Hindawi
Journal of Engineering
Volume 2019, Article ID 5175323, 9 pages
https://doi.org/10.1155/2019/5175323

Research Article

Design and Development of a Delta 3D Printer Using Salvaged E-Waste Materials

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Received 10 September 2019; Revised 21 October 2019; Accepted 26 October 2019; Published 27 November 2019

Academic Editor: Kevser Dincer

The next phase of industrialization in the world is the use of 3D printing technology. Various 3D printing technologies are employed all over the world and for different purposes, from 3D printed houses to 3D printed food nutrients. Printer movement is achieved by carriages moving in a clearly defined X, Y, and Z orientation. The 3D printer has a lower work rate; subsequently, many printouts consume a lot of time due to their complexity. This paper elaborates on the design and development of a faster and fixed build platform 3D printer (Delta 3D printer) using locally available materials and e-waste. The Delta 3D printer movement is faster with a stable bed. Printer movement is achieved using three vertical axes placed 120° apart. Accuracy and speed are achieved with the use of NEMA 17 stepper motors to drive the various carriages on the vertical axes. Design calculations show that the least force delivered by the stepper motor is 1.73 N which exceeds 0.8334 N, the weight of the load to be carried. Furthermore, a stepper motor must turn 80 steps (rotational motion) in order to achieve 1 mm advance (linear motion). This ensures a higher printout resolution. In place of traditional linear rails, locally sourced square pipes were adopted coupled with bearings and a 3D printed carriage support, and a relatively cheaper but stable linear rail was developed. The goal of this research was to develop an alternative easy-to-build Delta 3D printer using locally sourced materials. This goal of this research was achieved, and the developed prototype was test-run under load conditions. It is recommended that salvaged e-waste should be properly managed for easy acquisition.

1. Introduction

The next phase of industrialization in the world is the use of 3D printers. A 3D printer is unlike the common paper printers that are used to print graphics on a flat surface (2D printing). On a 3D printer, the object is printed in three dimensions (x, y, z). The object printed is built up layer by layer and hence has a volume. The whole process is called 3D printing, and they are being touted as one of the revolutionary technologies in the 21st century [1].

3D printing is an additive manufacturing technique and often used in the development of product prototypes and custom parts.

The three dimensions (x, y, z), useful at the beginning and the end of a production line are equally employed in 3D printers. 3D printers are used for rapid prototyping, bio-printing of prosthetic limbs, and the printing of apparels in the automotive, construction, and robot industry. These 3D printers give some flexibility to designers and promote the Do-It-Yourself (DIY) culture in the maker community.

The 3D printing community in Ghana is in its early stage, yet there seems to be high consumer interest in its utility and services. However, most of the locally made 3D printers are Cartesian 3D printers. Cartesian 3D printers are robust and accurate; however, they are characterised by a slower print rate and often highly restricted in terms of print height or volume. Cartesian 3D printers are by design not meant for tall prints as it becomes unstable leaving discontinuous gradients on tall printouts.

The Delta 3D printer uses the Cartesian coordinates; however, linear motion is employed indirectly in the deposition of print filament. In addition, the three arms move to a coordinate by changing the angle (∅) each parallelogram makes with the vertical axes [2]. This angle is shown in

Figure 1. The Delta 3D printer is faster, has a steady bed, and can produce tall print dimensions due to its design. This 3D printer was designed using locally salvaged photocopier machine parts and 3D printed components for the assembly. Figure 1 shows the Delta 3D printer motion structure.

Although the 3D printing community is growing in Ghana, most of the 3D printers available are foreign-built. There are two main problems regarding this and they are as follows:

(a) Increased production downtime during major printer part failure

(b) Limited control over the functionality of the printer

The logistical and supply chain channels in Ghana and most African countries are not as developed as in the advanced countries. This implies that whenever there is a machine part breakdown, a lot of money and time would be spent to get the replacement part. This is not ideal and hinders the growth and development of the maker community in Ghana and Africa as a whole.

The remedy to this problem is the development of such machines locally using readily available resources. Hence, this research seeks to develop a Delta 3D printer using readily available local resources and materials. The first phase of this work is to find a suitable replacement for the mechanical and some electrical parts of the Delta 3D printer. These parts include the linear rails, plastic moulds, and stepper motors.

2. Review of Related Works

References [3, 4] explored aiding rapid prototyping using 3D printers. It was observed that 3D printers allow designers to try out multiple variants of their design in an economical manner and in a short duration of time. However, the common budget 3D printers available to designers are the Cartesian 3D printers. Cartesian 3D printers are highly restricted in terms of print volume and print heights and hence the need for a Delta 3D printer. The designed Delta 3D printer uses smooth rods and linear bearings. These are not readily available in Ghana; hence, this design is not suitable for the Ghanaian maker space.

In [5], a comparative analysis of Cartesian and Delta 3D printers showed that Cartesian 3D printers have simple operability and are easy to troubleshoot. Comparing printouts, the 3D cloner Cartesian printer and the Rockstar MAX delta printer were used. A common 3D model was printed, and the quality of the printout was evaluated. It was observed the Cartesian printer produced a more dimensionally accurate result; however, the printout surface was better on the Delta printer.

In Ghana and most African countries, the supply chain channels for electronics components are partly developed. Companies in these regions experience supply chain disruptions which are not ideal. According to [6], 83% of companies in Ghana experience regular supply chain disruptions. This necessitates the need for businesses and makers in such regions to develop solutions using readily available resources or materials.

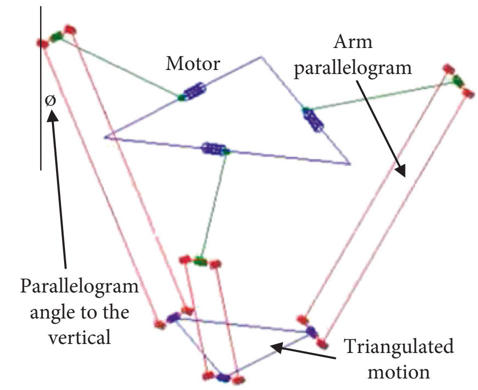

Figure 1: Delta printer motion structure [2].

3. Methods and Materials Used

This section of the work talks about the design concept, components used, and design calculation.

3.1. Design Concept. Using the adoptive machine design technique in the development of the locally made Delta 3D printer, some ideas were adopted from machines that have been validated. The machines considered for this work include the Delta Pi 3D printer from Thingiverse and the KLAKS 3D printer made in Ghana.

The Delta Pi 3D printer's concept of square pipe linear rails was partly adopted. This design was partly adopted because the square pipes served as linear rails and support structure for the base and top plates. However, it has a complex bearing carriage assembly which requires four (4) pairs of bearings per carriage. In addition, the 3D printed carriage is complex which is time-consuming to replicate and is prone to failure. Figure 2 shows the Delta Pi bearing carriage assembly.

From the KLAKS 3D printer, the bearing pair stack assembly was adopted which uses three (3) pairs of bearing per stack. A simple carriage support structure is developed for the adopted bearing stack design. Figure 3 shows the bearing stack assembly adopted from the KLAKS 3D printer.

Figure 4 shows the simple bearing stack carriage assembly design used for the designed Delta 3D printer.

3.1.1. Block Diagram Design Concept. Figure 5 shows a universal block diagram of the Delta 3D printer. The printing process begins with a power supply to the control board which in turn distributes it amongst the system components, and the print commands are also sent to the control board. The control board instructs the heating elements to melt the filament (printing material). With the help of the extruder motor assembly, a controlled amount of filament is deposited in a semiliquid form onto the build platform. This also controls the angle (∅) of each arm parallelogram to realise the shape of the 3D object.

All these mechanisms work together to aid the printer in the following x, y, and z coordinates to form the 3D object. The display helps the user to see the progress made for an

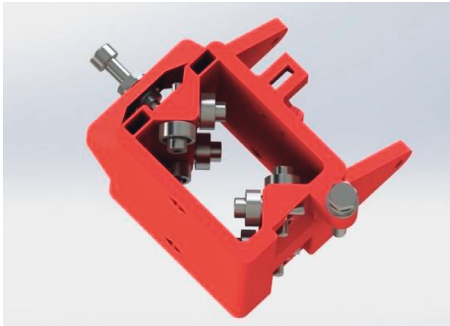

Figure 2: Delta Pi bearing carriage assembly.

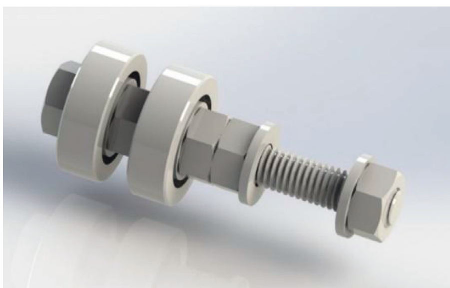

Figure 3: KLAKS 3D printer bearing stack assembly.

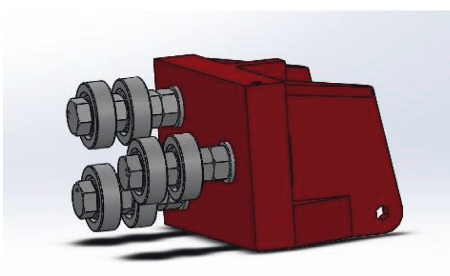

Figure 4: Simple bearing stack carriage assembly.

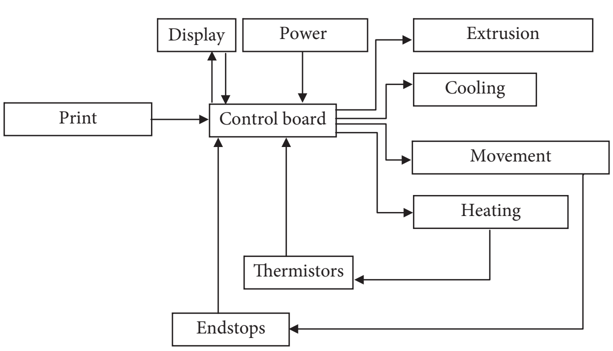

Figure 5: Block diagram of the delta 3D printer.

issued print as well as for menu selection. The cooling fans assist in keeping the control board cool as well as some parts of the extrusion mechanism. It also cools the printout as the printing is ongoing.

Considering these concepts and adaptations, SolidWorks 3D modelling software was used in the development of our proposed Delta 3D printer. Figure 6 displays a 3D model of the proposed Delta printer with the various parts labelled.

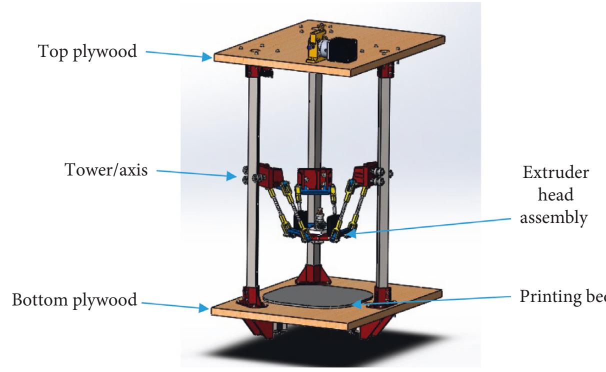

Figure 6: 3D model of the proposed Delta 3D printer.

3.1.2. System Operation. The Delta 3D printer has three similar towers or axes. The three coordinates axes are denoted A, B, and C. Each tower is made up of a square tube and a carriage that runs up and down the column. Each carriage has two parallel arms of the same length that connect to the effector platform (extruder holder).

To ensure that the arms are parallel, the connection points on each carriage and the effector platform should be at the same distance apart. The parallel arms of the carriages connect to the effector platform to force the plane of the effector to be parallel to the plane of the bed.

Unlike the Cartesian, the axes X, Y, and Z cannot be easily identified. However, the origin of these Cartesian coordinates is the centre of the Delta printer. The view from the top in Figure 4 shows the X and Y axes on the bed. Each tower is situated at equal distance from the origin and 120° apart.

The coordinates X and Y are obtained from the synchronized movement of the three pairs of arms for the nozzle to get to a specific point. The Z coordinate, on the other hand, is achieved when all carriages move up or down. Its origin is achieved when the nozzle touches the bed. All this is achieved through commands that the controller uses in controlling the position of each of the carriages [7]. Figure 7 shows the top view of the proposed design.

The movement of the carriage is achieved with the help of a NEMA 17 stepper motor, a pulley, a belt, and an idler. All parts assembled produce a tower and this is depicted in Figure 8.

(1) Extrusion Mechanism. The 3D printing technology used is Fusion Deposition Modelling (FDM). The extrusion mechanism also uses a NEMA 17 motor to pull the filament in a controlled manner. In order to reduce the weight on the hub and arms, the Bowden extrusion mechanism is adopted. With this type of extruder, the heavy motor assembly sits on the top plate and only the hot end and cooling fans sit on the hub. The Bowden extruder motor assembly is shown in Figure 9. Part of the extrusion mechanism is relocated by moving the motor and motor mount away from the hot end.

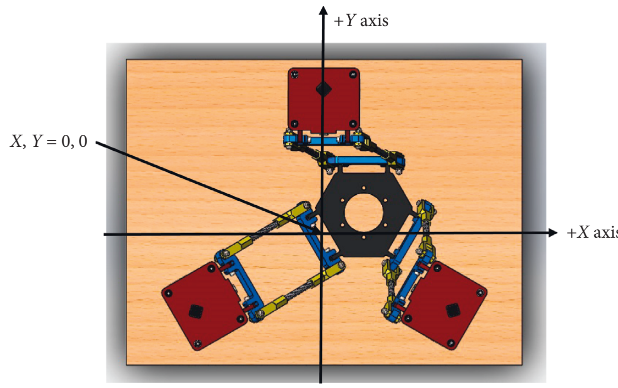

Figure 7: Top view of the proposed design.

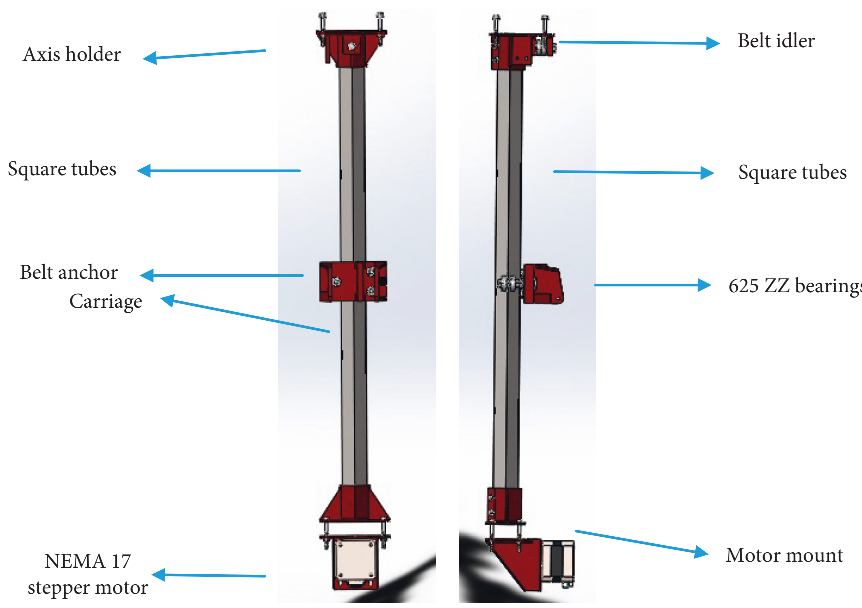

Figure 8: Tower assembly.

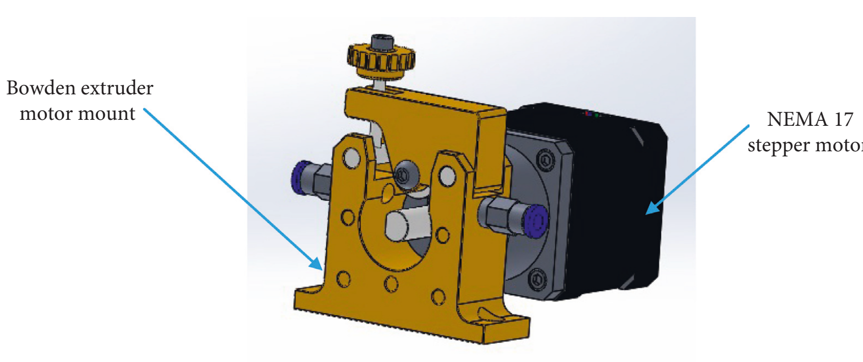

Figure 9: Bowden extruder motor assembly.

This reduces the weight of the moving parts, leaving only the hot end to be on the hub. Accurate printouts and higher print speeds are achieved since less momentum needs to be subsumed when changing directions [4]. A Teflon tube is connected from the Bowden extruder motor assembly to the hot end to direct the filament flow. Figure 10 shows the extruder head assembly.

(2) Printing Algorithms. The flowchart depicted in Figure 11 is the algorithm used for the 3D printer's functionality.

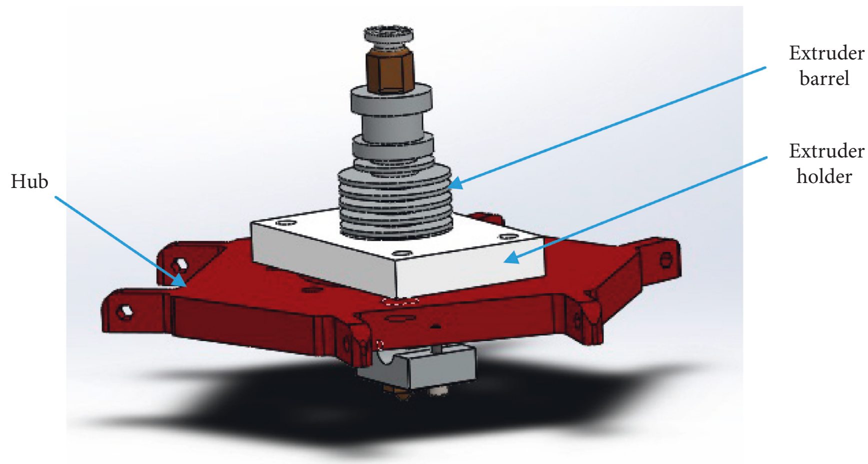

Figure 10: Extruder head assembly.

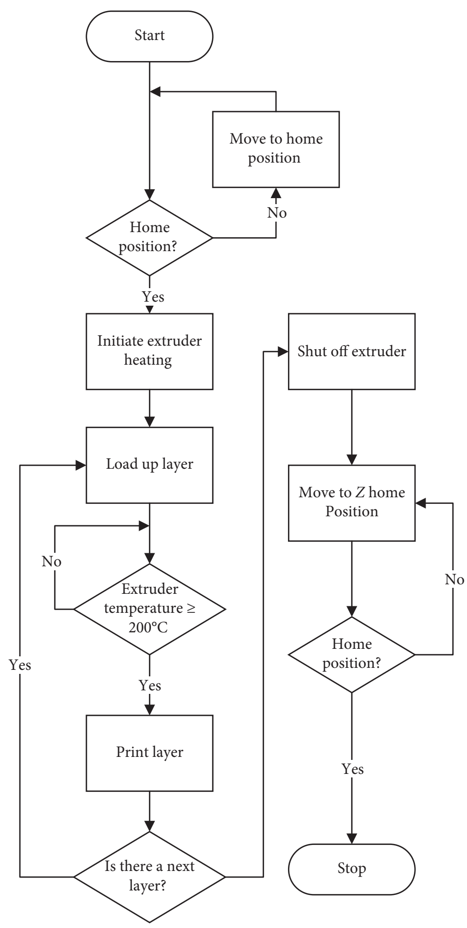

Figure 11: Flowchart of the printing algorithm.

When a print command is initiated, the printer initiates heating of the extruder. As the printer heats up the extruder by applying 12 V to the heating cartridge, it loads up the coordinates for the first layer of the print into its volatile memory.

When the optimum extruder temperature is reached, that is, 185 to 200°C for polylactic acid (PLA) and 220 to 240°C for acrylobutadiene styrene (ABS), the printer then homes the extruder nozzle. The home position corresponds to $x = 0.00$, $y = 0.00$, and $z = \text{MAX}$ coordinates. Mechanical endstops are employed to energise stepper motors once the limit is attained.

After homing the extruder nozzle, the printer moves the various motors to the corresponding coordinates whilst depositing the filament. After the first layer, the printer prints the next layer using the coordinates available in its memory from the G code file. When the last layer is printed, the control board shuts off the extruder, that is, 0 V is applied to the extruder. It then moves the extruder nozzle to the z-axis maximum position with the help of the endstops and the printing process is terminated.

For printing of ABS, heat bed is used to prevent the warping of the printout. In this case, the heat bed is also heated during the start of the print to optimum temperature (90°C to 110°C) and shut off after printing the last layer. The heated bed has a spring spacer that allows for bed levelling and prevents the transfer of heat from the heated bed to the plywood base plate. Figure 11 shows the flowchart of the printing algorithm.

(3) Programming of the Control Board. The Delta printer is programmed with Marlin firmware. The Marlin firmware is an open-source firmware based on Sprinter and grbl. The firmware is calibrated to suit the purpose of any Delta printer. The Marlin firmware makes it possible to choose between various electronics used in making 3D printers to enable good communication between software and hardware.

3.2. Components Used. In the design and construction, the major components used include square tubes, bearings, NEMA 17 stepper motor, and others. The following sections throw more light on these components.

3.2.1. Square Tubes. Square tubes are used in this design because they are locally found and rigid to stand as the frame of the Delta 3D printer. There are also the rails or paths for the carriage to roll up and down. However, smooth rods or aluminium extrusions are usually used for such purposes. The inconvenience with these smooth rods is that even though they can be sourced locally from e-waste, most of them are of different diameters and they also require the use of linear bearings which is not common to come by locally. Figure 12 shows a 3D model of a square tube.

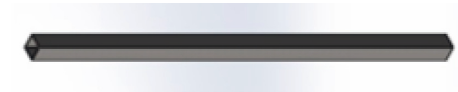

Figure 12: 3D model of a square tube.

3.2.2. Bearings. The bearings used in this design are roller bearings 625 ZZ as shown in Figure 13. The bearings were used as rollers and also as idlers. They are made of hardened steel and are capable of making the system rigid whilst providing less frictional resistance, operate at higher speeds without overheating, and are available in a wider range of sizes [8]. In addition, the 625 ZZ bearings were easily sourced locally. Figure 10 shows a 3D model of a bearing.

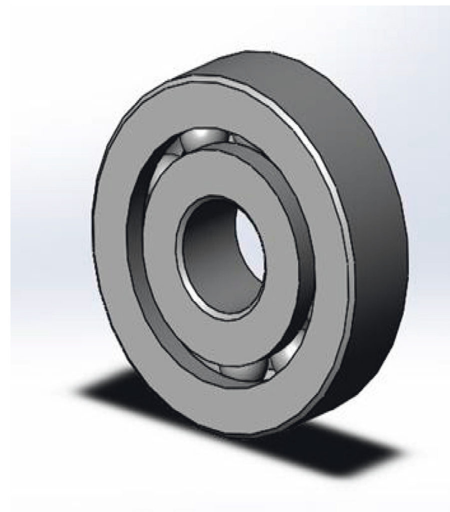

Figure 13: 3D model of a bearing.

3.2.3. Control Board. The control board of the Delta 3D printer was a combination of Arduino Mega 2560 and RAMPS 1.4 interface boards. The Arduino Mega 2560 is a development board which has an ATMEGA 2560 microcontroller. The Arduino Mega 2560 has fifty-four (54) digital input/output pins and sixteen (16) analogue inputs, hence making it possible to achieve the required control of the mechanism. The RAMPS 1.4 board serves as an interface between the Arduino Mega and the rest of the system. It serves to bring together all the electronics needed for the control of the 3D printer at a very low cost [9].

3.2.4. Full Graphic Smart Liquid Crystal Display. This component consists of an LCD display, a secure digital card slot, and a rotary encoder. The rotary encoder helps users make menu selections for printer control as well as send G code files for printing.

3.2.5. Pololu A4988 Stepper Motor Driver. The A4988 is a complete microstepping motor driver with built-in translator for easy operation. The A4988 stepper motor provides microstepping options for running stepper motors with overcurrent protection. The stepper motor driver also fits as a module on the RAMPS 1.4 interface board making it suitable for a 3D printing purpose. This stepper motor driver provides options for increasing current supply to stepper motors to overcome friction [10].

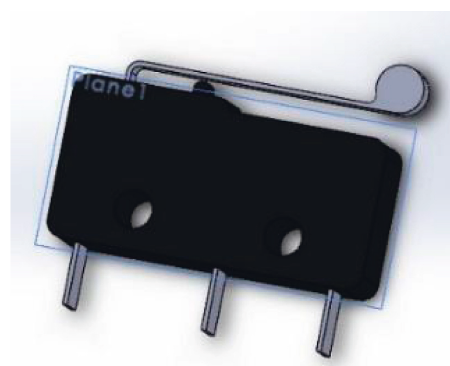

Figure 14: Endstop.

3.2.6. Endstops. Mechanical endstops are the most basic form of endstops, made of an ordinary switch. Endstops can be found in e-waste and are also strong enough to withstand a crash. Figure 14 shows the endstops used.

3.2.7. NEMA 17 Stepper Motor. The key parameters to consider in choosing motors for 3D printers are precision, size, and torque. The NEMA 17 stepper motor is a hybrid stepper motor which is able to achieve precision control without a feedback loop. This makes it an ideal choice compared to tin-can stepper motors which are also readily available in e-waste. Figure 15 depicts the NEMA 17 stepper motor.

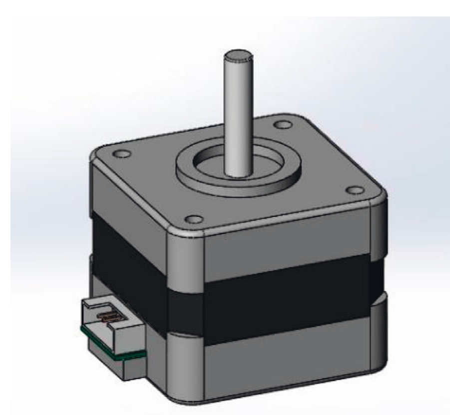

Figure 15: NEMA 17 stepper motor.

3.2.8. Thermistor. Thermistors are used to measure the level of heat at the extruder nozzle and the heat bed build platform. Negative temperature coefficient (NTC) thermistor was chosen because their resistances decrease as the temperature rises and they prevent heating of the semiconductors.

3.2.9. Screws, Nuts, and Washers. M3 Screws, nuts, and washers were used to fasten the square tube to the plywood. M5 screws, nuts, and washers were used to hold the 625 ZZ onto the square tube.

3.2.10. GT2 Pulleys and Belts. GT2 belts are often used for timing applications and offer excellent precision. The pulley used GT2 7 mm wide belt. The pulley has 20 teeth and 5 mm inner bore as shown in Figure 16. Three sets of screws were used to hold the pulley onto 5 mm diameter shaft, in this case, the stepper motor shaft. The pulleys are made of aluminium and hence they are light and durable. GT2 pulleys come with their belts having the same groove.

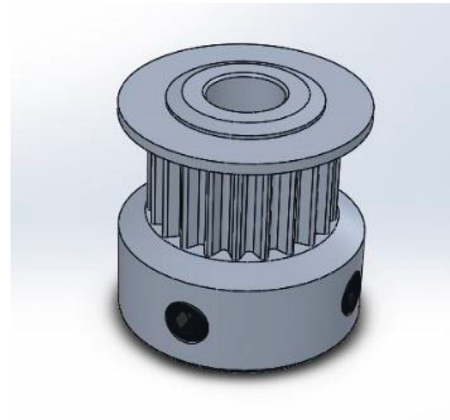

Figure 16: Pulley.

3.2.11. 3D Printed Parts. Some 3D printed parts were used because they are easy to customise and are of low cost and also can be easily replaced when damaged. The printing of the 3D printed parts also demonstrates the ability to fabricate new machines with 3D printing eliminating the need to employ costly injection moulding. Table 1 shows a list of all 3D printed parts used. All the 3D parts on this Delta Printer were printed using PLA.

Table 1: 3D printed part list.

SN	Part number	Quantity
1	Arm pivot	6
2	Bottom tube clamp	3
3	Carriage	3
4	Clevis	12
5	Extruder holder	1
6	Hub	1
7	Motor mount	3
8	Top tube clamp	3

3.3. Design Calculations. This section discusses the design calculations for the proposed Delta 3D printer. The number of microsteps per millimetre and the total weight to be moved by stepper motor were computed.

3.3.1. Number of Microsteps per Millimetre. According to Maker tutorials [11], the formula to calculate the steps per millimetre of the moving mechanisms using the NEMA 17 motors could be expressed as

$$\text{Steps (mm)} = \frac{\text{Mg} \times \text{Microstepping}}{\text{Travel at one turn of the motor in mm } (\beta)},$$

$$\beta = \text{Pitch of Belt} \times \text{Pulley Teeth}, \tag{1}$$

where pitch of belt = 2 mm, number of teeth of pulley = 20, and travels of turns in millimetre = 2 × 20 = 40 mm.

NEMA 17 stepper motors may have 1.8° per step or 0.9°/step. The stepper motors salvaged from e-waste in this experiment are of 1.8° per step type. Therefore, the corresponding steps/mm could be computed by using the following equation:

$$= \frac{360^\circ}{1.8^\circ} \text{ steps per turn},$$

$$\text{Microsteps of motor} = \frac{200}{\text{turns}},$$

$$\text{Microstepping of Pololu motor} = 16 \text{ micro} - \text{steps},$$

$$\text{Hence, Steps per mm} = \frac{200 \times 16}{40} = 80 \text{ steps per mm}. \tag{2}$$

Therefore, the required steps of the motor at every mm are 80 steps.

3.3.2. Total Weight to Be Moved. The mass of carriage and mass of bearing stack affect the total mass of objects that can be moved. The mass of the object to be moved is calculated empirically using the following equation:

$$M_O = M_C + (3 \times M_B) + M_E, \tag{3}$$

where M_o = mass of the object to be moved, M_C = mass of the carriage, M_B = mass of the bearing stack, and M_E = mass of the extruder.

Given M_c = 38.78 g, M_E = 37 g, and M_B = 3.1 g.

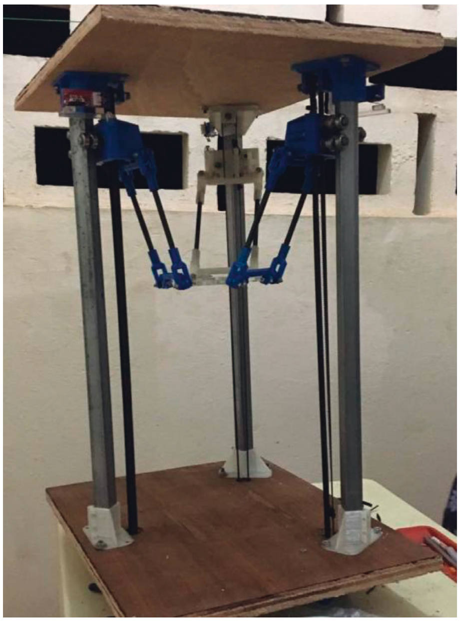

Figure 17: The prototype of the proposed design.

$$
\begin{aligned}
M_o &= 38.78 + (3 \times 3.1) + 37,\\
M_o &= 85.08\,\mathrm{g},\\
M_o &= 0.08508\,\mathrm{kg},\\
W_o &= M_o \times a,
\end{aligned} \tag{4}
$$

where W_o = weight of the object to be moved and a = acceleration due to gravity:

$$
\begin{aligned}
W_o &= 0.08508\,\mathrm{kg} \times 9.81\,\mathrm{ms}^{-2},\\
W_o &= 0.8346\,\mathrm{N}.
\end{aligned} \tag{5}
$$

The least force that the NEMA 17 stepper motor can deliver is 1.73 N which exceeds the weight to be moved (0.8346 N) and other components can easily travel along the square tube.

4. Development of Prototype

The final prototype was produced based on the design calculation and the complete programming of the controller. Tools such as a mitre saw, drill press, hack saw, and laser cutter were used for the prototyping of the 3D printer. In addition, some calibrations were done to make sure the extruder mechanism is dispensing the right amount of filament per millimetre as well as retracting at correct step rates. The calibration data are then fed to the control software and into the slicing engine which is used to convert 3D models into G code. Figure 17 shows the prototype of the proposed design after construction.

5. Cost Analysis

This section provides a breakdown of items and the cost of items used for the manufacture of the prototype of the Delta 3D printer. From Table 2, we can access the cost analysis of the proposed Delta 3D printer.

Table 2: Total cost of producing the 3D printer from e-waste.

Item	Quantity	Unit cost (GH¢)	Total cost (GH¢)
NEMA 17 motors	4	30.00	120.00
Belt and pulleys	3	Salvaged	Salvaged
Square tubing	1.5 m	11.00	11.00
Switches	2	Salvaged	Salvaged
Glass plate	1	Salvaged	Salvaged
Ethernet cables	3 cables	5.00	15.00
Plywood	—	60.00	60.00
DC fans	1	Salvaged	Salvaged
Power supply	1	70.00	70.00
Printed parts	1 kg	192.50	192.50
Bowden extruder and extruder hot end	1	118.16	118.16
Ramps 1.4 kit	1	156.14	156.14
625 ZZ bearing	24	7.00	168.00
Screws and washers	—	—	30.00
Total			940.80

Table 3: Printer cost comparisons.

Printer	Build volume (mm^3)	Printable materials	Cost (USD)
ROBO 3D R1 PLUS	$254 \times 230 \times 200$	ABS, nylon, PLA	799.99
Rostock MAX	$224 \times 224 \times 375$	ABS, exotics, PLA	999.00
Printrbot	$150 \times 150 \times 150$	ABS, exotics, PLA	349.00
Delta 3D printer	$\pi 100^2 \times 300$	ABS, PET, PLA	181.27

The cost analysis indicated that the total cost of developing the Delta 3D printer from salvage e-waste parts and printed components is GH¢940.80 which is equivalent to USD 181.27 (using an exchange rate of GH¢ 5.19 to USD 1.00 as on 30 March 2019; 10:45 GMT). The parts labelled salvaged were retrieved directly from Afful Nkwanta dumpsite in Kumasi, whilst the rest of the e-wastes were purchased from waste dealers at Adum and Bantama all in Kumasi, Ghana. Other materials were purchased at Suame Magazine in Kumasi with the exception of bearings which were purchased in Takoradi.

Table 3 shows the price and the build volume comparison of some renowned printers on the market [12] and the proposed Delta 3D printer.

6. Conclusion

A Delta 3D printer has been designed and developed using printed parts and salvaged e-waste materials. The overall build volume of the Delta 3D printer is $\pi 100^2 \times 300\,\mathrm{mm}^3$.

The printer achieves its movement through the use of three vertical axes which are placed 120° apart. For accuracy and speed, NEMA 17 stepper motor was employed to drive the various carriages on the vertical axes. Least force of 1.73 N can be delivered by the NEMA 17 stepper motor and this exceeds the 0.8346 N which is the weight to be moved.

In conclusion, the designed printer exhibited a considerably lower cost of GH¢940.80 which is equivalent to 181.27 USD. This Delta 3D printer is 4.4 times cheaper than ROBO 3D R1 PLUS whilst the Rostock MAX is dearer by 5.5 times.

7. Recommendation

This research after complete execution of the main objective suggests the following for future works:

(1) e-Waste should be properly managed for easy acquisition of salvaged parts for such works

(2) Design and sizing of the build platform should be carried out considering varying loads

Data Availability

This work was carried out from scratch with no data collection carried out.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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