18th INTERNATIONAL CONFERENCE

ON

MACHINE DESIGN AND PRODUCTION

CONFERENCE PROCEEDINGS
VOLUME I

Editorial Board

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umtik 2018

3-6 July 2018

ESKİŞEHİR- TURKEY

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DESIGN AND FABRICATION OF LARGE-SIZE FFF 3D PRINTER

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ABSTRACT

Additive manufacturing, also known as "3D printing" keeps diffusing into many industries with a rapid pace. The greatest advantage of 3D printers is that it allows the designers to produce a prototype in a very short time that can be tested and quickly remodeled if necessary. This significantly reduces the required time to advance from the design phase to the final product. Another great advantage is manufacturing components which have very complex and precise forms through this technique. It is also possible to speed the process of manufacturing of complex parts which can be produced in a long time with conventional methods. In this paper, the design and fabrication of a large size FFF 3D delta printer, also the challenges encountered during the fabrication are presented.

Keywords: 3D Delta Printer, Fused Filament Fabrication (FFF), Thermoplastic Polymer Materials

1.   INTRODUCTION

Three-dimensional (3D) printing is a new technology which was first invented in 1984 by Chuck Hull. 3D printing technologies have been developed rapidly over the last 30 years and provide practical solutions for many application areas. It allows for manufacturing any part regardless of the complexity with many different materials. 3D printer is a machine that transforms 3D computer data (i.e. an STL.file) into real solid objects that you can hold with your hands by

building the part layer by layer. This technology is capable of producing geometries that cannot be manufactured by conventional manufacturing methods. It also has other advantages such as cost-effective prototype production, which is also known as rapid prototyping, quicker launch to market, and ability to print customized products with very little waste [1-3].

The first application of the 3D printing technologies dates back to 1984, but in the past 20 years, this method has not received much attention apart from the rapid prototyping area. The Reprap (replicating rapid prototyper) project, which was started in 2006, has reached much wider masses. The increase of the compound annual growth rate of the 3D printing technology is shown in Figure 1. The compound annual growth rate (CAGR) from 2016 to 2024 is estimated to be 21.7% and the global market volume of the 3d printer estimated by Variant Market Research is expected to reach $ 3.628 billion [4]. Thanks to the Reprap project, many ordinary users, hobbyists and people in need to produce any parts themselves in their home or office can fabricate a 3D printer. Even about three years after the start of the project, many companies have been able to spread the technology to a wider user mass by taking advantage of the Reprap project to produce relatively low-cost and sell open source 3D printers [1]. According to Berman's study, the waste material in 3-D printing technology is reduced by 40% in comparison to machining/subtractive technologies. Furthermore, 95% - 98% of waste material can be recycled in 3-D Printing. In addition, the subtractive technologies such as machining can remove as much as 96% of the raw material when creating a product. In terms of the cost per part in mass production, the 3D printing technology doesn't have much advantage than injection molding and machining as yet [5].
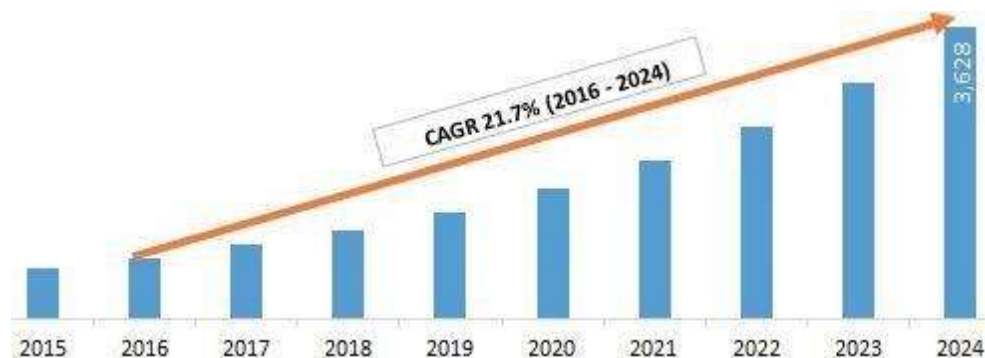

Figure 1. Global Automotive 3D Printing Market Size and Forecast, 2015 - 2024 ($ Million) [4]

3D printers can be built using many different technologies. Nowadays, the most popular method is material extrusion method which is a stacking technology and also known as Fused Filament Fabrication (FFF). Thermoplastic polymer materials (PLA, ABS) which can be formed by heat are used in this method. The heated material (filament) is extruded and the desired parts are produced with the principle stacking layers together in the FFF technology as shown

in Figure 2. The parts which have high strength are achieved with this technology, if the material of filament is plastic. In other respects, in FFF technology, it is quite troublesome to produce stalactite suspended structures in the air. In such situations, support structures are used to carry the bulk of the mass on the stalactite suspended structures [2-6].
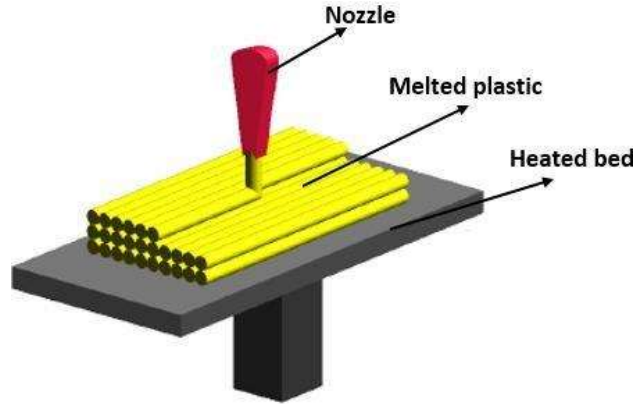

Figure 2. The operation method of the material extrusion process [6]

Acrylonitrile butadiene styrene (ABS) is a light and hard polymer widely used in products produced by molding. Its chemical formula is $(C_8H_8.C_4H_6.C_3H_3N)_n$. Pipes, automotive parts, protective helmets and toys (e.g. Lego) are just a few of its usage areas [4]. Poly (lactic acid) (PLA), one of the biodegradable polymers, is used in the field of medicine, wrapping, packaging and textile very effectively. There are various differences between PLA and ABS as shown in Table 1. The most important difference is that the filament from PLA is abundant, natural and renewable resource, nevertheless, ABS is petroleum based plastic. Thus, PLA is more harmless than ABS for human health. Second difference is that, it is necessary to heat the print bed to higher degrees when using ABS as a filament material since the ABS is more influenced by the temperature difference. Because of the lower printing temperature, when the PLA is properly cooled down, it is possible to print more sharp edges and features compared to ABS [4, 5]. The other difference is that PLA is generally used if the form is more critical than the function, because PLA is less stretchy than ABS. However, ABS has higher flexural strength and better elongation properties [6-9].

Table1. Comparison of PLA and ABS properties

Type of filament	Resource	Mechanical behavior	Print bed temperature	Printing temperature	Common Products
PLA	Organic	Brittle	20-60°C (optional)	180-230°C	Lego, automotive parts, electronic housing etc.
ABS	Petroleum-based	Ductile	80-110°C (mandatory)	210-250°C	Cups, plastic bags, cutlery etc.

1.1 Types of FFF 3D Printers

Delta and cartesian printers are the most popular FFF 3D printers on the market. However, there are important differences between the two. For instance, the delta 3D printer usually has a circular print bed that is immovable, because its natural shape is circle. On the other hand, the cartesian printer has a rectangular print bed. The volume of the 3D printer and its bottom

surface area (print bed) need to be increased when printing large parts, thus the moving parts of the cartesian printer heavier than the moving parts of delta printer. This situation influences sensitivity of positioning. At the same time, the fact that each element can move only in one direction for the cartesian printer affects the sensitivity of positioning. In the delta printer, the nozzle head can move in any direction quickly. Therefore, on the contrary to the cartesian printer, the delta printer is preferred to print large and big parts [10-12].

Moreover, the nozzle head of the cartesian printer can move only in X and Y axes. The z axis represents the direction in which the surface area can move. Unlike the cartesian printer, the delta printer moves the nozzle in X, Y, Z axes as shown in Figure 3. Hence, calibration of the delta 3D printers becomes more troublesome [11, 13].

In a study, in vase mode, print speeds of the delta and cartesian 3D printer have been compared. Cartesian printers achieve print speeds of up to 200 mm / sec, while delta printers have a speed of 350 mm / sec. The biggest reason of this situation is that the positioning speed and sensitivity of the nozzle in the delta printer is better than the cartesian printer [13].

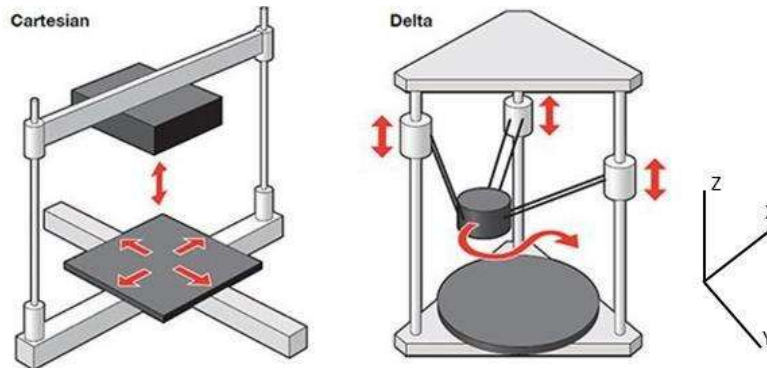Figure 3. Cartesian and delta printer [11]

Laplume et al. (2016) have studied on differences between MOST Prusa RepRap (Cartesian Printer) and MOST Delta RepRap Printers. Their study shows capital cost of the delta printer (400$) is lower than the cartesian printer (575$) as shown in Table 2. Also, the energy consumption to warm up the printer and for movement of axes is lower in the delta printer [12].

Table 2. Comparison of the delta printer and the cartesian printer [10-13]

Type of Printer	Capital cost ($)	Weight	Print speed	Sensitivity of positioning	The nozzle movement axes	Calibration
Delta Printer	400	Light	High	High	X,Y,Z	Difficult
Cartesian Printer	575	Heavy	Medium	Medium	X,Y	Easy

In this study, a delta type FFF printer is developed due to its above-mentioned advantages over the cartesian type printers. Furthermore, it is aimed to develop a large-scale printer to be able to print large parts with high accuracy, which differs from the existing delta type FFF printers in the literature. For this purpose, the product architecture of a delta type FFF printer is investigated first and details are provided in Section 2. Then, the development process of the large-scale printer is described in Section 3. An accuracy study is carried out and many challenging parts are produced and the results are given in Section 4. The challenges during the development process and the solutions suggested are explained in Section 5 and the conclusions are given in Section 6.

2. PRODUCT ARCHITECTURE

In the production process of a part using a delta type FFF printer, some steps should be followed as shown in Figure 4. First, a computer-aided design (CAD) file of the 3D model is created in "STL" file format. Afterwards, this file is sent to the slicing software which slices the 3D model to the thin layers and creates g-codes for these layers. These g-codes are sent to the controller (Arduino Mega). A Ramps 1.4 board is used together with Arduino which controls to electronic components such as servo motors. A few steps should be taken while printing a product from 3D printer.
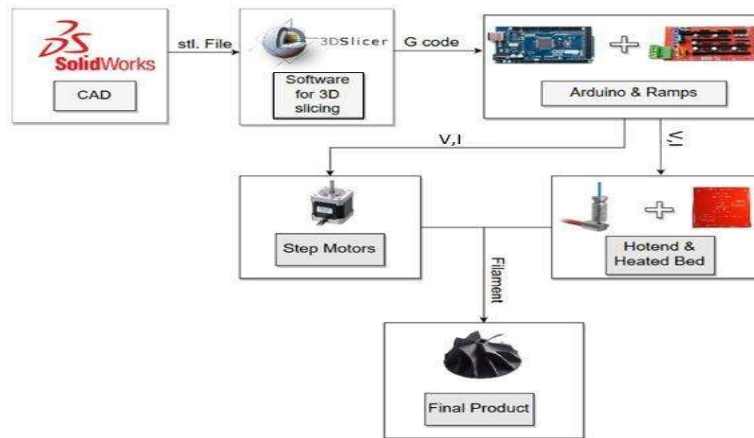

Figure 4. Operational flowchart of a delta type FFF printer

Step I: Designing the part to be printed

The CAD file formats such as part file (.prt), step file (.step) and Catia model file (.model) can be created using 3D modeling program such as Autocad, Solidworks, Catia, Simens NX etc. Then, the CAD file is converted to an STL file, which is the format that is sent to the slicer software tools such as Cura, Simplify 3D or 3D Slicer.

Step II: Generating G-code

G-code is created to determine the printing process of a product using a 3D printer. The generated G-code includes the type of movement of the nozzle head, setting units toinches/millimeters, setting absolute/relative positioning etc.. Also, there are M commands to indicate program end, enable/disable all stepper motors, turn off bed, turn off extruder etc..The definitions of some important G and M commands are listed in Table 3.

Table 3. Common G and M codes for 3D printer

G0	Rapid move
G1	Linear motion at feed rate
G4	Pause the printer for a period of time
G28	Move to origin
G90	Set to absolute positioning
G91	Set to relative positioning
M2	Program end
M17	Enable all stepper motors
M18	Disable all stepper motors
M104	Set extruder temperature

Step III: M**otor control**

The operation of a 3D printer needs motors with low torque and high accuracy, so the best motor to do this function is stepper motor. It is an electromagnetic device that converts digital pulses into mechanical shaft rotation. Advantages of step motors are low cost, high reliability, and high torque at low print speeds. They are also a special type of the synchronous motors which are designed to rotate a specific number of degrees for every electric pulse received by its control unit. In a delta type 3D printer, four stepper motors are needed to do the specific function, three of them are used for moving in X, Y, Z direction of the printer head, the 4th one is needed to move the filament.

Step IV. Printing

The final step is to print the product using ABS or PLA. The dimensions of the 3D printer must be introduced to slicer software tools before printing product. Also, process parameters determining to quality of product, printing time and density of the product should be regulated. Thereafter, the product in desired size can be printed by the delta printer.

3. DEVELOPMENT OF THE DELTA TYPE FFF 3D PRINTER

3.1. Mechanical design of the developed FFF printer

3D printers have several main design requirements such as mechanical design, kinematic analysis, and control system. In order to run the delta type 3D printer and produce the product, mechanical design must be done before creating the kinematic analysis and control system of the system. Therefore, the structural parts that create the basic shape of the printer and carry moving parts must be designed. These are principally aluminum profiles, angle brackets, linear rail system, carriage, carbon fiber rods and effector as shown in Figure 5. The definitions of the numbered components in Figure 5 are given in Table 4.
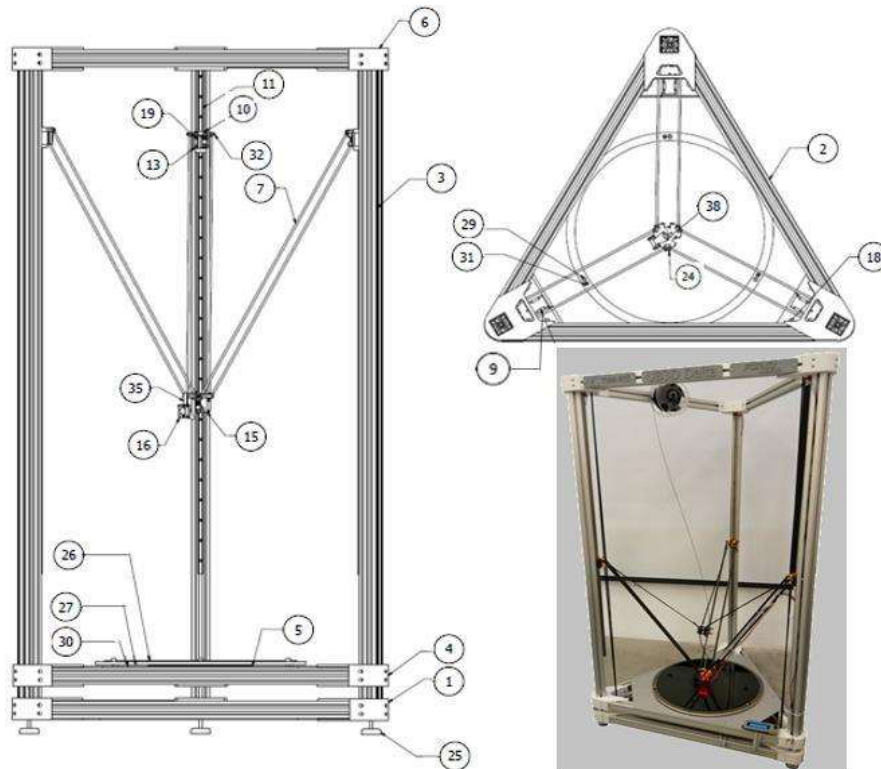

Figure 5. 3D CAD model of delta 3D printer

Aluminum sigma profiles given by number 3 in Figure 5 create the main frame of the printer

and carry the rail system. Therefore, in the development process of the delta type printer, first, the aluminum profiles were designed by considering the main dimensions of the printer. There are three different type of brackets used in this system, which enable the connections of the aluminum profiles, such as top, middle and bottom brackets, shown by numbers 6, 4, and 1 in Figure 5, respectively. These brackets provide enough support and rigidity. They are designed on a commercial CAD software Solidworks by accounting for the geometry of the aluminum profiles. These customized angle bracket designs are manufactured using PLA material in a cartesian type FFF printer. Also, linear rail system consists of stepper motor, timing belt, rods, effector and carriage, shown by numbers 7, 9, 13, and 14 in Figure 5, respectively. The carriage is used to carry rods from carbon fiber and PLA-made effectors. This rail system is moved by three different stepper motor and timing belt. It is connected to the aluminum profiles with hammer nuts. Detailed descriptions of the parts shown in Figure 5 are mentioned in Table 4.

Table 4. Bill of materials of delta printer fabricated

ITEM	QTY	PART NAME	DESCRIPTION
1	3	Bottom Angle Bracket (60 degrees)	3D Printed
2	9	50x50x850mm Sigma Profile	
3	3	50x50x2000mm Sigma Profile	
4	3	Mid Angle Bracket (60 degrees)	3D Printed
5	1	300x300mm Heated bed	
6	3	Top Angle Bracket (60 degrees)	3D Printed
7	6	900mm Carbon Fiber Rod	ID:8mm, OD:10mm. Ball Joints are included
9	3	Step Motor	Nema 17
10	3	HGH15CA	
11	3	[Z] HGR15R	
13	3	Carriage	3D Printed
14	1	Effector	3D Printed
15	1	Hot End Holder	3D Printed
16	2	FAN 40x40x10	
17	18	AS 1420 - 1973 - M5 x 30	ISO metric hexagon socket head cap screws
18	12	AS 1420 - 1973 - M5 x 20	ISO metric hexagon socket head cap screws
19	12	AS 1420 - 1973 - M4 x 12	ISO metric hexagon socket head cap screws
20	1	AS 1420 - 1973 - M3 x 14	ISO metric hexagon socket head cap screws
21	1	Cooling Fin	
22	1	Jhn_nozzle_v4(1.75m)	
24	6	AS 1420 - 1973 - M4 x 16	ISO metric hexagon socket head cap screws
25	3	Support	
26	1	Glass	Ø550mmx6mm
27	1	Aluminium Plate	Ø600mmx10mm

29	3	AS 1420 - 1973 - M8 x 30	ISO metric hexagon socket head cap screws
30	1	Sheet Metal	3mm thickness
31	3	AS 1421 - M12 x 20 Cup Point	ISO metric hexagon socket set screws
32	6	AS 1420 - 1973 - M4 x 25	ISO metric hexagon socket head cap screws
33	6	AS 1112 - M4 Type 5	ISO metric hexagon nuts, including thin nuts, slotted nuts and castle nuts
34	3	AS 1112 - M8 Type 5	ISO metric hexagon nuts, including thin nuts, slotted nuts and castle nuts
35	1	Nozzle Fan Holder	3D Printed
36	3	AS 1112 - M3 Type 5	ISO metric hexagon nuts, including thin nuts, slotted nuts and castle nuts
37	2	AS 1420 - 1973 - M3 x 20	ISO metric hexagon socket head cap screws
38	5	AS 1420 - 1973 - M3 x 16	ISO metric hexagon socket head cap screws
39	39	AS 1420 - 1973 - M4 x 20	ISO metric hexagon socket head cap screws

3.2. Kinematic analysis of the developed FFF Printer

In a cartesian printer, the mechanism moves along the rails independently of each other in the x, y, and z directions. With a delta configuration, it's not that simple. Moving any of the three vertical carriages upward and downward causes the nozzle head to move simultaneously in x, y, and z. Therefore, it is necessary to calculate how each of three carriages will move in order to move the nozzle head to the right place [14].

Figure 6. a) Delta printer diagram, b) Positioning of the carriage and effector

The delta robot has three columns as shown in Figure 6. These columns are called as A, B,

and C. Each column has a carriage that can move up and down on the column. Each carriage has two parallel arms which connect to the effector platform. It is crucial that each of the parallel arms (rods) is the same length and the platform of the effector must be parallel to the print bed in order to print correctly. In accordance with this purpose, the distance between the junction of the each carriage with columns and effector platform must be the same. Thus, the nozzle head moves parallel to the print bed when designed in this way [15].

After the rods, carriages and platform of the effector are positioned correctly, the positions of the carriages must be calculated by kinematic analysis so that the nozzle head can move to the desired point on the print bed. It is shown in Equations (1), (2), and (3).

$$a_{2z} = Z + t_0 + \sqrt{L^2 - a_a{}^2}$$

$$= Z + t_0 + \sqrt{L^2 - (a_{2x} - a_{1x})^2 - (a_{2y} - a_{1y})^2}$$

$$= Z + t_0 + \sqrt{L^2 - \left(s_p - (X + p_0)\right)^2 - (0 - Y^2)} \tag{1}$$

$$= Z + t_0 + \sqrt{L^2 - ((s_p - p_0)^2 - 2(s_{p-}p_0)X + X^2) - Y^2}$$

$$b_{2z} = Z + t_0 + \sqrt{L^2 - a_b{}^2}$$

$$= Z + t_0 + \sqrt{L^2 - (b_{2x} - b_{1x})^2 - (b_{2y} - b_{1y})^2}$$

$$= Z + t_0 + \sqrt{L^2 - (s_p cos120° - (X + p_0 cos120°))^2 - (s_p sin120° - (Y - p_0 sin120°))^2} \tag{2}$$

$$c_{2z} = Z + t_0 + \sqrt{L^2 - a_c{}^2}$$

$$= Z + t_0 + \sqrt{L^2 - (c_{2x} - c_{1x})^2 - \left(c_{2y} - c_{1y}\right)^2}$$

$$= Z + t_0 + \sqrt{L^2 - (s_p cos240° - (X + p_0 cos240°))^2 - (s_p sin240° - (Y - p_0 sin240°))^2} \tag{3}$$

Equations (1), (2), and (3) are analyzed in MATLAB^{TM} to obtain final position of the nozzle head. For example, the nozzle head moves from (0, 0, 0) to (150, -150, 300) with 200 mm/s velocity and 2000 mm/s^2 acceleration/deceleration. The Figure 7 shows the final position of the nozzle head.
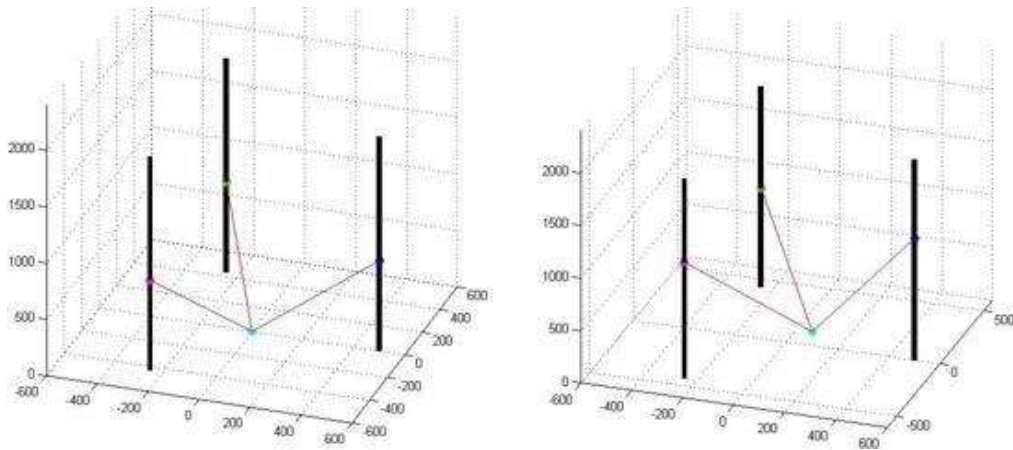
Figure 7. Matlab graphs of the position of the nozzle head at a) (0, 0, 0) and b) (150, -150, 300)

3.3. Control system of the developed FFF Printer

The diagram shown in Figure 8 points the detailed relationships between all electrical components such as Arduino Mega 2560, RAMPS 1.4 (RepRAP Arduino Mega Pololu Shield), A4988 Motor drivers (x4), 12v PSU, NEMA 17 step motors (x4), hot end and heatbed. The ATmega2560 (datasheet) is an Arduino based card. There are 54 digital I / O pins. 14 of them can be used as PWM output. PWM (pulse width modulation) is a way to control analog components using digital signals. Also, there are 16 analog inputs, 4 UART (serial port), 16 MHz crystal oscillator, USB connection, an adapter input, an ICSP output and a reset button.

The system takes the power from main supply and a direct current power supply regulates this power to send it to the controller. After that Arduino sends digital, PWM and analog signals to Ramps board. Ramps board uses these signals and controls the current from the dc power supply. All electronic components use this current to work.
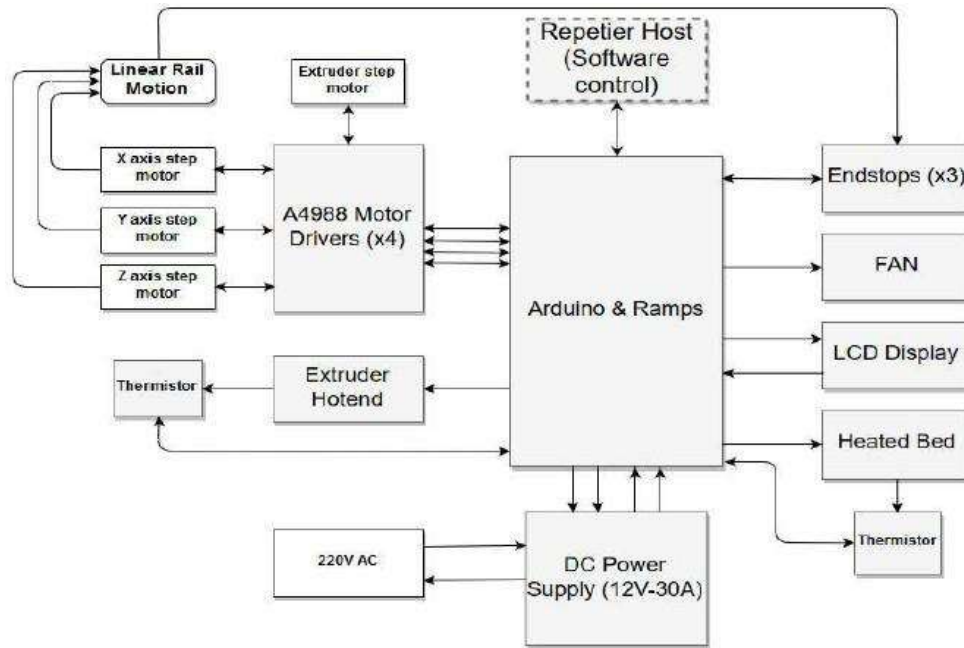
Figure 8. Electronic system diagram

3.4. Specifications of the developed delta type FFF printer

The developed 3D printer has a delta head and large build volume. Therefore, it has unique design compared to other 3D printers in the literature. The final specifications of the developed 3D printer are given in Table 5.

Table 5. Specifications of delta printer manufactured

Technology	Fused Filament Fabrication (FFF)
Control system	Arduino based control system, open source control software
Print head	Single
Maximum speed (mm/s)	200
Printer dimensions (mm)	1050 X 950 X2050
Build volume (mm)	500 diameter X 750 height
Nozzle temperature (°C)	280
Supported materials	ABS, PLA, PLA+
Noise level (dB)	65
Weight (kg)	90
XY resolution (mm)	0.03
Z resolution (mm)	0.06

4. PRINTING RESULTS

Several parts have been printed in different sizes by the developed delta type FFF 3D printer. First, a dimensional deviation analysis has been performed on 20*20*20 mm cubes, which are placed in different positions on the print bed, as shown in Figure 9. It is observed that deviation values are between 1.1%-0.1% in X axis, 2.5%-0.75% in Y axis and 2%-0.4 in Z axis. Table 6 shows the results of the dimensional deviation occurred in X, Y, Z axes.
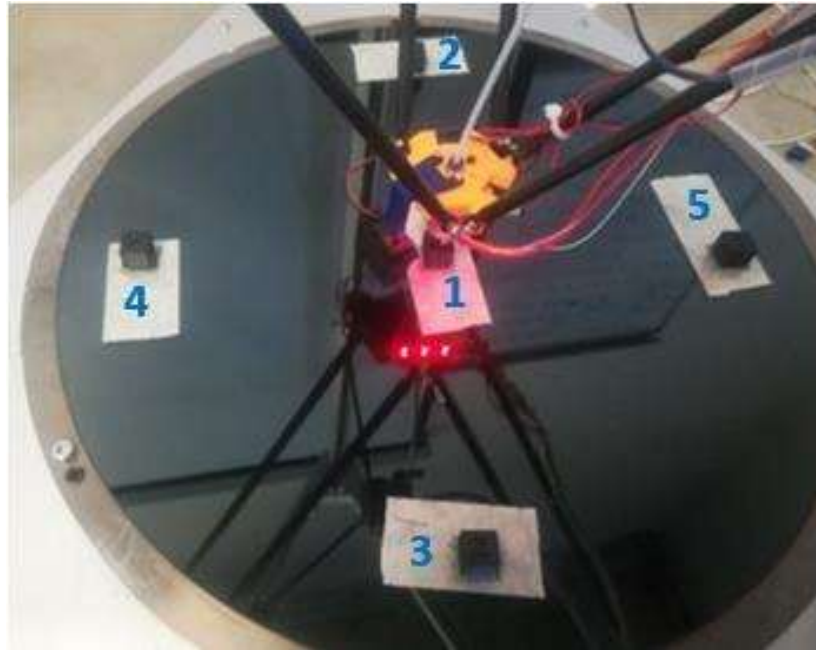

Figure 9. Cubes printed for dimensional deviation analysis

Table 6.Dimensional deviation values in X, Y, Z axes

Zone	Location		Actual Dimensions			Dimensions of Printed Part			Dimensional Deviation		
	X-coordinate (mm)	Y-coordinate (mm)	in X axis (mm)	in Y axis (mm)	in Z axis (mm)	in X axis (mm)	in Y axis (mm)	in Z axis (mm)	in X axis (%)	in Y axis (%)	in Z axis (%)
1	0	0	20	20	20	19,98	19,78	20,18	0,1	1,1	0,9
2	0	-220	20	20	20	19,98	20,15	20,08	0,1	0,75	0,4
3	0	220	20	20	20	19,86	19,62	20,14	0,7	1,9	0,7
4	-220	0	20	20	20	19,78	19,96	20,4	1,1	0,2	2
5	220	0	20	20	20	20,04	19,5	20,25	0,2	2,5	1,25

As can be seen from Table 6, the dimensional deviations of the printer parts compared to the actual dimensions are mostly less than 1.1%. In some cases (such as the Y axis deviation of

Zone 3, Y axis, and Y and Z axes of zone 5 those are less than 2.5%. These results show that the developed 3D printer can accurately print parts at any location of the 3D printer on XY plane.

Once the geometric deviation study has been completed, then various parts have been manufactured by the developed printer. First, small parts have been manufactured by the developed delta printer, then moved on to larger parts which can take up to 35 hours to print. The herringbone gear with an outer diameter of 70 mm and a thickness of 10 mm shown in Figure 10(a) has been printed in 3.5 hours using the nozzle with 0.4 mm radius. The spiral vase with a height of 300 mm in Figure 10(b) has been printed in 4.5 hours using the nozzle with 0.8 mm. It was printed in the vase mode at 200 mm/s print speed. The Eiffel tower with a height of 500 mm in Figure 10(c) has been printed in 26 hours using a nozzle with a radius of 0.8 mm. Although it has very small features, the developed printer was able to print those without any issues. The cylindrical hollow part shown in Figure 10(d) was printed in 36 hours using the nozzle with 0.4 mm radius. This part has a height of 650 mm which is used to test if the developed printer can print high parts in Z direction. This part is also designed using lattice structures with strut members having circular cross sections with a constant dimeter of 5 mm to have a lightweight design. It was shown by printing this part that the developed printer can manufacture large components with high complexity such as lattice structures with interconnected strut members.
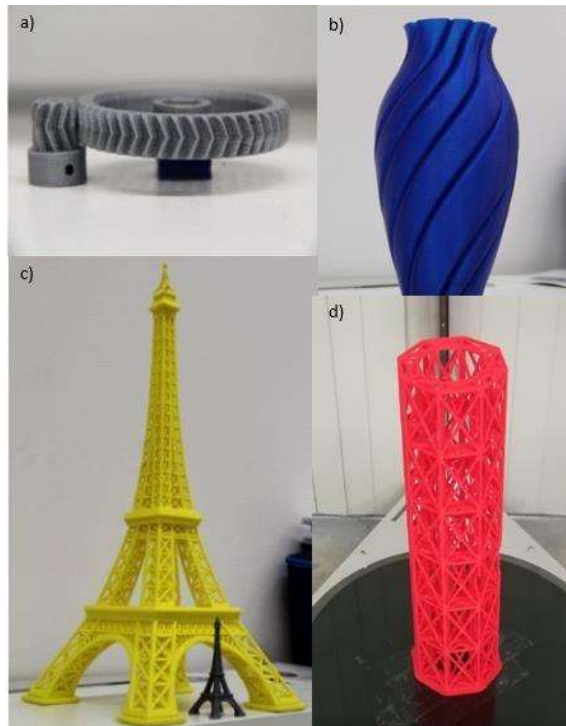

Figure 10. Sample parts printed by the developed delta printer

5. CHALLENGES IN THE DEVELOPMENT OF THE PRINTER

Some challenges have been encountered while developing 3D delta printer. Vibration is the most important problems occurred during the printing. Vibration mostly occurs due to height of the printer. Some head movements can resonate the system and magnify the vibration. As a result of vibration, waviness can be seen at the printed layer. To overcome this problem, the printer has been made rigid as much as possible. Another problem encountered is that the power of the extrusion becomes insufficient. When the Teflon tube is too long, the buckling between extruder system and cold end of the extruded filament has been occurred and in this case, the movement of the filament in the Teflon tube becomes more difficult. To solve this problem, the extrusion motor has been relocated by making a design change. Length of the Teflon tube is shortened by moving the extrusion system closer to the effector. This reduces the additional buckling in the Teflon tube. Therefore, required force for pushing the filament inside of the tube is decreased. Also the position of the potentiometers are adjusted, torque of the stepper motors are increased by 20%. Thus, sufficient power could be provided for the extrusion.

Moreover, initially, a fixed printing surface has been designed but the printing surface was not horizontally placed. Since the printing surface was fixed, no changes could be made to adjust its leveling setting. For this reason, the printing surface caused an inconsistent first layer of the print, which lead to failures in printing in later stages of the process. To address this issue, the printing plate redesigned in a way that its leveling setting can be adjusted by rotating the set screws on it.

The last challenge encountered during this study was stringing issue when the nozzle moves from one part of the print to another. To overcome problem, the retraction speed between two printed areas and excessive hot end temperature must be increased.

6. CONCLUSION

In this study, a large-scale delta type FFF 3D printer is developed and components with various sizes and complexities are modeled and manufactured to show its efficacy. The results showed that the developed printer can manufacture large scale parts with high accuracy. Some issues have been encountered during the development process such as the insufficient power of the extrusion, uneven printing surface, and the stringing issue. These issues are solved by making additional modifications on the design of the printer. As a result, it was possible to print with a dimensional error below 2.5% after the mentioned problems have been solved.. The dimensional tolerance of the 3D printers in the literature is also below 4%, which show that the developed printer can achieve better tolerance values than the existing printers. Unlike the

existing FFF 3D printers in literature, the developed printer, namely, UB3D, have a larger print volume and can manufacture large scale parts with high accuracy.

ACKNOWLEDGEMENTS

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