Development of a Low-Cost Fused Filament Fabrication (FFF) 3-D Desktop Printer

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Abstract

A low cost Fused Filament Fabrication (FFF) 3D printer was designed and fabricated, using in part local materials. The printer was based on the open source Replicating Rapid Prototyping (RepRap) design. The Arduino (Integrated Development Environment) IDE board was used for the implementation, and it uses the Repetier-Host software for the slicing and the printing operations. The print volume of the printer is 95 mm x 90 mm x 80 mm, and the printer uses the Polylactic Acid (PLA) filament. The optimum conditions to print the PLA material were achieved at a print temperature of 210 ºC; for a print speed of 55 mm/s and a layer height of 0.2 mm. At these conditions, the dimensional deviation of the printed object from the CAD model was an average of 0.05 mm. Further developmental activities, with the use of more locally sourced materials, may help boost the local economy, in accordance with the Nigerian local content act.

Keywords: Fused Filament Fabrication (FFF), Low Cost 3-D Printer, Polylactic Acid (PLA) Filament, Nigerian Local Content.

1.0 INTRODUCTION

Additive manufacturing (AM) is a group of processes that enables the fabrication of products from 3-D CAD data, by depositing successive thin layers of material until the final product is made. The terms AM and 3-D printing are many times used interchangeably, but they are not the same. AM is broader, as it encompasses all the different AM processes, namely; vat photopolymerization, material jetting, binder jetting, material extrusion, power bed fusion, sheet lamination and direct energy deposition. Whereas, 3-D printing is more of a singular production of artifacts on a desktop printer, which is almost synonymous with the material extrusion – FFF process (General Electric).

Also, the ISO defines 3D printing as the, 'fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology'. Whereas, AM is defined as the, 'process of joining materials to make parts from 3D model data, usually layer by layer' (ISO/ASTM: 2015).

The 3-D printing technology is considered to be one of the most significant development of the last two decades (Manners - Bell and Lyon 2012), and the rapid growth of 3-D printers has the potential to change manufacturing in the coming years (Rosli *et al* 2018). The AM is a disrupting technology and it is part of the main technologies of the currently hyped fourth industrial revolution (Industry 4.0), as AM is moving from prototyping to mainstream manufacturing. The 3-D printing has the potential to 'print' almost any physical object on request (Campell and Ivanova 2013). It has been forecast that commercial activity of transporting goods to customers, and the manufacturing of products on a large scale could be changed drastically by 3-D printers. Interestingly, this could reduce human activities that cause climate change, which makes 3-D printing an enabler of the United Nations Development Program's Sustainable Development Goals (UNDP -SDGs) (Richtopia).

The advent of 3D printing with plastics and polymers created the rapid prototyping processes in wide use today (Oluwajobi and Adebowale 2019). Fused Deposition Modeling (FDM) or FFF was developed in the late 1980s by S. Scott Crump and it was commercialized in 1990 by Stratasys (FDM; Chennakesava and Narayan 2014). The FDM extrudes a thermoplastic through a heated nozzle to deposit planar layers into a 3D part (Kempen, *et al.* 2013). The development of 3-D printers has advanced extensively due to the availability of open source systems. These hardware and software resources allow the 3-D printers to be developed at low cost, while anyone can build, modify and improve on them. Examples are RepRap, Fab@Home and Ultimaker; the RepRap is however the most famous and the most successful of all the open sources (Rosli *et al.* 2018). The RepRap was created by Adrian Bayer at the University of Bath in 2005 (Jones *et al.* 2011).

There are recent developments on locally made 3D printers in many African countries (Ishengoma and Mtaho 2014; 3D Printing in Africa; Simons *et al*, 2019). Also, there have been interests in 3-D printing in Nigeria, both among the academics (Raji 2017; Balogun *et al.* 2018; Nwaeche *et al.* 2019: Omole *et al.* 2019; Oyelami 2019), and in the industry (General Electric, Nigeria). There are already local initiatives to fabricate 3-D printers locally (Balogun *et al.* 2018), and this should be further encouraged. It has been noted that the adaptation of the 3D-printing has the potential to improve the manufacturing sector in Nigeria. In view of this, there is need for more active local development of the technology in Nigeria, in order to advance the capabilities of 3-D printing technologies and also to take full advantage of the benefits.

2.0 THE FUNDAMENTALS OF THE FFF 3D PRINTING

For the FFF 3D printer, a thermoplastic material is pushed through a nozzle under constant pressure and heated, then the extruded melt flow will deposit layer by layer to produce the 3D artefact (Lee and Chua 2017).

Melt flow analysis

The governing differential equations that describe the fluid dynamics of the melt flow are derived by considering the incompressible flow of the fluid: (Lee and Chua 2017, Alic and R. Zitko 2017).

- Conservation of mass
- Conservation of linear momentum
- Conservation of energy

Conservation of mass

The continuity equation is given by;

$$\frac{D\rho}{Dt} + \rho(\nabla.u) = 0 \quad ------(1)$$

Where ρ is the density and u is the velocity field, represents a mass conservation.

Conservation of Linear Momentum

The Navier-Stokes equation is given by;

$$\rho\frac{Du}{Dt} = -\nabla p + \nabla - \tau + \rho f \quad ------(2)$$

Where ρ is the density and τ is the viscous stress tensor velocity and f is the external force.

The viscous stress tensor is given by:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \lambda(\nabla.u)\delta_{ij} \quad -----(3)$$

where x_{ij} are the mutually perpendicular coordinate tions, μ is the dynamic viscosity, λ is the coefficient of bulk viscosity and is the δ_{ij} kroneckal delta operator.

Conservation of Energy

The energy equation is given by:

$$\rho\left[\frac{\partial h}{\partial t} + \nabla.(hu)\right] = -\frac{Dp}{Dt} + \nabla.(k\nabla T) + \Phi \quad -----(4)$$

h is the specific enthalpy, *T* is the absolute temperature and Φ is the dissipation function representing the work done against the work done against viscous forces.

To generate the control codes for the 3D printer, the software uses horizontal slices of the STL files (Jones *et al.* 2011). The software uses the Tang and Woo's algorithms to convert polygons into an interim CSG representation as intersections and unions of linear half-planes of the form

$$Ax + by + C <= 0 \quad ------(5)$$

The CSG polygons are then converted to bitmaps, and the slices are computed from the top to bottom of the parts to be built. The support material is calculated as follows:

Layer, L_{n+1} needs the following support, S_n from layer L_n

$$S_n = L_{n+1} - L \quad ---(6)$$

So the layer pattern at n potentially requiring support at layer n-1 would be

$$L_n \leftarrow L_n \cup L_{n+1} \quad ---(7)$$

The FFF Process Steps

The 3-D (FFF) printing process (Figure 1) involves the creation of the part to be made, using a CAD software. The CAD file is then converted to a stereolithographic (STL) file. Next, the STL file is converted to G codes, by using a suitable slicing software. These STL files would then be uploaded to the 3-D printer, for 'printing' (Steuben *et al.* 2015).

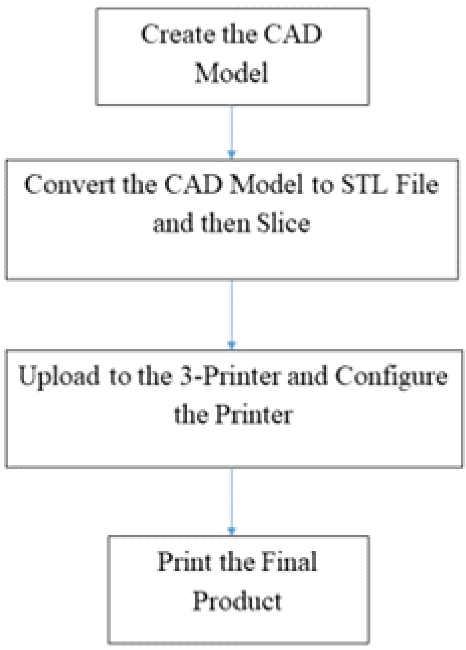

Figure 1: The FFF Process

3.0 DESIGN AND DEVELOPMENT PROCESS

The FFF 3D printer hardware consists of the following major parts, namely: the frame; the 3 axes (x-axis, y-axis and z-axis); the extruder; the print bed; the stepper motor; the controllers and the filament. The RepRap design was adopted and modified for the hardware development.

Frame

This is the body of the printer. It supports and carries the axes, motors, extruders and other parts of the printer. The frame is made of threaded rods, wood and printed plastic parts. The frame structure gives the printer the rigidity and support needed during the printing process.

Axes

To print a physical object in three dimensions, a 3D printer needs to be able to move on three coordinate axes. This is the "Cartesian coordinate system", used to specify the position of a given point in 3-dimensional space.

The three principal axes are linear and the printer makes use of fixed rods, timing belts and pulleys to implement these. This configuration enables to maneuver the print head and the print platform to the exact position needed. The timing belts and the pulleys are connected to stepper motors.

X-Axis

It consists of two 8 mm diameter stainless steel smooth rods with length of 170.5 mm, two printed parts which serve as the idlers, a stepper motor, two M5 x 45 screws, and a belt pulley. This is the axis that carries the complete assembly of the extruder and the extruder moves left to right within the frame. The belt pulley aids the left and right movement of the extruder on the axis. The end-stop is connected to the x-axis to define the limit of the movement of the extruder subassembly.

Belt Length Calculation for x-axis

The length of the timing belt used to move the extruder subassembly on the x-axis according to Hall *et. al.* (1961) is given by the following equation:
Belt Length, L

$$L = 2C + \frac{\pi (D_1 + D_2)}{2} + \frac{(D_1 - D_2)^2}{4C} \quad (8)$$

where C= Distance between shafts (mm)
D_1 = Motor pulley (mm)
D_2 = Idler pulley (mm)

Therefore

$$L = 2(170.50) + \frac{\pi(16+16)}{2} + \frac{(16-16)^2}{4(170.50)}$$

L = 391.27 mm

Y-Axis

This axis carries the print plate and it consists of the wood plate, printed parts, two 8 mm diameter stainless steel smooth rod with length of 170.5 mm, linear bearings, a stepper motor and a belt and pulley. The wood plate serves as the print bed. The dimension of the print bed is 210 mm x 120 mm. The print bottom plate has three linear bearings attached with zip ties. These bearings help prevent friction as they slide over the smooth rod. The stepper motors with the aid of the belt, helps in controlling the front and back movement of the print bed. An end stop helps to limit the movement of the y-axis.

Belt Length Calculation for y-axis

The total length of the timing belt used on the drive mechanism on the y-axis is calculated using the same formula as above. Similarly, by using equation (8);

L = 443.63 mm

Z-Axis

This axis carries the x-axis with its extruder assembly and causes it to move up and down the frame. It consists of two 8 mm diameter stainless steel smooth rod with length of 220 mm, two M6 threaded rods with length of 220 mm and two stepper motors which control each of the sides of the z-axis. This stepper motors drive the threaded rods.

Extruder

The Bowden style extruder was used in this printer. In this extruder, there's a flexible tube guiding the filament from the extruding motor (cold-end) to the nozzle (hot-end.) The cold end is part of an extruder system that pulls and feed the material from the spool, and pushes it towards the hot end. The hot end is the active part which also hosts the liquefier of the 3D printer that melts the filament. It allows the molten plastic to exit from the small nozzle to form a thin and tacky bead of plastic that will adhere to the material it is laid on. The hot end consists of a heating chamber and a nozzle. The hot end is also comprised of a print nozzle and a temperature sensor. The typical print nozzle's opening diameter may range in size between 0.2 to 0.5 mm and plays an important role in the print resolution of your object. The smaller the nozzle, the finer the print, but the longer it will take to complete the printing process..

Drive Force of the Extruder

The extruder subassembly travels horizontally on the x-axis from one point to another with the aid of

Firmware

The firmware is the computer program that resides in the printer's microcontroller chip on the controller printed circuit board. The firmware is the link between software and the hardware; it interprets commands from the G code file and controls the motion accordingly. The firmware configuration is unique to a particular printer. It knows the properties of the 3D printer, like the dimensions and the heating settings. It plays a major role in the quality of the print.

After customizing the firmware to suit the FFF 3D printer, the firmware can then be uploaded to the controller board. The customization includes setting the number of extruders available, the baud rate, the minimum and maximum temperature of the hot ends, the homing positions of the axes, etc. The Repertier-Host software was used for this implementation. It is a free online resource, which affords the execution of object placement, slice, preview and print for the 3-D printer.

End stops

These are mechanical devices used to limit the movement of the various axes. At the start of a print job, the three axes are moved to the home position. This is the reference or zero position of the axes.

Figures 2 and 3 show the drawings and the assembly of the FFF 3D-Printer

Material Selection

The frame of the printer was made from plywood. The choice of plywood was based on the following, viz:

(i) High uniform strength - wood is 25-45 times stronger along the grain than across the grain. Crossing the adjacent sheets tends to equalize the strength in all directions.

(ii) Freedom from shrinking, swelling and warping - Solid wood exhibits considerable movement across the grain but generally negligible

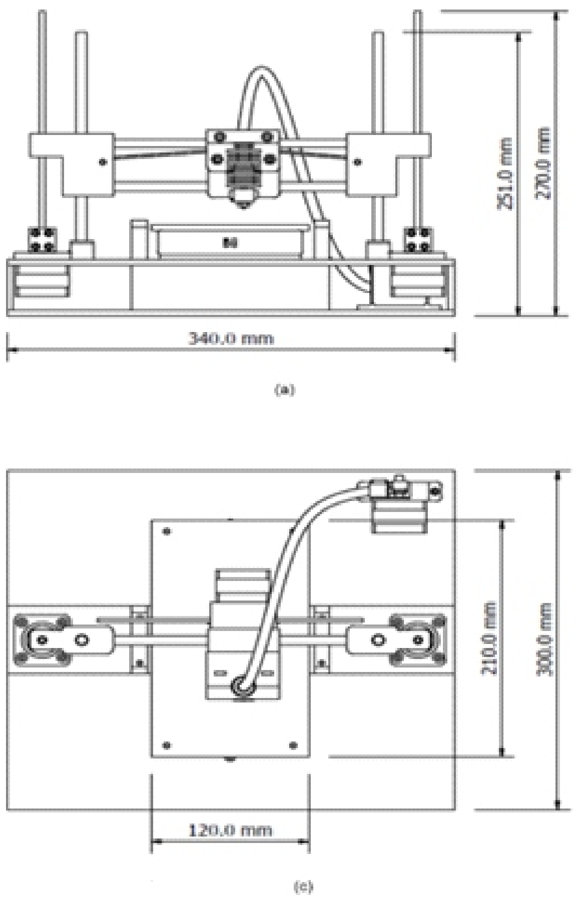

Figure 2:Isometric Drawings of the 3D printer drawn with Autodesk Inventor (a) Front View (b) Side View and (c) Plan

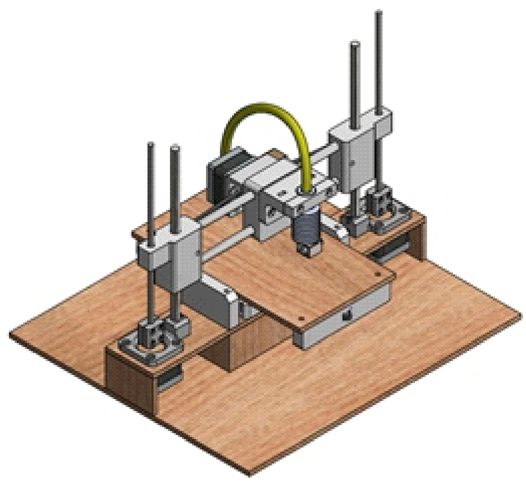

Figure 3: Complete Assembly of the 3D printer showing the Frame (Front view) drawn with Autodesk Inventor

a belt connection. The drive force displacement of the extruder is given by the following equation:

$$\text{Drive Force} = \frac{\text{Torque of stepper motor}}{\text{Pulley radius}} \quad (9)$$

Since, Torque of motor = 0.55 Nm and Pulley radius = 8 mm, Then,

$$\text{Drive Force} = \frac{0.55}{8} \times 1000 = 68.75 \text{ N}$$

Minimum Linear Displacement of the Extruder

The minimum linear displacement of the extruder subassembly as it travels on the x-axis is given by the following equation:

$$\text{Minimum movement} = \text{Stepper angle} \times \text{pulley radius} \quad (10)$$

Since, Stepper angle = 1.8º and
Pulley radius = 8 mm
Then, M ovement of the axis =

$$1.80 \times \pi/180 \times 8 = 0.25 \text{ mm}$$

Stepper Motor

The stepper motor used in this printer is the National Electrical Manufacturing Association (NEMA) 17 stepper motor. This was because of the torque required to do the job and also, it is the most commonly used motor for 3D printers, CNC routers and linear actuators. It has a (1.7 x 1.7 inch), (43.18 x 43.18 mm) faceplate. Five NEMA 17 stepper motors were used. One for the x-axis; one for the y-axis; two for the z-axis and one for the extruder.

Typically, the current, holding torque and motor weight for a particular stepper motor are fixed and given by the manufacturer. The most important parameter is the holding torque. For the NEMA 17 stepper motor, the holding torque is 0.55 Nm, rated voltage is 4.7 volts, step angle is 1.8º and the weight is 0.15 kg.

Power Required by the Drive Axes

The total power required includes the power required for the four stepper motors required to drive the three axes. The NEMA 17 stepper motor has a rated voltage of 4.7 volts and current of 1.7 ampere each.

Power required by one stepper motor, P = I x V (11)

=1.7 x 4.7
=7.99 W

Therefore,
Power required by four stepper motors = 7.99 x 4
= 31.96 W

Power Required by the Extruder

The extruder is controlled by a NEMA 17 motor, which has a current of 1.7 ampere and a voltage of 4.7 volts. The heater has a 12-volt DC cartridge rated 40 Watts and the fan's voltage is 12 volts with a current of 0.06 ampere.

Power required by a NEMA 17 stepper motor=1.7 x 4.7= 7.99 W
Power required by the fan = 0.06 x 12= 0.72 W
Total power required by the extruder = 7.99 + 0.72 + 40 = 48.71 W

Print Bed

The print bed was made from wood and it is where the extruded thermoplastic is deposited on. The three axes move together so that the nozzle moves directly above the print bed. The print bed located on the y-axis slides over screws which make them adjustable.

Controller Board

A controller is needed to control the printer. Part of the function of this controller board is to control the stepper motor that moves the axes and the extruder, the hot end and the fan. These stepper motors have fitted potentiometers, to control the amount of current that enters the stepper motor. An Arduino Mega 2560 with RAMPS 1.4 controller was used to develop this printer. The power range for the Arduino board is 7-12 volts. The controller board processes the G-code instructions, controls the end stops and the temperature of the hot end. (The hot end is fitted with a thermostat to ensure proper monitoring).

Power Requirement of the Board

The board can be powered via the USB connection or with an external power supply. The power source is selected automatically. The recommended range of power for the board is 7- 12 volts. For the power calculation, the upper limit of 12 volts was used.

Power = I x V
Power required by the board = 12 x 1.2
= 14.4 W

Total Power Requirement of the printer

Total Power required by the printer = Power required by the stepper motors + Power required by the controller + Power required by the extruder.

Total Power for the printer = 95.07 W

shrinkage or swelling in a longitudinal plane. The balanced construction of a plywood panel with the grain direction of adjacent veneers at right angles tends to equalize stress, thus reducing shrinkage, swelling and warping.

(iii) Plywood by virtue of the crossed laminations can be nailed or screwed near the edges without damage from splitting.

(iv) Low cost- Relative to other materials such as aluminum or iron, wood is cheap. This is a major consideration in developing a low cost printer.

The Hardware Assembly Process

The assembly process is shown step by step in Figures 4 – 8..

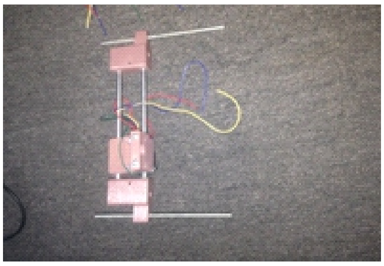

Figure 4: x-axis Fabricated with Stainless Steel Rods and 3D Printed Parts.

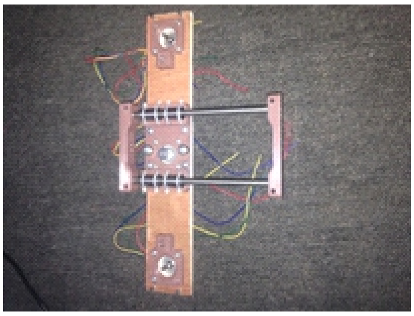

Figure 5: y-axis Fabricated with Plywood, Stainless Steel Rods, 3D Printed Parts and Stepper Motors.

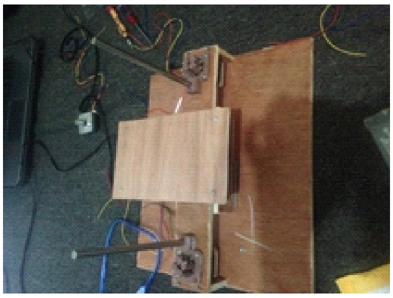

Figure 6: y- and z-axes Fabricated with Plywood, Stainless Steel Rods, 3D Printed Parts and Stepper Motors.

Figure 7: x, y and z-axes Assembled Together.

Figure 8: Completed Fused Filament Fabrication (FFF) 3D printer

Local Materials Used

Plywood was used for the frame of the 3D printer, as mentioned earlier, and other local materials employed are shown in Table 1. The axes' plain rods and the Z threaded rods were made of stainless steel. In addition, Table 2 shows the printer parts that were 3D printed, by another FFF 3D printer. The PLA filament material was used for the production of the parts. The fabricated 3D printer in this study can be deemed low cost, as shown in Table 3. This is more so because of the currency conversion rate and the cost of shipping of foreign printers. Also, the lower priced printers were on sales then. The printers featured were among the lowest priced on the platforms searched.

Table 1: List of Local Materials Used

S/N	Printer Parts	Materials Used
1	Base Plate	Thick Plywood
2	Base Support	
3	Print Bed	
4	X,Y and Z Plain Rods	Stainless Steel
5	Z Threade d Rods	
6	Bolts, Nuts and Washers	

Table 2: List of 3D Printed Parts

S/N	Printer Parts	Materials Used
1	Hot End Clamp A	PLA Print Material
2	Hot End Clamp B	
3	Z Motor Holders	
4	X Carriage (Idler) A	
5	X Carriage (Idler) B	
6	Extruder Grip Mechanism	
7	Y End Connections	
8	Linear Coupler	

The accuracy of the printer was evaluated by using a sample of 10 mm x 20 mm x 30 mm cuboid, created with Autodesk Inventor software and printed with the Polylactic Acid (PLA) material (Table 4). The Repetier-Host software was used for the slicing (Figure 9). The PLA material is a thermoplastic that becomes malleable when superheated, thus allowing for molding and sculpting into different shapes prior to cooling. This process can be repeated without affecting the integrity of the material. The PLA material used for 3D printing is usually available in spools of 1.75 mm and 3mm diameters. The 1.75 mm diameter element was used for the testing. The parameter settings chosen for printing the samples are; a layer height of 0.2mm, print speed of 55 mm/s, outer perimeter speed of 45 mm/s, infill speed of 65 mm/s and fill density of 70%. It should be noted that every printer has its own optimum print parameters that produce the best output. The temperature of the extruder was then varied between 190 ºC to 210 ºC for printing.

4. RESULTS AND DISCUSSION

Measurements of the samples were taken using a venier caliper and the deviation of the printed samples to the CAD model was measured. These values are recorded in Table 5. It should be noted that at the first two temperatures, the relatively high deviation could be as a result of the uneven melting of the PLA filament from the extruder nozzle. It can be observed that the most favourable temperature to print using Polylactic Acid (PLA) filament for the parameter setting is 210 ºC, because the least deviation was recorded at this temperature (Figure 10). Also it can be observed that the printer prints fairly accurately as the

Table 3: Cost of FFF 3D Printers in Nigeria**

S/N	Name of 3D Printer	Place of Purchase	Cost in Niger (Naira)
1	Anet A8	JiJi	200000
2	QIDI Tech	AliExpress	189729*
3	Anet A-S	Jumia	183950
4	CTC W5 Prusa i3 DIY	Ali Express	155764*
5	**The Fabricated Printer**	-	**80000**
6	Tronxy X1 Impresora	Ali Express	79532*
7	A8 High Precisi MKS Prusa i3	Ali Express	71486*

* The shipping cost has been included
** Cost as at August 2020

Table 4: Polylactic Acid (PLA) (Material Data Sheet)

Properties	Minimum	Maximum	Average
Modulus of Elasticity	0.085 GPa	13.8 GPa	2.91 GPa
Yield Tensile Strength	2.00 MPa	103 MPa	38 MPa
Ultimate Tensile Streng	14.0 MPa	117 MPa	47.2 MPa
Nozzle Temperature	150°C	235°C	198°C
Melt Temperature	130°C	243°C	190°C
Processing Temperature	30°C	220°C	149°C
Maximum Service Temperature	60°C	240°C	80°C

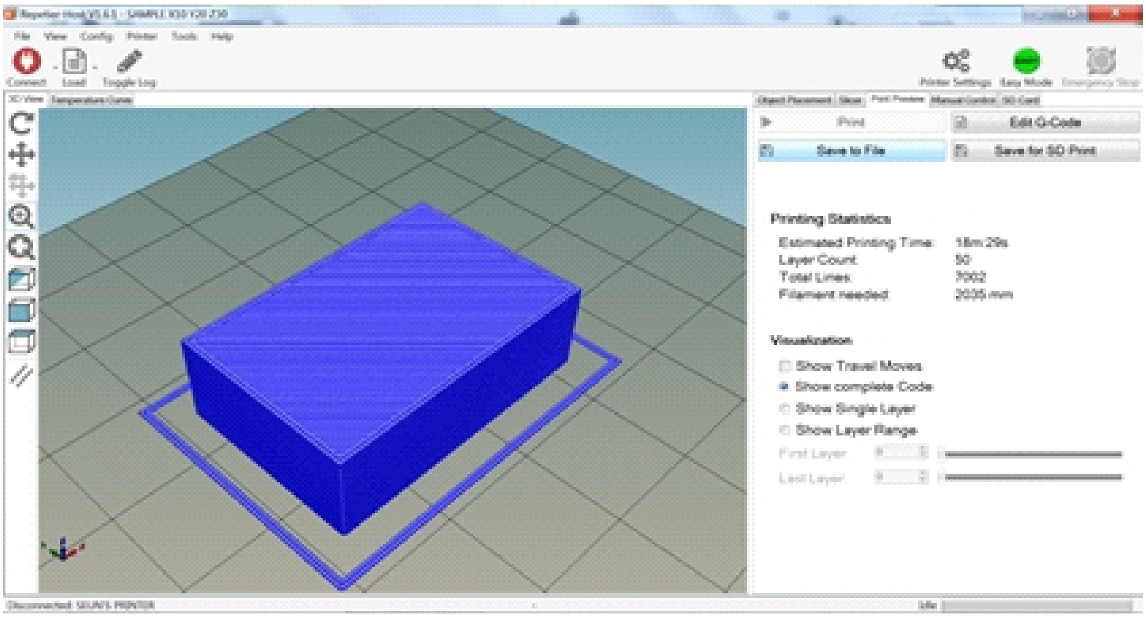

Figure 9: A Screenshot showing the sample of dimensions 10 mm x 20 mm x 30 mm after it has been sliced in the Repetier-Host software

Table 5: Deviation of Printed Samples from the CAD Model

S/N	Print Temperatu (°C)	Sample Print (Mm)	Deviatio (Mm)	Percentag Deviatio (%)	Average Deviatio (%)
1	190	x = 10.00 y = 20.25 z = 29.80	x = 0.00 y = 0.25 z = -0.10	x = 0.00 y = 1.25 z = 0.33	0.92
2	200	x = 09.80 y = 20.00 z = 29.80	x = -0.20 y = 00.00 z = -0.20	x = -2.00 y = 0.00 z = -0.67	0.83
3	210	x = 10.00 y = 20.15 z = 29.95	x = 0.00 y = 0.15 z = -0.05	x = 0.00 y = 0.75 z = -0.17	0.58
4	220	x = 10.05 y = 20.25 z = 29.85	x = 0.05 y = 0.25 z = -0.15	x = 0.50 y = 1.25 z = -0.50	1.25
5	230	x = 10.00 y = 20.30 z = 30.00	x = 0.00 y = 0.30 z = 0.00	x = 0.00 y = 1.50 z = 0.00	1.50

maximum deviation from the original size of the sample was just 1.50%.

5. CONCLUSION

This study focused on the fabrication of a low cost FFF 3D-printer. Locally sourced materials including plywood and stainless steel rods were used to ensure a relative low cost printer. The overall cost of the printer was around eighty thousand naira (N80,000) (Appendix). The reason for the low cost was due to the use of 3D printed parts for some of the components. Also, a hot bed was not included in this printer, which means that only PLA filament material can be used with the printer. Results from the evaluation carried out shows that the optimum print temperature to print PLA material was achieved at a temperature of 210 °C with a print speed of 55 mm/s and a layer height of 0.2 mm. Further developmental activities, with the use of more locally sourced materials, may help boost the local economy, in accordance with the Nigerian local content act.

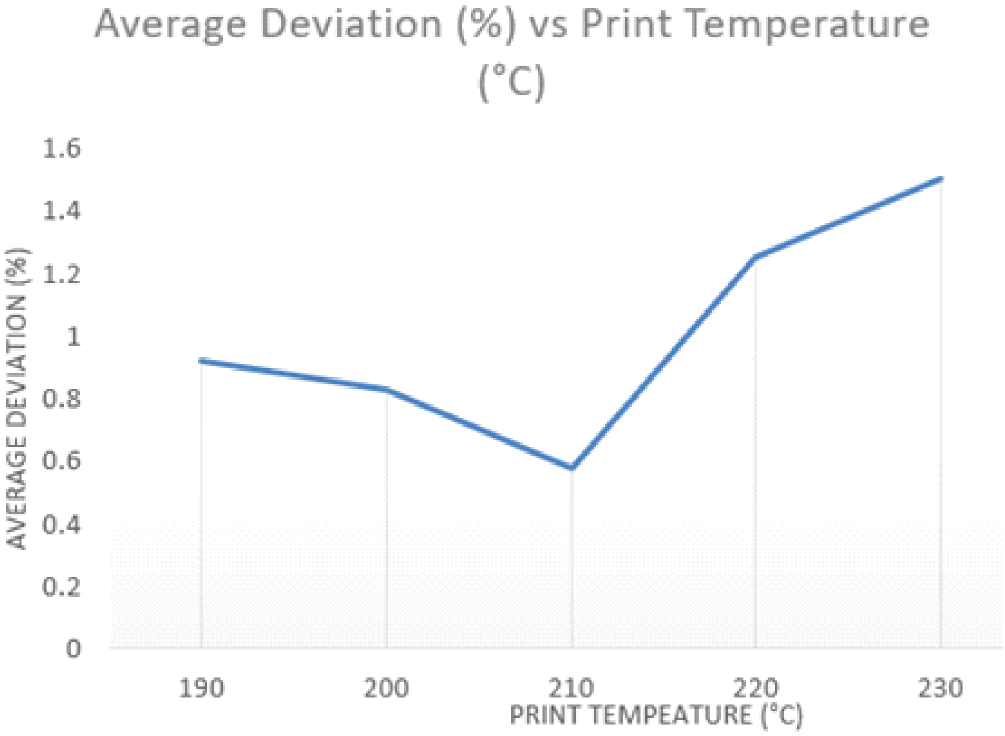

Figure 10: Plot of Average Deviation against Print Temperature.

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APPENDIX

Parts of the 3D printer with Price

S/N	PARTS	QUANTITY	PRICE (Naira)
1	STEPPER MOTORS	5	17000
2	LINEAR BEARINGS LM8UU 8mm	12	1900
3	BALL BEARING 624ZZ 8MM	10	1000
4	ARDUINO MEGA 2560 + RAMPS 1.4 CONTROLLER + LIMIT SWITCH + STEPPER DRIVERS	1	12400
5	ABS FILAMENT	1	10400
6	4-LEAD NEMA 17 STEPPER MOTOR	5	15000
7	E3D-V6 HOT END FULL KIT PRINT HEAD NOZZLE	1	5900
8	20 TEETH GT2 PULLEY BORE 5mm	2	800
9	2METERS GT2 TIMING BELT WIDTH	1	800
10	MK7 EXTRUDER DRIVE GEAR BORE 5mm FOR 1.75mm HOBBED GEAR	2	1200
11	PLYWOOD	1	1500
12	POWER PACK 12V550W	1	2500
13	WOOD SCREWS	24	500
14	PLAIN RODS M8 1M	1	4500
15	THREADED ROD M6 1M		1000
16	M3 SCREWS	24	150
17	M4 SCREWS	24	150
18	M5 HEX NUTS	6	100
19	M4 HEX-NUTS	12	150
20	M3 HEX NUTS	12	150
21	CABLE CONNECTORS	10	1500
20	MISCELLANEOUS		1400
		TOTAL	80,000