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Development and Evaluation of a Fused Filament Fabrication (FFF) 3-D Printer

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Abstract
A Fused Filament Fabrication (FFF) 3-D printer was fabricated by using in part locally sourced materials. The printer design was based on the Replicating Rapid Prototyper (RepRap) open source. The print volume of the printer is 200mm x 200mm x 300mm and it uses the Melzi V2 printer control board, coupled with the Repetier-Host firmware. The 3-D printer utilizes two major thermoplastic materials namely, the Polylactic Acid (PLA) and the Acrylonitrile Butadiene Styrene (ABS). The printer consists of a frame, fabricated from galvanized steel sheets, stainless steel threaded rods and wooded supports. The three main Cartesian axes of the machine were constructed from plain stainless rods with plastic printed parts as supporting members. Test results obtained for the PLA print material showed a dimensional deviation of 0.307 mm from the actual CAD model at a print temperature of 200°C and at a layer height of 0.2 mm. For the ABS filament, a dimensional deviation of 0.620 mm at a temperature of 255°C, was obtained. Local development and production of this 3-D printer can help in popularizing the benefits of the technology and consequently boosting the local economy.

Keywords: Fused Filament Fabrication (FFF), Low Cost 3-D Printer, Polylactic Acid (PLA) Filament, Acrylonitrile Butadiene Styrene (ABS) Filament, Local Materials

1.0 INTRODUCTION

Additive manufacturing (AM) or 3-D printing is a process of making a three-dimensional solid object of virtually any shape from a digital model. Rapid prototypes are produced by using an additive process, where successive layers of material are laid down. The AM technologies eliminate the conventional process of using jigs, moulds and tools, in manufacturing products [1]. The AM technology is developing rapidly and it has been effective in design and prototype production [2]. There are recent interests in 3-D printing and developments of locally made 3-D printers in Africa generally [3-5] and particularly in Nigeria [6-12]. 3-D printing in Ghana, South Africa, and Kenya are in transition from early to middle stage of development [4]. However, the 3-D printing technology might be considered to be in its infancy in Nigeria. There are already initiatives to fabricate 3-D printers locally [6, 10], and this should be further encouraged. Balogun et al. [6] developed a 3--D printer with over 50% locally sourced materials. They also investigated the impact of 3D printing technology on the Nigerian manufacturing GDP. The printer was estimated to cost about 500000 Naira. Farayibi and Abioye [9] conducted a survey to assess the awareness of AM technology in the South West Nigeria.

They found out that the level of awareness was about 40%. Farayibi et al. [10] also developed a 3-D printer using local materials. The printer has a maximum print volume of 200mm x 200mm x 200mm. The machine was designed among other things to be low cost, but this was not justified. Oluwajobi and Osunkoya [11] designed and developed a low cost FFF 3-D printer, by using local materials, which include plywood and stainless steel. The printer's print volume is 95mm x 90mm x 80mm and its overall cost was roughly 80000 Naira.

The cost of many of the reported 3-D printers is still high and the intention of this study is to reduce the cost considerably, for entry level configurations. This article is the second part of the paper on the design of a 3-D printer [12] and it deals with the development and the evaluation of the printer.

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2.0 METHODOLOGY

2.1 Development of the 3-D Printer

Design parameters were obtained in the first part of the paper, coupled with the electronics and the software requirements [12]. The development of the printer is based on the RepRap open source project [13] and standard mechanical components were used in the construction of the 3-D printer. These include the two GT2 timing-belts with a 2 mm pitch, one each on the x-axis and y-axis converts the rotary motion from the stepper motor to the translational (to and fro) motion of the extruder and the printbed respectively. Seven LM8UU linear bearings with rubber seal at both ends were used; two each were used on the z-axis Ø 8 mm plain stainless steel rod and three on the extruder back plate. Two 608Z cylindrical ball bearings with inner diameter of 8 mm, outer diameter of 22 mm and thickness of 7 mm were employed. Three SC8UU linear bearings with aluminum housing were used in the printbed sub-assembly to enable frictionless motion on the Ø 8 mm x 461.8 mm plain stainless steel rods on the y-axis. A nickel plated spring of wire diameter 1.2 mm, outer diameter 7.5 mm, internal diameter 5 mm and height 20 mm was used on the extruder filament drive mechanism. Two Ø 20 mm pulleys with 20 teeth on the x-axis and y-axis stepper motor were utilized for moving the extruder sub-assembly and the printbed sub-assembly. Figure 1 shows the assembled CAD model of the 3-D printer and Figure 2 shows the fabricated 3-D printer.

2.2 Material Selection and Consideration

The material selection for the component parts and the justification are given in [12]. Also, Table 1 shows the list of the parts that were sourced locally, as opposed to those imported. The threaded and plain rods; the support sheet frame; the base corner pieces, the Z-motor holders; the bolts, the nuts and the washers were all bought in the local market. Table 2 shows the parts that were 3-D printed, in line with the philosophy of the RepRap project [13], which includes the X and Y motor holders and the idlers. Table 3 shows the cost of FFF 3-D printers in Nigeria, or what it will cost to buy the printer online and zthen ship it to Nigeria. The printers were considered based on their print volumes, so as to be comparable. The costs of the printers are high, because of the foreign currency exchange rates and the shipping costs to Nigeria. It's worthy of note, that sometimes, the cost of the shipping could be higher than the initial cost of the printer. These current realities should spur and encourage production of 3-D printers in Nigeria, with available local materials. The estimated cost of the components for the developed 3-D printer are shown in the appendix. Note:The fabricated printer in this study has the lowest cost price in Table 3. The large difference in the cost, compared to other printers, apart from other factors, may be due to the fact that the printer parts weren't purchased in the current year.

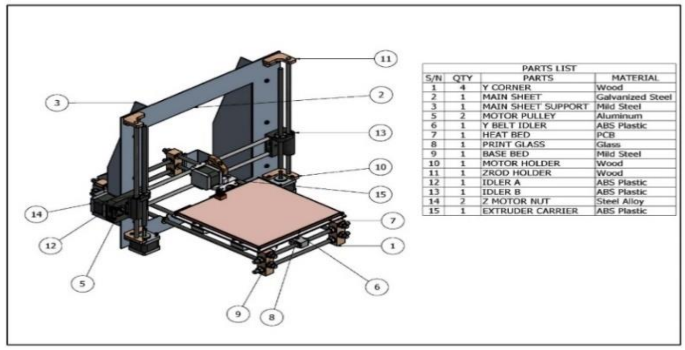


Figure 1: Completely assembled CAD model of the FFF 3-D printer

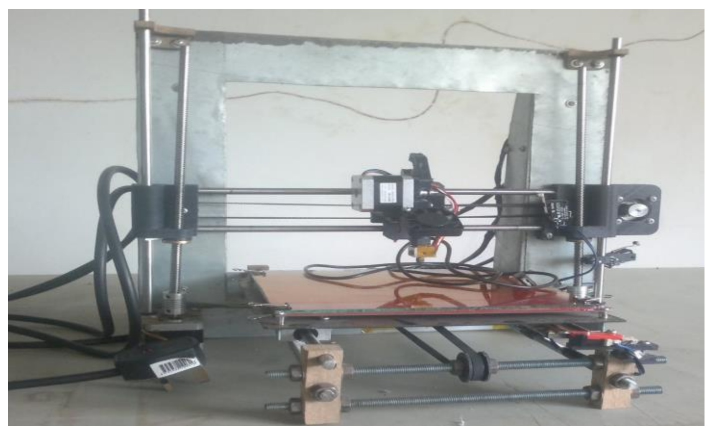


Figure 2: The developed FFF 3-D printer

Table 1: List of Local Materials Selection for the FFF 3-D Printer

S/N	Machine Components	Material Selected	Justification
1	Threaded and Plain Rods	Stainless Steel	Rigidity and resistance to corrosion
2	Support Sheet Frame	Galvanized Steel	Availability, workability and resistance to corrosion
3	Base Corner Pieces and Z-Motor Holders	Wood	Availability and ease of machining to achieve desired shape
4	Bolts, Nuts and Washers	Stainless Steel	Availability and resistance to corrosion

Table 2: List of 3-D Printed Parts

S/N	Printer Parts	Materials Used
1	X-Motor Holder	PLA Print Material
2	Y-Motor Holder	
3	X Carriage (Idler) A	
4	X Carriage (Idler) B	

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

S/N	Name of 3-D Printer	Print Volume	Place of Purchase	Cost in Nigeria (Naira)
1	Creality Ender 3 V2	220x220x250mm	JiJi	220000
2	Biqu B1	235x220x250mm	JiJi	190000
3	**The Fabricated Printer**	200x200x300mm	-	**107000**
4	WEEdo idex FDM X40	300x300x400mm	Ali Express	265969.50*
5	WanHao New Zebra Series D12/300	300x300x400mm	Ali Express	229319.74*

*The shipping cost has been included

2.3 Machine Calibration

The 3-D printer was calibrated before it was used to produce print samples. Each of the four steps stated below were used for the proper testing of this machine.

- Communication test
- Axes moment test
- Axes homing test
- Extruder and printbed heaters tests

2.3.1 Communication Test

The first step in testing the 3-D printer was to connect the printer electronics to the host computer, to verify communications with the printer (Figure 3). The correct serial port (COM port 30) was detected and selected for the printer, a baud rate of 115200 bps (bits per second); which is the speed at which the microcontroller communicates with the computer. Once the serial port and the speed (baud rate) was set, the Connect button on the host application (Repetier-Host) was selected to establish communications with the electronics.

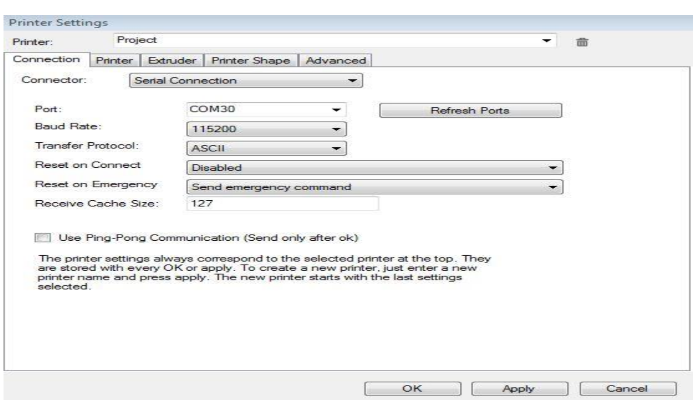


Figure 3: Serial port and baud rate selection settings

2.3.2 Axes moment test

Each axis was moved manually on the host application to verify that the connections of the stepper motors to the main board were properly made. The jog control on the Repetier-Host is shown in Figure 4. It consists of a circular bull's-eye for the x and y-axes and two vertical bars for the z and extruder axes. For x and y, the circular control is divided to four quadrants, +x, –x, +y, –y, with four rings to move each axis at a distance of 0.1 mm, 1 mm, 10 mm, and 50 mm in that direction. The four rings on the z-axis vertical control move in the distance of 0.01 mm, 0.1 mm, 1 mm, and 10 mm. The extruder control moves in slow downward increments of 1 mm, 50 mm and 100 mm with a fast reverse upward movement as those of the downward increments. During the manual axes' movement tests on the 3-D printer, incorrect axes movement resulted in changing the stepper motor polarity on the control board until all the axes moved in the specified directions.

2.3.3 Axes homing test

The 3-D printer was assembled with three endstops; one endstop each on the printer's axes to enable the printer pick a reference starting point on the printbed before every print. This is helpful for keeping the print on the printbed and to avoid driving the axes too far and hitting other component parts of the machine. The jog controls on the Repetier-Host software consists of three home keys for homing individual axis and a fourth key for homing all axis simultaneously.

2.3.4 Extruder and printbed heaters test

The final calibration checks carried out on the printer was to check the heaters used in the plastic extruder and the heated printbed. The hotend was heated up to a temperature of 270°C while the printbed was heated to a temperature of 120°C.

2.4 Performance Evaluation of the 3D Printer

The evaluation of the printer involved a test procedure and the determination of the optimum hot end temperature, optimum printbed temperature for the PLA and ABS materials and the print precision. The properties of the PLA and the ABS materials are shown in Tables 4 and 5 respectively.

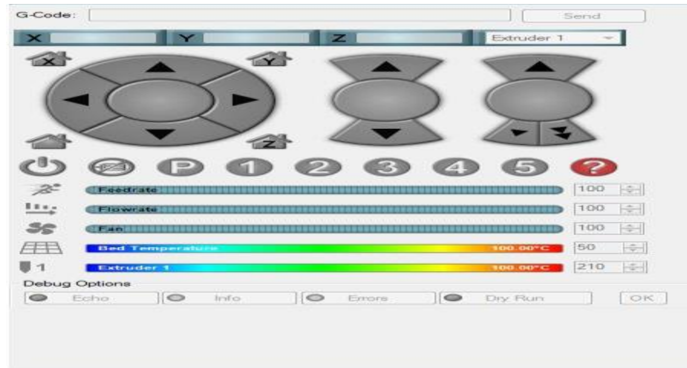


Figure 4: The 3-D printer jog control on Repetier-Host software

Table 4: Polylactic Acid (PLA) - Biopolymer (Material Data Sheet) [14]

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 Strength	14.0 MPa	117 MPa	47.2 MPa
Nozzle Temperature	150 ℃	235 ℃	198 ℃
Melt Temperature	130 ℃	243 ℃	190 ℃
Processing Temperature	30 ℃	220 ℃	149 ℃
Maximum Service Temperature	60 ℃	240 ℃	80 ℃

Table 5: Acrylonitrile Butadiene Styrene (ABS) - Extruded (Material Data Sheet) [15]

Properties	**Minimum**	**Maximum**	**Average**
Modulus of Elasticity	1.00 GPa	2.65 GPa	2.07 GPa
Yield Tensile Strength	13.0 MPa	65.0 MPa	45.1 MPa
Ultimate Tensile Strength	22.1 MPa	57.0 MPa	38.0 MPa
Nozzle Temperature	215 ℃	310 ℃	289 ℃
Melt Temperature	177 ℃	320 ℃	267 ℃
Maximum Service Temperature, Air	60.0 ℃	100 ℃	84.3℃

2.4.1 Test procedure

A CAD model with the following specifications (20 mm x 20 mm x 10 mm with an internal hole of diameter 10 mm) was generated using Autodesk Inventor Professional software. Then, it was printed by the 3-D printer, for the testing. A total of 20 test samples for both materials were printed to ascertain the machine print accuracy.

For the two print materials used, two test variables were adopted (fixed and variable test parameters). A variable print temperature parameter was used. Temperatures of 180°C, 190°C, 200°C, 210°C and 220°C were used for the PLA material test samples and temperatures of 250°C, 255°C, 260°C, 265°C and 270°C were used for the ABS material test samples. The samples were printed with a layer thickness of 0.2mm (print quality), print speed of 60m/s and fill density of 100%. The printed samples were then measured on a coordinate measuring machine (CMM), shown in Figure 5 to obtain precision measurements.

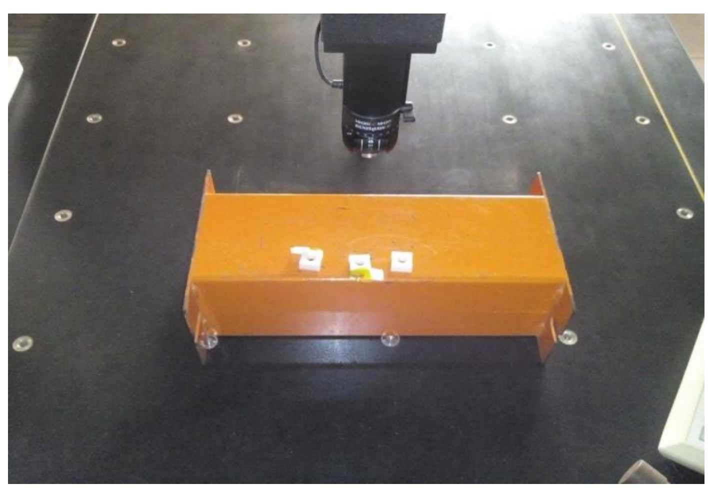


Figure 5: Printed test piece measurement on a coordinate measuring machine (CMM)

2.4.2 Key performance evaluation equation

The performance of the 3-D printer was evaluated based on the comparison of the print precision with the actual CAD model parameters. The accuracy is given as a percentage deviation from the original CAD model parameters [16].

$$Deviation = X_1 - \mu \tag{1}$$

$$Percentage\ Deviation = \frac{X_1 - \mu}{\mu} \text{ X } 100 \tag{2}$$

Where

X_1 = Printed component measurement

μ = CAD model measurements

3 RESULTS AND DISCUSSION

Figure 6 shows the variation of the percentage deviation with print temperature for the PLA material. The high percentage deviation results obtained for the temperatures 180 ℃ and 190 ℃ were due to uneven melting (beading) and layering of the print material from the extruder nozzle. Also, for temperatures 210 ℃ and 220 ℃, the high percentage deviations could be a result of the high print temperatures and slow cooling of successive print layers. A minimum deviation of 0.307 mm at a print temperature of 200°C was obtained as shown in Figure 6.

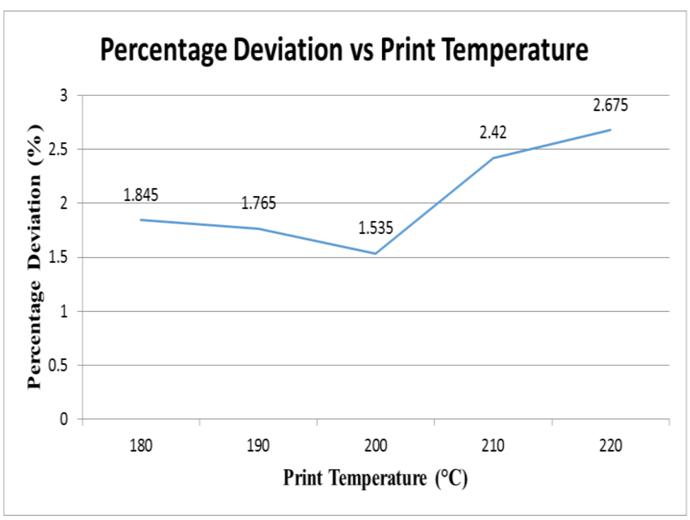


Figure 6: Plot of percentage deviation versus print temperature for PLA material

3.4 ABS Print Test Results

An ABS filament was used to carry out similar test print performance evaluation of the 3-D printer and Figure 7 shows the results. A minimum deviation of 0.123 mm and percentage deviation of 0.620 at a print temperature of 255°C were obtained as shown.

From the test print results obtained, it shows that the temperatures for the optimal print qualities with the minimum deviations from the original CAD models, keeping all other print parameters (layer height, print speed and fill density) constant, using this FFF printer for PLA and ABS, are 200ºC and 255ºC respectively.

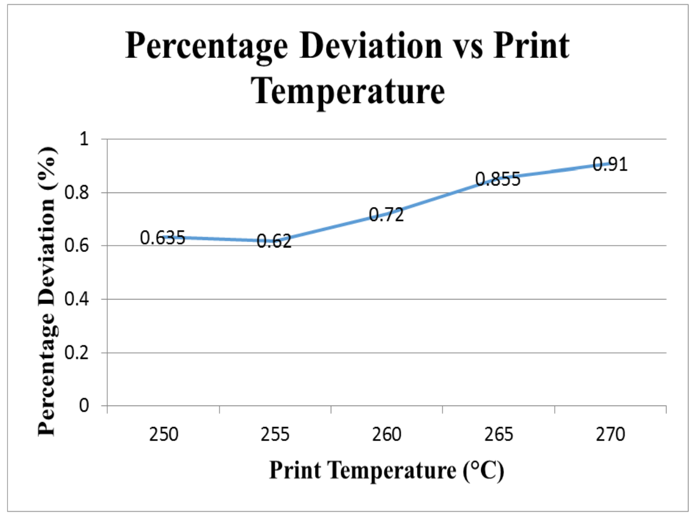


Figure 7: Plot of percentage deviation versus print temperature for ABS material

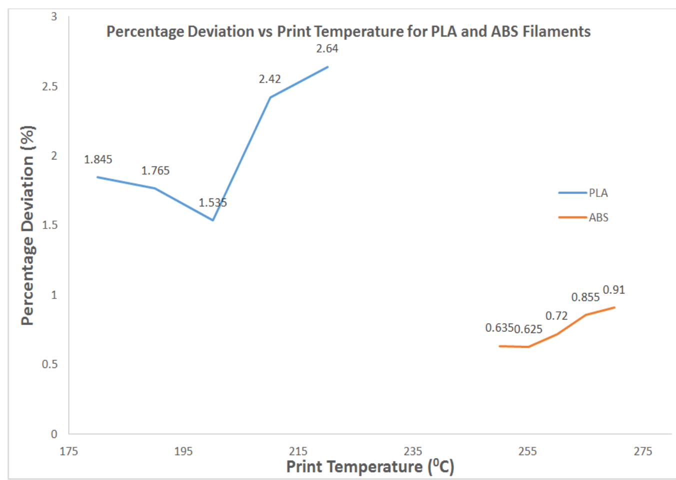
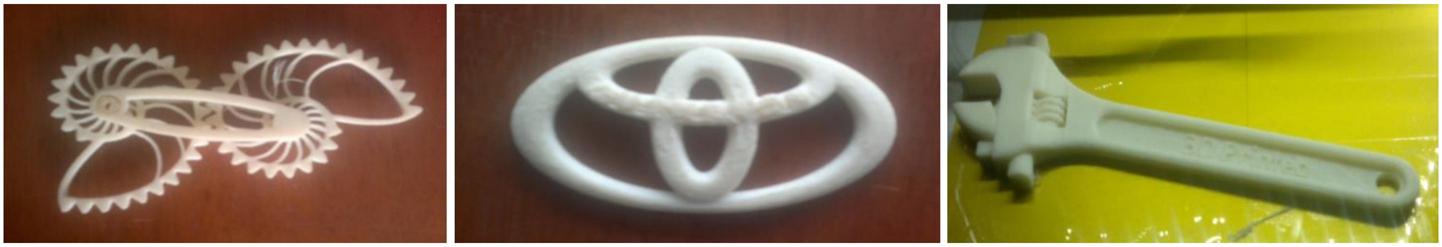


Figure 8: Comparison of the percentage variations for both PLA and ABS materials

The optimal printing temperature is dependent on the type of filament used and the various printing parameters used. The temperature ranges for the PLA and the ABS filaments are different. This is because the materials have different melting temperatures. So, the optimal printing temperature and parameters have to be evaluated for every printer. Figure 8 shows the comparison of the percentage deviation versus print temperatures for the PLA and the ABS filament materials. The average percentage deviation is lower for the ABS than for the PLA material. The ABS is a slightly stronger and a more durable material than the PLA (Tables 4 and 5). Figure 9 shows some printed artefacts and components, namely; a Nautilus gear assembly, a Toyota car logo and an adjustable wrench.



(a) (b) (c)

Figure 9: Printed artefacts and components: (a) a Nautilus gear assembly; (b) a Toyota car logo; (c) an adjustable wrench

4 CONCLUSION

In this study, a FFF 3-D printer was developed, tested and evaluated. The following can be concluded namely;

i. The locally sourced materials (e.g., wood, galvanized sheet and stainless steel stud) used in the fabrication of the machine frame performed effectively as to the overall stability and rigidity of the machine.
ii. The optimum print result using PLA material was achieved on the machine at a print temperature of 200°C, print speed of 60 mm/s and a layer height of 0.2 mm.
iii. The optimum print result using ABS material was achieved on the machine at a print temperature of 255°C, print speed of 60 mm/s and a layer height of 0.2 mm.

These results indicate that the 3-D printer can be used to print patterns for mold making, artifacts and architectural objects.

REFERENCES

[1] Rosli N. A., M. R. Alkahari, F. R. Ramli, S. Maidin, M. N. Sudin, S. Subramoniam, T. Furumoto "Design And Development Of A Low-Cost 3D Metal Printer", *Journal of Mechanical Engineering Research & Developments (JMERD)*, 2018, 41(3), 47-54

[2] Galantucci L.M., I. Bodi, J. Kacani and F. Lavecchia "Analysis of Dimensional Performance for a 3D Open-Source Printer Based on Fused Deposition Modeling Technique", Procedia CIRP , 2015, 28, 82-87

[3] Simons A., K.L.M. Avegnon and C. Addy "Design and Development of a Delta 3D Printer Using Salvaged E-Waste Materials", Journal of Engineering, Vol 2019, 2019ID 5175323, 9 pages, 3D Printing in Africa: 3D Printing in Ghana, <https://3dprint.com/242810/3d-printing-in-africa-3d-printing-in-ghana/>, Accessed 23.08.2020

[4] Ishengoma F.R. and A.B. Mtaho "3D Printing: Developing Countries Perspectives", *International Journal of Computer Applications*, Vol 104, 2014, (11), 30-34

[5] Balogun V. A., Otanocha O. B. and Ibhadode A. O. "The Impact of 3D Printing Technology to the Nigerian Manufacturing GDP", *Modern Mechanical Engineering.* Vol 8, (2), 2018, 140 -157.

[6] Nwaeche C. F., A. O. Fagunwa, A. A. Olokoshe, A. E. Aderonmu, V. C. T. Uzondu, O. Salami and W. B. Asiru "Comparative Studies on Additive and Subtractive Manufacturing in Nigeria Case Study: Helical Gear in a Juice Extractor'', *Asian Journal of Advanced Research and Reports* 2019, 7(3): 1-11

[7] Omole T. M., A. P. Olaiya, O. F. Sanni, R. K. Freddy, S. A. Oluwasola, W. Djibril, O. Aturaka, O. F. Ajani, Z. T. Gwa, M. Abdulsalam, L. A. Ajani, L. A. Olaide ''Additive Manufacturing/3D in the Optimization of Nigeria Vaccine Supply Chain'', *International Journal of Scientific and Research Publications*, 9, (11), 2019, 261 – 267.

[8] Farayibi P.K. and T.E. Abioye ''A Study on the Awareness Level of Additive Manufacturing Technology in South-Western Nigeria", *African Journal of Science, Technology, Innovation and Development*, 9(2), 2017, 157-162

[9] Farayibi P.K., J.O. Dioha, J. Orukotan and B.O. Omiyale "Development of a Fused Deposition Modelling Machine for Plastic-Based Additive Manufacturing Purposes''. *Assumption University E-Journal of Interdisciplinary Research*, 4(2), 2019, 1-11

[10] Oluwajobi A.O. and R.O. Osunkoya 'Development of a Low-Cost Fused Filament Fabrication (FFF) 3D-Desktop Printer', Nigerian Journal of Materials

Science and Engineering, Nigerian Journal of Materials Science and Engineering, Vol. 10, 2020, pp. 81-90.

[11] Oluwajobi A.O. and F.O. Kolawole 'Design of a Fused Filament Fabrication (FFF) 3D – Printer', *Nigerian Journal of Technology*, Vol 40, (2), 2021, pp. 252-260

[12] Jones R., P. Haufe, E. Sells, P. Iravani, V. Olliver, C. Palmer and A. Bowyer 'RepRap – The Replicating Rapid Prototyper', Robotica, 29(1), 2011, 177 – 191

[13] Matweb Material Property Data, Polylactic Acid (PLA) – Biopolymer, http://www.matweb.com/search/DataSheet.aspx?MatGUID=ab96a4c0655c4018a8785ac4031b9278&ckck=1. (accessed 23.08.2020)

[14] Matweb Material Property Data, Acrylonitrile Butadiene Styrene (ABS) - Extruded, http://www.matweb.com/search/DataSheet.aspx?MatGUID=3a8afcddac864d4b8f58d40570d2e5aa (accessed 23.08.2020)

[15] Brian Evans. (2012). Practical 3D Printers: The Science and Art of 3D Printing. Apress NY

APPENDIX

Table A1: Mechanical parts list of the 3-D Printer

S/N	PARTS	QTY	DIMENSION	PRICE (N)
1	THREADED STUD - 8 mm	4	237.800 mm	2000
2	X-PLAIN STUD - 8 mm	2	370.000 mm	2000
3	Y-PLAIN STUD - 8 mm	4	461.800 mm	2000
4	Z-PLAIN STUD - 8 mm	2	356.000 mm	2000
5	Z LEAD SCREW	2	M8 x 300	1200
6	Y CORNER	4		6500
7	MAIN SHEET	1	400 mm x 392 mm	2500
8	MAIN SHEET SUPPORT	2	392 mm x 261 mm	2500
9	YBRACE	1		2000
10	LINEAR BEARING HOUSING	3		3000
11	LINEAR BEARING	8		1450
12	LINEAR COUPLER	2		750
13	BELT PULLEY	4	16 mm	1200
14	PRINT GLASS	1	210 mm x 210 mm	600
15	BASE PLATE	1		1200
16	MOTOR HOLDER	2		1000
17	ZROD HOLDER	2		1000
18	IDLER A	1		6000
19	IDLER B	1		5500
20	Z MOTOR NUT	2	22 mm	1050
21	EXTRUSION GEAR	1	7 mm	600
22	FILAMENT CLIP A	1		700
23	FILAMENT CLIP B	1		800
24	BOLT - M4 x 16	30		500
25	BOLT - M3 x 25	25		4000
26	NUT - M8	40	M8	1400
27	NUT - M4	18	M4	600
28	NUT - M3	5	M3	600

29	WASHER - 8 mm	41	8 mm	5400
30	WASHER - 4 mm	36	4 mm	5000
31	WASHER - 3 mm	24	3 mm	1500
32	ADAPTER	1		3300
			Total	**69850**

Table A2: Electrical/Electronic parts list of the 3-D Printer

S/N	PARTS	QTY	DIMENSION	PRICE (N)
1	HEAT BED	1	214.5 x 214.5	1600
2	HOT END	1		5400
3	MELZI BOARD	1		7800
4	STEPPER MOTOR	5		14400
5	FAN	1		500
6	LIMIT SWITCH	3		700
7	POWER PACK	1		6750
			Total	**37150**