Design, Fabrication and Testing of a 3D Printer

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Abstract

Conventional manufacturing processes depend on the principle of removal of materials, which involves non-linear materials processing and have waste material left after the manufacturing is completed. However, there was always a desire to manufacture products in such a way that the wastage reduces to zero. The concept of additive manufacturing, in the form of 3D printing, made a breakthrough in this direction and has attracted the attention of researchers, engineers, and entrepreneurs. 3D printing has opened new opportunities in terms of manufacturing possibilities and shifted the manufacturing paradigms. This capstone design project aimed to in-house design, fabricate and test a 3D printer. A design was developed consisting of sets of screws, BLDC motors and one CNC controller controlled with Mach3 software. Our printer uses BLDC motors due to significantly higher levels of accuracy and efficiency as compared to the current practice of using stepper motor. Moreover, we used ball screws instead of the lead screws as they provide smoother, quieter, and efficient motion. These components make this design a novel one that has potential to compete with other 3D printers. Finally, the printer is tested to see if this creative combination can be used to advance this manufacturing process.

Keywords
Design, 3D Printer, Additive Manufacturing, BLDC Motor and Mach3 Software.

1. Introduction

Once a machine or device fails and requires repairing, the company maintains inventory of spare parts, which is a relatively expensive process. If the inventory is not maintained, then the order process for required parts will result in work delays. Therefore, a quick solution is need as a temporary solution until the spare parts arrive. These are one of the few problems faced by industries, which led to the development of Additive Manufacturing (AM) that precisely produces the required part of the product in a short time and low cost through layer by layer deposition of materials (Industry 2014). 3D printing is an upcoming revolution of the industrial prototyping and manufacturing that encourages and drives innovations for small companies and even individuals. The development process of the 3D printing technologies is shown in Table 1.

Table 1: Progression of 3D Printing Technologies since its Inception

Type of technologies	Discovery year	Patented by
Additive Manufacturing	1980	
Stereo lithography (Kocisko 2017)	1986	Charles (Chuck) Hull
Selective Laser Sintering (SLS)	1989	Carl Deckard
Fused Deposition Modelling (FDM)	1989	Scott Crump
Laminated Object Manufacturing (LOM)	1990	Michael Feygen
Digital Light Processing (DLP)	2012	Larry Hornbeck

The major difference in large variety of 3D printers are the technologies utilized in the printer, the printing method, and the materials used to print the object. A brief description of these technologies are given below.

1.1 Fused Deposition Modelling (FDM)

Fused Deposition Modelling (FDM) is one of the most commonly used 3D printing techniques, which prints using thermoplastic filaments such as ABS or PLA. FDM is based on extrusion process, as shown in Figure 1, where the printer works by heating and extruding a thermoplastic filament through a nozzle. The extrusion system pulls the filament from the spool during the printing process and the heater heats until it changes to semi-molten phase. The deposition of semi-molten material builds the desired object layer by layer, from the bottom to the top depending on the input data to the printer (Sandeep et al. 2017).

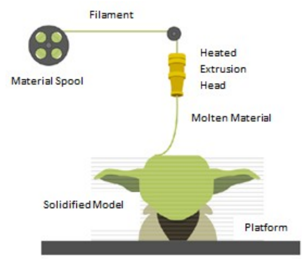


Figure *1*: Fused Deposition Modelling (FDM) Process (Jasveer et al. 2018)

1.2 Stereolithography (SLA)

Stereo lithography –SLA, is widely known to be the original 3D printing process, and the first to be commercialized. The working principle of SLA 3D printer is UV hardening of photopolymer materials (Sandeep et al. 2017). The properties of photopolymer materials change when exposed to UV laser (Crivello et al. 2013). The exposure to the UV laser causes the chains of atoms in the polymer gum to connect together and then cured to form a solid in a very precise way. The liquid photopolymer is placed inside a vat, which has a movable platform. Then, the laser beam is directed to follow a certain path on the surface of the photopolymer using a control system based on input data to the printer. The resin solidifies exactly at the points which the laser hits.

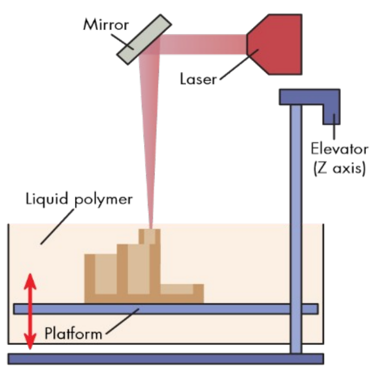


Figure 2: Stereolithography Process (Jasveer et al. 2018)

1.3 Selective Laser Sintering

Selective Laser Sintering (SLS) is based on the principle of sintering. These fused powder particles get attached to each other and cool down to form a solid. Typical materials used in this process are tiny particles of plastics, metals, ceramics, glass, silica, nylon, etc. (Sandeep et al. 2017). The working principle of the process is shown in Figure 3. The middle piston-cylinder part represents the working area where the object will be printed. The other two piston-cylinders on the two sides are powder containers used to supply the powder for printing. The levelling drum smoothens the powder layer over the surface of the bed and make it tightly compressed. Once done, the laser starts moving in the X and Y directions to print the first layer of the object according to the input data file. As the laser hits the powder at the desired location, it sinters the particles to each other, and they bond to form a solid. After completing the layer, the printing bed lowers and the powder containers elevate in the Z direction, and the leveling drum brings and smoothens new layer of powder over the printing area and laser process repeats to form the new layer. This process is repeated until the 3D object is completed with the required design.

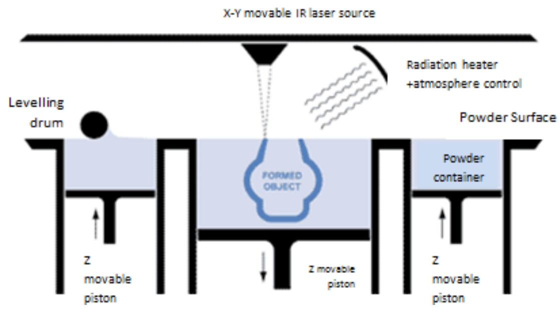


Figure 3: Basic Setup of Selective Laser Sintering (SLS) (Jasveer et al. 2018)

1.4 Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) process manufacture parts from a thin, continuous sheet of material. This action also causes the adhesive on the material's surface to melt (Jasveer et al. 2018). Depending on layer data input to the printer, a computer-controlled laser or blade starts cutting the material following the contour of that cross section (Sandeep et al. 2017). After forming the first layer of the object, the process repeats to form new layers till the final object is manufactured. The time required to print an object using LOM depends on the number of layers and the thickness of each layer.

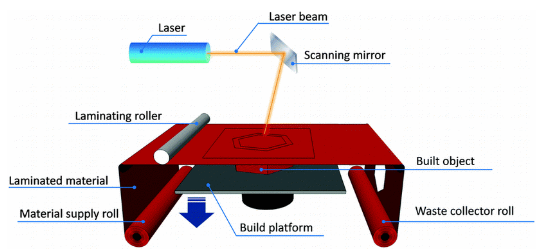


Figure 4: Laminated Object Manufacturing (LOM) Process (Jasveer et al. 2018)

As compared to other 3D printers such as SLA and DLP, LOM seems to be less costly. The other advantage of LOM is that it does not need to be contained within an enclosed chamber and it does not involve any chemical process. This makes it easier to build larger objects. However, LOM is not ideal for printing objects with complex geometries or producing functional prototypes. The other disadvantage of LOM is that it requires post processing to be done such as sanding, painting or varnish to keep out moisture.

2. Design Specifications and Constraints

2.1 Design Specifications

The process of setting design specifications started with gathering the necessary information of the product design requirements from the customer, the manufacturer, and the designer(s). Brainstorming was one of the techniques used to come up with various requirements. After identifying these, the complete set of requirements were divided into two lists: "must have" and "wish list". The "must have" requirements are necessary and cannot be ignored in the design, while "wish list" requirements do not hold the same importance. Finally, all the "must have" requirements were converted into engineering characteristics. These design specifications are more specific and not as general as the requirements. They are given a unit as well and a target range or value. These design specifications had to be met in the final design of the 3D printer in this project. Finally, the design specifications of the 3D printer for this project includes:

- Printer will use Additive Manufacturing (AM) based on ASTM F42 standard

- Maximum size of the printed object (6cm x 6cm x 4cm)
- All data communication will use STL format and G-code
- Moderate complexity of printed object
- Material used for printing is PLA plastic
- The speed of the 3D printer should be approximately 80 mm/sec
- Resolution will be between 100 to 500 µm
- The printer will use wires of circular cross-section as raw material with maximum diameter of 2 mm

2.2 Realistic Constraints

A design constraint is defined as a limitation or challenge imposed by the project stakeholders and surrounding environment in a way that affects our design. Seven different realistic constraints are identified for this project as explained in Table 2.

Table 2: Realistic Constraints

Constraints	Description
Size	Size is a major universal constraint in 3D printing. This has also led the group to select small size of object to be printed i.e. 6x6x4 cm^3
Time	Complete all design, fabrication and testing within 30 weeks of project duration
Budget	Available budget to complete the project is 1,500 USD
Manufacturing	a) All parts manufacturing has to be done within the college b) Manufacturing of non-standard parts/components in are constrained by the available material (material grade, cross-sections and thickness) and accuracy of the machines available in the workshop
Materials	Two type of constraints emerge due to the material issue. These are: a) During material selection process, it must be checked whether the material is available in the Central Workshop or in local market and within budget limits b) The selected materials must be machined within Central Workshop
Safety	All the electrical and thermal parts of the printer must be either insulated or placed in protective compartments in order to avoid any harm to the user
Ethics	Any literature or standards used while design, manufacturing, and assembly of the 3D printer must be correctly referenced

3. Conceptual Design

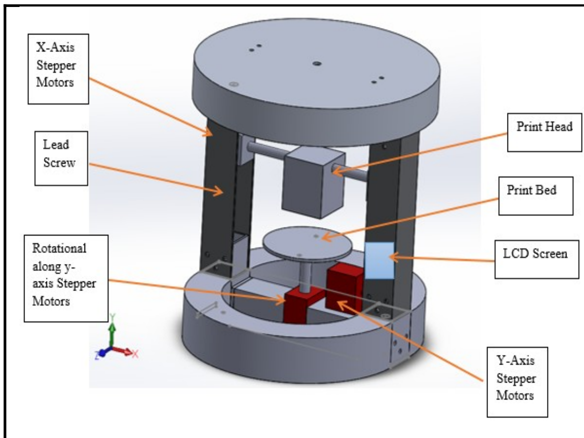
3.1 Concept Generation

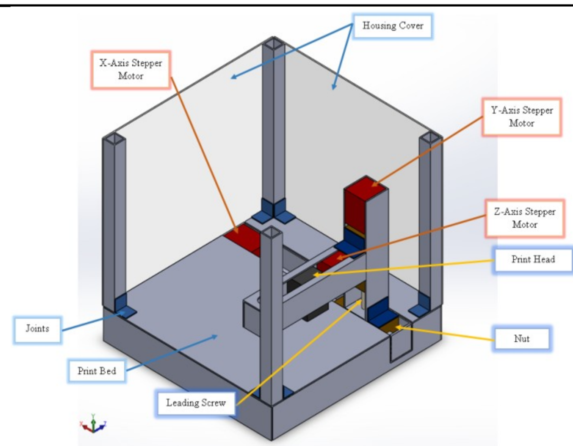
A conceptual design is like an outline that describes a rough technique of description/layout of how a product will look like and how it will perform its functions. A set of conceptual designs significantly contributes to the process of identifying the optimal design layout of the product. In the conceptual design phase, the design team first identified all functions that needs to be performed in order to successfully run the printer, such as: effective communication channels between the user and the printer, the motion along/about the X-, Y-, and Z-axes, heating and extruding the filament, controlling the system, etc. Subsequently, the team started generating different ideas to perform each of these product functions and, using morphological matrix method, these ideas were combined into four distinct conceptual designs of the overall system. Each of the four developed conceptual designs possess its own distinct motion system and configuration, but they all comply to the design specifications. A brief description about the structure and the working principle of each of these designs are illustrated in Table 3. Moreover, a 3D model of each conceptual design is generated using SolidWorks® software.

3.2 Concept Evaluation and Selection

The final step in this phase was to compare all four concepts and select one for further analysis. Each design was imagined and planned with its individual characteristics such as the important features, uniqueness and associated problems with each of them. Table 4 below shows the comparison between all four designs depending on this philosophy. After reading through the details of each design and comparing them side by side, only one design had to be selected in order to start performing its detail design. The team members have agreed after comparing the four designs that they should generate a design, which would benefit from all the individual four designs. It should include as much important features and uniqueness from the different designs but still avoid encountering the problems that they had. The final design that all the team members have agreed to is illustrated in Figure 5.

Table 3: Four Developed Conceptual Designs

<table>
<tr>
<td>

This design has a cylindrical-shaped structure with the print head having a translation motion along X- and Y-axes through a set of screws. The motion along the Z-axis is achieved by means of a rotation. The motors are controlled to allow the nozzle to move to any position in the printing space of this design.</td>
<td>

This design has a square-shaped structure where the print head moves along X-, Y- and Z-axes using a set of screws. Other principles are same as first. Moreover, this design has a housing to consider for the safety of the user as well as to prevent the dust from going inside the printer.</td>
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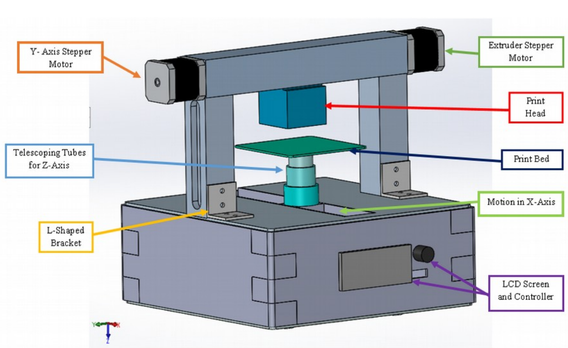
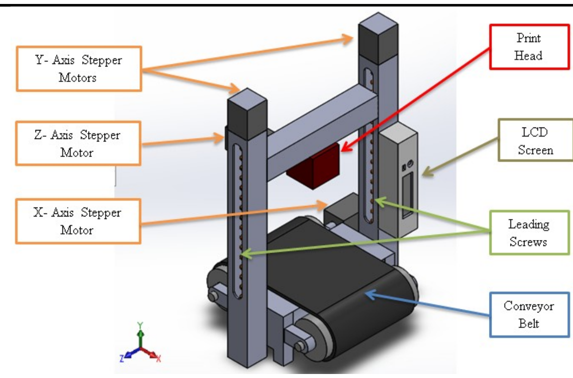
<td>

The motion system in this design follows the Cartesian coordinate system. The print head moves along the Y-axis and the print bed moves along the X-axis using sets of screws. This design utilizes the telescopic tubes to achieve the motion of the print bed along the Z-axis.</td>
<td>

The motion system in this design also follows the Cartesian coordinate system where the print head moves along Y- and Z- axes using a set of lead screws. Moreover, the print bed will achieve the motion along the X-axis by means of a conveyor belt and a motor.</td>
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In final selection, the vertical motion along Y-axis is performed using two linear motors, one at each side of the printer. A vertical connection is used to connect each of the linear motors' shafts to the upper part of the printer. In the upper part, the print head (with the nozzle attached at its bottom side) moves along X-axis on a lead screw that is connected to a stepper motor. An extrusion motor is placed on the upper part opposite to the X-axis stepper motor. This helps in structure balancing and have a relatively short path to the print head (because if the path is too long, the filament might tangle). A C-shaped horizontal beam was placed above the lead screw assembly for two reasons:

a) to protect it from the dust and b) for better appearance as a housing. The print bed in this design is a rotating plate, which delivers motion along the third axis (the Z-axis). This bed rotates using a motor installed inside the base. An LCD screen is placed on a fixed tilted plate in front of the printer as shown in figure 5. Below this plate, another inversely tilted plate is used. This plate can be opened and closed using a mechanical lock placed inside the base. This plate will work as a keyboard from inside that can be used for giving input to the controller. Most of the electric circuit will be placed within the base, which is a good safety feature of the final design. Almost all the load in the system will be transferred to the bottom plate, and from it to the ground through the vertical pillar supports at the four corners.

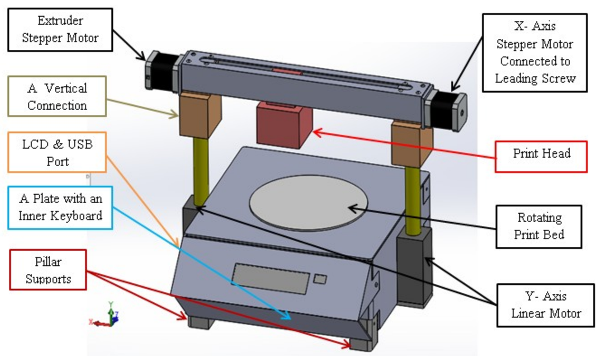

Figure 5: The final selected design

Table 4: Comparing Important Features, Uniqueness and Problems Associated with Each of the Conceptual Designs

	1st Design	2nd Design	3rd Design	4th Design
Important Features	• Ability to print 60*60*40 mm^3 object • Achieve the resolution size (0.4mm) • Circular base to give a good vibration distribution • A good thermal distributer	• Print maximum printed size of 60*60*40 mm^3 • Provide maximum working space • Has good housing - prevent the dust to go inside • Machining parts can be machined using the locally available equipment	• Can print the required size of 60*60*40 mm^3 • Assemble motors are to prevent heat dissipation to microcontroller and LCD screen • Unheated print bed • Data transfer to the printer by USB, SD card and Wi-Fi	• Printing space of 60*60*40 mm^3 • Overall dimension of the printer: 14 cm * 18 cm * 35 cm • Unheated printing bed • The printing bed is a rubber conveyor belt • File transfer via SD card or USB • LCD Display at the side
Uniqueness	▪ Rotating Bed and eliminate Y-axis	▪ Most cross sections are standards and available in the local market ▪ Housing	▪ Telescoping tubes is never used in any 3D printers yet ▪ Not many printer use Wi-Fi as connectivity	▪ The printed object can be detached from the printing bed automatically after finishing the printing process ▪ Can print objects larger than the printing bed
Problems	• Difficult to manufacture circular shell base	• The beam carrying the print head has high possibility of deflection	• Manufacture and control of telescopic tubes	• Problems associated with using the rubber conveyor belt for long time • Possibility of slipping

4. Detail Design

4.1 Revisiting The 3D Printer Design

Any design process that aims to produce a new product is challenging, yet very interesting and motivating. The design is always subjected to lots of changes during the product development phase due to many factors such as design constraints, environment, availability of resources, complexity of the product, etc. Same is true in our design. This section is dedicated to illustrate additional changes that the printer's design has gone through between the final selected concept, discussed earlier, and the design that was prototyped.

From Figure 5, the first change is the corner supports. Initially, they were to be square hollow tubes that would be welded to the bottom plate. However, a better idea was approached later; which is to use lead screws that are capable of supporting the whole structure. This was much better idea since, unlike welded parts, it allows the user to disassemble and reassemble the structure easily as well as adjusting the level of the plates to make them horizontal by just rotating the nuts. The second change was to use ball screws attached to BLDC motors to provide the motion along the Z-direction instead of just using linear motors for that purpose. Higher efficiency and less operational noise were the major reasons to select the ball screws and BLDC motors over the linear motors. Although the programming of the BLDC motors was still quite challenging, the linear motors would have been even more difficult for the design. The third and last significant change that took place in the design was using a print bed that moves linearly along the Y-axis instead of having a print bed that rotates about the Z-axis. After having more insight into the print bed motion and imagining how the printing process will go if the bed was rotating, the design team has found that there would be interferences at some filament deposition locations on the bed that would eventually lead to bad quality prints. Therefore, it was decided to select a bed that moves linearly along the Y-axis to have better quality of printed products'. Figure 6 illustrates the 3D CAD model of the final revisited design of the 3D printer as generated using SolidWorks® software.

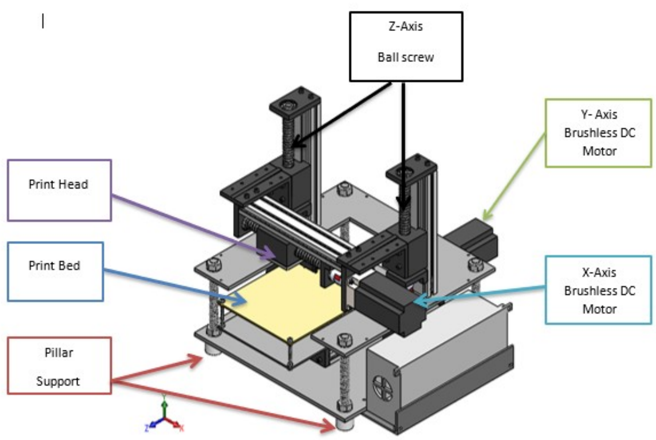

Figure 6: The final revisited design of the 3D printer

4.2 Detail Design and Selection of Components

Generally, within the design cycle of a specific product, the aim of the designers is to reduce its costs to the minimum possible value without affecting its performance. One of the efficient approaches to achieve this goal is to determine the source of various components in the system. In other words, whenever a component is to be used in our 3D printer, it will be obtained from one of the following sources: standard parts (available in the market) or complete design and manufacture of components. Using standard parts would always be the cheapest solution, and having to design and manufacture will be a costly solution. All components of this project are listed below in Table 5 and further design calculations are done based on the following three categories: a) Design (D), the component will be designed and fabricated using local resources; b) Select (S), the components will be selected and purchased based on technical specifications; c) Design and Select (D&S), the components will be first designed and then selected or manufactured.

4.2.1 Screw

The ball screw is one of the most critical components because it is responsible to move the extruder from one point to another in order to print the product. Therefore, one has to confirm that it will sustain the load that it will carry without having any significant deformation that might affect the precision of the print process. Hence, the deflection of the ball screw needs to be determined. The selected ball screw (16 mm diameter and pitch of 5 mm) is of larger dimension as compared to the designed screw (8 mm diameter and pitch of 2mm) due to market availability. There are two loads that can cause the deflection, which are the weight of the ball screw and the extruder's applied load. Free body diagrams of both loads are shown in Figure 7. The maximum deflection calculated was $0.737*10^{-6}$m. Since the total deflection is much smaller than the minimum specified layer thickness ($100*10^{-6}$m), this ball screw would be fine for our design. In addition, simulation was done using finite element method to determine the total deflection. Figure 7 shows that the deflection contour obtained by simulation with a maximum value of $0.763*10^{-6}$m, which is close to analytical value.

Table 5: List of Components and their Classification

Component #	Component	Quantity	Designed (D)/ Selected (S)
1	Printer Structure	1	D
2	Motors	5	D&S
3	Ball screw	4	D&S
4	Linear Motion Guides	4	S
5	Controller	1	S
6	Extruder with heat sink	1	S
7	Nozzle	1	S
8	Power Supply Unit	2	S

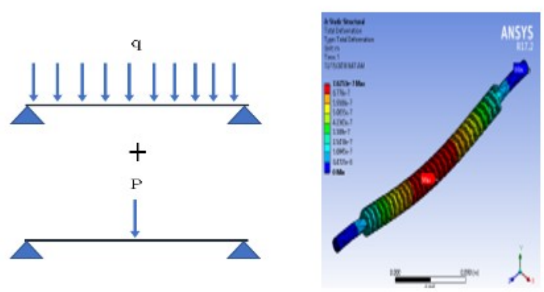

Figure 7: FBD of Screw (Left) and FEA Maximum Deflection Result of Screw (Right)

4.2.2 Motor and Controller

First the motion profile was generated for the motor based on its velocity and for what percent of the time will it accelerate and decelerate. The standard norm is to use 5% each for acceleration and deceleration.

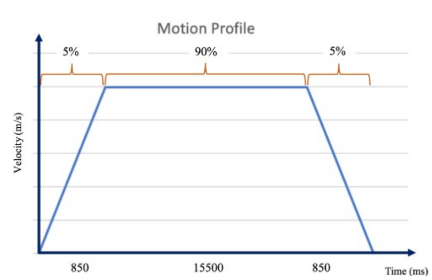

Figure 8: Motion Profile for the Motor

From Figure 8 and additional power and acceleration calculations, either the stepper or brushless DC (BLDC) motor could be used. The 3D printer requires a total of five motors i.e. four for motion control and one for extrusion purpose. Therefore, a controller is required to control and organize the motion of the motors to meet the design specifications such as the print speed, resolution of the layers, positioning as well as to control the heating element of the extruder to reach the melt temperature and to dissipate unnecessary heat to avoid adverse effect on adjacent components. After searching among the available controllers in the market, we have shortlisted two possible choices, which are the Arduino and CNC NVUM. Finally, by comparing between these two types, we established that the NVUM is better than Arduino because it is regarded as professional controller.

4.2.3 Printer Structure

The main purpose of the structural component is housing. The function of the housing is to hold all components like the motors, controller and link structure and protect it from dust. The structural part includes two aluminum plates which are the top and bottom plates, steel studs, nuts and washers that connect the two plates, acrylic side plates and the print bed which is made of brass. Aluminum plates were chosen because they were the only locally available material, which was light in weight yet strong. Brass was selected to be the material for the print bed as it is easy to polish and have better surface finish.

5. Results and Discussion

After assembling all components, the final step was to complete this project was to model some drawings on SolidWorks® software and print with the 3D printer. First simple drawings were made, and then more complicated drawings were experimented with. Figure 9 shows the results from left to right for the trial runs.

Figure 9: Various trials of 3D printed objects

After successfully printing these objects, the next task was to check the repeatability of the 3D printer to determine whether it can print objects with same dimensions and accuracy for a given product. From Figure 9, the second object from the right was chosen to be repeatedly manufactured. This object was chosen because it has many geometric features. Figure 10 shows the same object printed twice but with different colors.

Figure 10: Same object was printed three times to check repeatability

Table 6 shows the difference in the dimensions of all three printed objects. When comparing the average dimensions to the actual dimensions, it can be seen that the width error is less than five percent, which is acceptable. However, the reason for the increase in percentage error difference of the height is because one edge of the height is very sharp. This sharp edge was not printed properly due to the fact that our nozzle diameter is large and could not deposit material at the tip.

Table 6: Results from repeatability test

Dimension	CAD Model (mm)	White (mm)	Grey (mm)	Green (mm)	Average (mm)	Error (%)
Height	30	27.3	27.86	27.56	27.57	8.1
Width	20	20.6	20.9	20.5	20.67	3.33

6. Conclusion

A 3D printer is designed in this final year project based on FDM process. Initially, four different concepts were generated following a set of design specifications. The final concept was developed through a selection process and combining the good features from others. It had the print bed moving linearly along Y-axis while the print head moves along the other two axes. In detail design calculations, decisions were made to select a component based on design calculations or manufacturing by ourselves in the workshops. Standard parts like motors and controller were selected and bought online. A CNC controller was used to control all movements and the filament feed. Load determination and safety calculations for the housing and the printer structure were done and found to be safe. All the standard parts and fabricated parts were then assembled to build the 3D printer. Finally, a dry run was done to test the complete motion system of the printer. Once the dry run was successful, the printer was finally assembled and then tested by modeling an object on SolidWorks® software and then printing it using our 3D printer. After couple of unsuccessful attempts and error debugging processes, the printer worked excellently to print different products. It was noted that the printer can print simple to moderately complex objects with exact dimensions but for complicated models it needs better nozzle. The surface roughness of the printed objects varies with its complexity. Furthermore, the printer was tested to print the same object multiple times with different colors, and it was found to have an excellent repeatability.

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Biographies

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