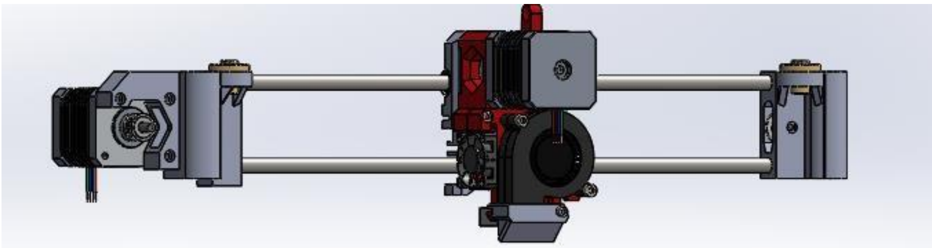
- Assembling the frame.

- Mounting the Y-axis on the frame.

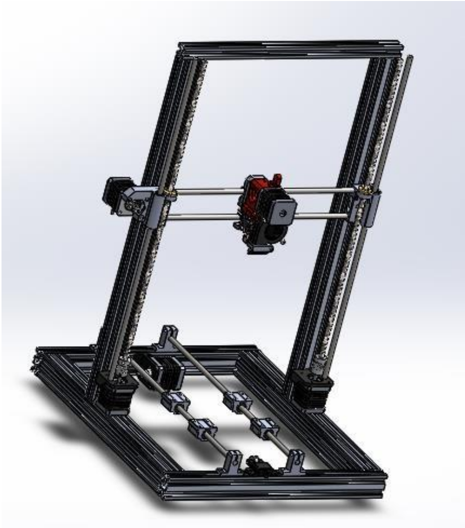


- Mounting the Z-axis.

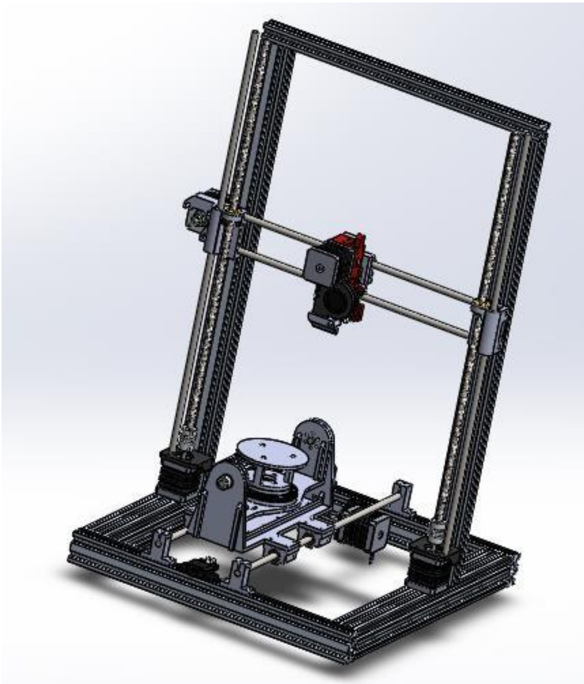
- Mounting the extruder on the X-axis.



- Mounting the X-axis on Z-axis.



- Mounting the table on the Y-axis.



Electronics:

The electronics board known as microcontroller or motherboards controls the entire printing process. Several electronics options are available for 3D printers, most of them support up to 5 stepper motors.

The designed printer uses 7 stepper motor, and for that we need a board that allows more than 5 stepper motors.

For our printer we are using a board called Duet 2. The Duet 2 supports the addition of an expansion board that allows up to 5 additional stepper motors.

Figure 4.23: Duet 2 board. [65]

Power supply:

The motherboard cannot be connected directly to an AC outlet for power. It requires a low DC voltage, either 12V or 24V.

DC power supply unit are used rectify the AC voltage from the wall to supply a constant DC current.

The needed power supply's wattage is calculated by multiplying the output current (A) by the voltage (V) of each component.

Price Estimation

To realize the 3D printer different parts are needed. Some of these parts are to buy, and to keep the price of the printer at lowest other parts are better to be printed. Next tables give an estimated price of the component.

List of parts to buy and prices

Table 4.1: Parts to buy and prices

COMPONENT	Price for Unit	Quantity	Total Price (DA)
Linear Rail 40X40	3300	1	3300
Linear Rail 20X40	2100	2	4200
Linear Rail 20X20	1200	1	1200
Corner Plates (90 Degree)	450	4	1800
Corner Plates (T Shape)	400	4	1600
Corner Brackets	100	2	200
Linear Bearing (ID=8mm)	300	7	2100
SCS8UU 8mm Linear Motion Ball Bearing	600	4	2400
Linear Rod (D=8mm)	1200	4	4800
Linear Rod (D=8mm)	2600	2	5200
Lead Screw (D=8mm)	3500	1	3500
Brass Nuts (ID=8mm)	1600	2	3200
NEMA 17 Stepper Motor (X, Y and Z axes & extruder)	3000	5	15000
NEMA 17 Stepper Motor (B and C axes)	5000	2	10000
NEMA 17 Coupler	350	2	700
E3D -V6 Extruder	9000	1	9000
Timing Pulley GT2 20 Teeth	400	4	1600
Timing Pulley GT2 40 Teeth	600	2	1200
Idler Pulley	700	2	1400
SK8 Linear Shaft Support (4)	1000	1	1000
Slewing Ring Bearing	25000	1	25000
Locking Shaft Collar (ID=8mm)	200	2	400
Pololu Hub	1800	2	3600
Flange Bearing (ID=8mm)	170	2	340
MK8 Extruder Pulley	250	1	250
Radial Fan	300	1	300
Belt (X, Y, B, C)	400	4	1600
Power Supply	5800	1	5800
TOTAL PRICE			**110690**

List of parts to print

To estimate the price of the printed part, we used an open-source slicing software called "Cura".

When using the software, we have to choose two things before starting:

- The printer used: For these parts we used the printer: Creality Ender- 3 Pro.
- The material used for printing: we used PLA.

After uploading the STL file of the part to the software. The software gives you the weight of the used material and the printing time. The price estimation is based on the weight of the material used and the printing time.

Table 4.2: Prices of printing parts.

PARTS	Quantity	Estimated Price (DA)	Total Price
X-axis Carriage	1	800	800
X Left Carriage	1	1000	1000
X Right Carriage	1	800	800
Y-axis Motor Holder	1	300	300
Y-axis Tensioner	1	300	300
Y-axis Pulley Tensioner Holder	1	400	400
Z-axis Stepper Motor Bracket (Left & Right)	2	400	800
Extruder Body	1	1000	1000
Extruder Cover	1	400	400
Extruder Air Duct	1	300	300
Extruder Idler	1	300	300
5-axis Profile	1	3200	3200
Slewing Ring Adaptor	1	300	300
V-axis Shaft	1	300	300
B-axis Motor Bracket	1	600	600
Bed Support + Bed	1	1000	1000
TOTAL PRICE			**12300**

Conclusion

In this chapter, we presented the design of the various parts of the 3D printer on SolidWorks, and the assemblies of the 3D printer. The printer is composed of 5-axie, the Z axis which is the vertical axis moving up and down, and moving along with it the X axis, which moves horizontally from left to right, and right to left, the Y axis is placed on the lower part of the frame moving the table forward and backward, the table itself has two rotational axes, one axe moves around the Y axis, and the other around the Z axis, at last we made a price estimation for how much it cost to build this 3D printer.

General Conclusion

General Conclusion

The objects printed using a regular 3-axis 3D printer have some undesired characteristics such as uneven structural strength and support structure. To overcome these problems, like 5-axes CNC machines, 5-axes systems have been used in 3D printing.

Having a 5-axes 3D printer allows you to deposit material in curved layers and eliminate the need for support structure, making the printing process shorter, printed parts of higher quality surface, more flexibility, higher strength. However, 5-axes 3D printers are much more complicated and they are not affordable for individuals.

This thesis presents a design model for a 5-axes FDM printer. The designed printer can be built from scratch, or it can be taken as a design to modify and improve a 3-axes FDM printer, since all the needed parts can be printed.

The designed 5-axes 3D printer is made according to the specification given in the statement of work and the given budget. The design of the printer is made using SolidWorks.

In the future, I hope that this 3D printer will be constructed because, I think that its realization will not be very expensive and not very complicated, and it can be very helpful for the laboratory as practical work and for research at the level of the ENP mechanical engineering department.

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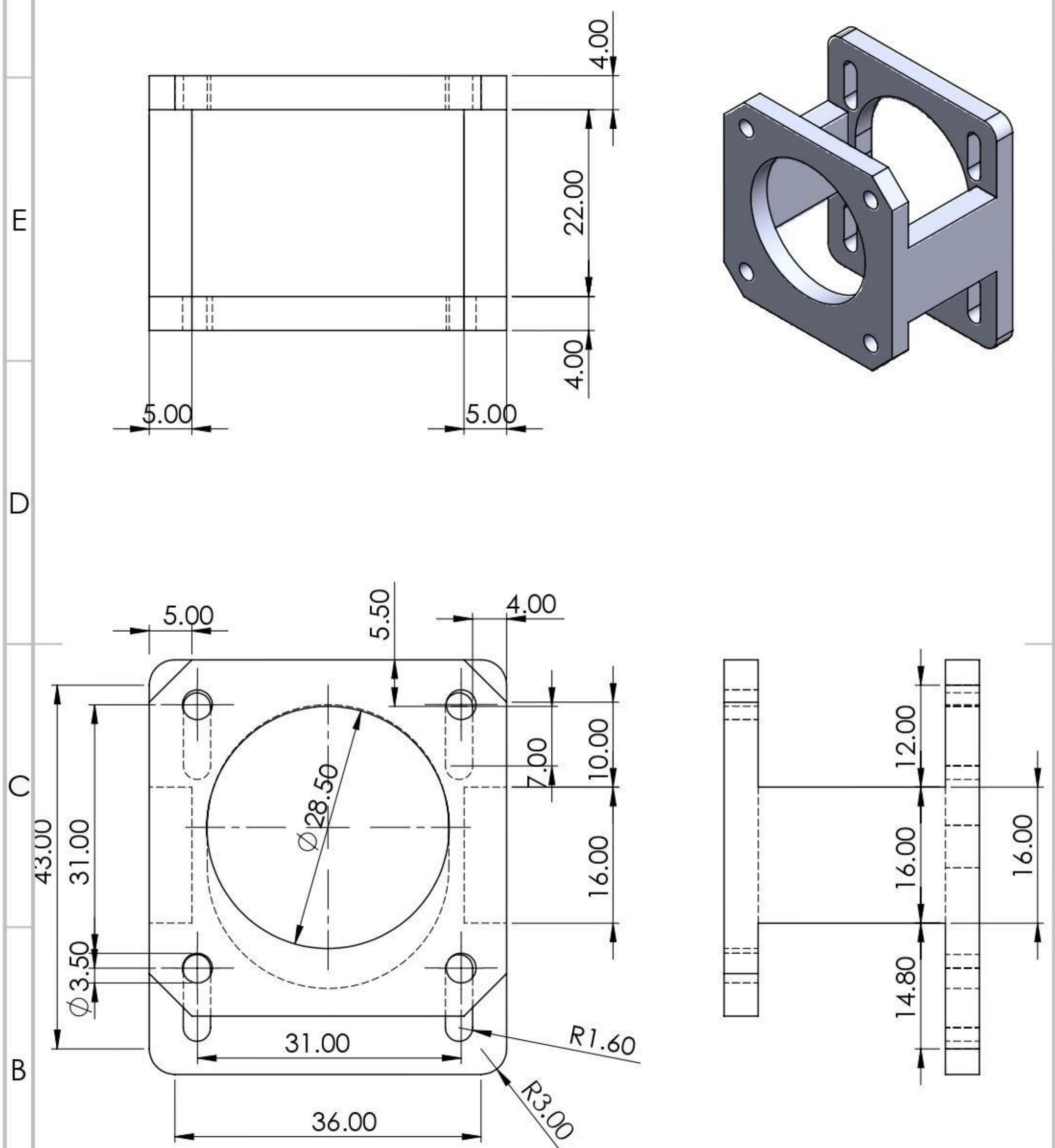
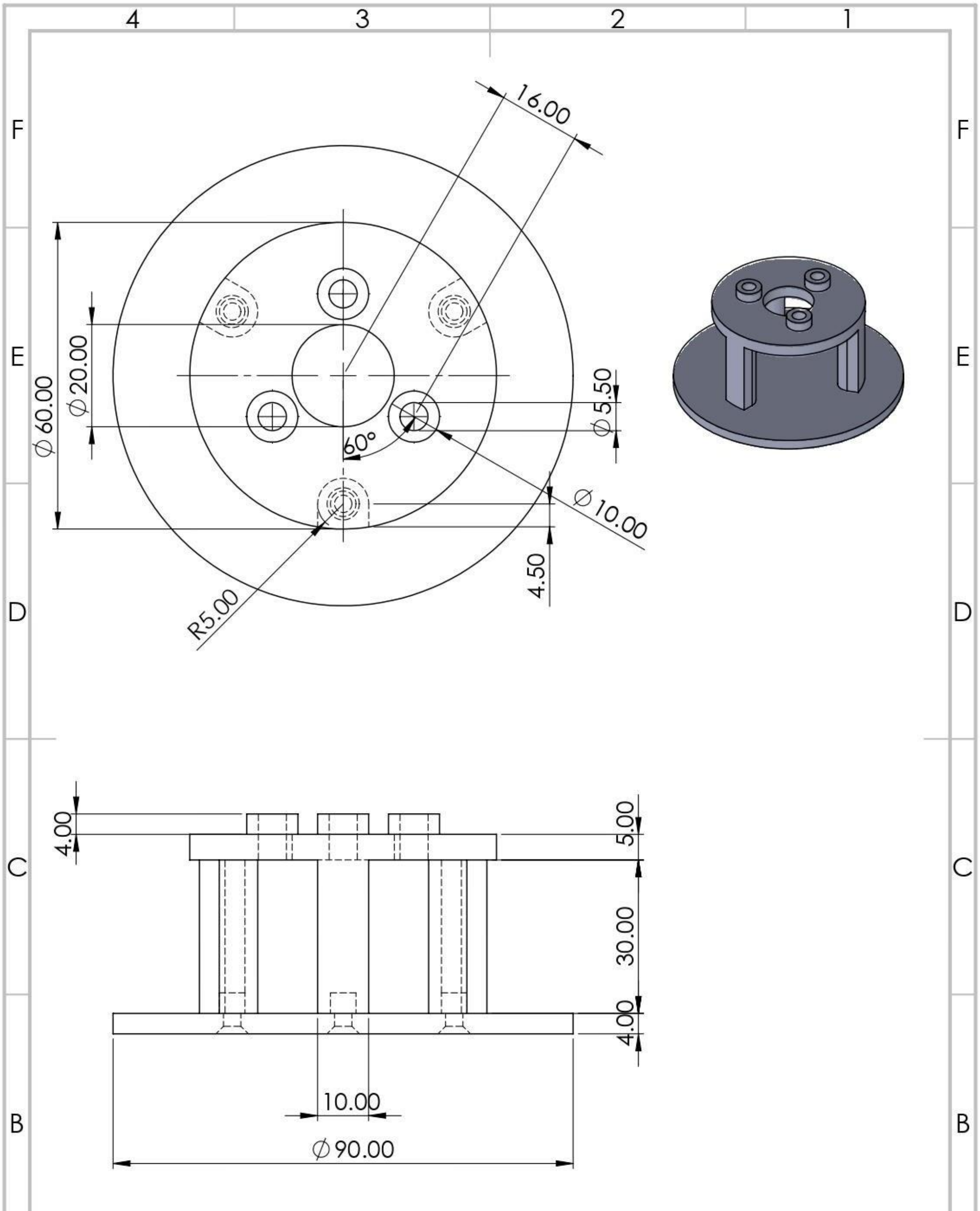
Annex

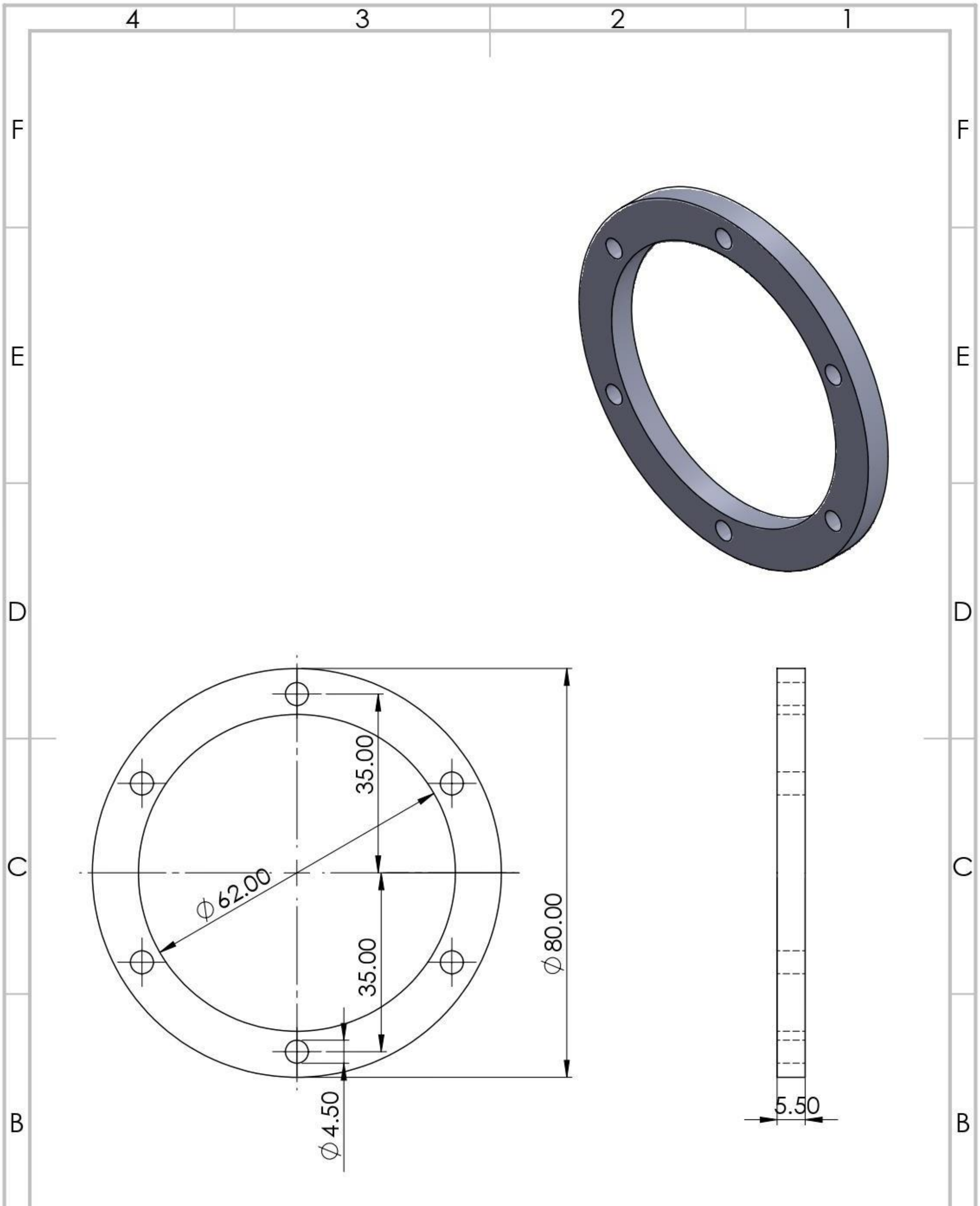


ECOLE NATIONALE POLYTECHNIQUE ALGER

SCALE	MATERIAL	b axis motor bracket	DEP: Mechanical Engineering
3:2	**PLA**		
STUDENT	BOUAB		
Supervisor	BELHABIB		24/06/2022
Supervisor	SEDJAL		

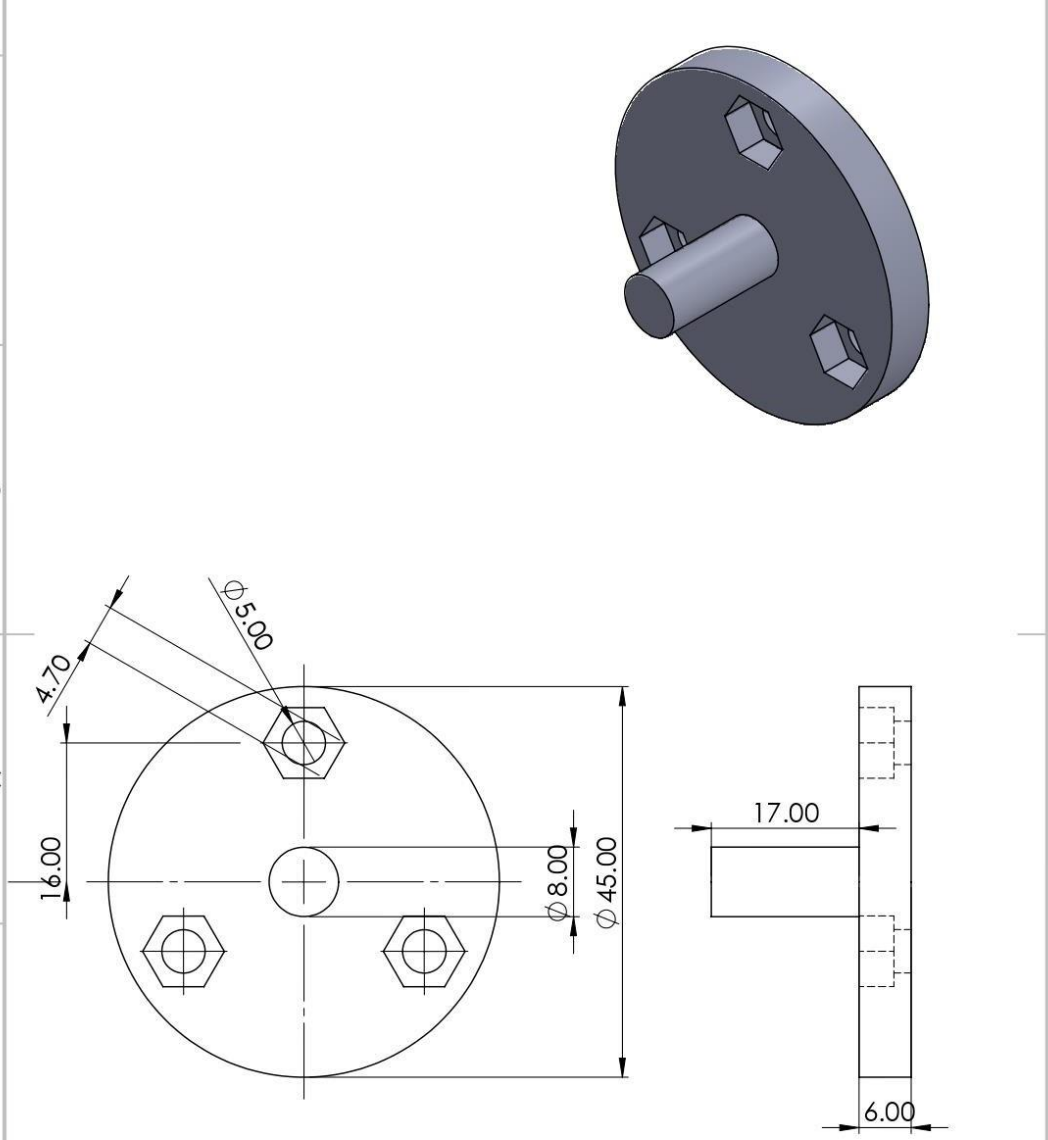


ECOLE NATIONALE POLYTECHNIQUE ALGER				
SCALE	MATERIAL		bed support	DEP: Mechanical Engineering
1:1	**PLA**			
STUDENT	BOUAB			
Supervisor	BELHABIB			24/06/2022
Supervisor	SEDJAL			

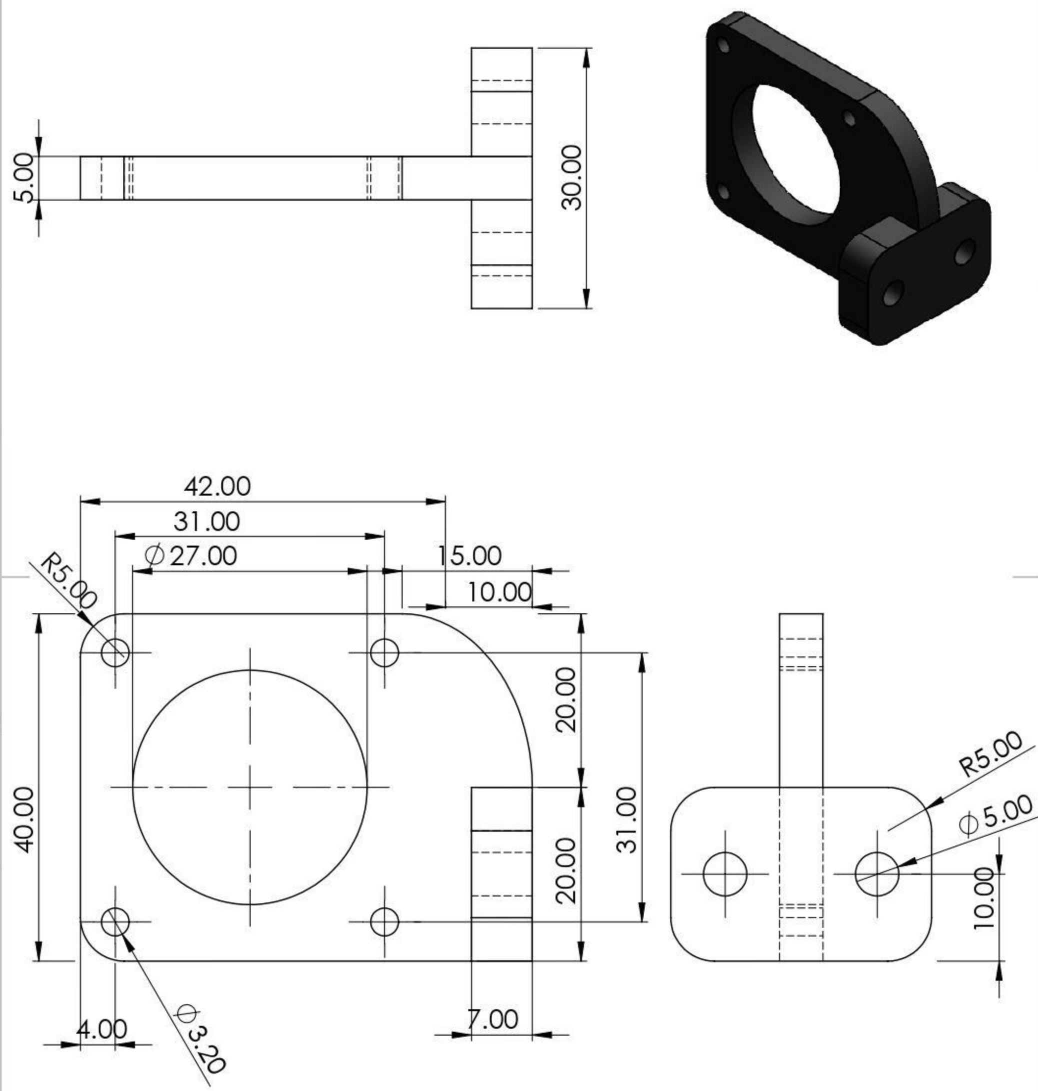


ECOLE NATIONALE POLYTECHNIQUE ALGER

SCALE	MATERIAL	sweling ring adaptor	DEP: Mechanical Engineering
1:1	**PLA**		
STUDENT	BOUAB		
Supervisor	BELHABIB		24/06/2022
Supervisor	SEDJAL		

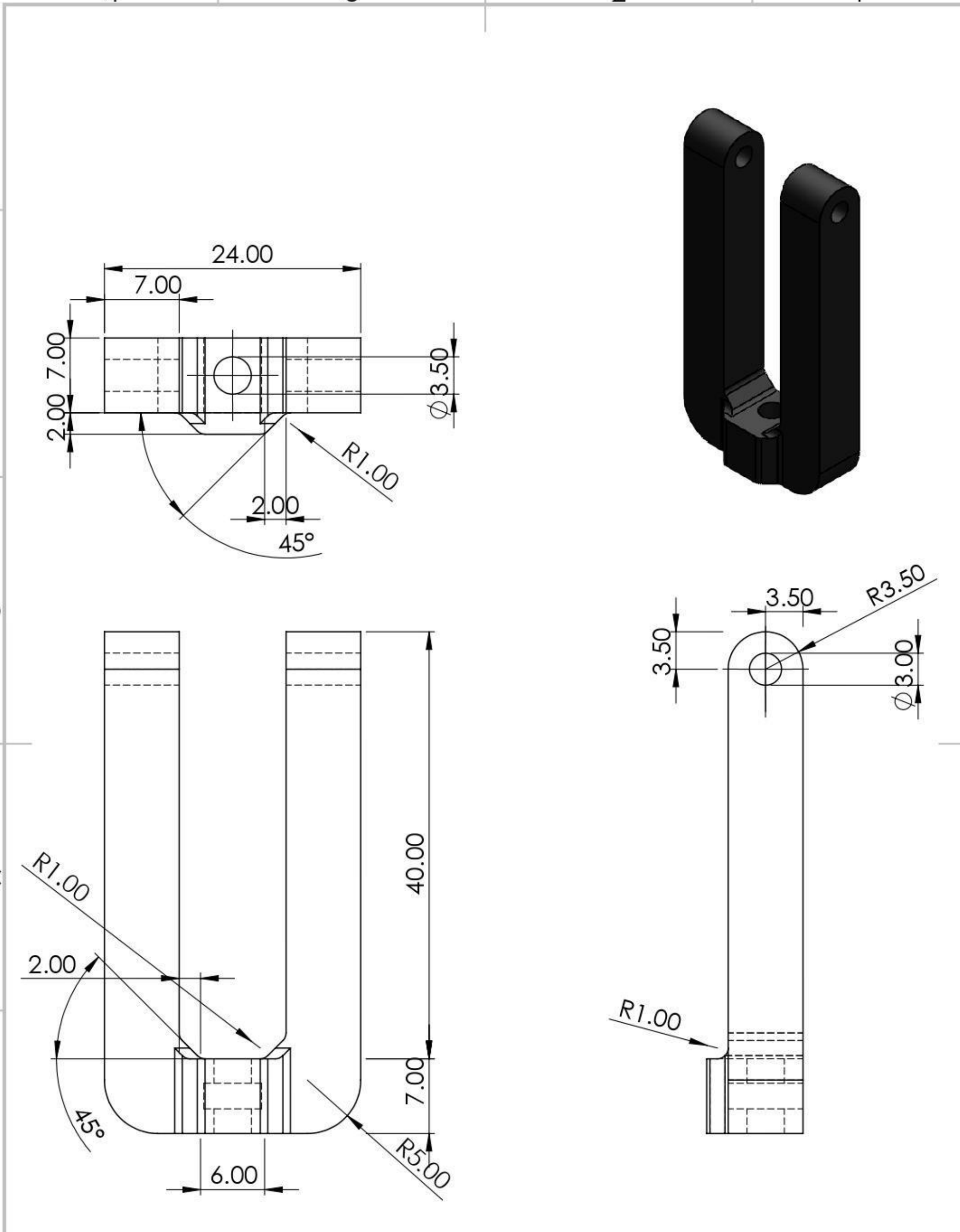


ECOLE NATIONALE POLYTECHNIQUE ALGER				
SCALE	MATERIAL		c axis shaft	DEP: Mechanical Engineering
3:2	**PLA**			
STUDENT	BOUAB			
Supervisor	BELHABIB			24/06/2022
Supervisor	SEDJAL			

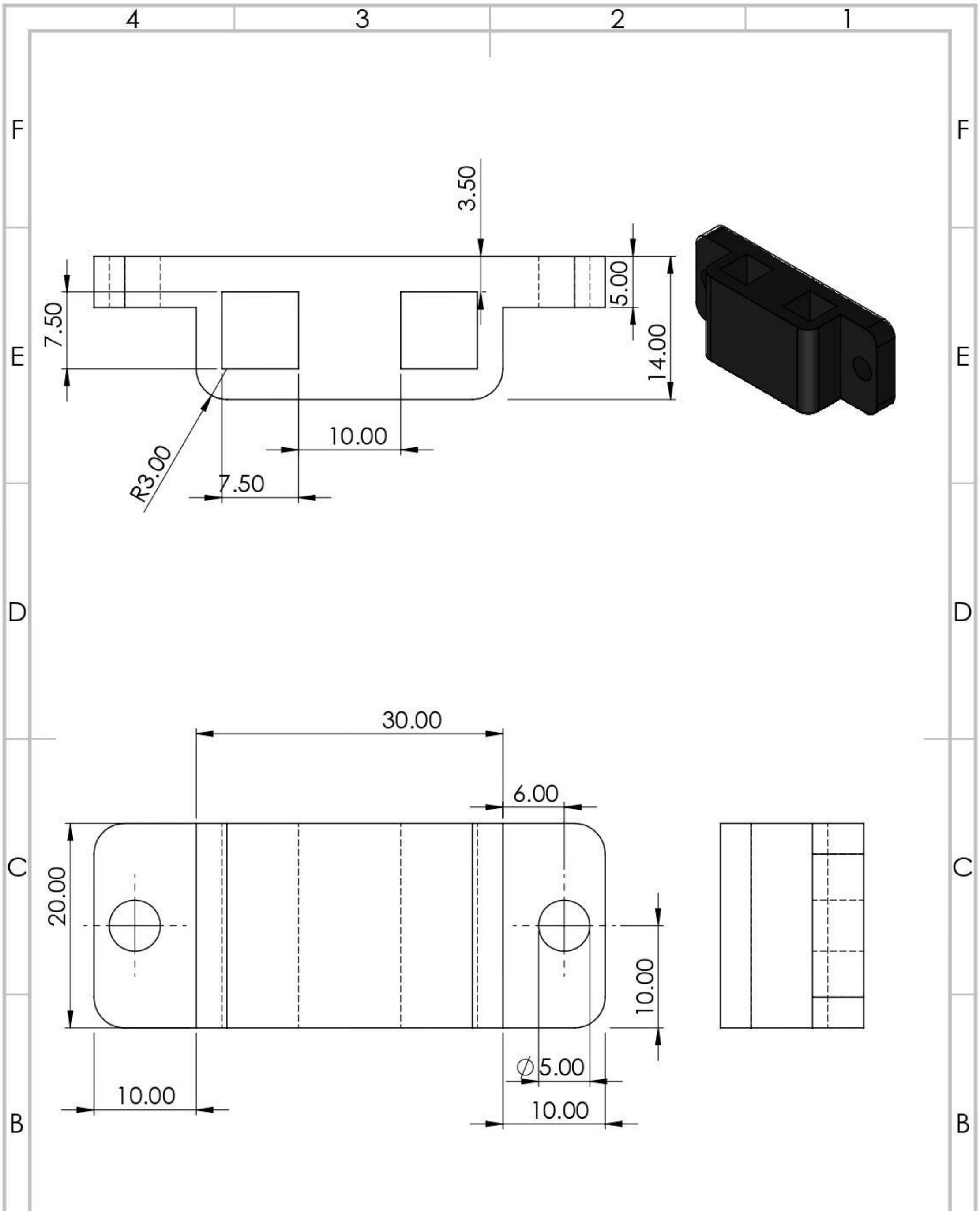


ECOLE NATIONALE POLYTECHNIQUE ALGER

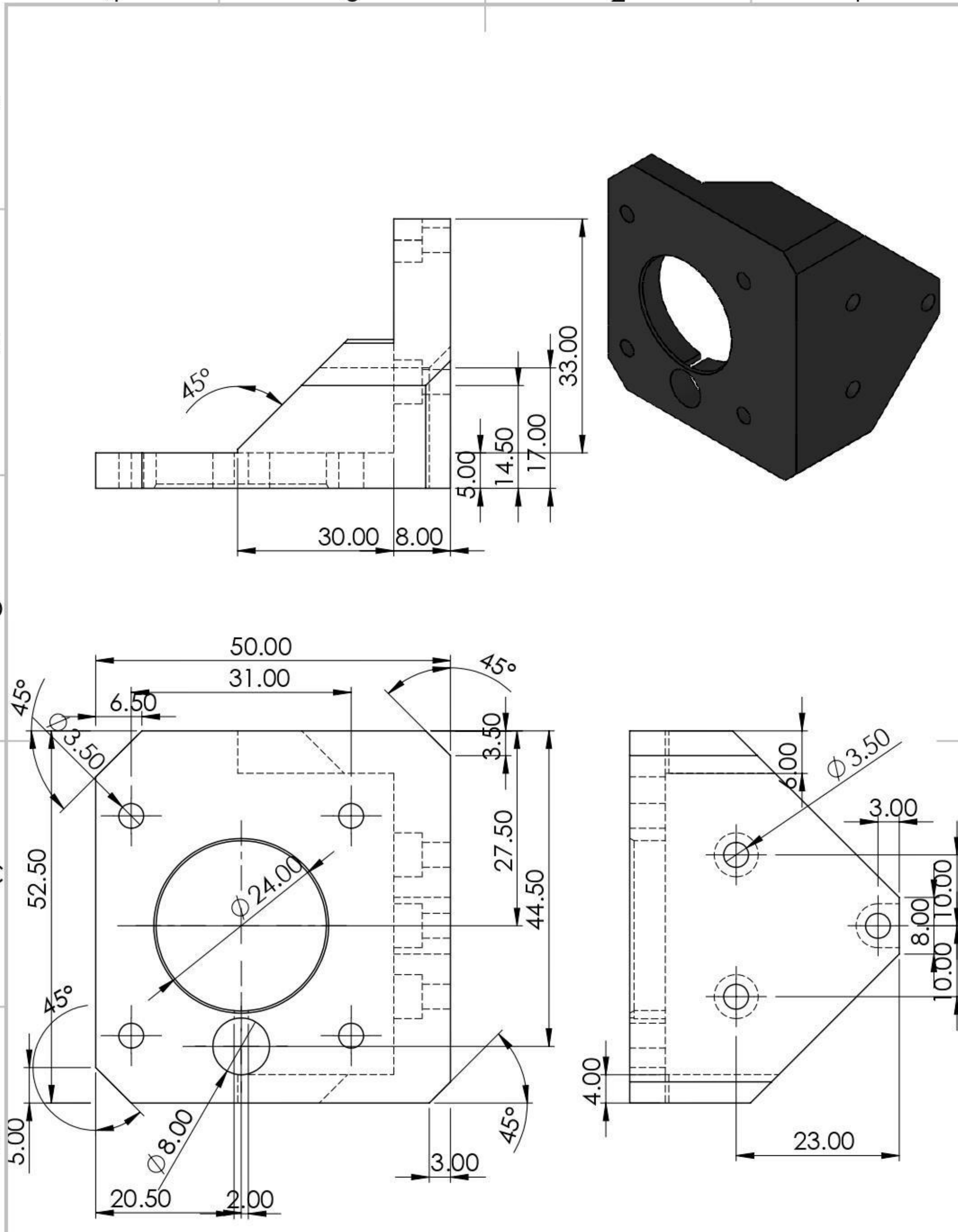
SCALE	MATERIAL		DEP: Mechanical Engineering
3:2	**PLA**	y motor bracket	
STUDENT	BOUAB		
Supervisor	BELHABIB		24/06/2022
Supervisor	SEDJAL		



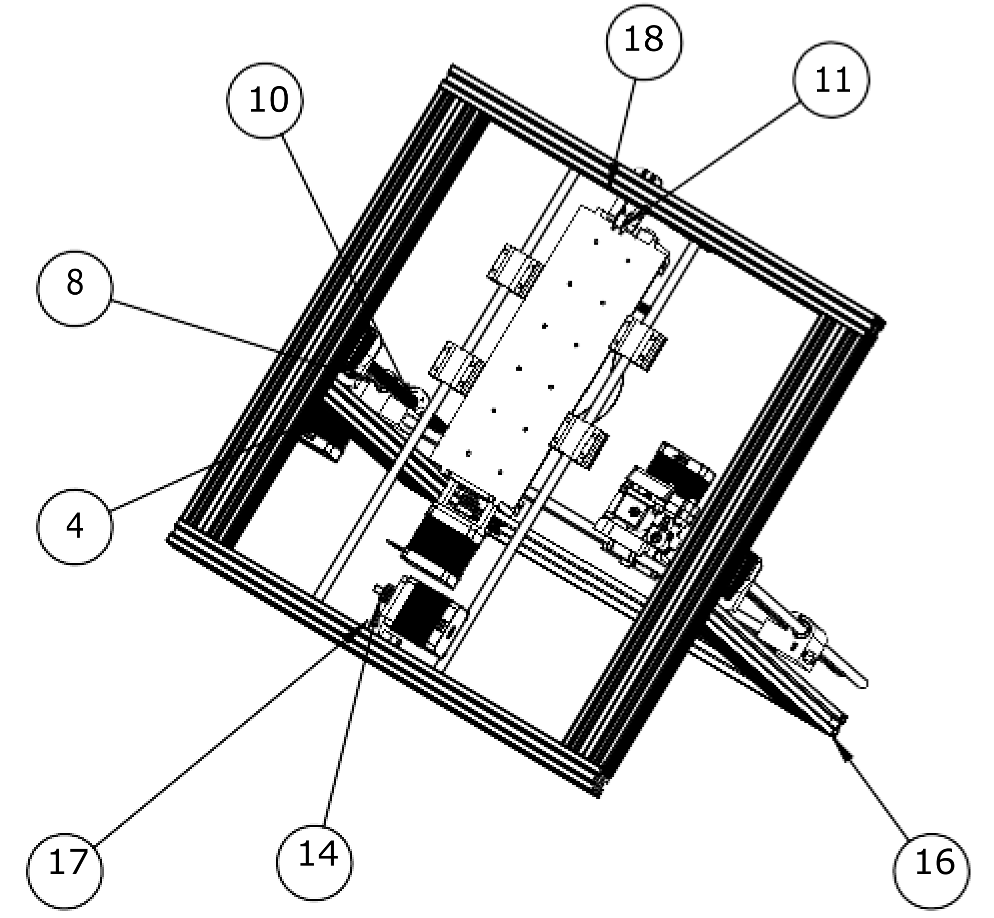
ECOLE NATIONALE POLYTECHNIQUE ALGER			
SCALE	MATERIAL	y tensioner pulley	DEP: Mechanical Engineering
2:1	**PLA**		
STUDENT	BOUAB		
Supervisor	BELHABIB		24/06/2022
Supervisor	SEDJAL		

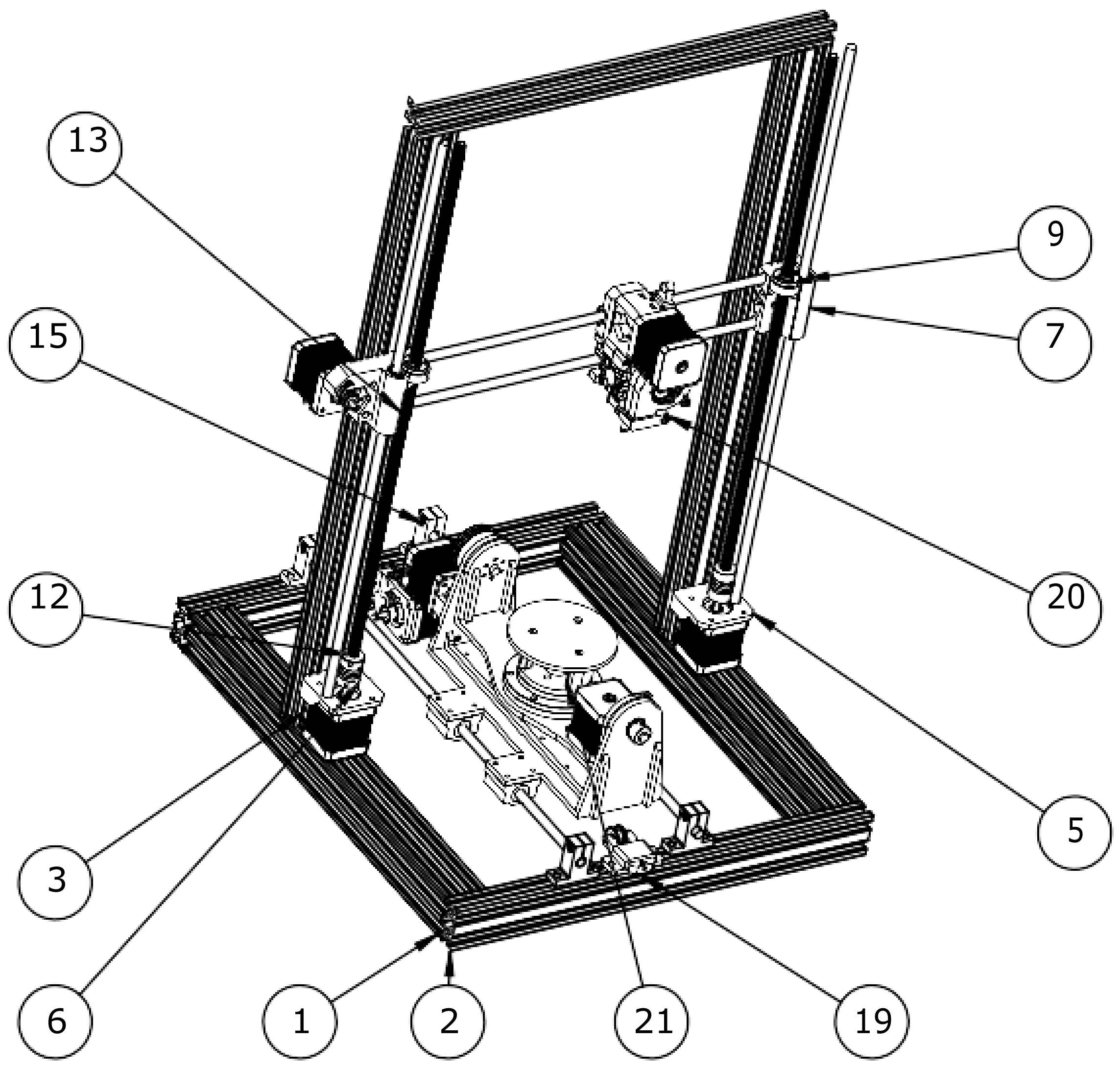


ECOLE NATIONALE POLYTECHNIQUE ALGER			
SCALE	MATERIAL	y tensioner	DEP: Mechanical Engineering
2:1	**PLA**		
STUDENT	BOUAB		
Supervisor	BELHABIB		24/06/2022
Supervisor	SEDJAL		



ECOLE NATIONALE POLYTECHNIQUE ALGER				
SCALE	MATERIAL		z motor bracket	DEP: Mechanical Engineering
1:1	PLA			
STUDENT	BOUAB			
Supervisor	BELHABIB			24/06/2022
Supervisor	SEDJAL			





ITEM NO	PART NUMBER	DESCRIPTION	QTY.
1	v-slot 40X40	Aluminum 6063	2
2	v-slot 20X40	Aluminum 6063	2
3	v-slot 20X40 (Z axis)	Aluminum 6063	2
4	NEMA 17 stepper motor		7
5	Z-axis stepper motor bracket	Polylactic acid (PLA)	2
6	Flexible coupler		2
7	X end idler	Polylactic acid (PLA)	1
8	Linear rod	Carbon steel	6
9	Linear bearing		7
10	Nut	Brass	2
11	Idler pulley		2
12	Leadscrew	Carbon steel	2
13	X end motor	Polylactic acid (PLA)	1
14	GT2 timing pulley 20 teeth		2
15	Shaft support	Stainless steel	2
16	v-slot 20X20	Aluminum 6063	1
17	Y -axis stepper motor bracket	Polylactic acid (PLA)	1
18	Y tensioner	Polylactic acid (PLA)	1
19	Y idler pulley holder	Polylactic acid (PLA)	1
20	Extruder		1
21	Rotary table		1

ECOLE NATIONALE POLYTECHNIQUE

SCALE	MATERIAL		5-axes FDM 3D Printer	DEP: Mechanical Engineering
1:6	-			
STUDENT	BOUAB	Ouadia		
Supervisor	BELHABIB	Soufiane		DATE:26/06/2022
Supervisor	SEDJAL	Hamid		