



# **Fused-Deposition-Modeling 3D printer**

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Submitted to the College of Engineering  
in partial fulfillment of the requirements for the degree of  
Bachelor degree in Mechatronics Engineering

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# شكر وتقدير

بعد أن من الله علينا بفضله وكرمه وجوده جل في علاه بإنهاء هذا المشروع فإننا نتقدم بجزيل الشكر والعرفان لكل من ساعدنا و ساهم معنا في انجاز هذا العمل ونخص بالذكر مشرفنا الأستاذ الدكتور كريم طهبوب، ومساعد المشرف المهندس جاسر المحتسب.

كما ونتقدم باسمنا واسم كلية الهندسة بجامعة بوليتكنك فلسطين بالشكر من كلية الهندسة في جامعة القدس على جهودها الحثيثة في مساعدتنا بتوفير المواد الخام وطباعة القطع المستخدمة في مشروعنا نخص بالذكر المهندس محمد شناعة الذي لم يأل جهدا في مد يد العون لنا وتزويدنا بما لديه من خبرات لاتمام هذا العمل.

## Abstract

3D printer is a machine used to make three dimensional solid objects from a CAD "Computer Aided Design" models using additive manufacturing process where designed object divides into small layers then prints layer over layer. FDM "Fused-Deposition-Modeling" 3D printers uses a PLA thermoplastic filament, which is heated to its melting point then extruded on a heated plate through a nozzle. The printer mechanism is based on Cartesian robot style which moves an independent linear motion in each of 3 axes (X, Y and Z) to print the desired shape. Printing process starts by converting CAD design into layers (slicing) then generates G-code instructions using specific software after that, the G-code instructions will be transferred to 3D printers' microcontroller which drives the actuators according to these instructions to print the desired model. The printer motion is an open loop system without feedback control. The heat of the extruder and heated plate controls using software PID controller. The aim of this project is to build and implementation a first FDM 3D printer in Palestine Polytechnic University, additionally trying to add some features such as wireless printing capability and fault detection system. The printer

## ملخص

يهدف هذا المشروع إلى بناء وتشغيل وإضافة بعض الميزات واختبار طابعة FDM ثلاثية الأبعاد، حيث أن تصميم الطابعة متوفر كمصدر مفتوح على الشبكة العنكبوتية. الطابعة ثلاثية الأبعاد هي عبارة عن آلة تعمل على تحويل الرسومات والتصاميم ثلاثية الأبعاد- المرسومة باستخدام برامج الرسم على الحاسوب- إلى مجسمات ثلاثية الأبعاد. وذلك عن طريق وضع طبقات متتالية من المادة المطبوعة فوق بعضها البعض فيما يعرف بتكنولوجيا "التصنيع بالإضافة". تستخدم طابعات FDM خيوط بلاستيكية رقيقة تسخن إلى درجة الانصهار ومن ثم يتم بثقها عبر فوهة فوق صفيحة ساخنة حسب الكمية والمسار المحدد من خلال ال G-code لإنتاج الشكل المطلوب. تبدأ عملية الطباعة بتقسيم التصميم ثلاثي إلى الأبعاد إلى عدة طبقات باستخدام برنامج خاص والذي يقوم أيضا بإنتاج الأوامر والتعليمات التي ترسل إلى المتحكم الدقيق للطابعة والذي يقوم بتنفيذ هذه التعليمات عن طريق التحكم بحركة المحركات. يعتمد تصميم الأجزاء المتحركة للطابعة على نظام الروبوت الديكارتي والذي يتحرك حركة خطية مستقلة في كل من المحاور الثلاثة. نظام التحكم بحركة الطابعة هو نظام لا يحتوي على تغذية راجعة، أما التحكم بالحرارة فيتم باستخدام متحكم "PID".

# List of Contents

شكر و تقدير .....	III
Abstract .....	IV
List of Contents.....	V
List of Figures.....	VIII
List of Tables.....	XI
List of Abbreviations.....	XII
<b>CHAPTER 1: Introduction</b> .....	<b>1</b>
1.1    3D Printing overview .....	2
1.1.1    What is 3D printing? .....	2
1.1.2    History .....	2
1.1.3    3D Printing technologies .....	3
1.1.4    FDM 3D printer styles.....	5
1.1.5    Advantages of 3D printing.....	7
1.1.6    Disadvantages of 3D printing .....	8
1.1.7    Limitation of printed shapes .....	8
1.1.8    Applications .....	10
1.2    This project.....	10
1.2.1    Project idea.....	10
1.2.2    Project objectives .....	11
1.2.3    Project Schedule and Time Plan .....	11
1.2.4    Final approximate cost .....	13
<b>CHAPTER 2: The design and the component</b> .....	<b>14</b>
2.1    Conceptual Design.....	15
2.2    Specification .....	16
2.3    The Design and the Components .....	17
2.3.1    The frame .....	17
2.3.2    Stepper motors.....	18
2.3.2.1    Stepper motor specification.....	18
2.3.2.2    Calculation of steps per millimeter .....	19
2.3.3    The Extruder .....	20
2.3.4    Printplate.....	20
2.3.5    Horizontal motion along the Y-axis .....	21
2.3.6    Motion along Z-axis and X-axis.....	22
2.3.7    Megatronics V2.0 controller board .....	23

2.3.8	Endstop switches.....	25
2.3.9	Raw material (Thermoplastics).....	25
2.4	Software .....	26
2.4.1	3D modeling software .....	27
2.4.2	Slicer .....	27
2.4.3	Pronterface: supervision and control interface .....	27
<b>CHAPTER 3: Mathematical model .....</b>		<b>28</b>
3.1	Introduction.....	29
3.2	Forward kinematics .....	29
3.3	Jacobian matrix.....	30
3.4	Dynamic model.....	31
<b>CHAPTER 4: Test and assembly .....</b>		<b>34</b>
4.1	Introduction.....	35
4.2	Stepper motor module .....	35
4.2.1	Operating the stepper motor with Pololu A4988 driver .....	35
4.2.2	Operating the stepper motor with Pololu DRV8825 driver.....	37
4.3	Assembly .....	39
4.3.1	Y axis assembly .....	39
4.3.1.1	Assembly steps .....	39
4.3.1.2	Testing of Y axis .....	44
4.3.2	Z axis assembly .....	45
4.3.3	Extruder mechanism assembly.....	50
4.3.4	X axis assembly.....	53
4.4	Finishing.....	56
<b>CHAPTER 5: Practical work and experiments .....</b>		<b>58</b>
5.1	Introduction.....	59
5.2	Printing procedure .....	59
5.3	Simple cube print .....	59
5.4	Curved object printing.....	62
5.5	Extruder small gear .....	63
5.6	Simple test for support material .....	63
<b>CHAPTER 6: Future work and adding features .....</b>		<b>65</b>
6.1	Introduction.....	66
6.2	Adding features .....	66
6.2.1	Wireless 3D printing .....	66
6.2.2	Monitoring and display.....	67

6.2.3	Fault diagnosis and detection.....	68
6.2.4	Fail-safe.....	69
6.2.5	Z axis endstop calibration device.....	69
<b>Appendix A</b>	.....	<b>76</b>
<b>Appendix B</b>	.....	<b>76</b>
<b>User Manual</b>	.....	<b>76</b>
<b>References</b>	.....	<b>93</b>

# List of Figures

## CHAPTER 1: Introduction

Figure 1.1 SLA process.....	3
Figure 1.2 SLS process .....	4
Figure 1.3 FDM process.....	5
Figure 1.4 Delta robot 3D printer.....	6
Figure 1.5 Delta and Cartesian 3D printer styles.....	6
Figure 1.6 45 degree overhang layers.....	9
Figure 1.7 types of overhangs .....	9
Figure 1.8 Big and small holes .....	9
Figure 1.9 Filed horizontal overhangs .....	10

## CHAPTER 2: The design and the component

Figure 2.1 3D printing process work flow .....	16
Figure 2.2 3D CAD model .....	16
Figure 2.3 3D view .....	17
Figure 2. 4 connection way of the wooden parts.....	18
Figure 2.5 NEMA 17HS8401 stepper motor.....	18
Figure 2.6 the extruder.....	20
Figure 2.7 Printplate.....	21
Figure 2.8 Top view of the CAD model.....	21
Figure 2.9 linear bearing.....	22
Figure 2.10 MK2 heatbed .....	22
Figure 2. 12 X-end motor part.....	23
Figure 2.11 X-end idler part.....	23
Figure 2. 13 Front view of the 3D CAD model.....	23
Figure 2.14 Megatronics V2.0 controller.....	24
Figure 2. 15 connection circuit with other electronics parts .....	24
Figure 2. 16 endstop switch .....	25
Figure 2.17 PLA filament .....	25
Figure 2.18 3D printing used software stages.....	26
Figure 2.19 slicing principle .....	27

**CHAPTER 3: Mathematical model**

Figure 3. 1 3D printer diagram ..... 29

**CHAPTER 4: Test and assembly**

Figure 4. 1 motor wiring with pololu A4988 ..... 35

Figure 4. 2 Arduino program to control the A4988 driver ..... 36

Figure 4. 3 Microstepping resolution truth table..... 36

Figure 4. 4 Stepper motor wiring with pololu DRV8825 ..... 37

Figure 4. 5 position profile ..... 37

Figure 4. 6 Arduino program to operate the stepper motor as specified profile ..... 38

Figure 4. 7 Base and power supply..... 39

Figure 4. 9 Motor with T.5 pulley and two ball bearings ..... 40

Figure 4. 8 Y axis base..... 40

Figure 4. 10 Front and back wood frame assembly ..... 40

Figure 4. 11 The lower side of the print bed ..... 41

Figure 4. 12 The upper side of the print bed..... 41

Figure 4. 13 Y axis rods fixed with frame ..... 42

Figure 4. 14 Print bed connecting with timing belt..... 42

Figure 4. 15 Print bed connecting with timing belt..... 43

Figure 4. 16 Heatbed connecting on print bed ..... 43

Figure 4. 17 Y axis testing code ..... 44

Figure 4. 18 Fixed Z axis motor..... 45

Figure 4. 19 Fixed nut in printed part..... 45

Figure 4. 20 Fixed bearings in printed part ..... 46

Figure 4. 21 5/8mm Aluminum coupler on motor shaft ..... 46

Figure 4. 22 X axis motor on printed part ..... 47

Figure 4. 23 pulley on printed part..... 47

Figure 4. 24 Threaded and smooth rods upper end..... 48

Figure 4. 25 X axis rods in printed first part ..... 48

Figure 4. 26 X axis rods in printed second part ..... 49

Figure 4. 27 Z axis balance text ..... 49

Figure 4. 28 Ball bearing on extruder printed part ..... 50

Figure 4. 29 Extruder parts..... 51

Figure 4. 30 small and big printed gear .....	51
Figure 4. 31 full assembled extruder mechanism .....	51
Figure 4. 32 Hot end test.....	52
Figure 4. 33 material extrusion test .....	52
Figure 4. 34 First X axis printed part.....	53
Figure 4. 35 second X axis printed part .....	53
Figure 4. 36 bearings under extruder.....	54
Figure 4. 37 Timing belt fixing with extruder .....	54
Figure 4. 38 Y axis endstop switch.....	55
Figure 4. 39 Z axis endstop switch.....	55
Figure 4. 40 X axis endstop switch .....	56
Figure 4. 42 untidy wires .....	56
Figure 4. 43 tidy wires .....	57
Figure 4. 44 End result of the assembly .....	57

## **CHAPTER 5: Practical work and experiments**

Figure 5. 1 25x25x25 mm cube .....	59
Figure 5. 2 cube printing first trial.....	60
Figure 5. 3 cube printing second trial.....	60
Figure 5. 4 cube printing third trial .....	61
Figure 5. 5 cube printing trial result.....	61
Figure 5. 6 curved object 1.....	62
Figure 5. 7 curved object 2 .....	62
Figure 5. 8 Extruder small gear.....	63
Figure 5. 9 Simple curved object with support material .....	63
Figure 5. 10 Simple curved object without support material .....	64

## **CHAPTER 6**

Figure 6. 1 comparison between wireless technologies .....	66
Figure 6. 2 HC-06 Bluetooth module .....	67
Figure 6. 3 wiring connection of LCD with Megatronics controller.....	68
Figure 6. 4 The expected location of the optical sensor .....	69

# List of Tables

<b>Table 1.1:</b> First semester time plan .....	12
<b>Table 1.2:</b> Second semester time plan .....	13
<b>Table 1.3:</b> Final approximate cost .....	13

# List of Abbreviations

FDM	Fused Deposition Modeling
CAD	Computer Aided Design
PID	Proportional-Integral-Derivative
AM	Additive manufacturing
SLA	Stereo Lithography Apparatus
UV	Ultraviolet
SLS	Selective Lased Sintering
FFF	Fused Filament Fabrication
DOM	“ Digital Object Maker”
PLA	Polylactic Acid
CAM	Computer Aided Manufacturing
STL	Stereo Lithography
ABS	Acrylonitrile Butadiene Styrene
NC	Numerical Control
CNC	Computer Numerical Control

# **CHAPTER 1**

## **Introduction**

## 1.1 3D Printing overview

### 1.1.1 What is 3D printing?

3D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive manufacturing process (AM), where successive layers of material are laid down in different shapes. This makes it different from traditional machining techniques (subtractive processes), which depends on removal of material by methods such as cutting or drilling [1].

The 3D printing technology is used for both prototyping and manufacturing with applications in architecture, construction, industrial design, education, food and many other applications.

### 1.1.2 History

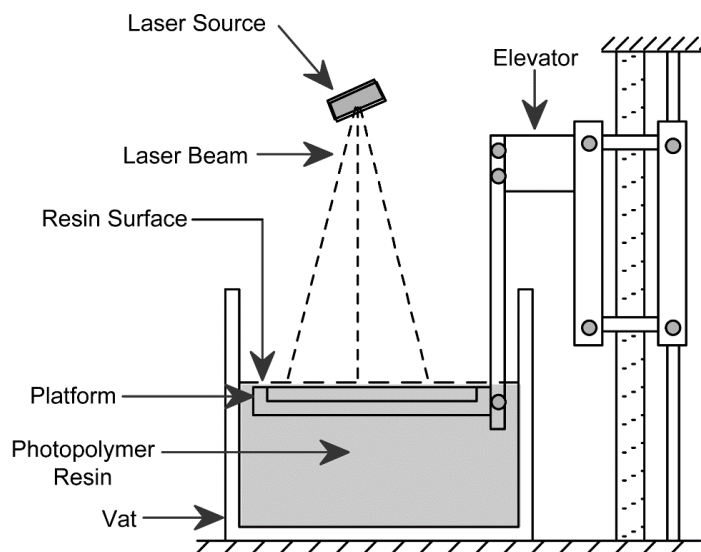
- In 1980's the earliest 3D printing technologies starts. They were called Rapid Prototyping (RP) at that time. This technology was first developed by Charles Hull in 1984. He named the technique as stereo lithography apparatus (SLA) as (explained in section 1.1.3.1). A patent for that technique was issued in 1986 [2].
- In 1986: Carl Deckard files for a patent for selective laser sintering (SLS), another 3D printing technology (as explained in section 1.1.3.2). The first commercial machines are built in 1989 by DTM [3].
- In 1991, Fused Deposition Modelling (FDM) which is a new technology of 3D printing (as explained in section 1.1.3.3) was available from "Stratasys" [2].
- In 2000's – Introduction of new printing materials (biocompatible materials, metals, wax and even cells) [2].
- In 2005, Z Corp. launched a breakthrough product, named Spectrum Z510, which was the first high definition color 3D Printer in the market [2].
- In 2007 another breakthrough in 3D Printing occurred with the first generation of an open source project, named Rep-rap, which was aimed at developing a self-replicating 3D printer [3].
- In 2009 commercially 3D printer available in kit form and based on the Rep-Rap concept was offered for sale [2].

### 1.1.3 3D Printing technologies

#### 1. StereoLithography Apparatus (SLA)

Stereo lithography (SLA) was one of the earliest commercial methods of 3D printing. The printer sweeps a laser beam over the surface of a special type of plastic, a UV-sensitive photopolymer that hardens when exposed to UV light. Each sweep of the laser traces the outline and cross section of the printed shape in consecutive layers. After each sweep of the laser, a moveable table which holding the printed part is lowered a fraction of a millimeter equals to the thickness of one layer. The part sinks a bit into the liquid, and fresh photopolymer floods the top side of it. But there is some SLA printers work in the opposite direction by aiming the laser upwards into the photopolymer, then lifting the printed object to flood its base with fresh liquid [4]. SLS process is shown in *Figure 1.1*.

When the printing process complete, there is some work still to be done. Excess material needs to be rinsed off and the surfaces sometimes need to be sanded by hand. Depending on what's printed, sometimes further curing is done in an UV light oven [4].

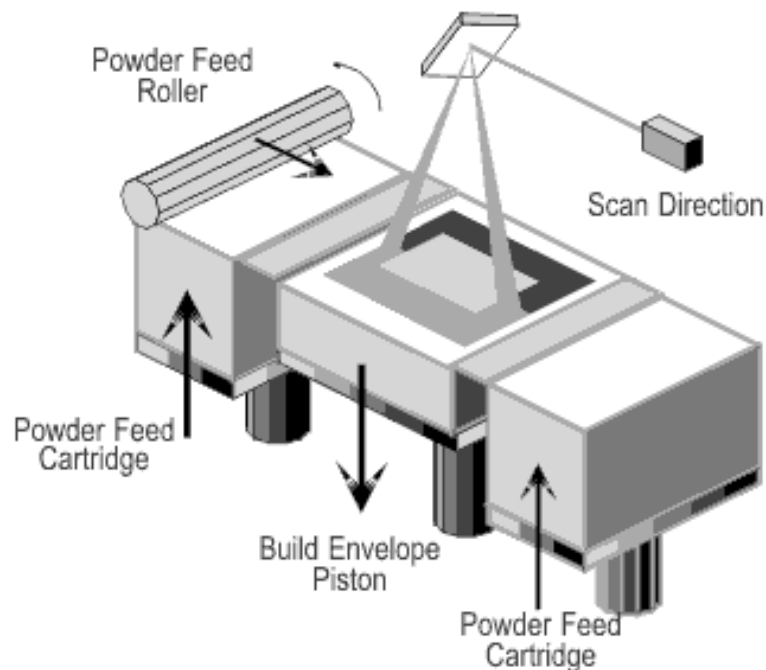


*Figure 1.1 SLA process*

## 2. Selective Laser Sintering (SLS)

Selective laser sintering follows a technique similar to SLA, but instead of using liquid photopolymers, SLS printers use powder. SLS process is shown in *Figure 1.2*. These printers trace a high-power laser beam over the surface of a bed of powder. The powder melts where impact by the laser. A roller inside the printer brushes a fresh layer of powder on the top and lowers the print bed a distance equal to a layer thickness [4].

Printing with powder instead of liquid materials has some advantages. An object printed in powder is less likely to collapse during the printing process since the unfused powder acts as a built-in support. In some cases, unused leftover loose powder can be recycled and used in another print job. Also powdered material is more versatile because many raw materials can be obtained in powdered form, including powdered nylon, steel, bronze, and titanium. On the downside, SLS printers create objects whose surface tends to be not smooth. SLS printers currently cannot print different types of powders at once time. SLS printers are not yet a good fit for home or office use, because it is expensive and some powders have a tendency to explode if handled incorrectly. An SLS printer requires a sealed chamber filled with nitrogen. Also the SLS printing process is hot. A completed printed object cannot be removed quickly out of the machine. Depending on the size and thickness of the layers, larger parts might need to cool for up to a day [4].



*Figure 1.2 SLS process*

### 3. Fused deposition modeling (FDM)

The FDM technology, which also called Fused Filament Fabrication (FFF), creates objects from molten plastic extruded through a nozzle as shown in *Figure 1.3*. The plastic filament is heated by a thermal resistance then it is supplied to the extrusion nozzle while the nozzle or the object (or both) are moved along three axes by a computer-controlled mechanism. The material hardens immediately after extrusion. Stepper motors or servo motors are typically used to drive all of these movements, as well as for pushing the filament into the extruder [1].

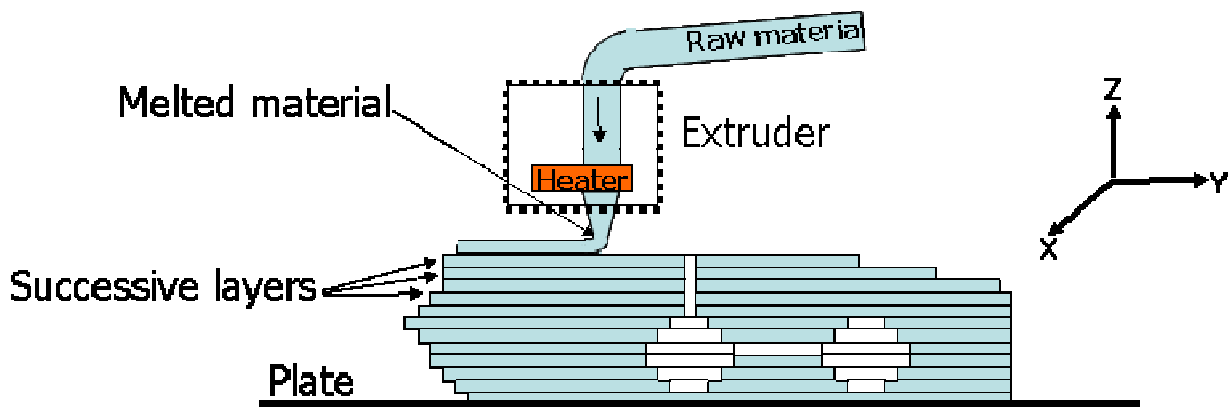


Figure 1.3 FDM process

#### 1.1.4 FDM 3D printer styles

There is two common styles of FDM 3D printer, one is based on Cartesian serial robot, and other is kind of Delta parallel robots.

##### 1. Delta style FDM printer

Delta 3D printers are one application of Delta robots, which are a type of parallel robots. Delta printer shown in Figure 1.4 uses fixed print bed and three vertical rods arranged in an equilateral triangle each rod attached to an independent stepper motor. Also every rod is connected to a central carriage, which known as end effector in delta robots, and hotend or nozzle in 3D printer, with two arms. The end effector would stay parallel with the printplate by fixing the pairs of arms parallel to each other The central carriage have three degree of freedom and it is moved in X-Y-Z-space by moving the carriages on the vertical rods up and down[5].

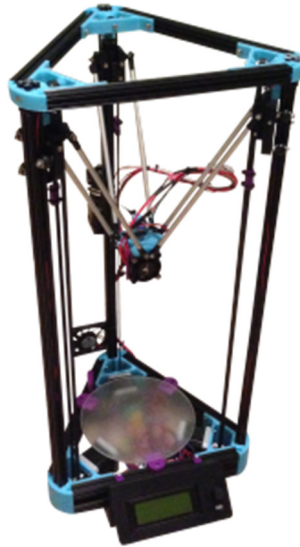


Figure 1.4 Delta robot 3D printer

## 2. Cartesians style FDM printer

These 3D printers style is an application of Cartesian robot which is a machine that moves in three linear direction (X, Y and Z) by using individual motor for each axis that means the movement of each axis is independent from other axes. The motion transmitted from motors using sliding joints, belts and pulleys or screws [6]. *Figure 1.5* shows Cartesian and Delta 3D printers principle of motion.

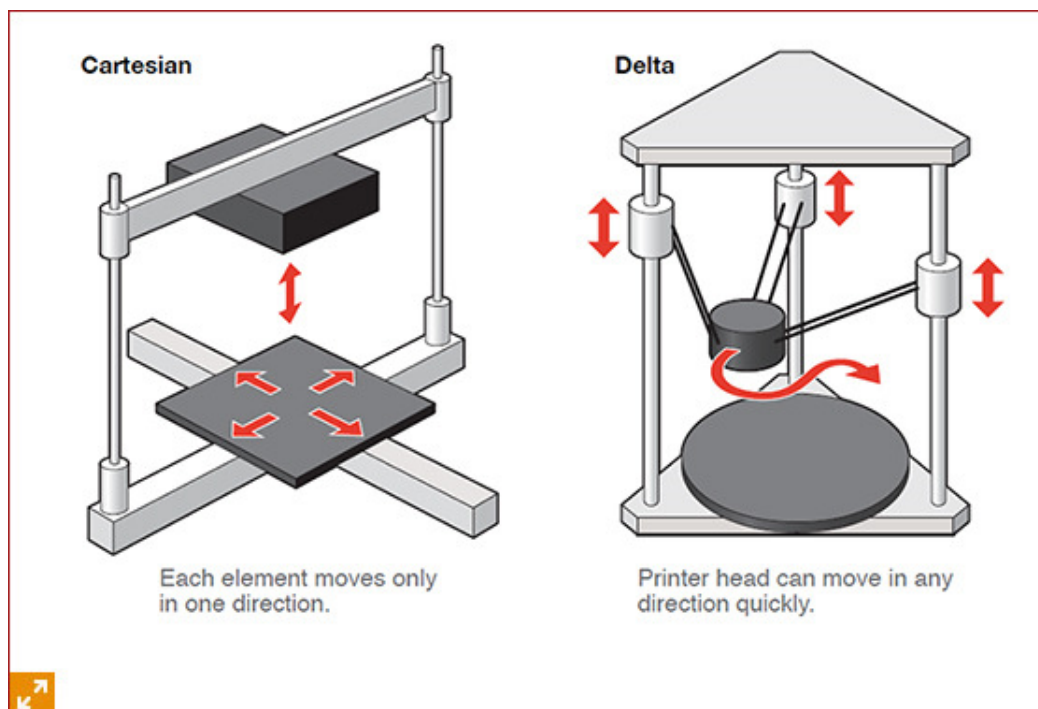


Figure 1.5 Delta and Cartesian 3D printer styles

Delta printers have lightweight moving parts so it is easier to move and faster in printing than Cartesian, and they can move equally speed in three axes. Because its fix print bed there is no effect of printed objects' weight so delta is better in building higher objects. The overall construction is less complicated and uses less parts so it will be lower weight [5].

In down sides the construction of Delta printer must be much taller than the maximum printed height. Also to estimate the nozzle position much more complicated mathematical model should be used this is making control and calibration more difficult. The X,Y,Z axes movement are dependent on each other that will make mechanical problems harder to track down and fixed [7].

On other side Cartesian printers is more common, and it is using easier way to move and control because the movement of each axis is independent from other axes so it is much easier to calibrate and use, but the moving part are quite heavy so it will be less accurate, harder to move and slower than Delta.

### **1.1.5 Advantages of 3D printing**

- Rapid prototyping: Engineers and designers have been using 3D printers for more than a decade mostly to make prototypes rapidly and cheaply.
- Customizations: 3D printing processes allow for mass customization the ability to personalize products according to individual needs and requirements.
- Close to zero waste: Creating parts layer by layer (additive manufacturing) instead of subtractive traditional methods leads to less amount of waste and lower costs in raw material.
- Complexity: 3D printing can create many complex shapes which cannot be made by traditional manufacturing processes.
- Toolless: For low to medium volume applications industrial 3D printing can eliminate the need for tool production therefore, the costs, lead times and labor associated with it will decrease.

### 1.1.6 Disadvantages of 3D printing

- Size limitations: Printing size is limited by the dimensions of the printer. Typical printing volume of common FDM printers is 20x20x20 cm<sup>3</sup> [1].
- Energy consumption: When melting plastic with heat or lasers, 3D printers consume about 50 to 100 times more electrical energy than injection molding to make an item of the same weight [8].
- Air emissions: 3D printers may pose a health risk when used in the home, according to researchers at the Illinois Institute of Technology. The emissions from desktop 3D printers are similar to burning a cigarette [8].
- Shape: some models and shapes cannot be printed using 3D printer or they are need some kind of support structures (This will be explain in section 1.1.7).
- Build time: the time a part spends in the machine to be printed. In general 3D printing takes long time, maybe few hours depending on the size of object.
- Materials: the ability of printing only materials that can be extruded through a nozzle, and cannot print different types of materials at the same time [4].

### 1.1.7 Limitation of printed shapes

FDM 3D printers usually cannot produce extreme overhangs. Because parts are built layer-by-layer, each layer must be supported by something underneath it. If these cannot be avoided, an extra thin support structure may be added into the object, which can be broken or cut away after the print process. Most slicing software can create automatically such support structure [1].

Support material is the scaffolding that is generated to support overhanging geometries, which wouldn't be printable otherwise without any support below them. Support material is very often generated using the same material as the object, in this case the software needs to find the best compromise between the support effectiveness and its removability to be able to remove it after printing.

#### Tips for designing a printable 3D object

To avoid droop in 3D printed object if there is no supporting, this tips are recommended for 3D model design [1]:

1. Overhang should be less than 45 degrees, because each layer on a 45 degree slope is offset exactly 1/2 bead width from the layer below it as shown in *Figure 1.6*. Otherwise it cannot be printed without supporter. *Figure 1.7* shows the ability of print each type t of overhangs.

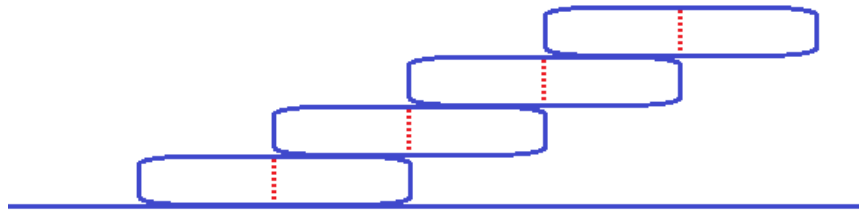


Figure 1.6 45 degree overhang layers

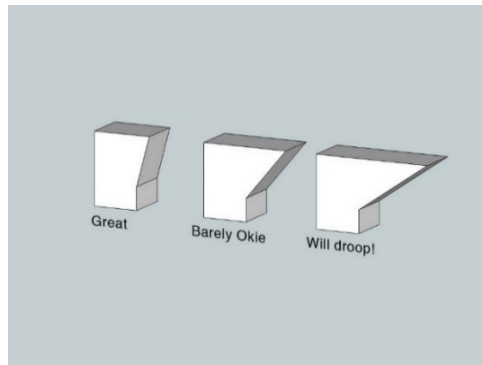


Figure 1.7 types of overhangs

2. Big holes should be avoided in the models. For example a 2mm circular hole will print just fine with no tear dropping, but a 2 centimeter hole will start to get droopy loops this shown in *Figure 1.8*.

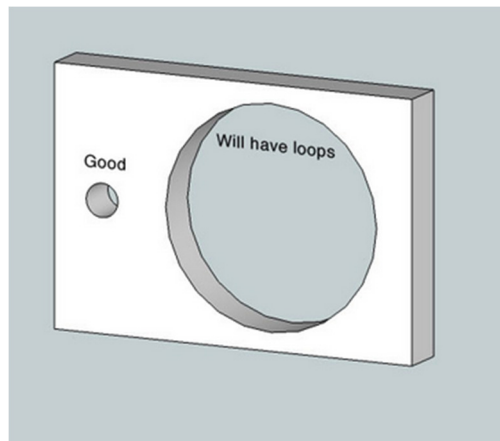
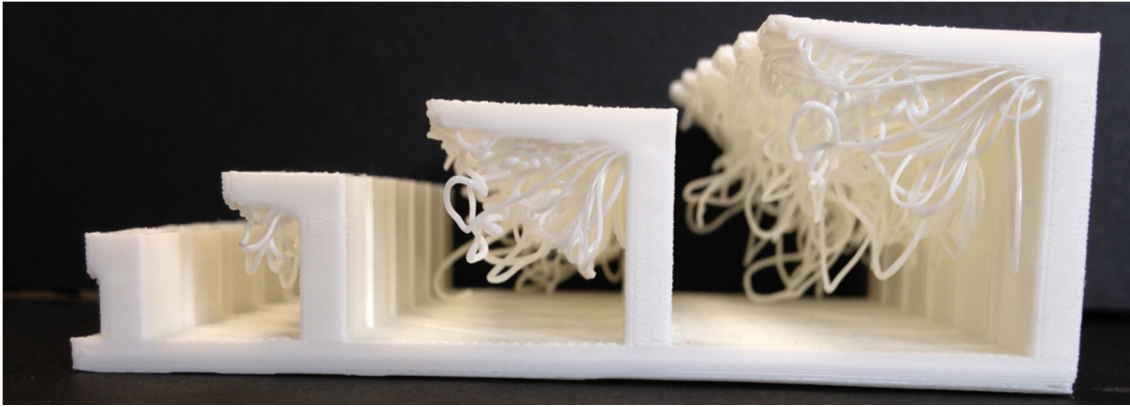


Figure 1.8 Big and small holes

3. Strongly extended horizontal overhangs also should be avoided. If an edge of a layer is resting almost on air it will droop like in the *Figure 1.9* below.



*Figure 1.9 Filed horizontal overhangs*

### **1.1.8 Applications**

There is a rapid increasing in 3D printing applications. The expectations to become “A machine that can make almost anything” [4].The largest application for 3D printing is prototyping, but there is many other applications such as metal casting, architecture, education, geospatial, and healthcare. A robotics hobbyist would find a 3D printer useful for printing out small gears or wheels that are unique in size or shape and cannot be purchased in stores [9].

Nowadays, 3D printing is used to make automobiles and aircraft components, jewelry, food, fashions [10], human tissues [11] [12], and many other applications.

## **1.2 This project**

### **1.2.1 Project idea**

In this project we will design, build, implementation and test a 3D printer based on FDM technology and Cartesian robot design. We will adapt an open source design available from Fab Lab “fabrication laboratory” “under name of “DOM” Digital Object Maker. This can be found in websites [13, 14]. A Fab Lab is a community inventors’ workshop offering digital fabrication on a personal scale, in which new products can be built by both businesses and individuals [15].

This design is using a PLA “polylactide acid” plastic filament which supplies to an extrusion nozzle. The nozzle is heated to melt the PLA then extruded it in on a base which called printplate. The nozzle and printplate are moving used three dimensional Cartesian mechanism drives by stepper motors and controlled by computer to make the desired object layer by layer.

### 1.2.2 Project objectives

- Build a workable 3D printer as mechatronics design approach.
- Make rapid prototyping for many complex models difficult to produce by other processes.
- Using CAD / CAM interface to generate G-code.
- Working on precision plastic extruder for the first time in the university.
- Produce other 3D printers using parts printed by this printer which called “self-replicating” process.
- Make this 3D printer as an educational device for CAM students beside other CNC machines.
- Improve machine code and design to add some new features like monitoring and fault detection.

### 1.2.3 Project Schedule and Time Plan

- **Task 1: Select the idea**  
Determine the project’s idea, motivation, and what to be done in the project.
- **Task 2: Collecting data**  
Looking for open source design files, understanding the concept of the design, collecting information.
- **Task 3: Select mechanical and electrical parts**  
In this step the required components (hardware and software) and there costs will be determined, and starting to provide them.
- **Task 4: Dynamic modeling and Simulation**  
Mathematical model that describe the system motion should be done in this stage  
After dynamic modeling complete, then it will be simulated by using Matlab software.
- **Task 5: Documentation**  
Documenting all work steps form the first to last.
- **Task 6: Assembly and installation**  
Start building modules, then assembly parts of printer.
- **Task 7 : Testing and calibration**  
For each module by itself, then for whole collected design.

- **Task 8: Implementation and validation**  
By reaching this step the design is completely assembled. Implementation and make sure there is no problem in running the system should be achieved.
- **Task 9: Code improvement**  
After the machine works well, trying to developed code to add some features like fault detection, monitoring and fail safe.
- **Task 10: Writing graduation final report**  
Writing notes and make any necessary addition and modification for project documentation.
- **Task 11: Preparing the final presentation**  
Finally we should be ready for the project discussion day.

## First Semester:

Table 1.1: First semester time plan

Week \ Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T1	■	■	■													
T2				■												
T3					■	■	■	■	■	■	■	■	■	■	■	■
T4						■	■	■								
T5					■	■	■	■	■	■	■	■	■	■	■	
T6													■	■	■	■

## Second Semester:

Table 1.2: Second semester time plan.

Week \ Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T5																
T6																
T7																
T8																
T9																
T10																
T11																

### 1.2.4 Final approximate cost

Table 1.3: Final approximate cost

Name	Number	Price	Total Price (NIS)
NEMA 17 stepper Motors	5	136	680
Stepper motors driver	5	100	500
Extruder hot end	1	288	288
thermistor 2k	2	19	38
12v 30A power supply	1	250	250
Megatronics v2.0	1	495	495
Heatbed MK2	1	95	95
Endstop limit switch	3	11	33
Bluetooth module	1	60	60
RepRap kit	1	350	350
other mechanical parts and materials	-	-	550
Wooden frame	1	400	400
PLA 3mm 1kg	1	320	320
Wires&cables&connectors	-	-	
Bearings and Rods	-	335	335

Total cost =4394 NIS

## **CHAPTER 2**

### **The design and the components**

## 2.1 Conceptual Design

This section describes the 3D printing workflow, the inputs and the outputs of each step. 3D printing workflow which shown in *Figure 2.1* includes:

1. **3D modeling:** The first step in the process is to have a good 3D model. This model must be in form of STL file format. STL file can be produced using any 3D CAD software or downloading it from an online source. Also the model must be scaled to appropriate the maximum size of the printer.
2. **Slicing:** After preparing the 3D model, it will be ready to process for printing. Slicing process will slice the model into successive layers and generate the tool path that tells the extruder where to go and when to extrude material. This operation will be implemented using “**slic3r**” software. The user inserts a STL file for desired 3D model in “**slic3r**”, select some parameters such as the height of the layers, then “**slic3r**” generates a set of G-code [Appendix A] commands for printer to follow.
3. **Printer interfacing:** This process is done by a host application called “**Pronterface**”, which will provide some modifications on generated G-code such as the temperature for extruder and printplate. Then transferring it to the printer’s microcontroller, from this application. The user also could set and monitor the printing process, starts and cancels printing. As well, this application will provide a visual indication for the model during printing.
4. **Microcontroller processing:** The microcontroller connects with other electronics such as power supply, motor driver, and endstops by main board. There is a special code installed on microcontroller called firmware. The firmware is interpreting the G-code commands then send it to the electronics to manage the movement of all components together to build 3D objects.
5. **Three axes movement:** The design of the 3D printer is based on Cartesian robot. The printer moves in 3 axes, the movement of each axis is independent from other axes, so separated stepper motor is used to control each axis. The printplate moves horizontally in one axis. The extruder moves in other two axes. Also there is a stepper motor to feed material into the extruder.

All these motors moves by firmware code orders which control the rotation of motors until the extruder reach to specific position, and then extrude the exact amount of material on printplate.

### 3D printing work flow:

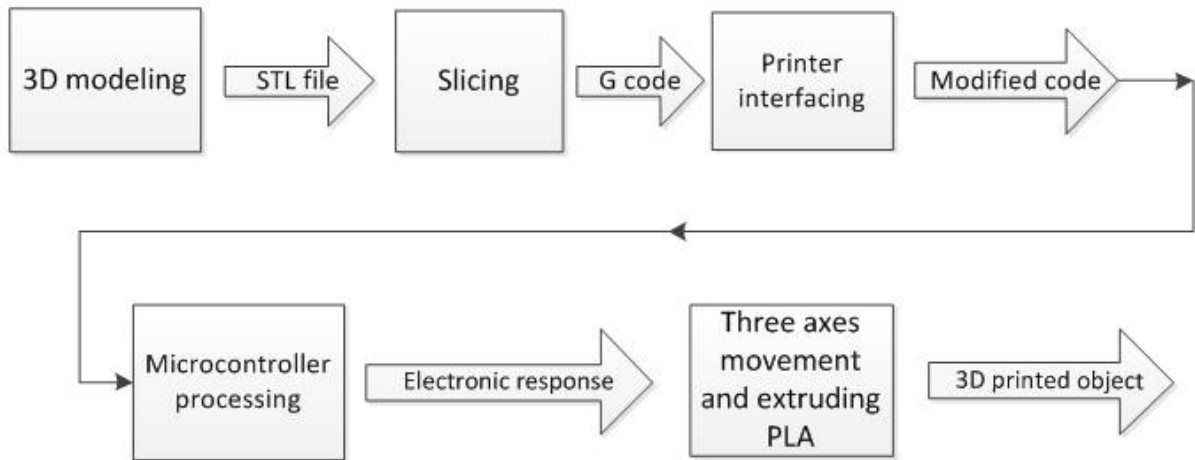


Figure 2.1 3D printing process work flow

## 2.2 Specification

The specifications of the 3D printer are based on the open source design 3D printer have the name of “Digital Object Maker V2” which available in websites [13] and [14]. This design shown in *Figure 2.2*.

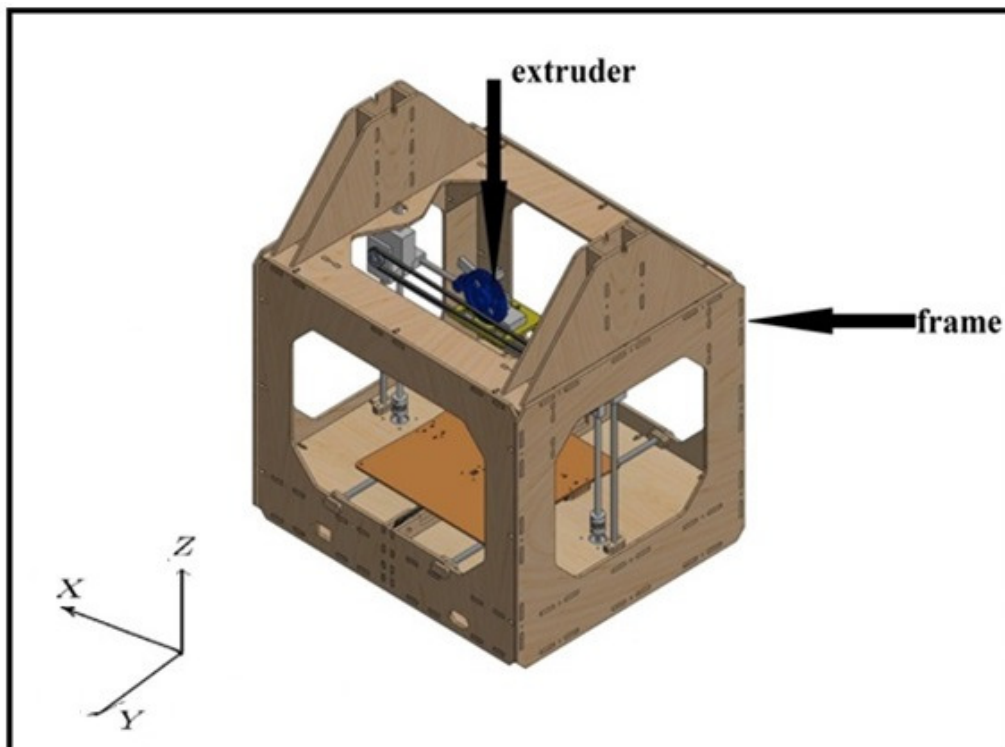


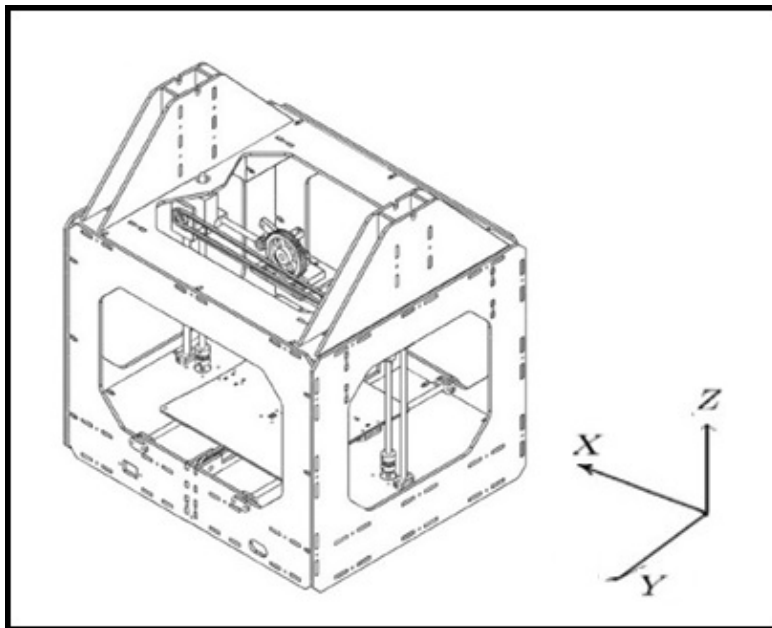
Figure 2.2 3D CAD model

- The printing material is PLA “polylactide acid” diameter of 3mm.
- Maximum print volume is 20x20x20 cm<sup>3</sup>.
- Printing speed 60 mm/s.
- Extruder heat must be in range (185-215 C°).
- Heatedbed temperature should be around 70 C°.
- The system is open loop, no feedback for moving parts, but there is a software PID temperature controller for extruder and printplate.
- The printer connects with computer using a USB port.
- The power connect to 220 V AC.

## 2.3 The Design and the Components

### 2.3.1 The frame

The frame is shown in *Figure 2.3* 3D view with dimension of 49x42x40 cm<sup>3</sup>, made from wooden parts connected together as shown in *Figure 2.4*. The three axes of the 3D printer will be added to this frame.



*Figure 2.3* 3D view

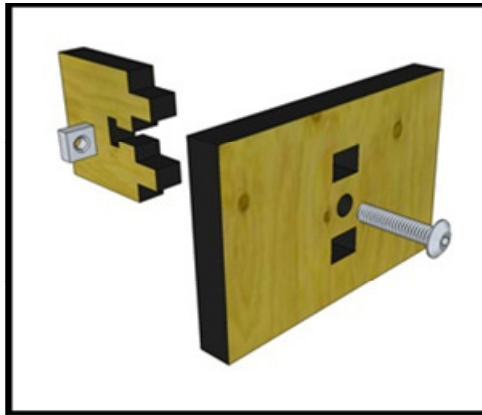


Figure 2.4 connection way of the wooden parts

### 2.3.2 Stepper motors

The 3D printer contains five stepper motors type of “NEMA 17HS8401 “shown in *Figure 2.5* motor such that:

- One to move the Y-axis components (printplate).
- One to move the X-axis components (extruder)
- Two to move the Z-axis components (X-carriage)
- One to feed the PLA through the extruder

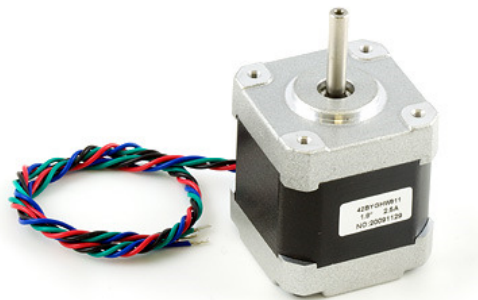


Figure 2.5 NEMA 17HS8401 stepper motor

#### 2.3.2.1 Stepper motor specification

- Series model: 17HS8401
- Step angle (degree): 1.8
- Rated current (A): 1.8
- Holding torque (N.cm): 52
- Detent torque (N.cm): 2.6
- Number of steps per revolution: 200

### 2.3.2.2 Calculation of steps per millimeter

#### X and Y-axes movement steps:

For the x- and y-axes, the following formula is used to calculate the steps per millimeter:

$$\text{steps} = \text{motor steps per revolution} \times \text{driver microstep} \div \text{belt pitch} \\ \div \text{number of teeth on pulley}$$

To start filling in these blanks, the NEMA 17 motors are of the 1.8 degrees per step variety, meaning that they move 1.8 degrees for each step of the motor; so to complete a full rotation, the motor needs to step 200 times. The stepper drivers on the control electronics are often set to a mode called microstepping, allowing the driver to move the stepper motor in increments of a normal step. So for instance, a 1/16th microstepping stepper driver is able to move the stepper motor 16 times for each 1.8 degree step. The belt pitch is determined by the distance between the teeth on the timing belt. So a T2.5 belt has teeth spaced every 2.5 millimeters. Finally, The number of teeth on the stepper pulley that determines the overall gear ratio of the timing-belt drive. If these numbers plugged into the formula, the following equation becomes:

$$\text{steps} = 200 \times 16 \div 2.5 \div 16 = 80 \text{ steps/mm}$$

#### Z-axis movement steps:

For the z-axis, things are a little different because the use of lead screws to drive the axis instead of a belt. The formula for figuring out the steps per millimeter on the z-axis looks as follows:

$$\text{steps} = \text{motor steps per revolution} \times \text{driver microstep} \div \text{thread pitch}$$

Instead of the gear ratio between the belt and pulley, the thread pitch of the screws substituted. The 3D printer use standard M8 threaded rod that has a thread pitch of 1.25. Plug this into the formula to get the following:

$$\text{steps} = 200 \times 16 \div 1.25 = 2560 \text{ steps/mm}$$

#### Extruder Steps:

The last bit of math is to calculate the number of steps that the extruder needs to drive 1 millimeter of filament through the extruder. The extruders use a Nema17 stepper motor that is geared down to increase torque using printed drive gears, a special stepper motor with an integrated gearbox. This gear ratio along with the diameter of the drive gear are considered in the following equation:

$$\text{steps} = \text{motor steps per revolution} \times \text{driver microstep} \times \text{big gear} \\ \div \text{small gear} \div \pi \div \text{drive gear diameter}$$

The steps per revolution and microstep stay the same. The listed gear ration is 47:9, so we can use that as the big gear and small gear values.

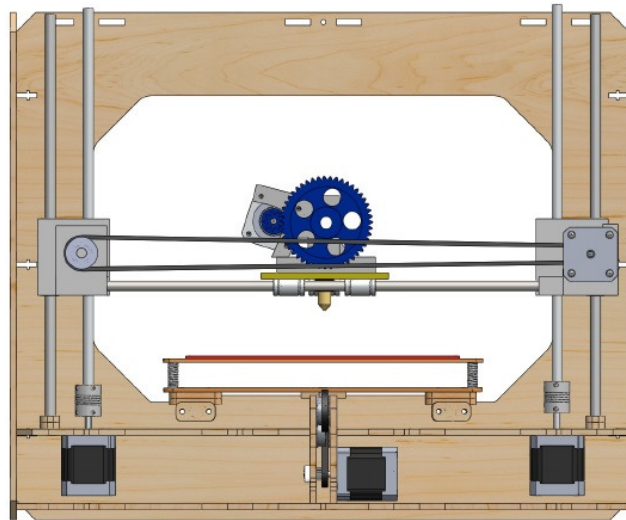
Finally, the drive gear for the extruder has a diameter of 10 millimeters. Plug that in for the following result:

$$\text{steps} = 200 \times 16 \times (47 \div 9) \div \pi \div 10 = 1385.2846 \text{ steps/mm}$$

### 2.3.3 The Extruder

The extruder is used to heat the PLA filament to the melting point, then the stepper motor moves the material through the extruder.

The assembled extruder shown in *Figure 2.6* is mounted on the X-axis carriage. The X-carriage use linear bearings to slide in linear motion on the rod, and controlled by one stepper motor and a timing belt.



*Figure 2.6 the extruder*

### 2.3.4 Printplate

Printed parts are printed on the printplate shown in *Figure 2.7*. The three axes components moves relative to each other so that the nozzle can move above the print plate in the Cartesian coordinate.

The print plate consists of two plates: the print bottom plate that is mounted on the Y-axis smooth rods with linear bearings and the print top plate that is mounted on the bottom plate and that forms the print surface, and the heatbed attached to the top plate. The top print plate is mounted with four springs slide over four screws so that it can be easily adjusted.

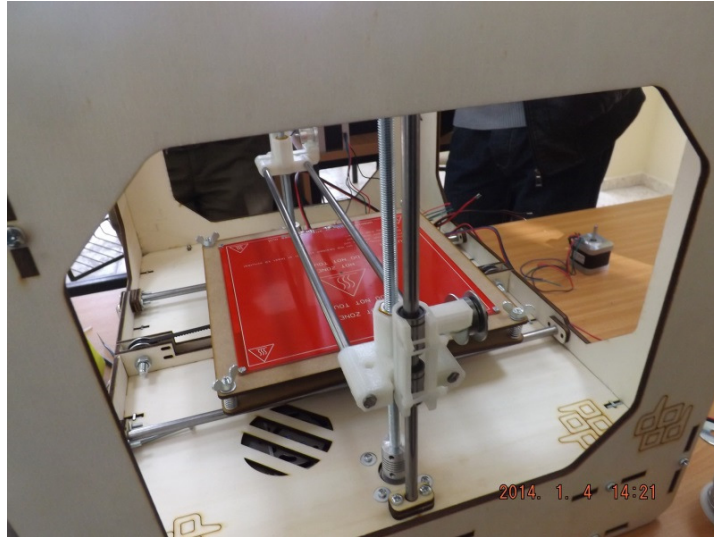


Figure 2.7 Printplate

### 2.3.5 Horizontal motion along the Y-axis

The print bottom plate (24 x 24 cm) assembled on the Y-axis smooth rods (8mm diameter). The Y-axis has one degree of freedom: it can move between the front and the back of the frame. The Y-axis is controlled by a timing belt attached to a stepper motor with pulley (T2.5). The print bottom plate has linear bearings (LME8UU) attached to it.

Y-axis components is shown in *Figure 2.8*, and the bearings shown in *Figure 2.9* slide over smooth rods and provide almost no friction when moving up and down the rods.

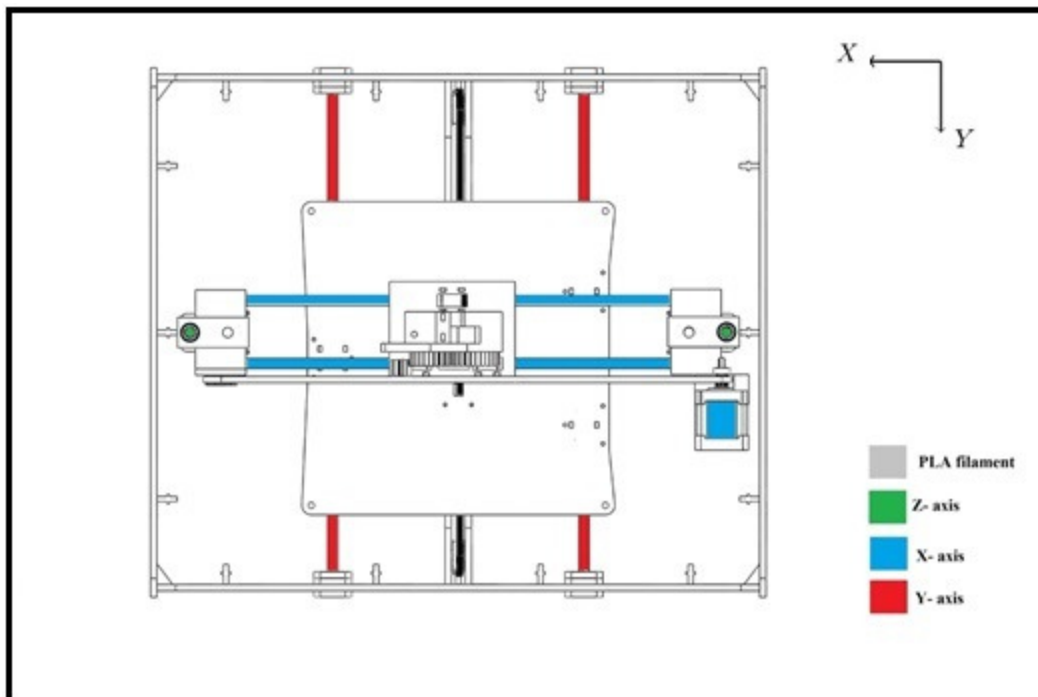


Figure 2.8 Top view of the CAD model



Figure 2.9 linear bearing

The heated bed (MK2) shown in *Figure 2.10* attached to the printplate to improve printing quality by helping to prevent warping. As extruded plastic cools, it shrinks slightly. When this shrinking process occurs to the printed part, the result is a warped part. This warping is commonly seen as corners being lifted off of the build platform. Printing on a heated bed allows the printed part to stay warm during the printing process to prevent shrinking.



Figure 2.10 MK2 heated bed

### 2.3.6 Motion along Z-axis and X-axis

The two Z-axis motors moves the X-axis components up and down the frame. The X-axis motor moves the extruder left and right within the frame. The Z and X-axis construction consists of two printed parts called the X-end idler shown in *Figure 2.11*, and X-end motor shown in *Figure 2.12*. The X-end idler has two vertical sections: a circular open box and a hexagon structure. In the circular open box two linear bearing are glued. This box serves as a guide for the vertical smooth rod. In the hexagon structure two M8 bolts are mounted. A threaded rod is turned into these bolts. This threaded rod

is also connected to the stepper motor. The stepper motor will turn the threaded rod around its axis that will make the X-end idler move up and down.

The X-end motor has the same two sections and is assembled in a similar way. The Z-axis is controlled by two stepper motors to improve accuracy.

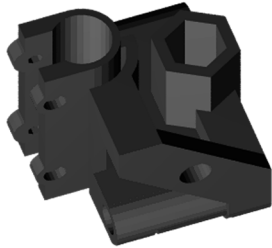


Figure 2.12 X-end idler part

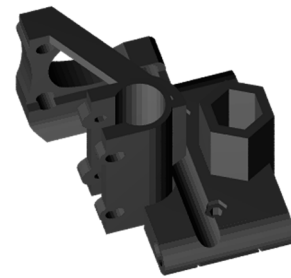


Figure 2. 11 X-end motor part

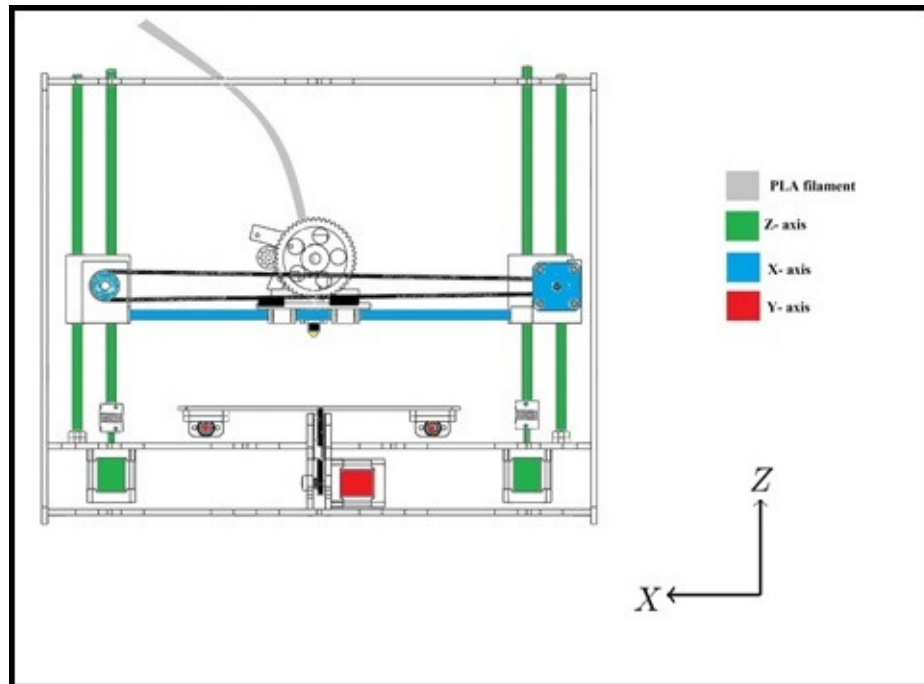


Figure 2. 13 Front view of the 3D CAD model

### 2.3.7 Megatronics V2.0 controller board

The electronics board controls the printing process and connects all the different hardware needed by a 3D printer to the microcontroller; it is essentially the brain of the entire system, Megatronics V2.0 controller board which used in this printer is shown in *Figure 2.14*, and *Figure 2.15* shows the connection of Megatronics with other parts.

The Megatronics V2.0 controller board has several functions:

- Process the G-code instructions.
- Control the four stepper motor drivers (pololu A4988, there are five stepper motors but both Z-axis-threaded-rod motors are connected to the same stepper motor driver).
- Monitor the end-stops (end-stops are used for homing the three axes)
- Control and monitor the temperature of the extruder hotend and the heatedbed with a PID controller used to:

Control the temperature of the hotend nozzle and also of the heatedbed a software PID “proportional- integral-derivative” controller is used. A PID controller calculates the difference between the measured temperature and the desired temperature, which called setpoint, this difference is called error. Then PID controller determines the exact output power value required to reduce and eliminate the error and reach to the required setpoint. The output power can range from 0 to 100% depending on how close of the measured point to the setpoint. The parameters values of the PID tuned in the code manually. PID controller is used for more accuracy, less power consumption and less overshoot than on/off controller.

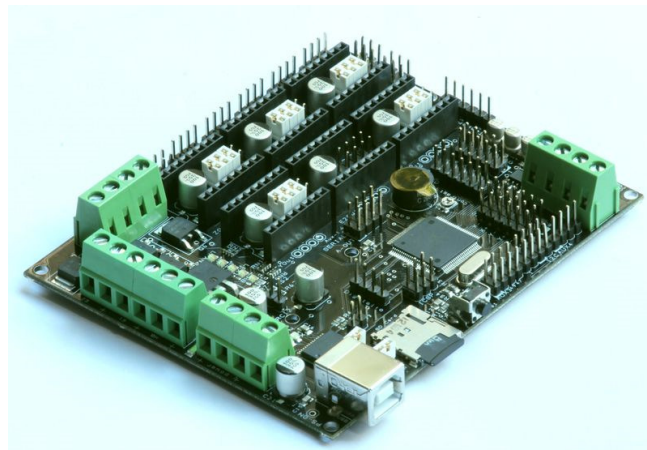


Figure 2.14 Megatronics V2.0 controller

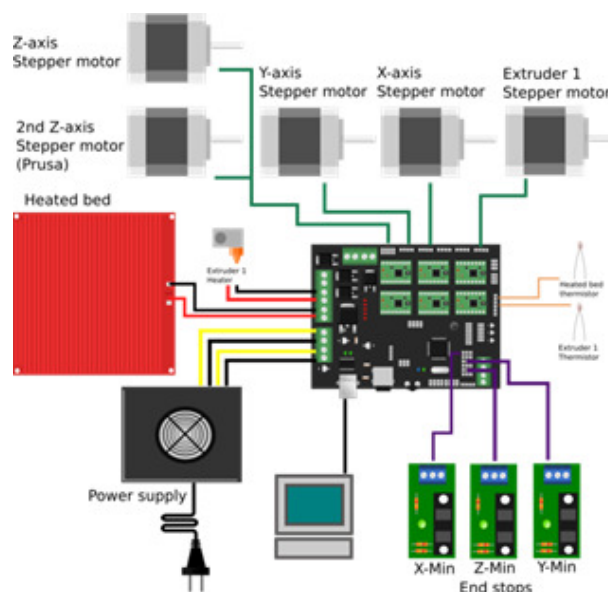


Figure 2. 15 connection circuit with other electronics parts

### 2.3.8 Endstop switches

At the start of a print job all three axes have to be moved to their starting or homing position. This is the zero position of the Cartesian robot.

To achieve this, three endstop switches need to be installed, one for each axis at the position where the axis should not move beyond:

- For the X-axis this should be the position where the nozzle reaches the left-hand side of the printplate.
- For the Y-axis this should be on the back-side of the axis so that the printplate is moved to the back far enough that the nozzle ends up on the forward of the print plate.
- For the Z-axis this should be the position where the nozzle barely touches the print plate. When printing the software will make sure the Z-axis is lifted a little before printing the first layer.



Figure 2. 16 endstop switch

### 2.3.9 Raw material (Thermoplastics)

The 3D printer is most often used to print either of two thermoplastics filaments: ABS or PLA. The plastic material is arranged in filament with diameter 3mm. ABS and PLA are very different plastics and they each require specific printer configurations. ABS is made from petroleum and is more flexible than PLA. PLA is biodegradable, is more rigid than ABS and will dissolve in water. ABS is more prone to warping than PLA, and ABS is toxic when it heated and used in printing. PLA Filament is shown in *Figure 2.17*

In this 3D printer PLA will be used, which has an average tensile strengths of 29.7 MPa, average elastic moduli of 1282.13 MPa, and average impact energy 1.3J. So it can be considered as mechanically functional in tensile applications [16].



Figure 2.17 PLA filament

## 2.4 Software

The 3D Design software generates a mathematical 3D model. This model is converted by the Slicer software into instructions (G-code) that will be executed by the Firmware of the 3D printer to drive its actuators (X, Y, Z and extruder motors, extruder and heated bed heaters) these stages shown in *Figure 2.18* below.

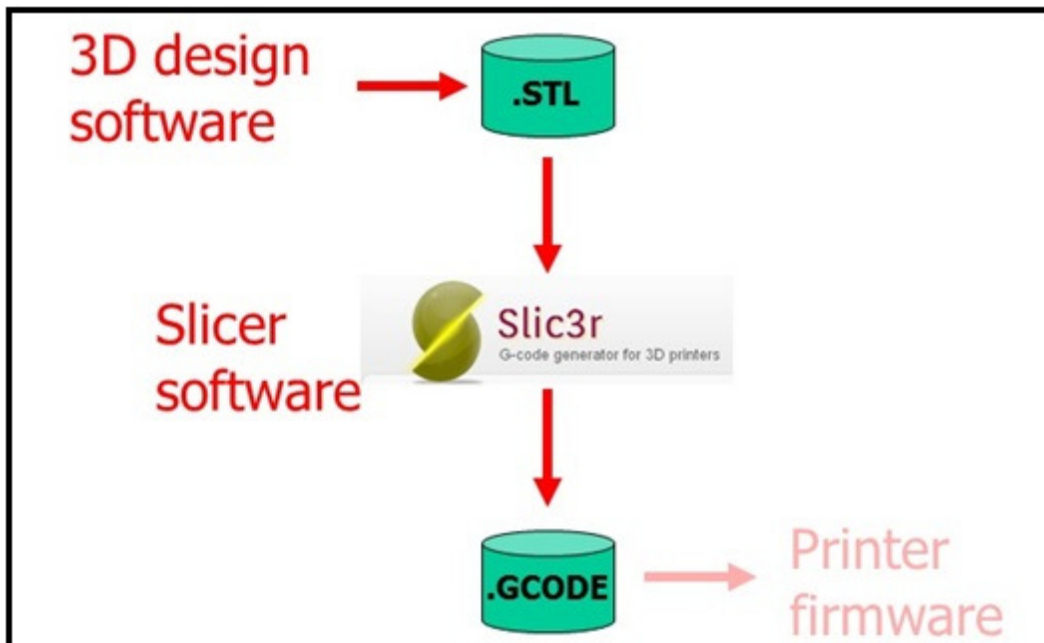


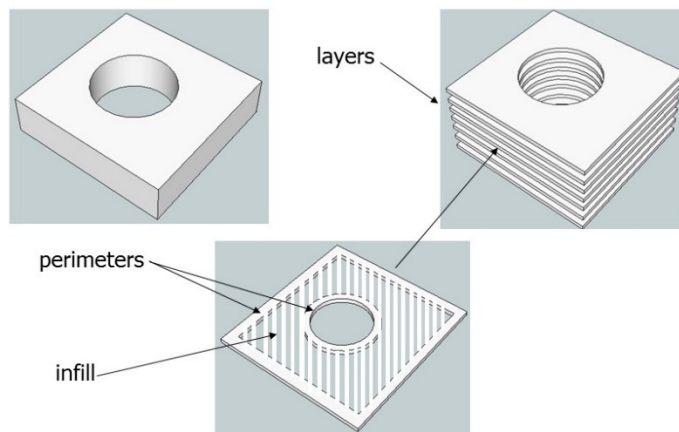
Figure 2.18 3D printing used software stages

### 2.4.1 3D modeling software

The 3D modeling software creates the STL (Stereo Lithography) file based on triangles modeling, supported by many software packages such as CATIA, sketchup, SolidWorks, and other 3D Design software.

### 2.4.2 Slicer

The slicer cuts the model into horizontal slices (layers) as shown in *Figure 2.19*, generates tool paths to fill them and calculates the amount of material to be extruded. Also Slic3r software generates the G-Codes that tell computer numerical control devices how to move and behave.



*Figure 2.19 slicing principle*

### 2.4.3 Pronterface: supervision and control interface

This program allow to:

- Downloading the G-Code to the microcontroller.
- Monitoring the printing.
- setting and monitoring the temperature for the extruder and the printbed
- Executing step by step initializations of the printer
- Changing parameters in real time

# **CHAPTER 3**

## **Mathematical model**

### 3.1 Introduction

In this chapter the equations describe the kinematics and dynamics of the 3D printer will be illustrated [17].

### 3.2 Forward kinematics

This 3D printer is designed as a Cartesian manipulator which have 3 DOF as a translation motion in three axes X, Y and Z without any rotation as shown in *Figure 3.1*. The kinematic describes the motion of the bodies without consideration of forces or torques caused that motion [17]. The kinematics description of this manipulator is the simplest of all manipulators and they are defined as:

$$\begin{aligned} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} &= \begin{bmatrix} q_1 \\ 0 \\ 0 \end{bmatrix} \\ \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} &= \begin{bmatrix} 0 \\ q_2 \\ 0 \end{bmatrix} \\ \begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix} &= \begin{bmatrix} q_1 \\ 0 \\ q_3 \end{bmatrix} \end{aligned} \tag{3.1}$$

Where  $q_1, q_2, q_3$  are joint displacements.

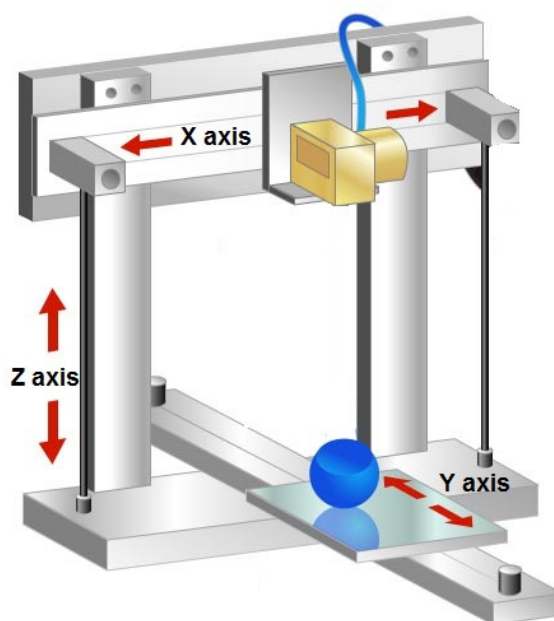


Figure 3.1 3D printer diagram

### 3.3 Jacobian matrix

The Jacobian matrix  $J(q)$  is a multidimensional form of the derivative. This matrix is used to relate the joint velocity  $\dot{q}$  with the Cartesian velocity  $\dot{x}$ .

$$\dot{x} = J(q)\dot{q} \quad (3.2)$$

Where  $\dot{x}$  is the velocity on Cartesian space and  $\dot{q}$  is the velocity in joint space, and  $J(q)$  is the Jacobian matrix of the system. In order to obtain the Jacobian matrix of the three degrees of freedom Cartesian robot it is necessary to use the forward kinematics which is defined in (5.1). By doing the partial derivation of  $x$  in reference to  $q_1, q_2, q_3$  we have:

$$\begin{aligned} \frac{\partial x}{\partial q_1} &= \frac{\partial q_1}{\partial q_1} = \dot{q}_1 \\ \frac{\partial x}{\partial q_2} &= \frac{\partial q_1}{\partial q_2} = 0 \\ \frac{\partial x}{\partial q_3} &= \frac{\partial q_1}{\partial q_3} = 0 \end{aligned} \quad (3.3)$$

The partial derivation of  $y$  in reference to  $q_1, q_2, q_3$  are:

$$\begin{aligned} \frac{\partial y}{\partial q_1} &= \frac{\partial q_2}{\partial q_1} = 0 \\ \frac{\partial y}{\partial q_2} &= \frac{\partial q_2}{\partial q_2} = \dot{q}_2 \\ \frac{\partial y}{\partial q_3} &= \frac{\partial q_2}{\partial q_3} = 0 \end{aligned} \quad (3.4)$$

The partial derivation of  $z$  in reference to  $q_1, q_2, q_3$  are:

$$\begin{aligned} \frac{\partial z}{\partial q_1} &= \frac{\partial q_3}{\partial q_1} = 0 \\ \frac{\partial z}{\partial q_2} &= \frac{\partial q_3}{\partial q_2} = 0 \\ \frac{\partial z}{\partial q_3} &= \frac{\partial q_3}{\partial q_3} = \dot{q}_3 \end{aligned} \quad (3.5)$$

Where the Jacobian matrix elements are defined using the equations (3.3), (3.4) and (3.5):

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} \quad (3.6)$$

Jacobian transpose matrix is:

$$J(q)^T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3.7)$$

### 3.4 Dynamic model

Dynamic modeling means deriving equations that explicitly describe the relationship between force and motion [17]. These equations are important to consider in simulation of robot motion, and in the design of control algorithms.

$$K(q, \dot{q}) = \frac{mv^2}{2} = \frac{q^T M(q)q}{2} \quad (3.8)$$

Where  $K$  is a kinetic energy,  $v$  is a velocity  $M(q)$  is a positive inertial matrix.

Considering velocity, it is defined as:

$$v = \frac{d}{dt} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (3.9)$$

After driving (3.1)  $v^2$  is:

$$\begin{aligned} v_1^2 &= \dot{q}_1^2 \\ v_2^2 &= \dot{q}_2^2 \\ v_3^2 &= \dot{q}_1^2 + \dot{q}_3^2 \end{aligned} \quad (3.10)$$

By replacing the values on  $v_1^2, v_2^2$  and  $v_3^2$  in (3.8) the kinetic energy of each link become:

$$\begin{aligned} K_1(q, \dot{q}) &= \frac{m_1 \dot{q}_1^2}{2} \\ K_2(q, \dot{q}) &= \frac{m_2 \dot{q}_2^2}{2} \\ K_3(q, \dot{q}) &= \frac{m_3 (\dot{q}_1^2 + \dot{q}_3^2)}{2} \end{aligned} \quad (3.11)$$

Where  $m_1, m_2$  and  $m_3$  are the masses of links X, Y and Z respectively. By adding the kinetic energy of each link:

$$K(q, \dot{q}) = \frac{m_1 \dot{q}_1^2}{2} + \frac{m_2 \dot{q}_2^2}{2} + \frac{m_3 (\dot{q}_1^2 + \dot{q}_3^2)}{2} \quad (3.12)$$

Obtaining the total kinetic energy in the following form:

$$K(q, \dot{q}) = \frac{(m_1 + m_3)}{2} \dot{q}_1^2 + \frac{m_2}{2} \dot{q}_2^2 + \frac{m_3}{2} \dot{q}_3^2 \quad (3.13)$$

The potential energy  $U(q)$  is obtained considering in this case  $h = q_3$  and

$$m = (m_1 + m_3)$$

$$U(q) = (m_1 + m_3) g q_3 \quad (3.14)$$

Lagrangian is the difference between kinetic and potential energies.

$$L(q, \dot{q}) = K(q, \dot{q}) - U(q) \quad (3.15)$$

Lagranges equation for printer is equal:

$$L(q, \dot{q}) = \frac{(m_1 + m_3)}{2} \dot{q}_1^2 + \frac{m_2}{2} \dot{q}_2^2 + \frac{m_3}{2} \dot{q}_3^2 - (m_1 + m_3) g q_3 \quad (3.16)$$

Lagranges equation for a conservative system as given by:

$$\frac{d}{dt} \left[ \frac{\partial L(q, \dot{q})}{\partial \dot{q}} \right] - \frac{\partial L(q, \dot{q})}{\partial q} = \tau - f(\tau, \dot{q}) \quad (3.17)$$

Where  $q, \dot{q}$  are position and velocity in joint space,  $\tau$  is a vector of applied torque, and  $f(\tau, \dot{q})$  is the friction vector. To solve it part by part:

$$\frac{\partial L(q, \dot{q})}{\partial \dot{q}} = \begin{bmatrix} m_1 + m_3 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} \quad (3.18)$$

$$\frac{d}{dt} \left[ \frac{\partial L(q, \dot{q})}{\partial \dot{q}} \right] = \begin{bmatrix} m_1 + m_3 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} \quad (3.19)$$

$$\frac{\partial L(q, \dot{q})}{\partial \dot{q}} = \begin{bmatrix} 0 \\ 0 \\ (m_1 + m_3)g \end{bmatrix} \quad (3.20)$$

Thus, the dynamic model of the Cartesian robot is:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} m_1 + m_3 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ m_1 + m_3 \end{bmatrix} g \quad (3.21)$$

Being  $\tau_1, \tau_2$  and  $\tau_3$  the applied torques. As we can observe, the dynamic model represented in (3.21) it is not under a friction influence.

Considering the following physical parameters:

Description	Notation	Value	Units
Mass of link X	$m_1$	1.75	Kg
Mass of link Y	$m_2$	1.4	Kg
Mass of link Z	$m_3$	1	Kg
Gravity acceleration	$g$	9.81	$m/s^2$

The dynamic model of the 3D printer become:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} 2.75 & 0 & 0 \\ 0 & 1.4 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 2.75 \end{bmatrix} g \quad (3.22)$$

# **CHAPTER 4**

## **Test and assembly**

## 4.1 Introduction

In this chapter the operation and controlling of stepper motors, steps of assembling the printers parts and the tests done while assembly will be illustrated.

## 4.2 Stepper motor module

One of the most important parts of the 3D printer is stepper motor which drives all moving parts, so before starting the assembling of the machine it is important to understand how to operate and control this motors.

### 4.2.1 Operating the stepper motor with Pololu A4988 driver

In this experiment a A4988 Pololu driver which is a complete micro-stepping motor driver is used to operate the bipolar stepper motors in full, half, quarter, eighth, and sixteenth step modes, with an output drive capacity up to 35V and 2 A. Procedure:

- Start by connecting the stepper motor coil with the Pololu A4988 driver. Also connecting the driver with Arduino Mega 2560 microcontroller as shown in *Figure 4.1*

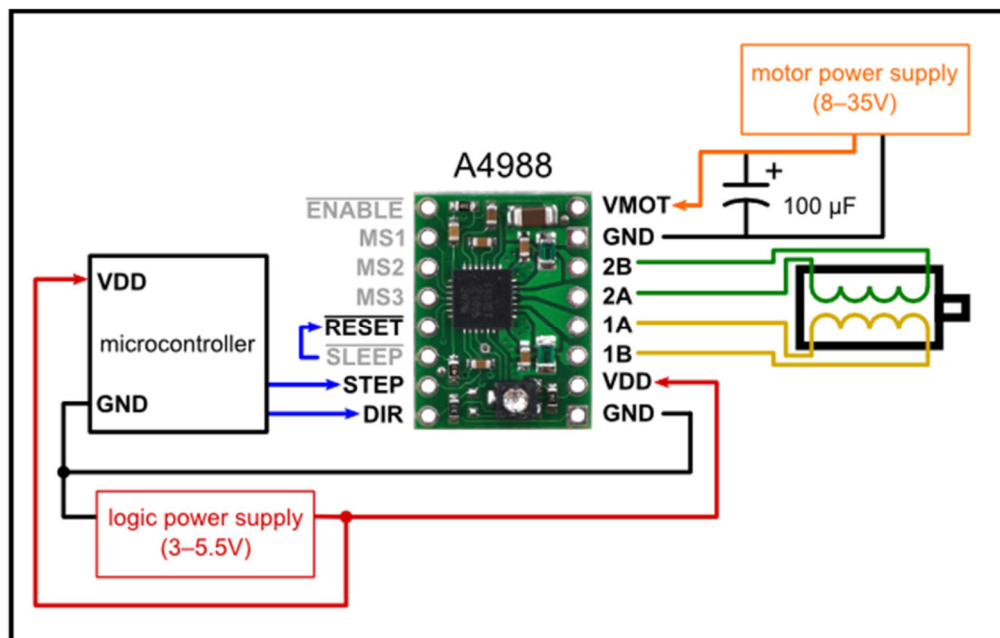


Figure 4.1 motor wiring with pololu A4988

-Upload Arduino Mega 2560 code which shown in *Figure 4.2*. This code is used to operate the stepper with specified speed, direction and micro-stepping.

```

v1_0 | Arduino 1.0.5
File Edit Sketch Tools Help
v1_0$
int MS1 = 34;
int MS2 = 35;
int MS3 = 36;
int a = 0;

void setup()
{
  pinMode(stp, OUTPUT); // set pin as output
  pinMode(dir, OUTPUT);
  pinMode(MS1, OUTPUT);
  pinMode(MS2, OUTPUT);
  pinMode(MS3, OUTPUT);
}

void loop()
{
  digitalWrite(MS1, LOW); // full step mode
  digitalWrite(MS2, LOW);
  digitalWrite(MS3, LOW);
  digitalWrite(dir, LOW);

  digitalWrite(stp, HIGH); // generate pulse
  delay(25); // delay 25 ms
  digitalWrite(stp, LOW);
  delay(25);
}
Done compiling

```

Figure 4.2 Arduino program to control the A4988 driver

- Adjust power supply voltage to the operation voltage of the stepper which is 12V. Then supply it to the circuit.
- To change the micro-stepping mode the code modified by changing the value of MS1, MS2, and MS3 depending on A4988 datasheet as shown in Figure 4.3

MS1	MS2	MS3	Microstep Resolution
L	L	L	Full Step
H	L	L	Half Step
L	H	L	Quarter Step
H	H	L	Eighth Step
H	H	H	Sixteenth Step

Figure 4.3 Microstepping resolution truth table

Now the motor can be seen working and the difference between the operating micro-stepping modes can be noticed.

### Conclusion from first experiment

In full stepping mode provides improved torque and speed performance. Driving the stepper motor with micro-stepping mode make the operation of the motor smother, reduce the vibration, and increase the resolution, but produces roughly less torque than full stepping mode.

#### 4.2.2 Operating the stepper motor with Pololu DRV8825 driver

The difference in this driver is that the driving current can operate up to 2.5A, and some difference in connection with the stepper motor as shown in *Figure 4.4*, also this driver can operate the stepper motor with step resolution 1/32-step.

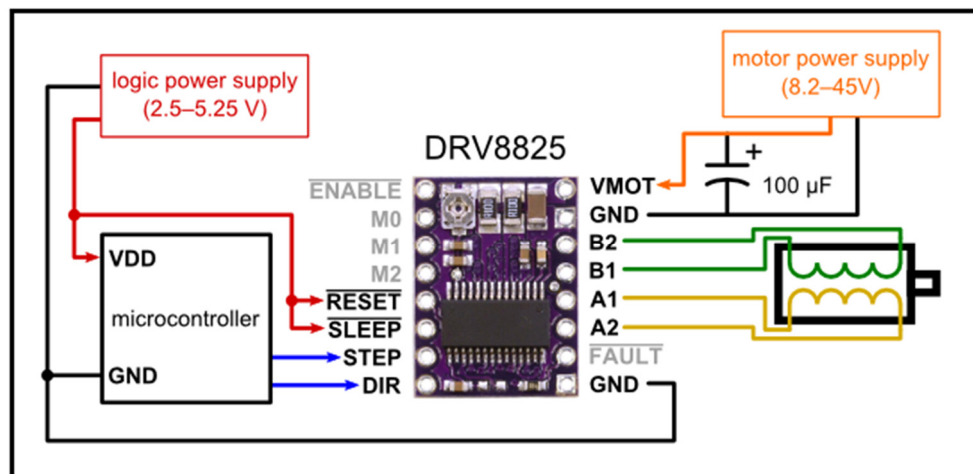


Figure 4.4 Stepper motor wiring with pololu DRV8825

In this experiment the motor operate to follow a specified position profile shown in *Figure 4.5*.

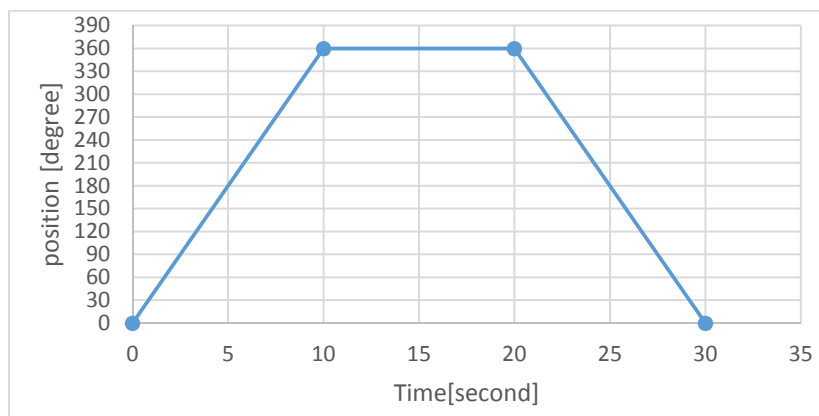


Figure 4.4 position profile

After prepare and connect the components as desired, Arduino program codes shown in *Figure 4.6* **Error! Reference source not found.** Prepared and deployed to the Arduino microcontroller to operate the stepper with in the specified profile.



```
sketch_dec08a | Arduino 1.0.5
File Edit Sketch Tools Help
sketch_dec08a $
int dir = 7;
int stp = 8;
int M0 = 9;
int M1 = 10;
int M3 = 11;
int a = 0;

void setup()
{
  pinMode(stp, OUTPUT); // set pin as output
  pinMode(dir, OUTPUT);
  pinMode(M0, OUTPUT);
  pinMode(M1, OUTPUT);
  pinMode(M2, OUTPUT);
}

void loop()
{
  digitalWrite(M0, LOW); // 1/4 microstepping mode
  digitalWrite(M1, HIGH);
  digitalWrite(M2, LOW);

  for(;a<800;a++)
  {
    digitalWrite(dir, LOW);
    digitalWrite(stp, HIGH); // generate pulse
    delayMicroseconds(6250); // delay 6.25 ms
    digitalWrite(stp, LOW);
    delayMicroseconds(6250);
  }

  if(a==800)
  {
    delay(10000); //delay 10 s
    a++;
  }

  for(;a<1600&&a>800;a++)
  {
    digitalWrite(dir, HIGH);
    digitalWrite(stp, HIGH); // generate pulse
    delayMicroseconds(6250); // delay 6.25 ms
    digitalWrite(stp, LOW);
    delayMicroseconds(6250);
  }
}
```

*Figure 4.5* Arduino program to operate the stepper motor as specified profile

## Conclusion for 2nd experiment

The DRV8825 driver could be used to operate the stepper motor that used to feed the PLA to the extruder, due to the need of continuous operation and reverse the direction and this make the operating current high.

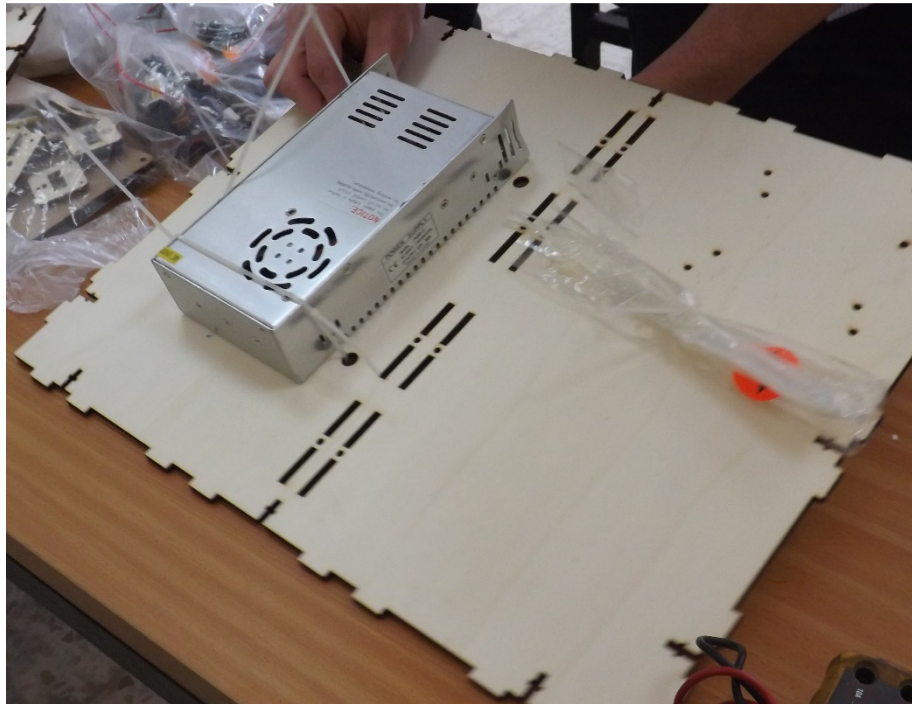
## 4.3 Assembly

### 4.3.1 Y axis assembly

#### 4.3.1.1 Assembly steps

Before start with Y axis, base and main components fixed on it should be installed. The following steps explain the producer of assembling Y axis and all necessary parts for completing assembly of other axes.

- Fix the power supply on the base of the frame as shown in *Figure 4.7*



*Figure 4.6 Base and power supply*

- Connect T2.5 aluminum pulley on the motor shaft
- Install the motor and the 4 ball bearings 8mm with the wood pieces as shown in *Figures 4.8 and 4.9.*

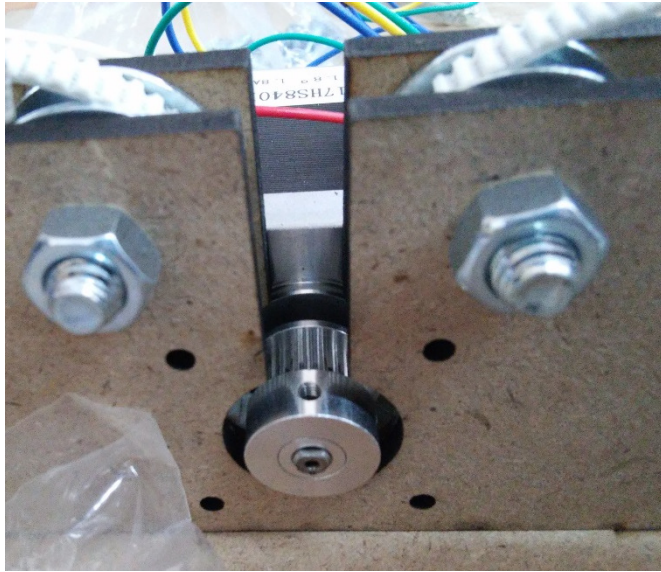


Figure 4.8 Motor with T.5 pulley and two ball bearings



Figure 4.7 Y axis base

- Connect the front and the back sides of the wooden frame using screws and square nuts as shown in *Figure 4.10*.

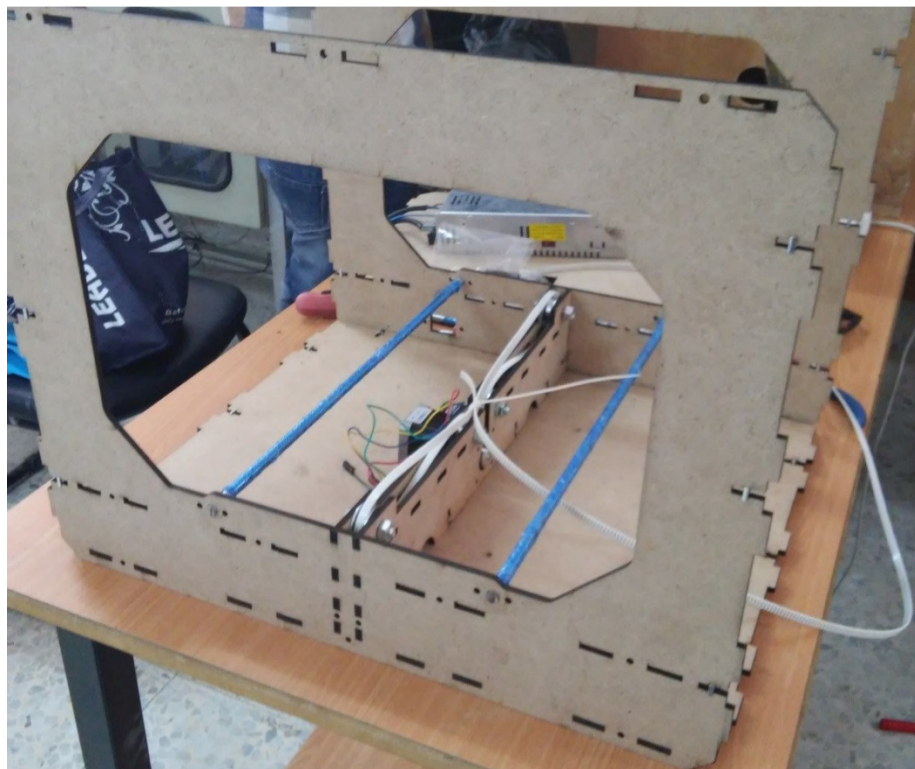


Figure 4.9 Front and back wood frame assembly

- Prepare two smooth chromium-plated rods approximately 42 cm for each on.
- Fixing the linear bearing on the lower of the print bed using “cable tie” as shown in *Figures 4.11* and *4.12*.

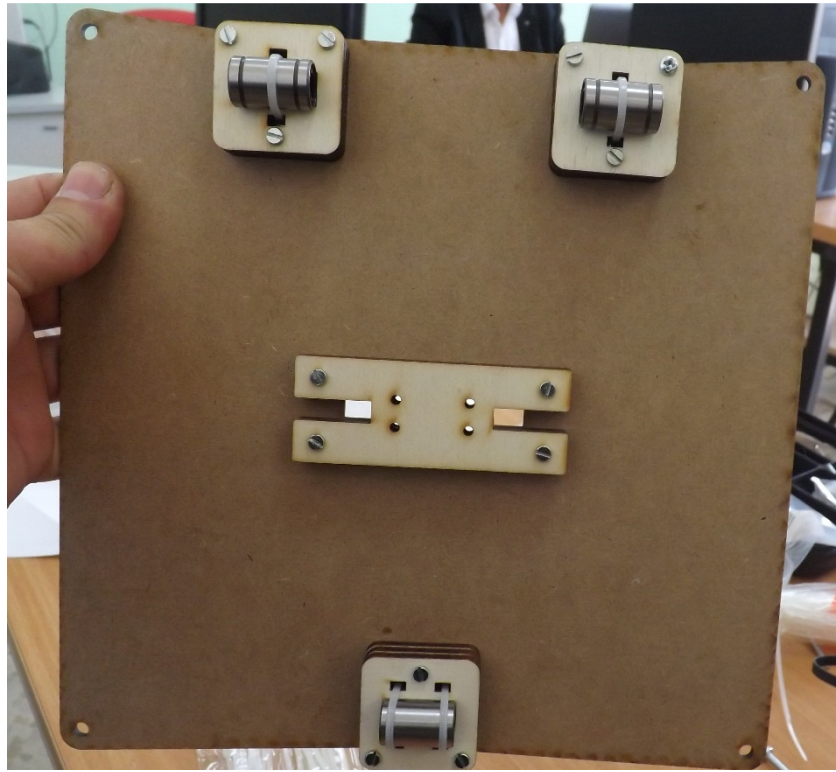


Figure 4.10 The lower side of the print bed

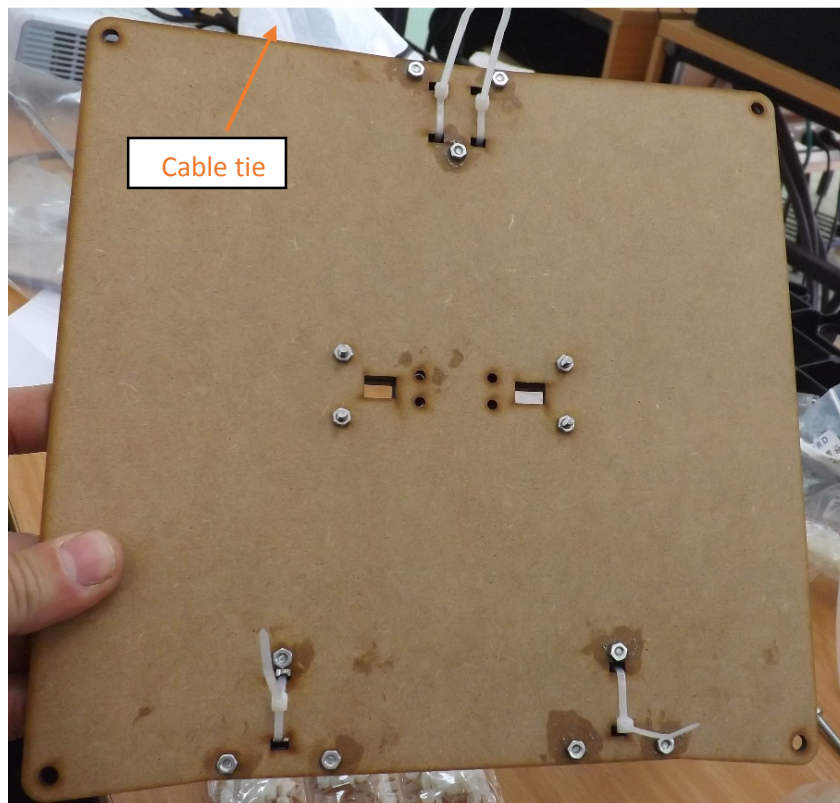
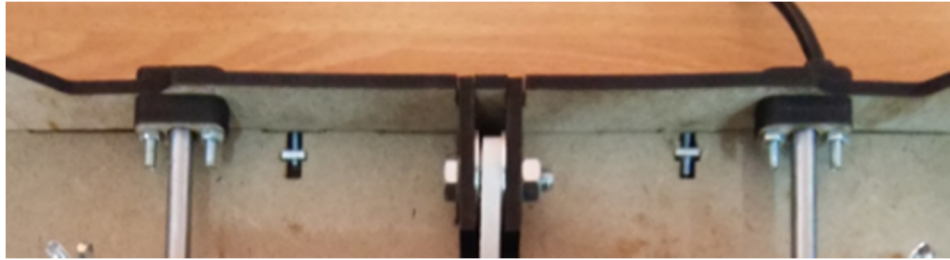


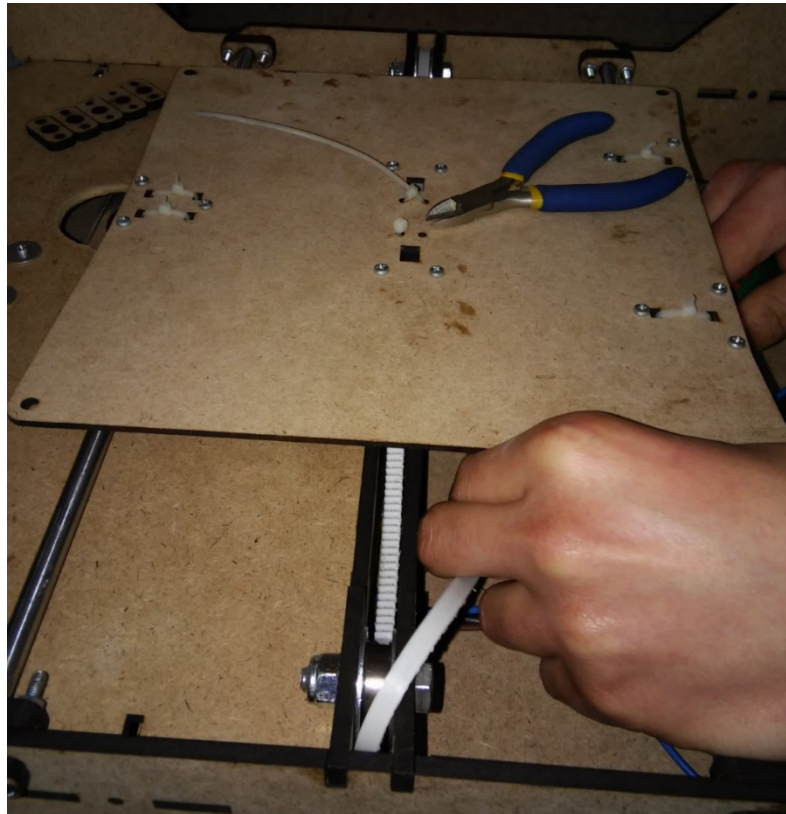
Figure 4.11 The upper side of the print bed

- Insert the rod inside linear bearing then fix the rods between two frame sides using small wooden pieces, then assembly them by screws and nuts as shown in *Figure 4.13*.



*Figure 4.12 Y axis rods fixed with frame*

- Use cable ties to connect the timing belt with the bed as shown in *Figures 4.14* and *4.15*



*Figure 4.13 Print bed connecting with timing belt*



Figure 4.14 Print bed connecting with timing belt

- Connect heated bed with wooden base using screws and nuts then install this collected part on the bed base using springs, screws, and wing nuts as shown in Figure 4.16

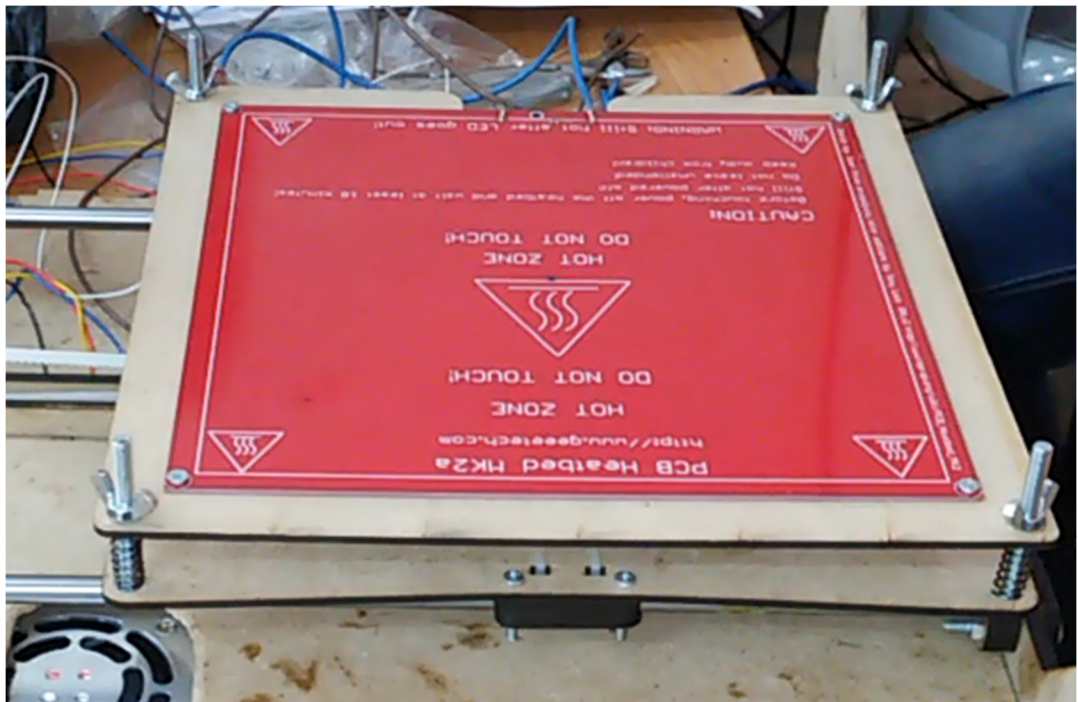
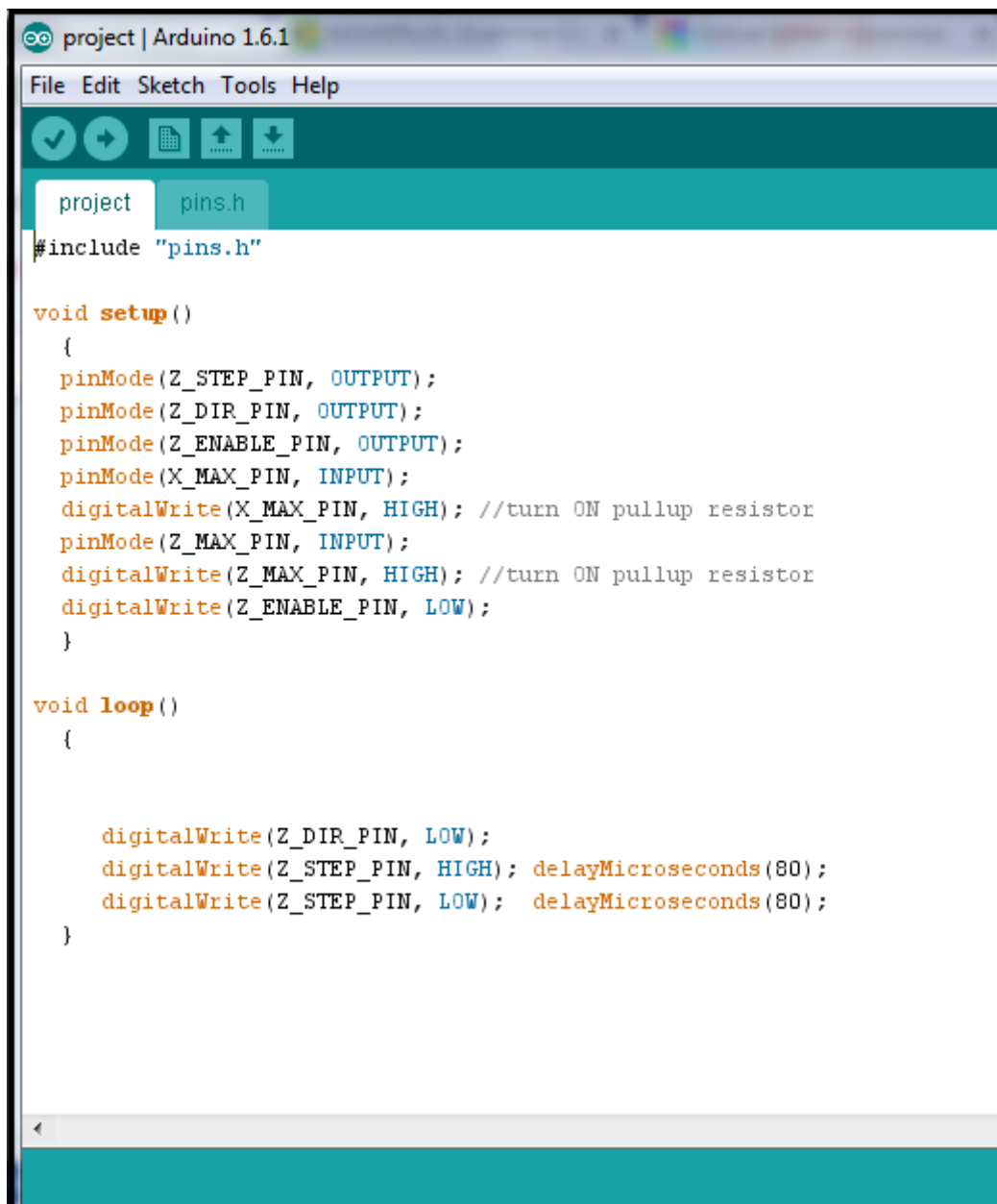


Figure 4.15 Heatbed connecting on print bed

### 4.3.1.2 Testing of Y axis

After assembly of Y axis complete it was tested using code written using C language and installed on Megatronics kit this code shown in *Figure 4.17*, the Y axis motor also connected on Megatronics. In this test the motor hardly moves the bed and there was a strange sound in the starting and the ending of the stroke the cause of that was an excessive tension in the timing belt and the rotary bearing do not rotate with the timing belt. After adjust the tension of the belt and bearing then test again the movement become smooth without sounds and vibration.



```
project | Arduino 1.6.1
File Edit Sketch Tools Help
project pins.h
#include "pins.h"

void setup()
{
  pinMode(Z_STEP_PIN, OUTPUT);
  pinMode(Z_DIR_PIN, OUTPUT);
  pinMode(Z_ENABLE_PIN, OUTPUT);
  pinMode(X_MAX_PIN, INPUT);
  digitalWrite(X_MAX_PIN, HIGH); //turn ON pullup resistor
  pinMode(Z_MAX_PIN, INPUT);
  digitalWrite(Z_MAX_PIN, HIGH); //turn ON pullup resistor
  digitalWrite(Z_ENABLE_PIN, LOW);
}

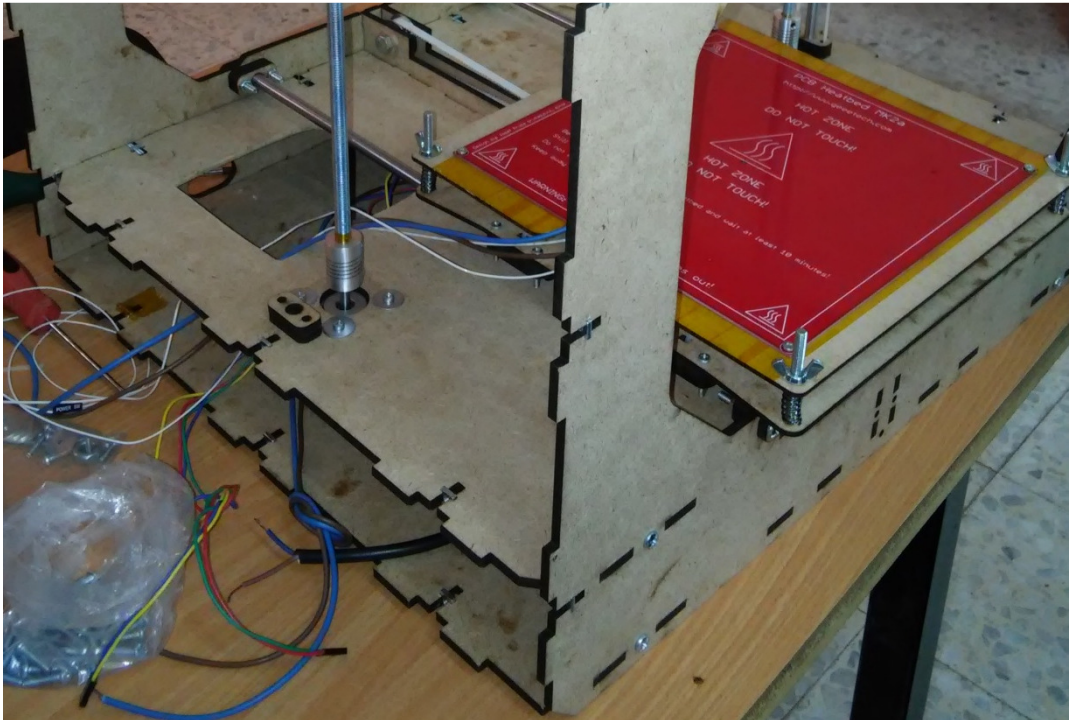
void loop()
{
  digitalWrite(Z_DIR_PIN, LOW);
  digitalWrite(Z_STEP_PIN, HIGH); delayMicroseconds(80);
  digitalWrite(Z_STEP_PIN, LOW); delayMicroseconds(80);
}
```

Figure 4.16 Y axis testing code

## 4.3.2 Z axis assembly

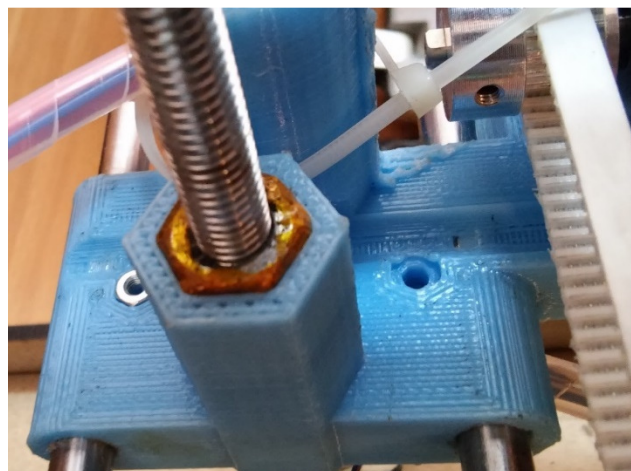
### 4.3.2.1 Assembly steps

- Connect Z axis motors with wooden pieces using screws then connect this pieces on its place in the frame shown in *Figure 4.18* as s ( it is needed to disassembly Y axis rods from one side to let the wooden pieces enter their positions ).



*Figure 4.17 Fixed Z axis motor*

- Fix two nuts and fix two linear bearing in each of X axis printed as shown in *Figures 4.19* and *4.20*.



*Figure 4.18 Fixed nut in printed part*

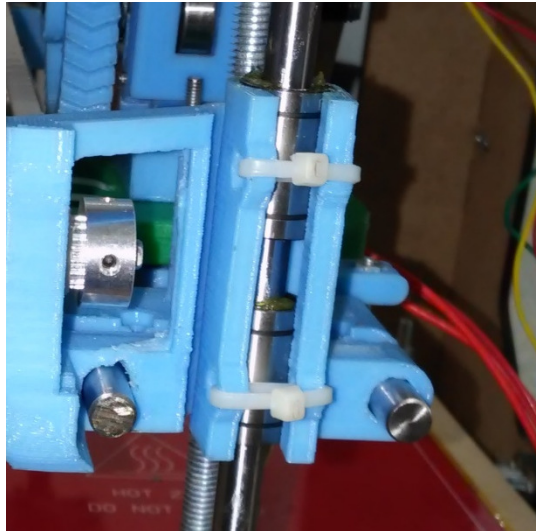


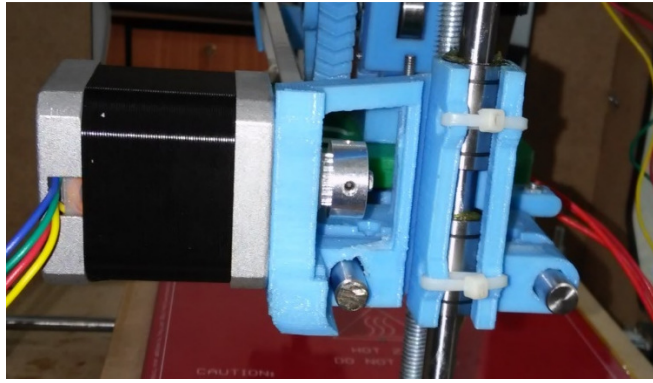
Figure 4.19 Fixed bearings in printed part

- Install the 5/8 mm Aluminum coupler on the shaft of each Z axis motors, insert the threaded rod from the hole in the top frame piece then connect it to the other side of the coupler and tight it shown in *Figure 4.21*.

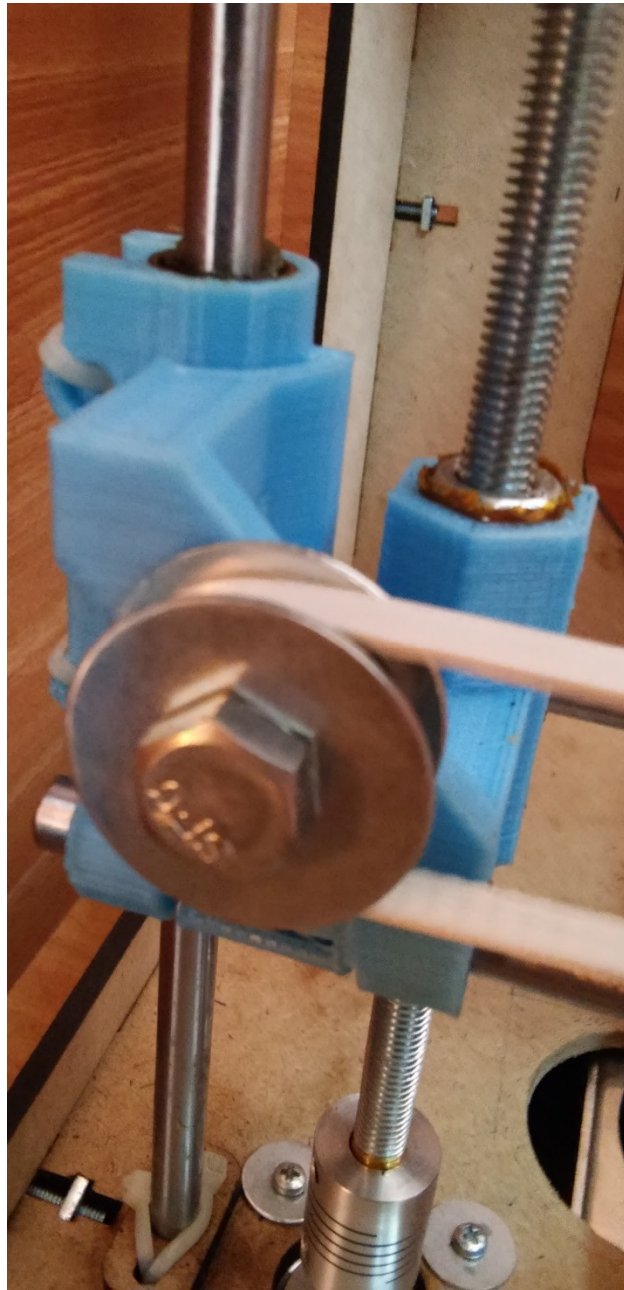


Figure 3.20 5/8mm Aluminum coupler on motor shaft

- Prepare two chromed- painted rods in length of 33 cm, and two threaded rods in length of 32.5 cm.
- Insert Z axis threaded rod into nuts and rod chromed- painted in linear bearing fixed in each of X axis printed parts (before that connect the X axis motor and pulley on the printed parts). As shown in *Figures 4.22* and *4.23*.



*Figure 4.21 X axis motor on printed part*



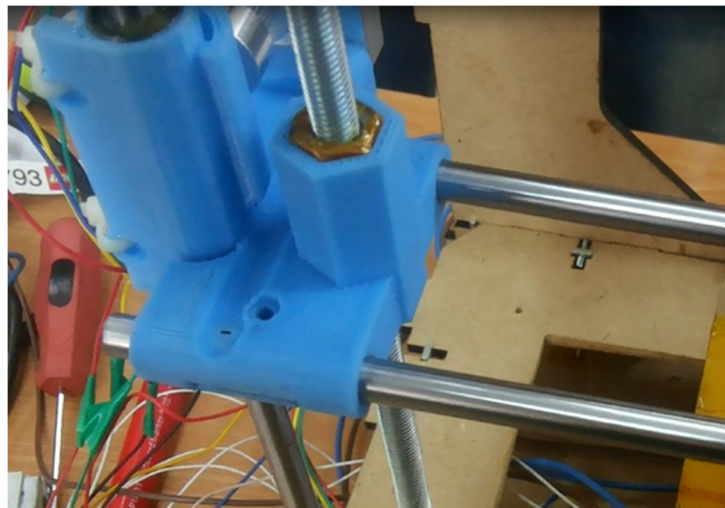
*Figure 4.22 pulley on printed part*

- Insert threaded rods from the hole in the top frame part, collect the top piece of the frame with sides as shown in *Figure 4.24*.



*Figure 4.23 Threaded and smooth rods upper end*

- Fixe rods from two ends using small wooden piece and cable tie.
- Place X axis rods in their place without fixing them as shown in *Figures 4.25* and *4.26*.



*Figure 4.24 X axis rods in printed first part*



Figure 4.25 X axis rods in printed second part

- Balance the X axis rods and parts connected to them and make sure they are at same level using bubble level tool or caliper.

#### 4.3.2.2 Testing of Z axis

Connect Z axis motors wires to the Megatronics Z axis motor slot, connect power to the Megatronics, then connect it to the computer and download the code which is similar of the code used to test Y axis motion but controls two motor instead of one. In this test the motors moves in the same speed and X axis parts connected to the motors moved up and down. In another test a mobile with bubble level application calibrated and fixed on X axis rods as shown in *Figure 4.27*. The result was it still balance from the start to the end of stroke and the reading was the same.

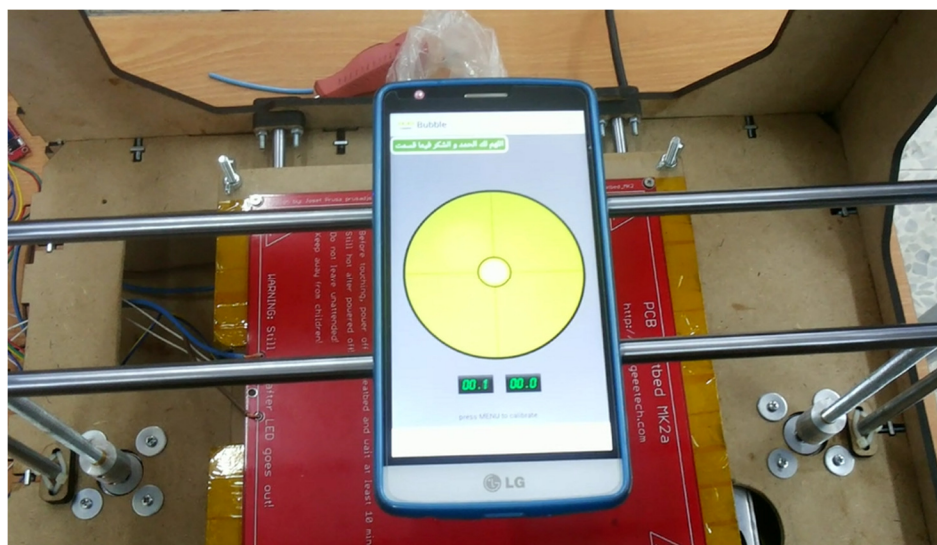
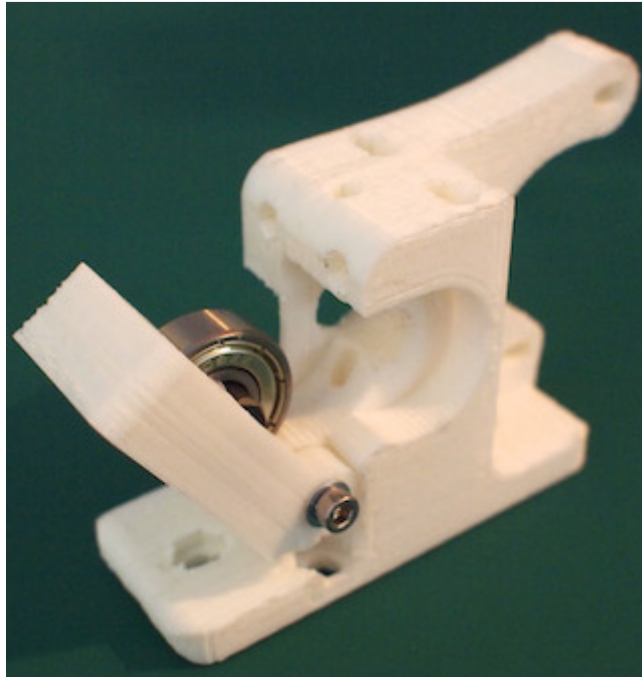


Figure 4.26 Z axis balance test

### 4.3.3 Extruder mechanism assembly

#### 4.3.3.1 Assembly steps

- Fixed 8mm ball bearing in its place in printed part and connect this part with other printed part as shown in *Figure 3.28*.



*Figure 4.27 Ball bearing on extruder printed part*

- Connect the 8mm screw with the big printed gear, then insert 2 washers, fixed another 8mm ball bearing in its place on printed part insert screw through bearing. Then also insert special turned box and other 8mm ball bearing and a washer through screw then tight Nylonck nut which is a nut prevent backing off as shown in *Figure 4.29*.

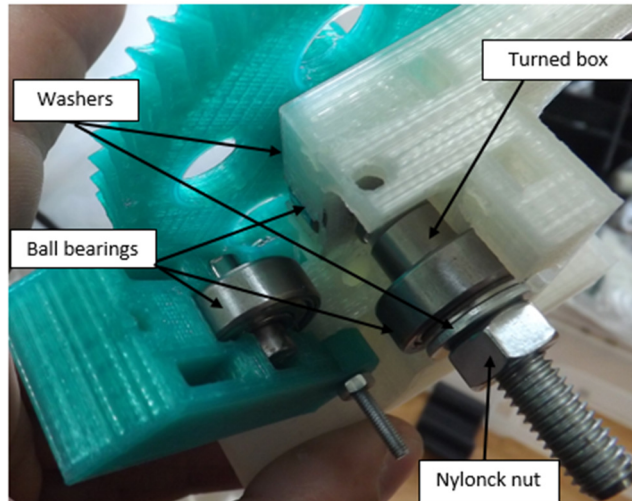


Figure 4.29 Extruder parts

- Fixed small printed gear on the motor shaft, then place motor on printed part as shown in Figure 4.30.

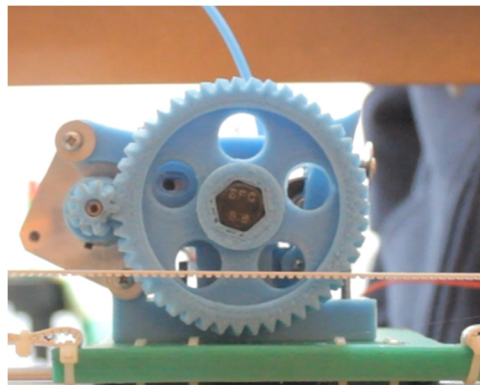


Figure 4.28 small and big printed gear

- Insert the spring into a screw then connect it to the nut after put it in its place then tight it as shown in Figure 4.31.

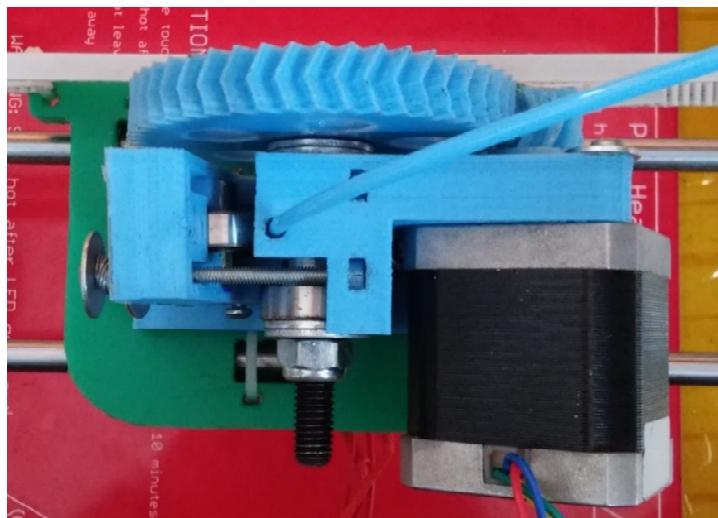


Figure 4.29 full assembled extruder mechanism

### 4.3.3.2 Testing of extrusion mechanism

#### 1. Hot end and Manual extrusion test

In this test hot end was connected to Megatronics and controlled by “Pronterface” software to make sure it is work well before connecting it to the extrusion mechanism the result is the temperature reach the target value. After that the material was pushed into the extruder by hand and it is melted and exit from the nozzle the result shown in *Figure 4.32*.



*Figure 4.30 Hot end test*

#### 2. Material extrusion

In this experiment the extrusion mechanism was tested to make sure that is working properly before connecting the hot end. The Filament was entered in the groove then the spring was tightened. As a result the motor drives the mechanism and filament exits from the hole as shown in the *Figure 4.33*.



*Figure 4.31 material extrusion test*

### 3. Complete extrusion mechanism test

In this test after confirmed that every part is working correctly, whole parts connected together and tested. The material extrudes at temperature 185 C using marlin firmware and “Pronterface” software.

#### 4.3.4 X axis assembly

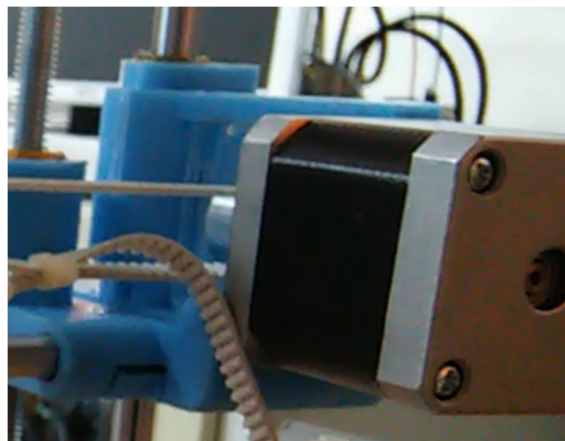
##### 4.3.4.1 Assembly steps

Notes that first 3 steps should be done while assembling Z axis to not be compelled to disassemble other parts.

- Connect T2.5 pulley with motor shaft
- Fix motor on one X axis printed part and pulley on the other (before insert Z axis rods inside it) as shown in *Figures 4.34* and *4.35*



*Figure 4.32 First X axis printed part*



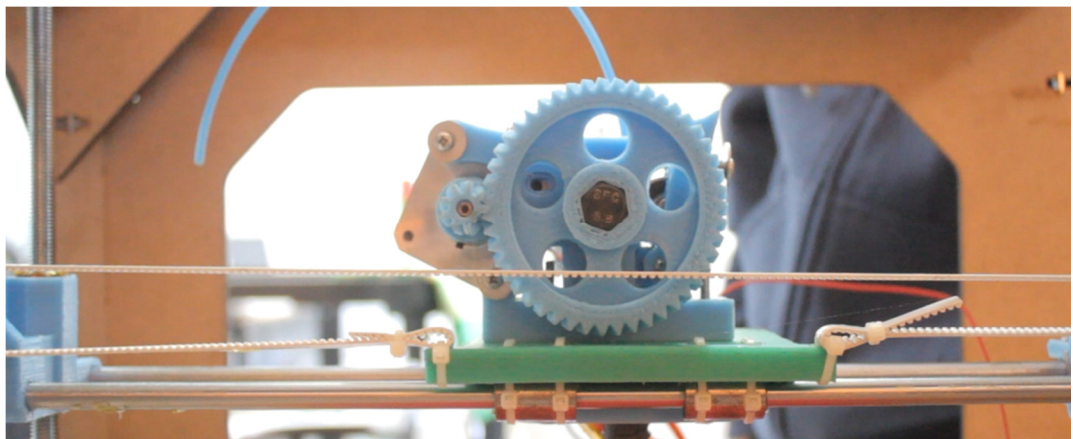
*Figure 4.33 second X axis printed part*

- Connect X axis printed parts with Z axis rod (as shown in Z axis assembly part).
- Fixed 3 linear bearings in their places under extruder holder as shown in *Figure 4.36*



*Figure 4.34 bearings under extruder*

- Insert X axis rods (40 cm length) into linear bearings.
- Put timing belt on the pulleys and fix it with extruder holder part using cable ties as shown in *Figure 4.37*.



*Figure 4.35 Timing belt fixing with extruder*

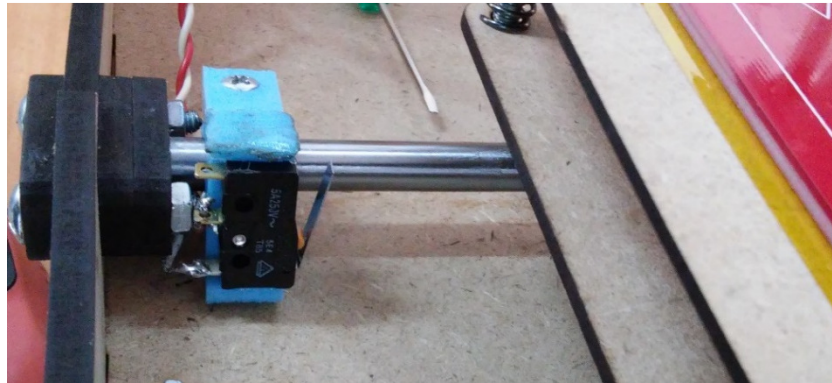
#### 4.3.4.2 Testing of X axis

In this test after completing the assembly the motor was connecting to the Megatronics and controlled with the same code used to test Y axis motion. In first time there was a vibration because the timing belt was not tight enough. In second try after tighten the belt the vibration disappeared and the problem solved.

#### 4.3.5 Endstop switches installation

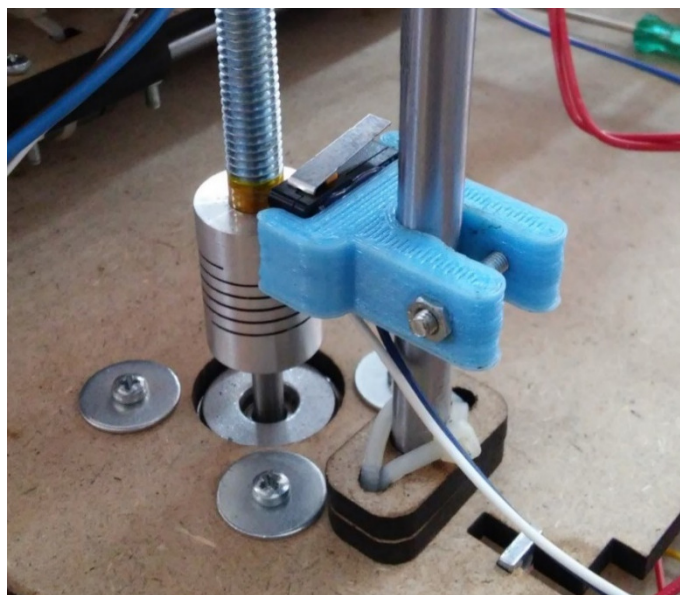
A limit switch should be connected to each axis to determine the homing position

- Y axis endstop switch shown in *Figure 4.38*.



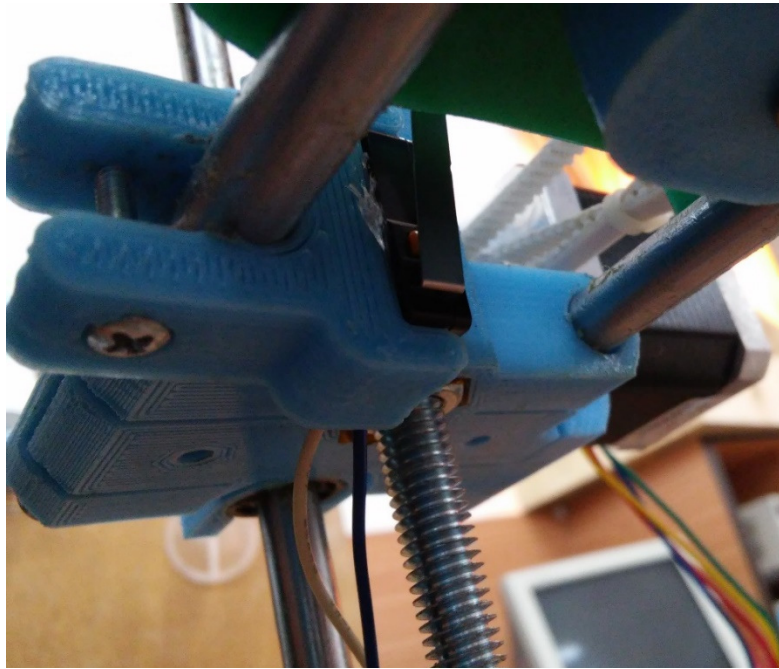
*Figure 4.38 Y axis endstop switch*

- Z axis endstop switch shown in *Figure 4.39*.



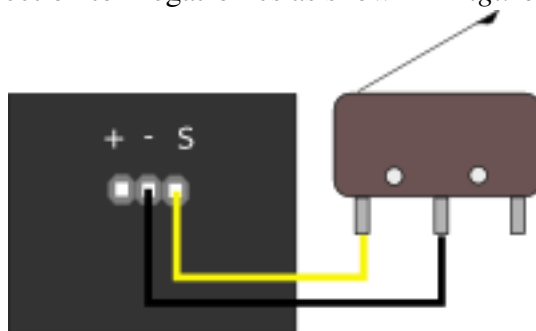
*Figure 4.36 Z axis endstop switch*

- X axis endstop switch shown in *Figure 4.40*.



*Figure 4.37 X axis endstop switch*

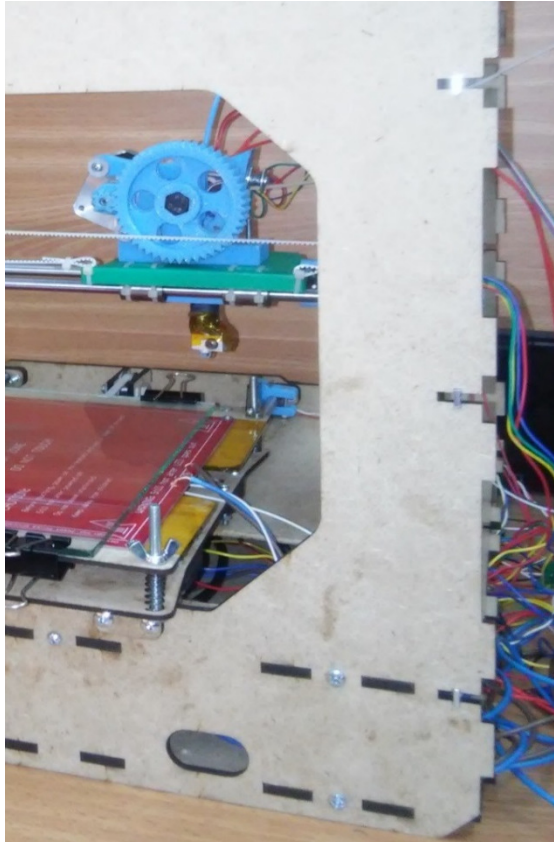
- Limit switch connection to Megatronics as shown in *Figure 4.41*.



*Figure 4.41 Endstop connection with Megatronics*

## **4.4 Finishing**

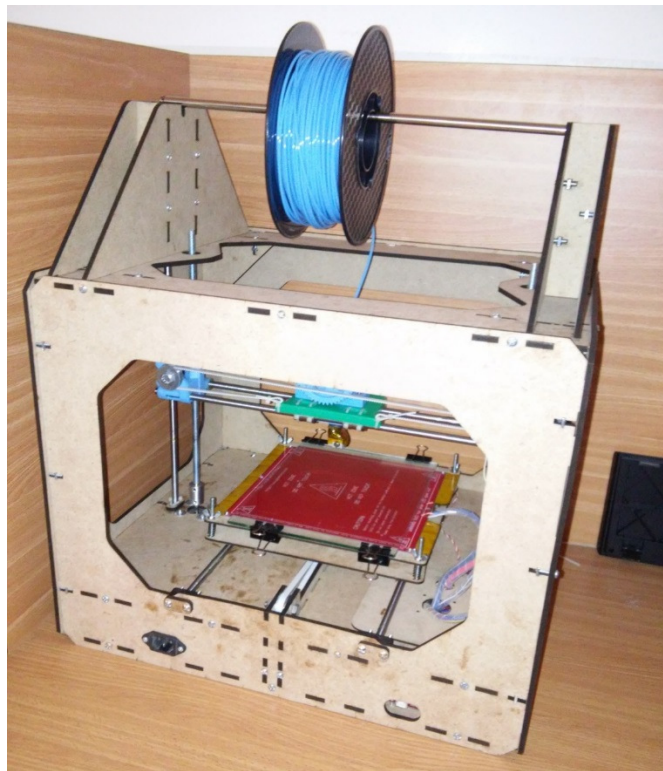
Until this step all parts of the printer were successfully assembled, but there is still some work to be done. All wires used to connect motors, heaters, sensors and limit switches are untidy as shown in *Figures 4.42* and *4.43*. Also Megatronics are not fixed in their places on the base. So in this step every group of wires connects together and as shown in the figure and Megatronics are fixed then the final side of the frame is connected. The final result of the assembly is shown in *Figure 4.44*.



*Figure 4.40 untidy wires*



*Figure 4.41 tidy wires*



*Figure 4.42 End result of the assembly*

# **CHAPTER 5**

## **Practical work and experiments**

## 5.1 Introduction

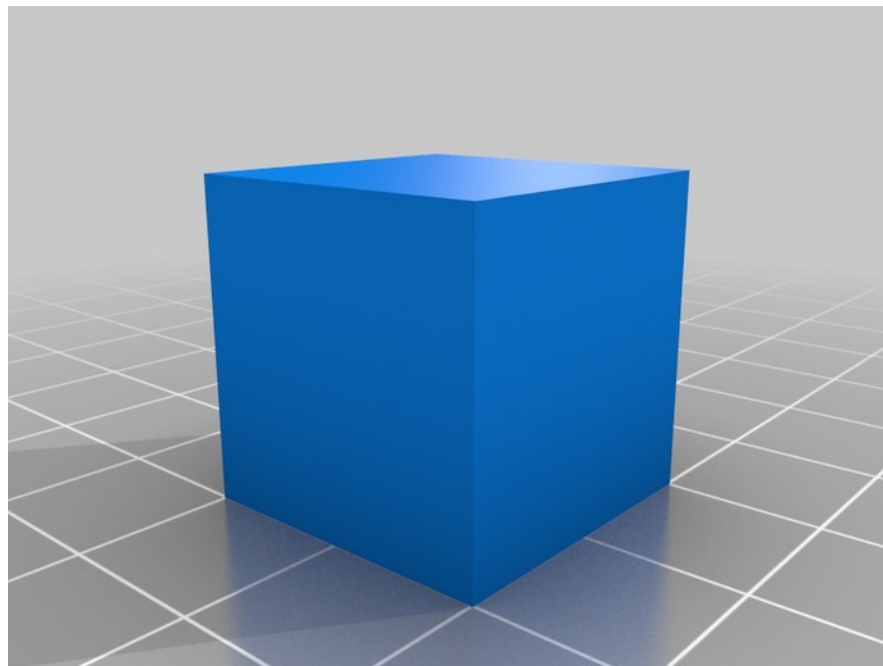
This chapter include the experimental and practical work of the 3D printer to produce printed objects with different shapes, and also include the calibration process of the 3D printer.

## 5.2 Printing procedure

- Prepare the design of the object as STL file.
- Using sli3er program, load the STL file to generate a G-code.
- Connect the power supply and the Megatronics controller to the user pc.
- Using Pronterface program that connect the Megatronics with the pc, set the extruder and the hotbed to the desired temperature.
- After making sure that the printing surface is flat relative to the extruder's hotend and the temperature reached the desired values, load the generated G-code and start the printing process.

## 5.3 Simple cube print

At the beginning of printing tests a simple cube is used to monitor the printing process and the object that constructed layer by layer. *Figure 5.1* shows the cube that used in this experiment with dimension 25x25x25mm.



*Figure 5.1* 25x25x25 mm cube

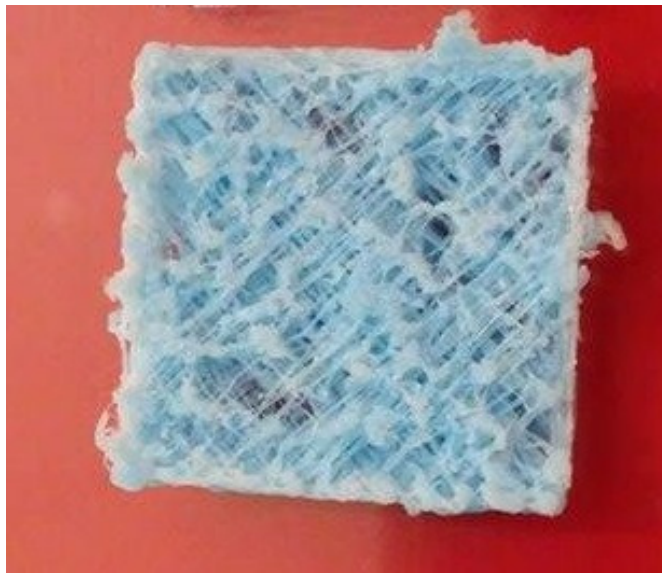
The first print trial is shown in *Figure 5.2*.



*Figure 5.2 cube printing first trial*

Noticed that the melted material don't stick to the printbed due to that the distance between the nozzle is high and the melted material flow is low, so the distance is reduced and the flow rate is increased by factor 1.2 .

The second print trial shown in *Figure 5.3*. After modify sli3er setting by increasing the flow rate and after decrease the distance between the hotend and the printbed.



*Figure 5.3 cube printing second trial*

The result is printed cube with bad surface and have a deformation in the layer, due to high speed and some material stick to the hot end.

The third trial the speed is reduced nearly by 70%, extruder temperature increased from 185 to 195 C, hotbed temperature form 60 to 70 C, and using hairspray to assist the material to stick. The printed cube is shown in *Figure 5.4*.



*Figure 5.3 cube printing third trial*

The result is printed cube with higher surface quality and less deformation. *Figure 5.5* shows the three trial of printing the same cube after modify the 3D printer setting and calibration.



*Figure 5.4 cube printing trial result*

The fourth trial is printing a cube with bigger dimension 40x40x5 mm, the result is printed object with good surface with the same desired dimension, but a warping happened to the bottom of the cube due to low temperature in bed and the cube removed from the printbed and don't cooled in slow way.

The solution of this problem is to increase the heatbed temperature to 80C and let the printed object to cool in slow way after it is finished.

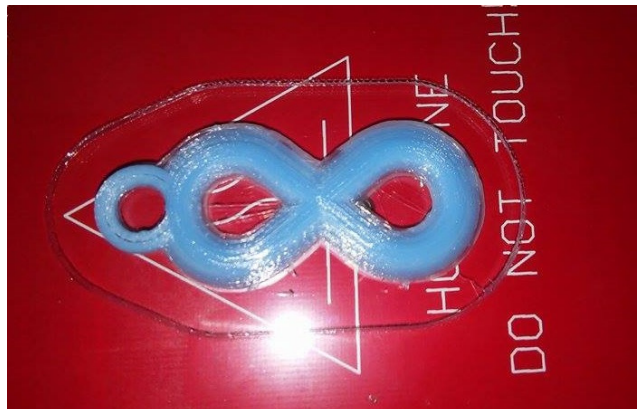
## 5.4 Curved object printing

In this experiment more complex object is used in printing process start with the first shape in *Figure 5.6* below.



*Figure 5.5 curved object 1*

The second printed object shown in *Figure 5.7* below.

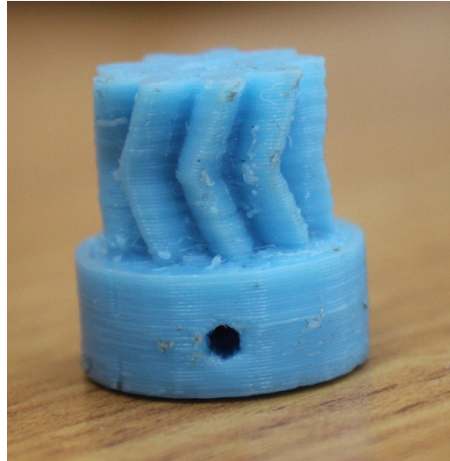


*Figure 5.6 curved object 2*

And the result is printed object with smoothly curved and with the desired dimension.

## 5.5 Extruder small gear

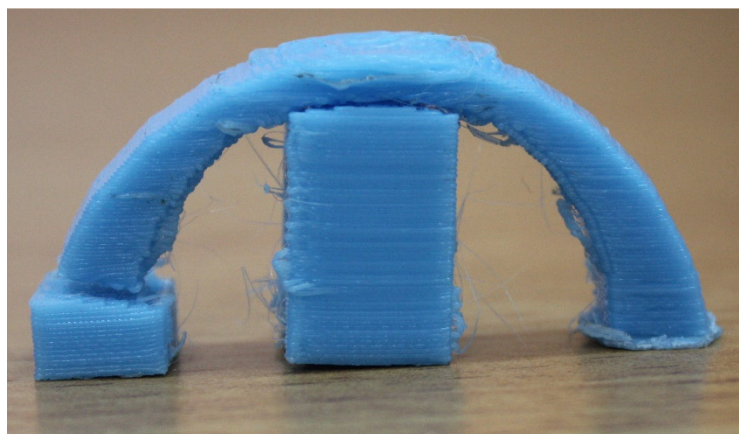
In this experiment the extruder small gear is printed to check the resolution and the accuracy of printing. And the result is shown in *Figure 5.8*, which is a gear with dimension as desired, and a high resolution and quality.



*Figure 5.8 Extruder small gear*

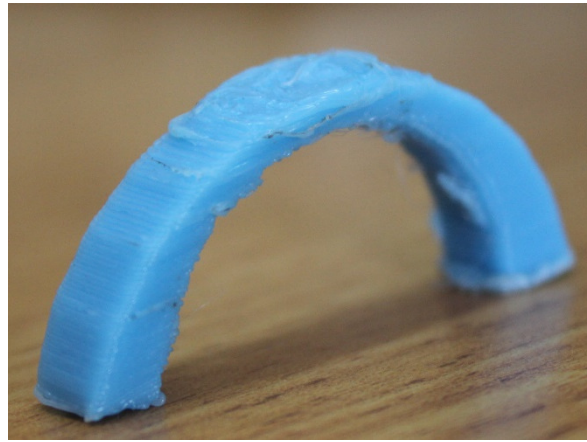
## 5.6 Simple test for support material

In this experiment a simple curved object shown in *Figure 5.9* is used to test the support material that generated in sli3er software to support the hanged object when it's printed.



*Figure 5.9 Simple curved object with support material*

And the result shown in *Figure 5.9* with the support material that can be easily remove from the desired object to get the final shape as shown in *Figure 5.10*.



*Figure 5.10 Simple curved object without support material*

## **CHAPTER 6**

### **Future work and adding features**

## 6.1 Introduction

In this chapter, some of future work suggestions to improve the performance of the printer and adding new features some of them are existed in other printer styles other is new and could be done for the first time.

## 6.2 Adding features

### 6.2.1 Wireless 3D printing

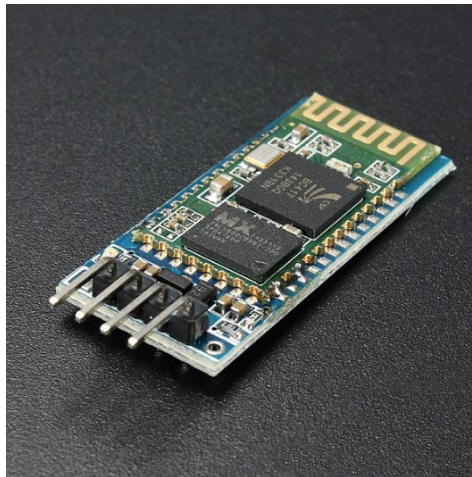
Adding wireless capability to 3D printer so there is no need for cable connection with computer, and ability to monitor and control printing from other place within the range of the wireless signals. There is many protocols to use for that such as Bluetooth, WiFi, ZigBee...etc. In *Figure 6.1* there is a comparison between advantages and disadvantages for each technology.

WIRELESS CONNECTIVITY TECHNIQUES			
	Bluetooth	ZigBee	Wi-Fi 802.11
Data rate	1 Mbit/s	20, 40, and 250 kbits/s	11 and 54 Mbits/s
Range	10 m	10 to 100 m	Up to 100 m
Networking topology	Ad-hoc, small networks	Ad-hoc, peertopeer, star, or mesh	Point to hub
Frequency	2.4 GHz	868 MHz (Europe), 900 to 928 MHz (North America), 2.4GHz(worldwide)	2.4 and 5 GHz
Power consumption	Low	Very low	High
Typical applications	Inter-devicewirelessconnectivity, e.g., phones, PDAs,laptops,headsets, cameras, printers, serial cable replacements	Industrial control and monitoring, sensor networks, buildingautomation, toys, games	Wireless local-area network (WLAN) connectivity, broadbandInternet, security cameras

Figure 6.1: comparison between wireless technologies

According to the comparison shown in *Figure 6.1*, the suitable design for 3D printer application is Bluetooth technology. To apply this technology and connect HC-06 Bluetooth module shown in *Figure 6.2* to Megatronics v2.0 this is the procedure:

1. Program the HC-06 module using AT commands and select suitable baud rate by special software while it is connecting with computer.
2. In Marlin code enter “configuration.h” file to change baud to the same value in previous step.
3. Connect serial port pins of Mega2560 (TX, RX, GND and 5V) in Megatronics v2.0 with Bluetooth module pins but note that the modules works on 3.3V and TX, RX of Megatronics works on 5.5V so you should build a circuit to convert from 5V to 3.3V .
4. In the host computer change the configuration of the Bluetooth as the same baud to receive data from printer.
5. In the interface program make sure it uses the same baud and then you can upload G-code to printer wirelessly and printing start as usual.



*Figure 6.2 HC-06 Bluetooth module*

## **6.2.2 Monitoring and display**

In the 3D printer there is many important status can be monitoring and displayed on a LCD screen to give a useful information to the user during the printing process, such that:

- 1) The temperature of the extruder and the heatbed:

Using the thermistor sensor to measure the temperature as signal, and this signal can be processed to give the temperature as a number that can be display on the LCD.

- 2) X,Y,Z position :

Form the command that the Megatronics controller generate to control the position of the three axis components, the current position of the end-effector “the extruder” can be obtained.

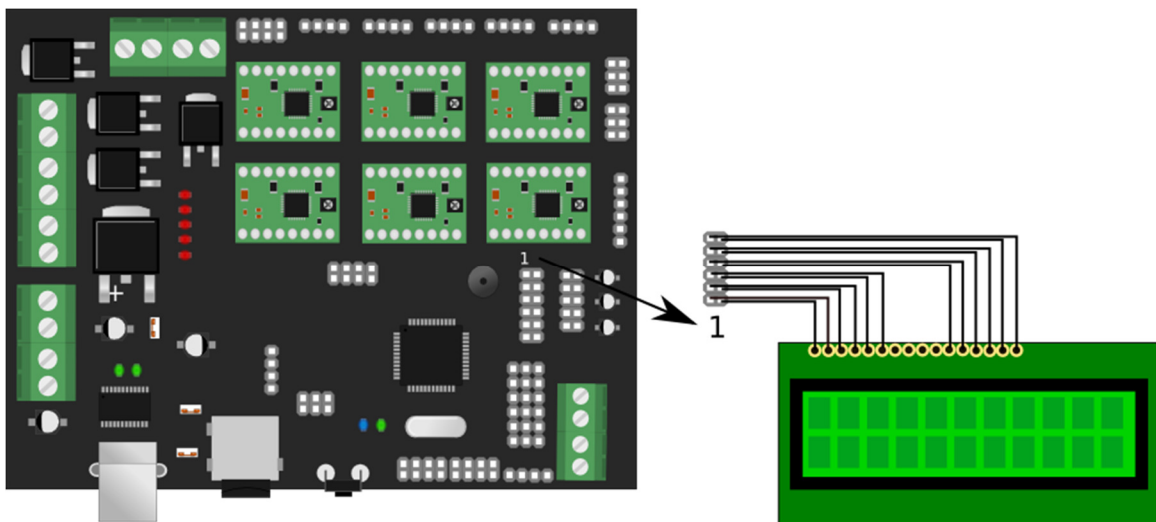
The other way is to use linear or rotary encoder to measure the current position.

3) Percent of achieved work:

From the available information such the speed of printing, the volume of the object and the percent of fill, the percent of achieved work can be calculated and displayed on the LCD.

### Wiring diagram

From Megatronics V2 datasheet shows that it is Compatible with most LCD screens, the *Figure 6.3* shows the wiring of LCD with Megatronics controller.



*Figure 6.3 wiring connection of LCD with Megatronics controller*

### 6.2.3 Fault diagnosis and detection

As the readings of the sensors are displaying in monitoring system, they could use for error detection by comparing this reading with predefined expected values and if there is differences between them this means an error happened. At that time an error message of the expected error will be shown on LCD. This is two examples of errors:

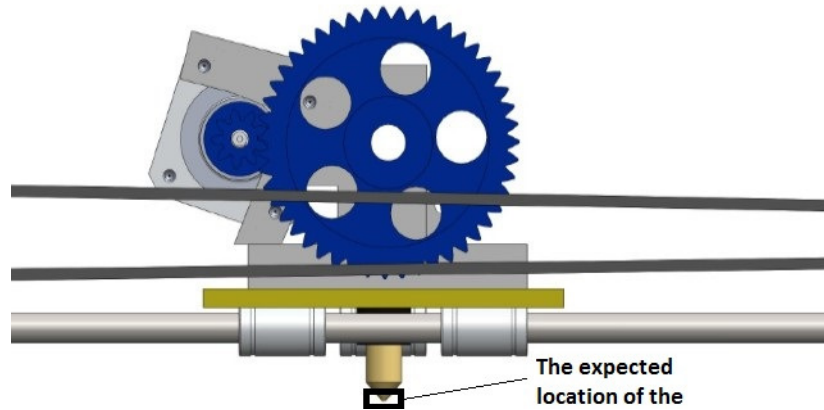
#### 1. Temperature fault

The temperature values are always measured by heat sensors fixed on extruder and heatbed, so if there is an error of that value, either it is out of rang or it is still constant, an error message " E1: extruder temp error" or "E2: heatbed temp error" will be displayed on LCD.

#### 2. Extrusion fault

When there is no filament gets out from extruder while the printer is running" X,Y and Z axes motors work properly" that means there is a problem in extruder " explained in

previous section “. This problem can be detect by adding an optical end stop at the nozzle outlet “can be connected in Megatronics v2.0” the end stop will give a digital signal if there is no filament passing throw it so an error massage” E3: extrusion problem” will be displayed on LCD. This method should be tested to make sure optical sensor can detect the outlet filament because it is very thin and some colors are transparent. The expected location of the sensor is shown in *Figure 6.4*.



*Figure 6.4: The expected location of the optical sensor*

If the method dose not success to detect the outlet filament there is another choice to detect similar but fewer errors by fixing the optical sensor at the inlet of extruder instead of its’ outlet as explained in next paragraph.

#### **6.2.4 Fail-safe**

Fail-safe means when failure happens for any reason the machine response must be in a way that will cause a minimum harm for the user and the parts of the machine. In the 3D printer a fail-safe feature can be added so that if there is any failure happened to the system it will stop in a certain procedure to achieve the minimum harm.

#### **6.2.5 Z axis endstop calibration device**

Before printing starts some calibrations must be done such as: ensure that the printplat surface is horizontal without inclination, and Z axis distance between nozzle and printplate should be calibrate to suitable distance not too high and not too low to have a good shape and thickness for the first layer filament. This operation usually done manually and estimated by eye. To make this easier and more accurate a small device with a scale is suggested to be added. By this an exact distance will be adjusted easily and with more accuracy.

# Appendix A

## Stepper motor:

Stepper motors are electromagnetic, rotary, incremental devices which convert digital pulses into mechanical rotation. The essential property of the stepping motor is its ability to translate switched excitation changes into precisely defined increments of rotor position ('steps'). Stepper motors have current-carrying winding on the stationary part (the 'stator') and teeth of magnetically permeable material the rotating part (the 'rotor'). Figure 1 show the main parts of the stepper motors [18].

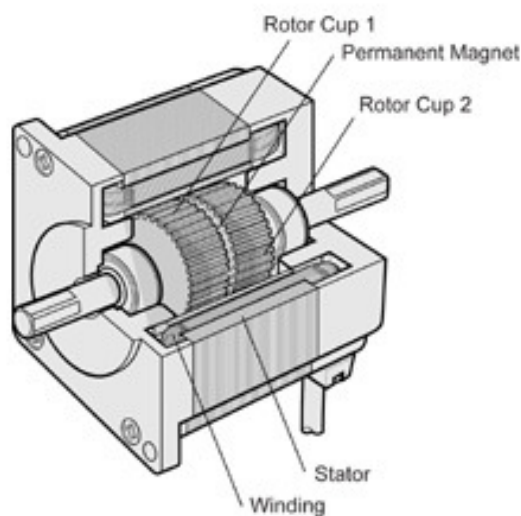


Figure 1: stepper motor parts

## Stepper Motor Theory of Operation:

Stepper motors provide a means for precise positioning and speed control without the use of feedback sensors. The basic operation of a stepper motor allows the shaft to move a precise number of degrees each time a pulse of electricity is sent to the motor. Since the shaft of the motor moves only the number of degrees that it was designed for when each pulse is delivered, the control the pulses that are sent lead to control the positioning and speed. The rotor of the motor produces torque from the interaction between the magnetic field in the stator and rotor. The strength of the magnetic fields is proportional to the amount of current sent to the stator and the number of turns in the windings.

The stepper motor uses the theory of operation for magnets to make the motor shaft turn a precise distance when a pulse of electricity is provided. When power is applied, the rotor is directed to only one of the stator pairs of windings, which will cause that winding pair to become a magnet.

One of the coils for the pair will become the North Pole, and the other will become the South Pole. When this occurs, the stator coil that is the North Pole will attract the closest rotor tooth that has the opposite polarity, and the stator coil that is the South Pole will attract the closest rotor tooth that has the opposite polarity. When current is flowing through these poles, the rotor will now have a much stronger attraction to the stator winding, and the increased torque is called holding torque.

When no power is applied to the motor, the residual magnetism in the rotor magnets will cause the rotor to detent or align one set of its magnetic poles with the magnetic poles of one of the stator magnets. When the rotor is in a decent position, it will have enough magnetic force to keep the shaft from moving to the next position. This is what makes the rotor feel like it is clicking from one position to the next as you rotate the rotor by hand with no power applied.

Figure 2 shows the sequence of excitation for the stator winding that yield to the movement of the rotor.

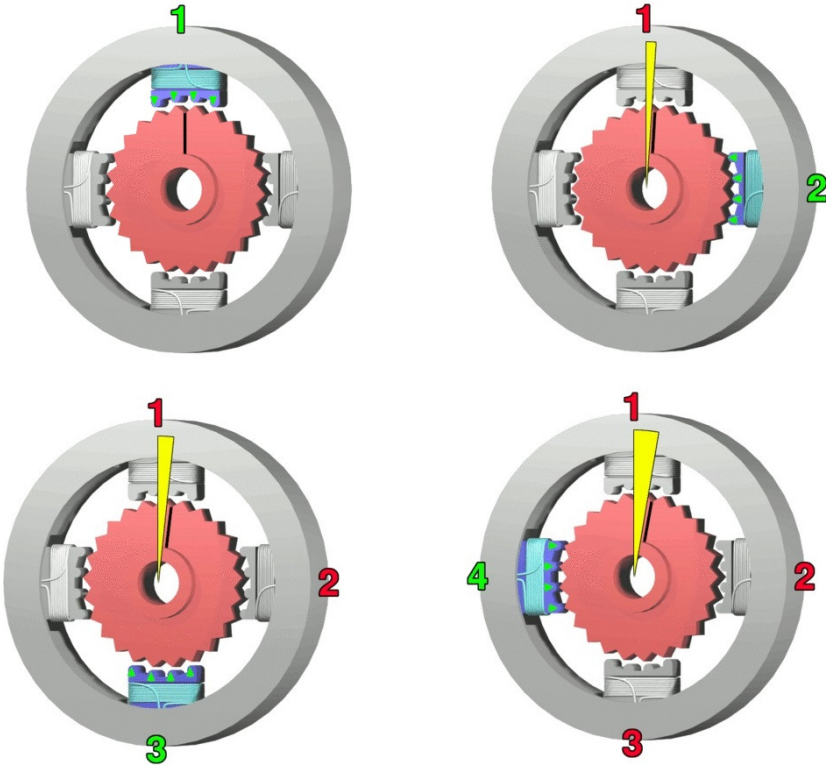


Figure 2: stator winding and rotor

## Stepper Motor Advantages and Disadvantages[19]

### Advantages:

1. The rotation angle of the motor is proportional to the input pulse.
2. The motor has full torque at standstill (if the windings are energized)
3. Precise positioning and repeatability of movement.
4. Excellent response to starting/stopping/reversing.
5. Very reliable since there are no contact brushes in the motor. Therefore the life of the motor is simply dependent on the life of the bearing.
6. The motors response to digital input pulses provides open-loop control, making the motor simpler and less costly to control.
7. It is possible to achieve very low speed synchronous rotation with a load that is directly coupled to the shaft.
8. A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses.

### Disadvantages:

1. Resonances can occur if not properly controlled.
2. Not easy to operate at extremely high speeds.

## Step Modes:

Stepper motor "step modes" include Full, Half and Microstep:

### Full step:

Standard hybrid stepping motors have 200 rotor teeth, or 200 full steps per revolution of the motor shaft. Dividing the 200 steps into the 360° of rotation equals a 1.8° full step angle. Normally, full step mode is achieved by energizing both windings while reversing the current alternately. Essentially one digital pulse from the driver is equivalent to one step.

### Half step:

Half step simply means that the step motor is rotating at 400 steps per revolution. In this mode, one winding is energized and then two windings are energized alternately, causing the rotor to rotate at half the distance. Although it provides approximately 30% less torque, half-step mode produces a smoother motion than full-step mode.

## Microstep:

Microstepping is a relatively new stepper motor technology that controls the current in the motor winding to a degree that further subdivides the number of positions between poles to 1/8 or 1/16 of the full step. Microstepping is typically used in applications that require accurate positioning and smoother motion over a wide range of speeds. Microstepping provides less torque than half-step mode.

Figure 3 shows the input signal for each phase of stator winding for the three step modes.

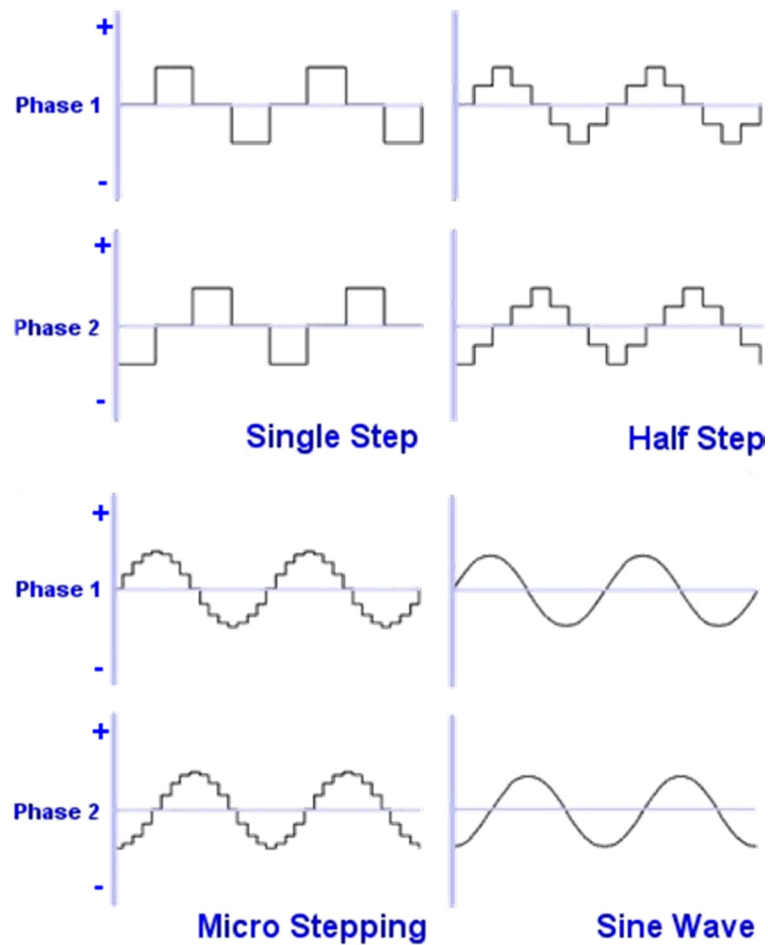


Figure 3: input signal for each phase

# Appendix B

## Numerical control programming language (G-code)

In slicing stage of 3D printing work flow which mentioned in previous chapter, slicing software will generate a set of G-code commands form STL file then transfer it to microcontroller to control the movement of Cartesian robot. In this section some information about G-code will be explained.

G-code: is the common name for a numerical control (NC) programming language. This language is mainly used for controlling automated machine tools in Computer Aided Manufacturing (CAM). G-code enables users to communicate with machine tools through a series of symbols and numbers to tell it where and how to move [20].

Every program code has three parts start, main and end part. Main program code consists of group of instructions called blocks. Each block is a line describing a particular set of machining operations. A line contains words each word refer to a specific cutting or movement command or machine functions. Each word is composed from a letter called the address, along with a number [21].

The G-codes are grouped into categories such as Group 01, containing codes G00, G01, G02, G03, which cause some movement of the machine table or head. For example G00 code rapidly positions the cutting tool while it is above the workpiece from one point to another point on a job.

There is a general G-codes groups used in all machines supporting G programming language such as Group 01. Otherwise there is a special codes differing according the machine type and the manufacturer company.

The main addresses and there functions [21]:

**N:** refers to the block number.

**G:** refers to the G-code (Preparatory function).

**X:** refers to the absolute/incremental distance travelled by the slide tool in the X axis direction.

**Y:** refers to the absolute/incremental distance travelled by the slide tool in the Y axis direction.

**Z:** refers to the absolute/incremental distance travelled by the slide tool in the Z axis direction.

**F:** refers to the feed rate.

**M:** refers to the M code (Miscellaneous function).

**S:** refers to the spindle speed.

**T:** refers to the tooling management.

An example of a 3D printer G code block [22]:

**G1 X-9.2 Y-5.42 Z0.5 F3000.0 E0.0377**

**G1**

The first statement part of the statement is the command. In this case we have G1. G1 simply means a move. What follows are the instructions for the movement.

**X-9.2 Y-5.45 Z0.5**

These are the arguments for the command. These give commands to the X, Y, and Z Axes.

**F3000**

For the purposes of 3D printing these F codes refer to the frequency the motor is moving at. In the older CNC world they referred to the feed rate. The Feed rate is expressed in mm/minute. Therefore, in this case we are working at 3000 mm/minute. The Feed rate for the stepper motors will vary considerably over the path of the print.

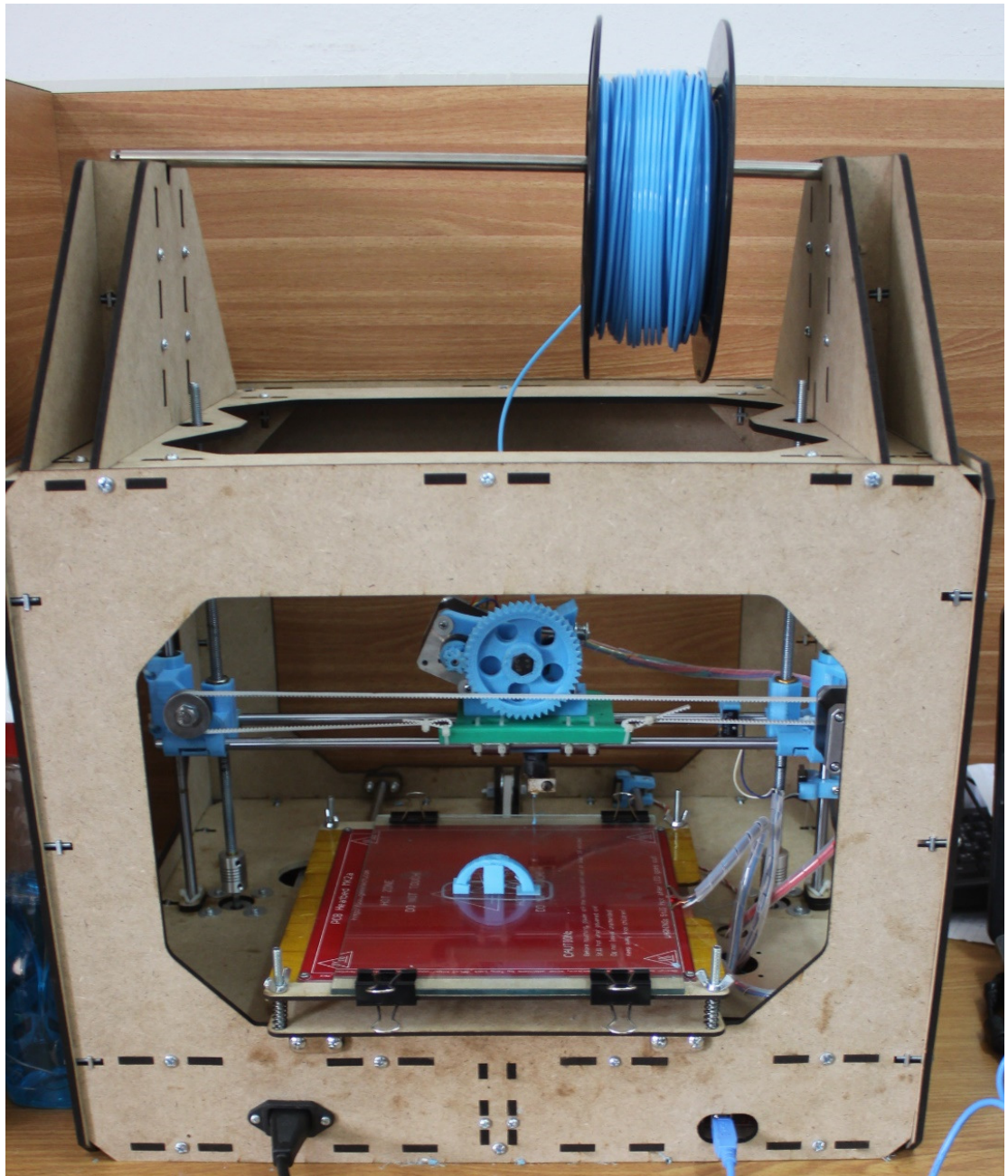
**E0.0377**

The E code controls the amount of extrusion going on. In this case no feed rate is given, the speed is taken at default.

# Digital Object Maker

FDM 3D Printer

*User Manual*



# Contents

<b>Introduction</b> .....	78
<b>Specifications</b> .....	78
<b>How it is work</b> .....	79
<b>Printer components</b> .....	79
Main diagram .....	79
More detailed diagrams .....	80
- <b>Front view</b> .....	80
- <b>Side view</b> .....	81
- <b>Front view</b> .....	82
<b>Software downloading</b> .....	83
- Slic3r .....	83
- Pronterface .....	83
<b>Printing Procedure</b> .....	84
<b>Troubleshooting</b> .....	90
Introduction .....	90
1. Object do not stick on the print bed .....	90
2. Difficulty in removing the printed object from print bed .....	90
3. Leaning prints or shifted layers .....	90
4. Under extrusion .....	91
5. Over extrusion .....	92
6. Axis sticking problem .....	92

## Introduction

This User manual is designed to start using Digital Object Maker 3D Printer in the right direction. Even if you are familiar with other 3D printers, it is essential that you read through this manual.

## Specifications

### Printing

**Print Technology:** Fused Deposition Modeling

**Print Volume:** 20 x 20 x 20 cm.

**Layer Resolution:** 100-250 micron

**Filament Diameter:** 3mm

**Nozzle Diameter:** 0.45mm

### Software

**Interface software:** Pronterface

**Slicing software:** Slic3r

**File Types:** STL

### Electrical

**AC Input:** 220 V, 50 Hz

**Power Requirements:** 12 V DC and 30 Amps

**Connectivity:** USB

### Mechanical

**Chassis and body:** MDF wood

**XYZ Bearings:** LME8UU Linear bearing

**Stepper Motor:** 1.8° step angle  
1/16 micro stepping

### General

**Frame Dimensions:** 49x42x55 cm<sup>3</sup>

**Printing Material:** PLA

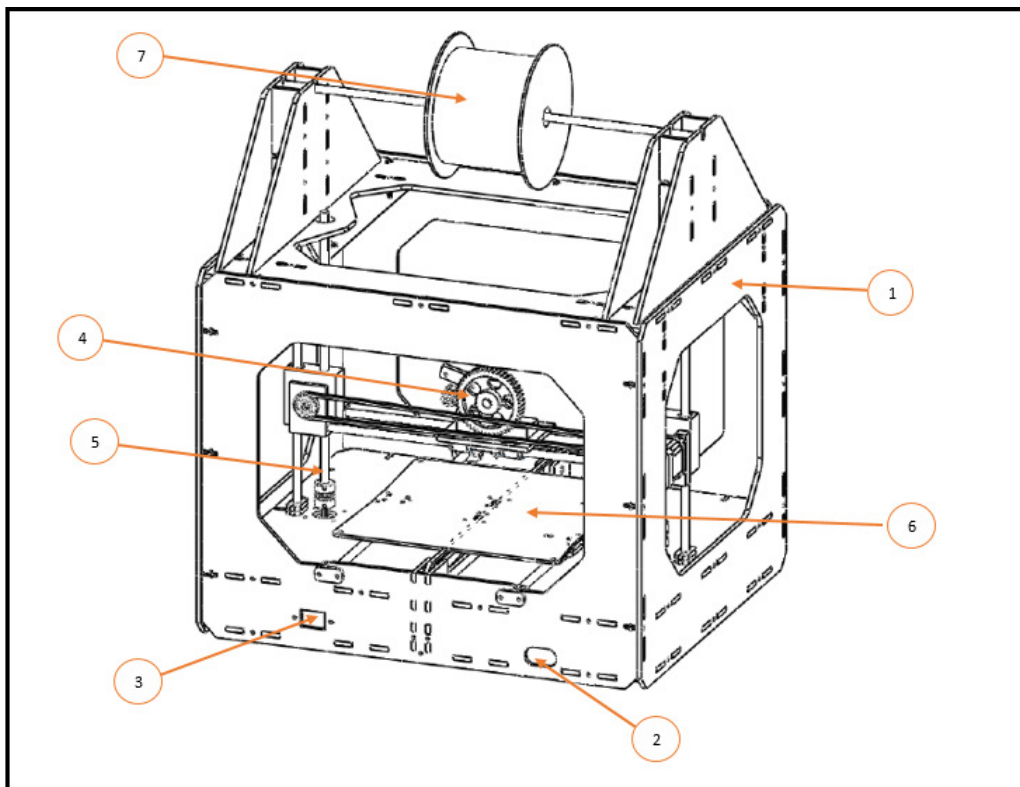
**Filament Diameter:** 3mm

## How it is work

The DOM makes solid, three-dimensional objects out of melted PLA Filament. Your 3D design files are translated into instructions for the DOM and sent to the machine via USB cable. Then the DOM heats the PLA Filament and squeezes it out through a nozzle to make a solid object layer by layer. This method is called Fused Deposition Modeling [FDM] [23].

## Printer components

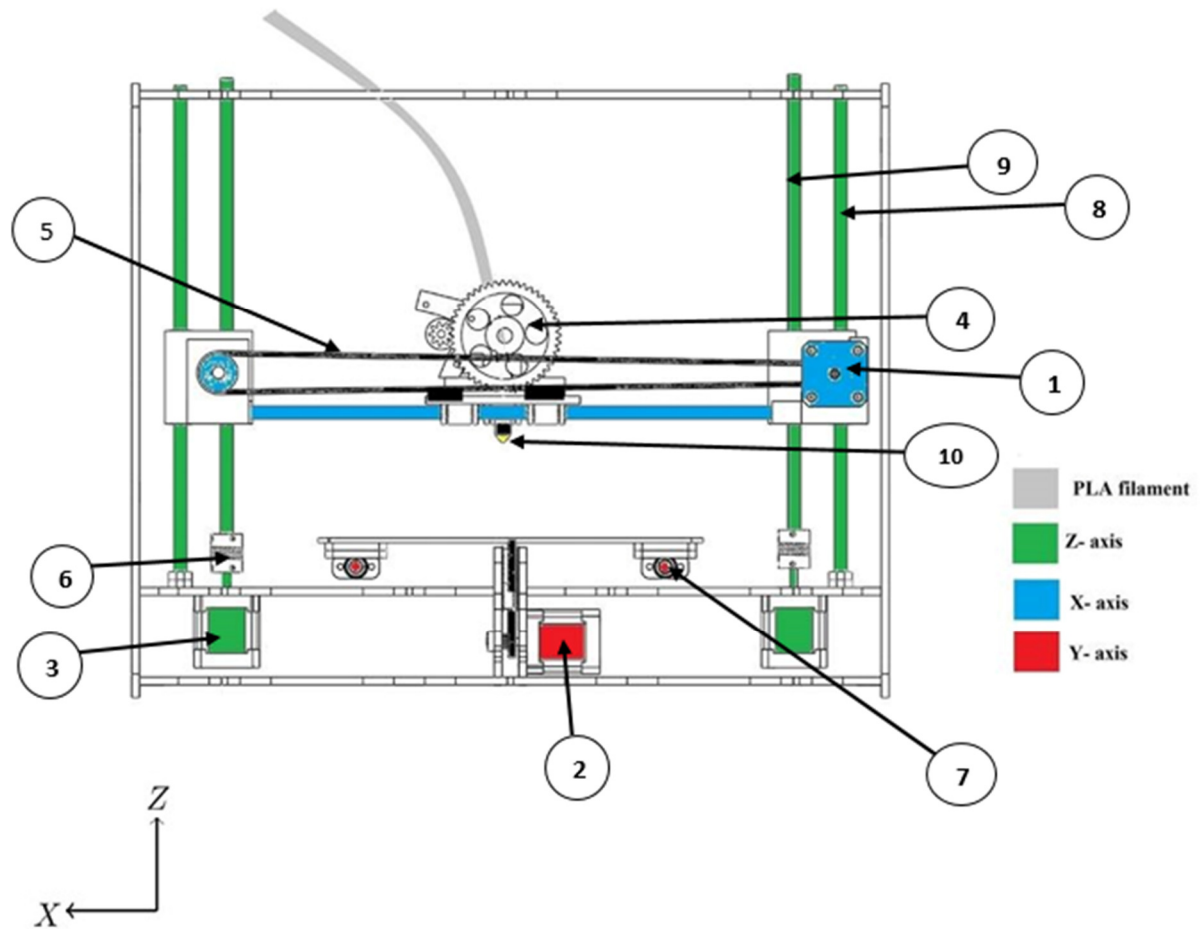
### Main diagram



1. Frame
2. USB cable inlet
3. Power cable inlet
4. Extruder
5. Z axis threaded rod
6. Print bed
7. PLA filament

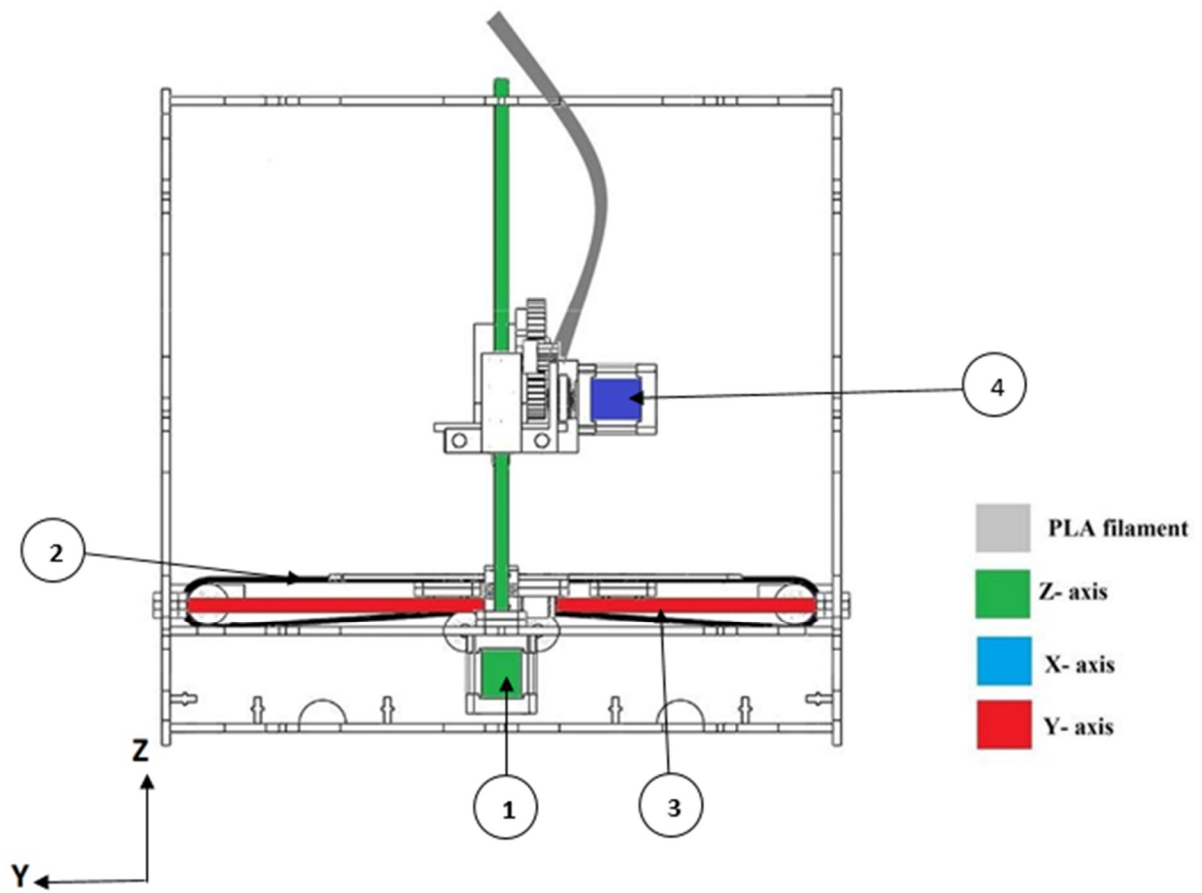
## More detailed diagrams

### - Front view



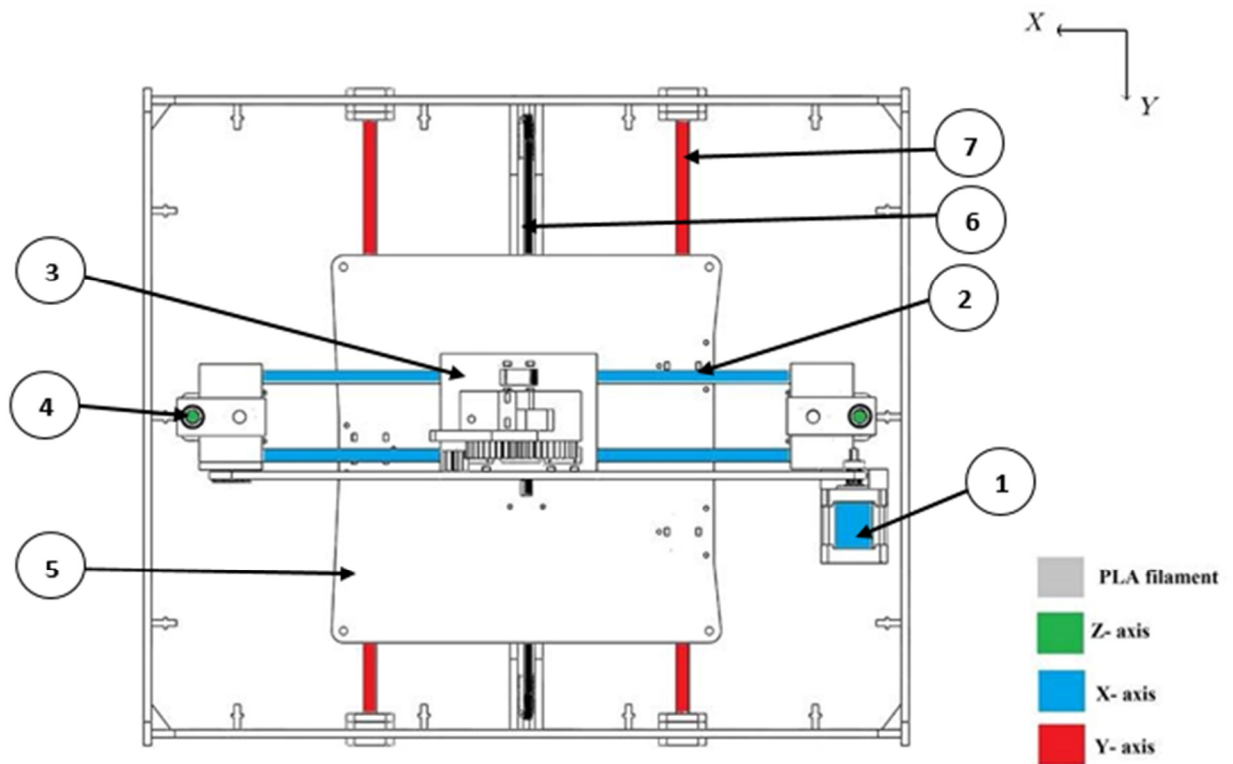
1. X axis motor
2. Y axis motor
3. Z axis motors
4. Extruder
5. Timing belt
6. 5/8 mm coupler
7. Y axis linear bearing
8. Z axis smooth rods
9. Z axis threaded rods
10. Nozzle

- Side view



1. Y axis motor
2. Timing belt
3. Y axis smooth rod
4. Extruder motor

- **Front view**

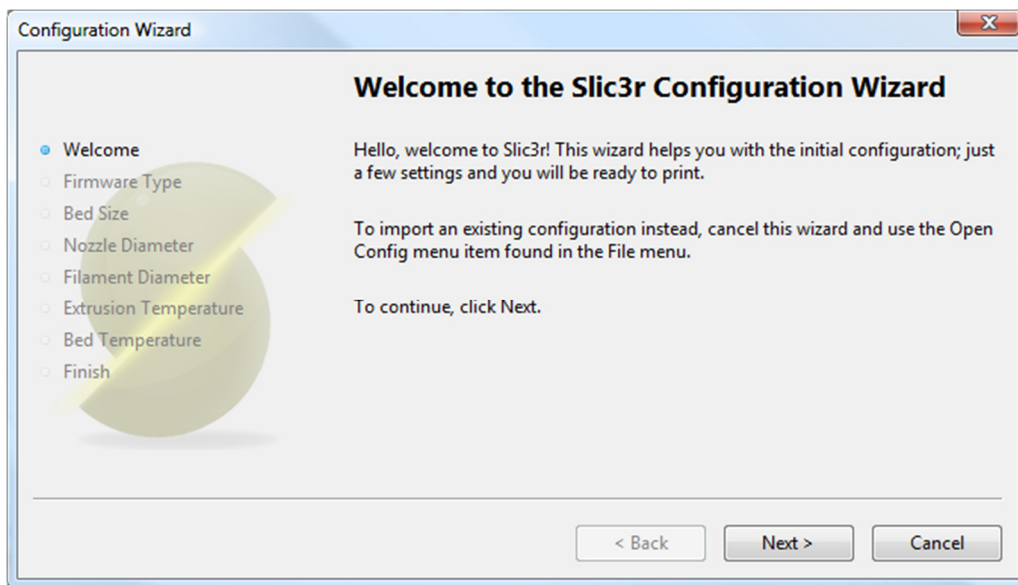


1. X axis motor
2. X axis smooth rod
3. Extruder
4. Z axis linear bearings
5. Print bed
6. Y axis timing belt
7. Y axis smooth rod

## Software downloading

### - Slic3r

Download “Slic3r” software from this link (it is an open source software): <http://slic3r.org/download>. Notice that when you setup “Slic3r” and open it for the first time. The configuration wizard asks a series of questions and creates a configuration for Slic3r to start with.



For this printer choose these values respectively:

- Firmware Type: “RepRap (Marlin/Sprinter)”
- Bed size: x 200 y 200 mm
- Nozzle Diameter: .45 mm
- Filament Diameter: 2.85 mm
- Extrusion Temperature: 200 C
- Bed Temperature 80 C

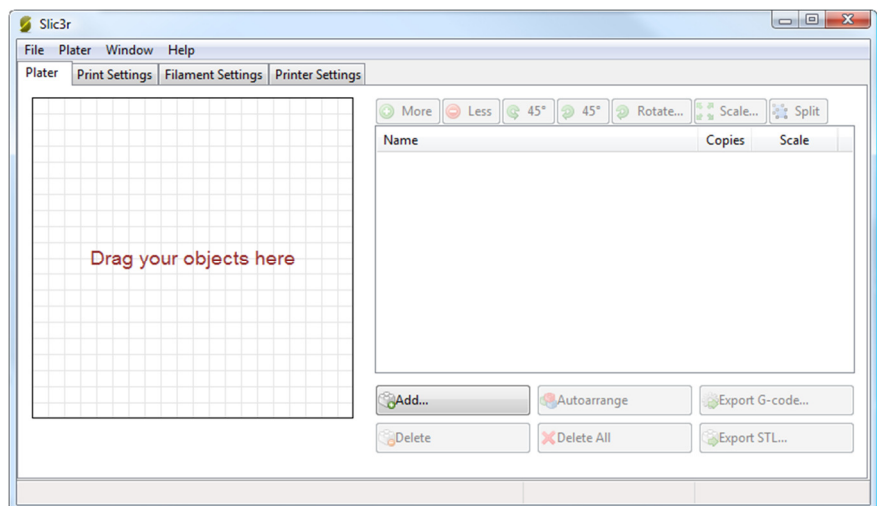
Notice that you can change these settings from inside the software at any time (if you see that the temperature should be higher or lower for example).

### - Pronterface

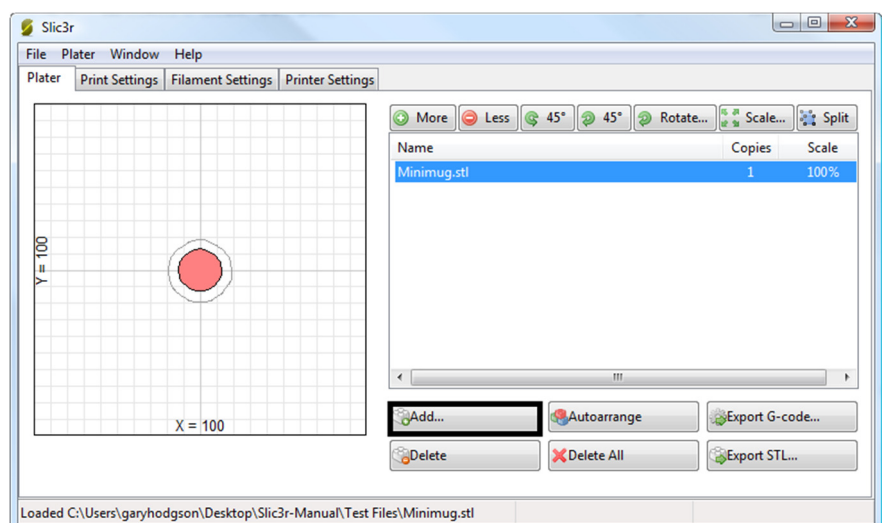
Download the latest version of “Pronterface” software from this link (it is an open source software): <http://koti.kapsi.fi/~kliment/printrun/> .

## Printing Procedure

1. Connect the printer to the computer using USB 2.0 cable.
2. Prepare you printer by:
  - Ensure that the print bed is clean.
  - Ensure that the print bed is flat, if not adjust it using four wing nuts.
  - Manually adjust the position of Z-axis limit switch to satisfy a suitable distance between the nozzle and the print bed (check it by pass a thin piece of paper between them).
3. Prepare 3D model in “.stl” file format you can download it from an online websites, such as "Thingiverse" or "GrabCAD", or create it using any CAD program such as "SolidWorks" or "SketchUp".
4. Open “Slic3r” software

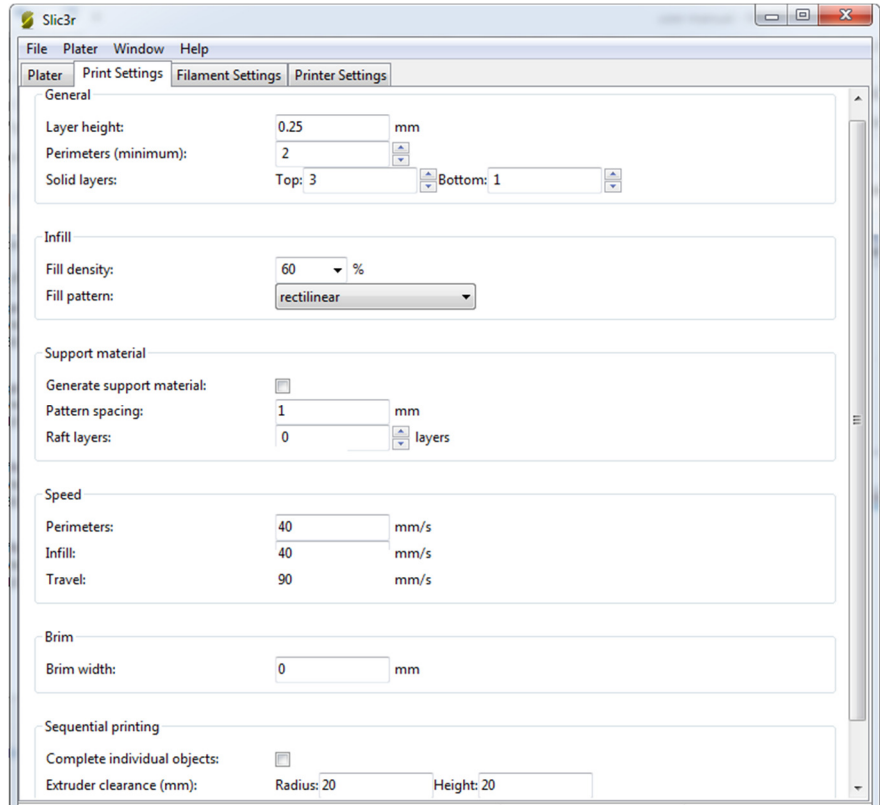


5. Load the 3D model to the Plater window from “Add” icon

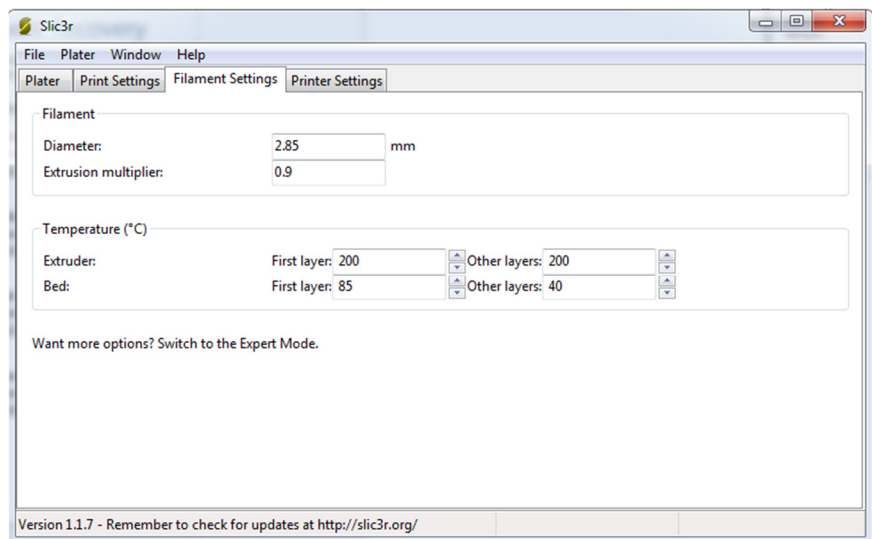


## 6. Adjust **Print Settings** as shown

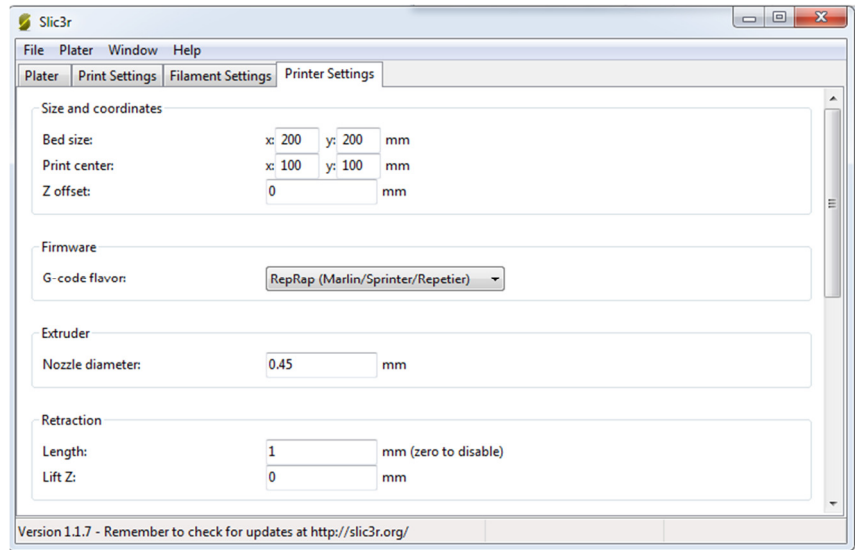
(The majority of these settings is chosen and tested by trial and error, so if it is needed you can change them to achieve better results, and this is the same for settings shown in next steps except the physical setting that relates to the dimensions of the printer and the filament).



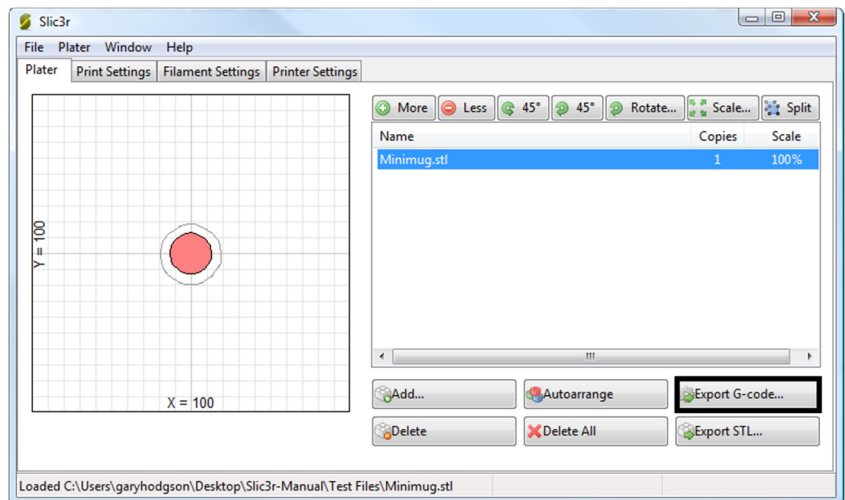
## 7. Also adjust **Filament Settings** as shown



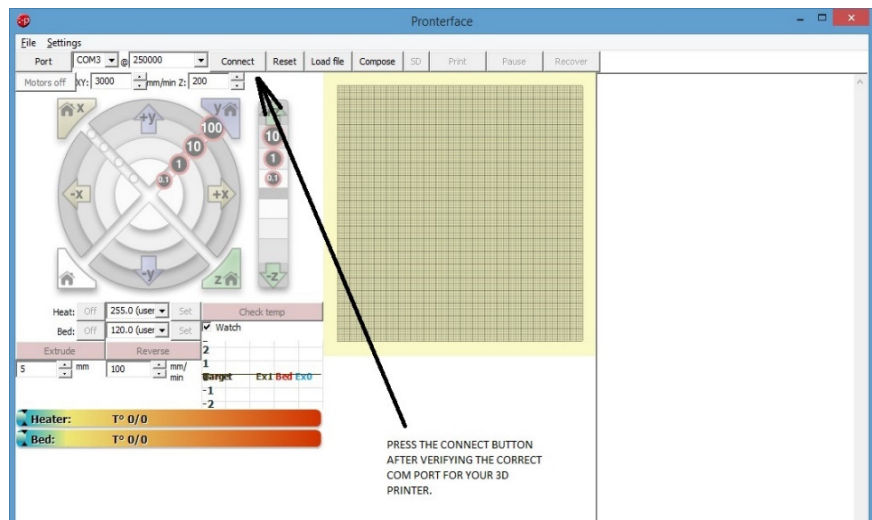
## 8. Finally adjust **Printer Settings** as shown



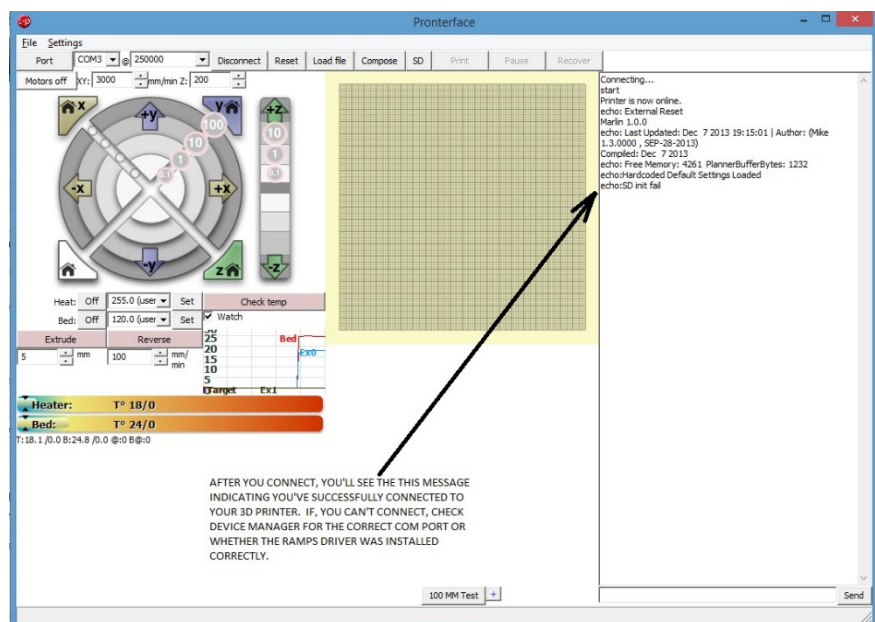
## 9. Export G-code



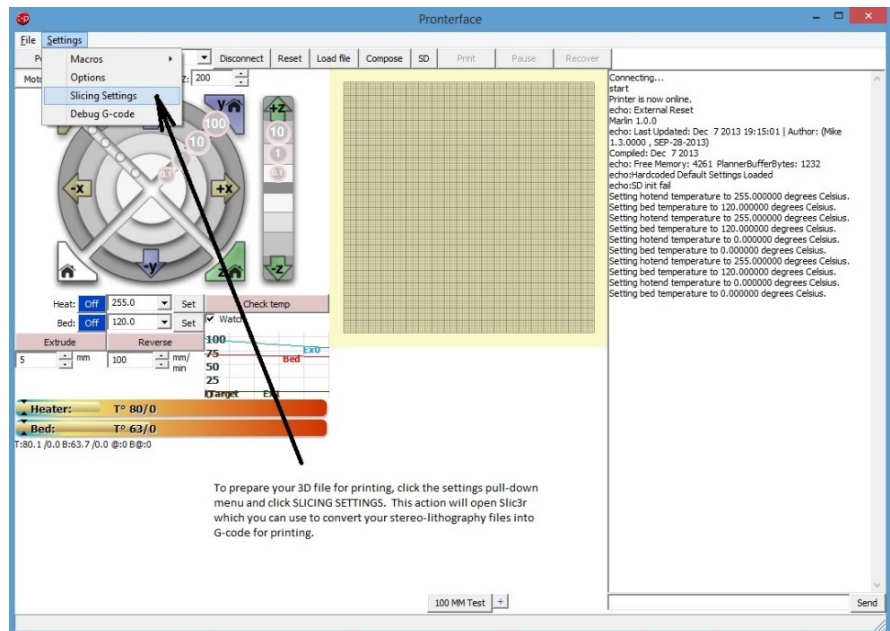
## 10. Open “Pronterface” software and connect it to your printer



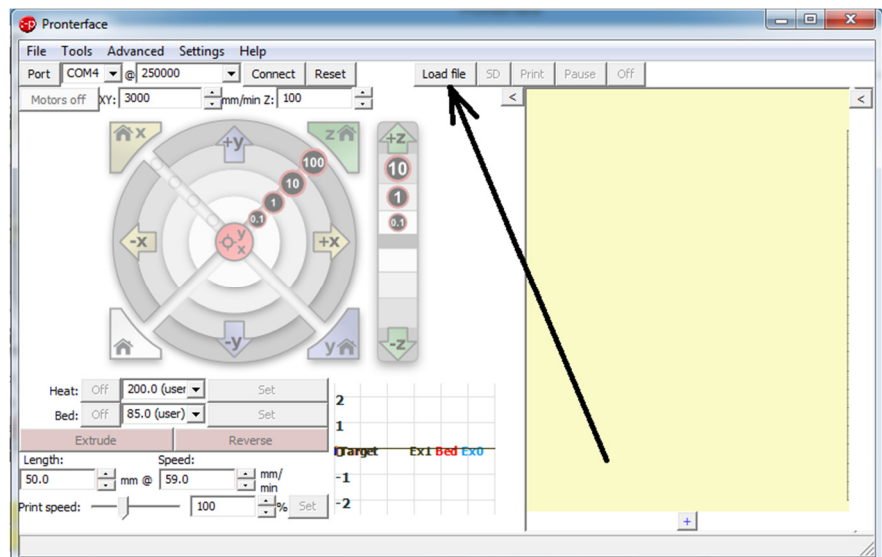
(You will see a message in the right column of Pronterface indicating that the printer has successfully connected)



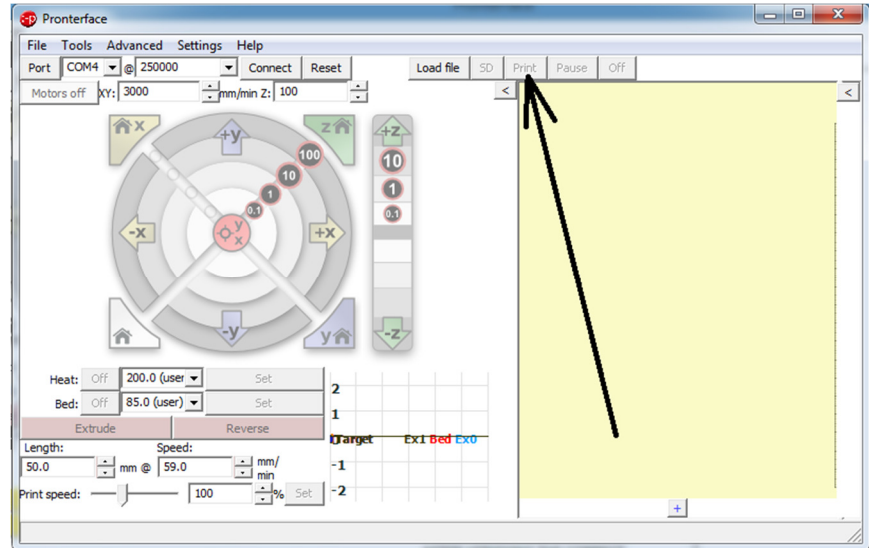
- From settings list Adjust settings as the same of “slic3r” settings (not as numbers shown in figure)



- Load the G-code of 3D model which was exported form slicer



13. Click print icon to start printing (it will be enabled if the printer is connected and G-code is loaded)



# Troubleshooting

## Introduction

In this part there are some common problems may happen in the printing process using DOM 3D printer and some suggested solutions to these problems.

### 1. Object do not stick on the print bed

When a printed object is not stuck on the glass above the print bed either at starting or while printing, try these solutions [23]:

- Ensure that the glass is clean. Because dust and oil from hands can prevent sticking on the glass.
- Ensure that the distance between the nozzle and the print bed is suitable (check it by passing a thin piece of paper).
- Increase the bed temperature by 5 degrees.
- You can add some adhesives on the print bed like hair spray or any other.

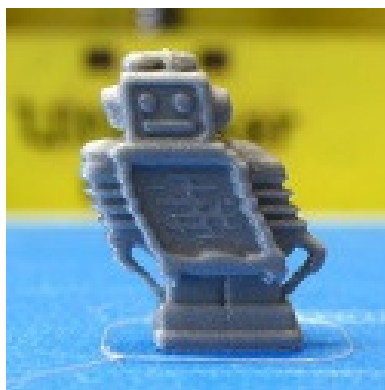
### 2. Difficulty in removing the printed object from print bed

Printed object sticks on print bed and cannot be removed after complete printing. Solutions for this problem [23]:

- Wait for the print bed to cooling down so the object will remove easily.
- Use metal craft spatula or small screw and carefully put it under the edge of the object, then twist it slightly.

### 3. Leaning prints or shifted layers

A leaning print (as shown in the figure below) is usually caused by one motor moves a shorter distance than expected due to friction or slipping in one of the motors or wrong step per millimeter factor in marlin software [24]. Solutions:

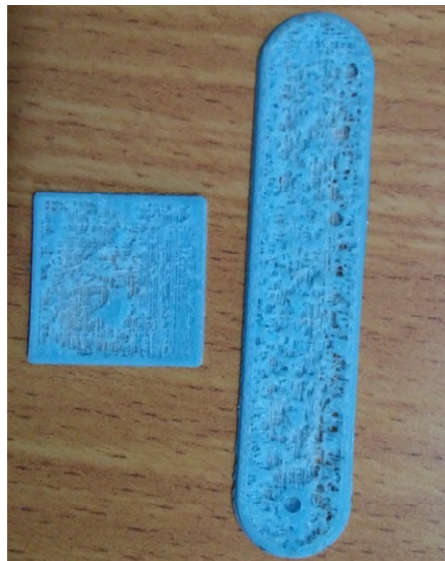


- Ensure that all the pulleys on X and Y axes are tied properly.
- Ensure that there is no touching between the timing belts and frame or any other parts while moving because this will generate friction.
- Put some lubricant on the bearings and rods to decrease frictions.
- In marlin software there is a file called “configuration.h” contains a step per millimeter factors for all motors try to change it to suitable numbers.

#### 4. Under extrusion

That means the printer cannot supply the needed amount of PLA. This will cause missing layers, or layers that have random dots and holes (as shown in the figure below). There are many causes of this problem such as:

- Printing speed is higher than the capability of the printer.
- The temperature is not enough to melt the PLA so it requires higher pressure to push it.
- The nozzle is blocked or partially blocked by dirt or burned material.
- There is a problem in extruder mechanism.



Try these solutions:

- Decrease printing speed.
- Increase printing temperature, but not more than 215 °C.
- If there is a jamming in extruder increase the temperature, then extrudes some material if it is still blocked you should clean it.
- Check that the screws on the extruder is tight well. Then check if extruder mechanism work probably by giving it an order to extrude a certain length of PLA then measure the distance of filament entered the extruder if there is a significant difference that means there is a problem in the mechanism.

## 5. Over extrusion

This problem is the opposite of the under extrusion problem and it means that the extruded material is more than required (as shown in the figure below) it can be caused if the temperature is too high, so the filament become like liquid, or if the filament diameter sets in Sli3er is too low value than its real value.



Solutions:

- Decrease printing temperature.
- Ensure that the filament diameter value is the same in settings and reality.

## 6. Axis sticking problem

This problem happens when axis does not move smoothly or one motor stalls (stop rotating) while printing process.

Solutions:

- Make sure rods are clean and linear bearings run smoothly.
- Ensure that belt alignment is correct, and the belt is not contact unduly with belt guides or anything else.
- Ensure there is no mechanical obstruction to the movement of the belt, or bearings on the smooth rods.

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