NIPES

Advances in Engineering Design Technology

Journal homepage: www.nipesjournals.org.ng

Design and Development of a Low-Cost Cartesian 3D Printer

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Article Information

Article history:
Received 11 August 2023
Revised 23 August 2023
Accepted 15 Sept 2023
Available online 10 Dec 2023

Keywords: *Additive Manufacturing Delta 3D printer, Fuse Deposition Modelling, ABS &PLA, CAD Softwar,, Arduino 2560 Sofware..*

https://doi.org/10.5281/zenodo.10340709

Abstract

The conventional subtractive method of manufacturing prototypes faces challenges like time and energy consumption, inaccuracy, material waste, and complexity in producing intricate parts. This research aims to address these issues by developing a low-cost, Cartesian rapid prototyping 3D printing machine using FDM technology. The machine, capable of printing with ABS and PLA plastic filaments, was designed and built using locally sourced materials like stainless steel bars, aluminum extrusion, stepper motors, and an Arduino microprocessor board. Controlled by Repetier (slic3r) software, it converts CAD models into G-code, which guides the printing process. The printer, powered by a DC source, successfully produced high-precision 3D models, demonstrating its potential for both hobbyist and professional applications.

1. Introduction

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file. The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the entire object is created. Each of these layers can be seen as a thinly sliced horizontal cross-section of the eventual object [1]. It was not long ago that the concept of three-dimensional (3D) printing, additive manufacturing by industrial terminology, was reserved for the rapid prototyping field of engineering and production. Interest in 3D printing, however, has grown dramatically over the past few years, a change set in motion in part through the expiration of patents [3].

There are many technologies and processes utilized for 3D printing including Fused Deposition Modeling (FDM), Stereo lithography (SLA), Solid Laser Sintering (SLS). Each of these processes have advantage and disadvantages. However, most of these 3D printing technologies require expensive components like lasers or expensive resins which we could not afford due to time and funding constraints. There are basically two types of 3D printers which are: The Cartesian 3D printers, The delta 3D printers but our design focus was on the Cartesian type.

We chose Fused Deposition Modeling (FDM) process for our 3D printer because it required less expensive parts that we could salvage from electronic waste, fabricate ourselves or were readily available to purchase off the shelf. The FDM 3D printer also used a plastic filament which could be recycled from plastic waste and was also readily available off the shelf.

The printing process employed in fused deposition modeling, FDM technology's development and revolution were greatly aided by Scott Crump, its creator [2].

A fused Deposition model (FDM) printer uses a special plastic material fed into the machine in a wire or coil form called filament. This filament is melted by a hot end in the machine and deposited on top of a build platform made of glass or metal. The material is melted and deposited on the build plate which is under computer control in both X, Y and Z axes, depending on the G-CODE generated by the intermediate software (slic3r) via the CAD model of the object, until the entire object is formed.

The challenges we set out to mitigate with this project include the following:

1. Lack of access to hardware parts/materials needed for product design and development, both at hobby and professional level due to the unavailability of a technology ecosystem as well as hardware infrastructure.
2. Lack of access to digital prototyping equipment and/or services to facilitate product design and hardware projects.
3. Unavailability of digital fabrication labs (Fab labs) and maker spaces to democratize the spread of technology and innovation and empower hardware startups throughout the country.
4. Lack of affordable, easy to use and maintain 3D printers. This was especially important due to the low purchase power in the country. This is mainly due to the lack of spare parts and sufficient trained personnel to maintain imported machines.
5. Availability of electronic waste salvaged from old printers, scanners and copiers and other electronics that could be repurposed to build low cost 3D printers.

The aim of this paper is to develop and design a low-cost Cartesian 3D printer that is meant to solve a number of challenges faced by makers, hobbyists, product designers, artists, architects and manufacturers here in Nigeria, who specialize in converting ideas to reality.

2.0 Methodology

Our design was based on a thorough evaluation of the design of 3D printers using the FDM process, as well as the components that were readily available locally, at low cost as well as those ones we could easily purchase off the shelf. Another factor we took into consideration was the ease of configuration of the printer host controller software. Our established design objective is to develop and design a modular low-cost easy to maintain 3D printer using locally available materials. The design was aimed towards achieving the following: to make 3D printing parts more locally sourced, to make 3D printing more operable and easier to use, to increase rapid prototyping among Nigerian designers which would help check for design flaws and aid design improvements and to make relatively cheap procurement of a 3D printers in Nigeria. Once this objective was established, we decided on a design methodology to make the task easier.

2.1 Design Concept and Consideration

Our design concept and consideration consist of the following stages; Pre-Design/Project Evaluation, Design Specifications, Material Selection, Component Procurement, Subcomponent Production/Assembly and Performance Evaluation

a. Pre-Design/Project Evaluation: This was the conception stage of the design of a modular low-cost 3D printer from locally available materials. At this stage, we considered the different 3D printing technologies, our budget and availability of precision production tools and equipment and well as time and funding constraints. We also ensured that the parts we would need for building were locally available, could be produced or bought off the shelf and would not exceed our budget before deciding to embark on the project.

b. Design Specification: At this stage, we decided on the Specifications of the proposed 3D printer based on the design objectives we set out to achieve as well as the constraints we had earlier identified. We chose the Cartesian model because it was easier to build and calibrate with basic tools than the Delta type of printers and parts available from electronic waste would also suit the Cartesian model more. At this stage we also decided on the size of the machine, the build volume, and size of each axis, the motion system of each axis, as well as the Printer controller and stepper motor drivers to choose. The final specification was a 3D printer that could easily be disassembled and fit into a backpack or travelling suitcase for easy mobility.

c. Material Selection: This was the stage that we finally decided on the materials to select based on the design Specifications we set out in the previous step. Each material selected was given due consideration based on availability and ease of sourcing as well as funding constraints. Stainless steel tubing was chosen for the x-axis frame because of its resistance to corrosion, availability at low cost. Aluminum Extrusion was chosen for the Y and Z axis because of availability and ease of attaching components to the frame for easy assembly and disassembly. Heated Bed was chosen so it could print plastics like ABS at higher temperatures without warping.

d. Component Procurement: At this stage, we procured the components specified by the design and also commenced the Computer Aided modeling of the 3D printer once most of the components had arrived. Once all the components had been modeled and assembled in CAD software, production files and drawings were generated and printed.

e. Subcomponent Production/Printer Assembly: This was the stage where we produced individual subcomponents like the extruder, the X axis subcomponent, the Y axis sub-component and the z-axis subcomponent, after which all the subcomponents were assembled on the frame. Once mechanical assembly was completed, the electronic components were installed and wired together to the controller.

Each of the electronic components including the Stepper motor, limit Switches, hot-end, graphical LCD controller and heated bed were tested at this stage to confirm functionality before final assembly. The printer controller was also connected to and configured using Marlin software in the Cartesian configuration.

f. Performance Evaluation: In this stage, the 3D printer was put through its paces to calibrate the precision of each axis. Different test objects like the 20mm cube was printed and used to calibrate the X, Y and Z axis. A benchy model was also printed and used to calibrate the extruder, infill and print speed for different layers. From the calibration settings, the parameters of the 3D printer were tweaked using the marlin firmware for the host controller and the printing parameters optimized for maximum print performance. A number of parts were also printed from the print controller, and from the graphical LCD controller to determine optimum settings.

2.2 Operational Procedure of the Modular Printer

The general workflow for 3D printing process using Fused Deposition Modeling (FDM) included the following:

a. CAD Design (Computer Aided Design of the object or part)
b. Slicing (Conversion of the CAD model to G-CODE)
c. Pre-Printing Configuration (Bed Levelling, Filament Feed/Adjustment)
d. Actual 3D Printing (Print Controller or Graphic Controller SD Card)
e. Post-processing (Sanding, Painting, Finishing of the part)

2.3. 3D Printing Workflow (Detailed Breakdown)

This section is a detailed breakdown of each of the processes involved in 3D printing outlined earlier, starting from the Computer Aided Design (CAD) modeling to the actual printing and post processing of the 3D printed part or object.

i. Computer Aided Design (CAD) Modeling

This is the first step in the 3D printing workflow. At this stage, the object to be printed is designed using a CAD modeling software or program capable of generating 3D models e.g. AutoCAD or Fusion360. In this step, the objects dimensions, shape and geometry are reproduces using the software to the exact dimensions, and once completed the Stereo lithography (STL) files of the given object was generated by the software. The software we used for this was Fusion360, because it was free to use for students and hobbyists, as well as it's simple and intuitive user interface. Fusion360 also has the ability to convert the finished file into STL format, which is needed for the next step of the process.

ii. Slicing

The next step in the 3D printing process workflow is slicing. Slicing is the process of converting the STL files generated from the CAD model into a set of instructions required to control the 3D printers movements needed to create the object. The slicing software features a number of settings which takes the digital model file and calculates the tool-paths and movements that the nozzle needs to follow, as well as the amount of filament required to be deposited and at which points. Once slicing is completed, a G-CODE file is generated which contains precise instructions to control the actual movements of the printer. The slicing software we used for our printer was Slic3r because of the ease of configuration of individual printer settings and parameters like layer height, infill type and density as well as the print speed. Slic3r was also used because it was easy to configure and integrate with Marlin for the 3D printer controller host software.

iii. Pre-Printing Configuration

Before the main printing commences, there are a number of Pre-Printing Configuration and steps to prepare the machine. The first one is feeding the filament into the extruder through the hot-end and calibrating the hot-end to move the filament a precise distance. Thereafter, bed leveling of the build platform is done to enable the first layer to adhere firmly to the printing bed.

iv.Actual printing

After the generation of the G-CODE model, we used the software Matter Control to control the printer directly over a USB connection. Matter Control was chosen as the Printer control software because it could be used to calibrate and control the printer directly before the actual commencement of the print, as well as store STL files in an organized manner before selecting any of them for configuration or printing. Our 3D printer was also designed to have a graphical LCD controller as well, from which we could modify set parameters on the fly, as well as print from an SD card without being attached to a computer system. The graphic controller had a rotary encode, which served as a user interface (GUI). For the actual printing process, we selected the file required either from the SD card or from the print controller and sending the print job to the machine. The machine starts printing if all the required materials and power have been supplied to it.

v.Post-processing/Finishing

This is an optional step, and depends on the geometry and surface finish required of the 3D printed part. Most parts require some level of post-processing before use, especially if the part has additional support attached to enable overhangs print properly or allow a part stuck to the bed.

Post processing can therefore include removal of support layers, cleaning of printed holes to make them fit, sanding the printed part to remove visible layers as well as painted in any required color.

2.3. System block diagram and software flow chart

The block diagram and the software flow chart of a 3D printer can be illustrated using the accompanying figure 1 and 2 below. [2]

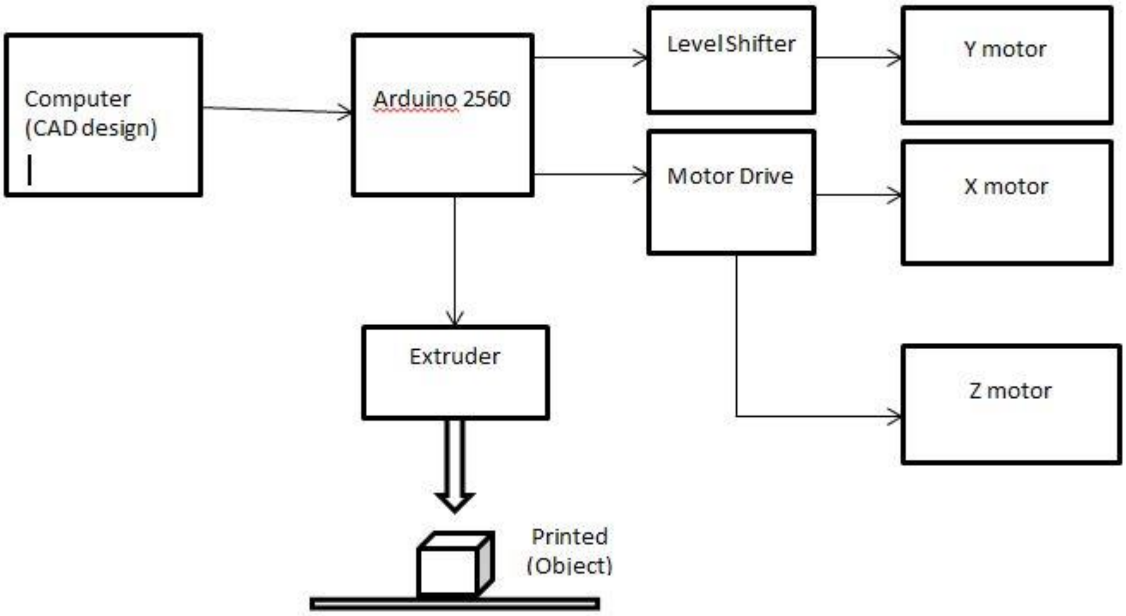

Figure 1 Block diagram of the system

Figure2.Software flow chart

For effective usage of the 3D printer, this study recommends:

1. The cleaning of the glass bed before any new print to remove any remains from previous prints and dust particles.
2. The printing of parts on a stable place to avoid unnecessary vibrations which may bring about distortion of the print.
3. Printing in with stable power supply to avid shutdowns in-between prints which would mean starting over on that print on the return of power.

2.4 Description of Components/ Units

The Low-Cost rapid prototyping machine comprises of the following units/components as shown in Figure 3 below; The Base 20 * 40(mm) structural support, X axis / linear rail and printing bed assembly, Y-axis aluminum extrusion assembly, Z axis / linear screw rails and aluminum support assemblies, extruder and heater end assembly, 15 * 10(mm) stainless steel top support, LCD screen Arduino microprocessor board assembly.

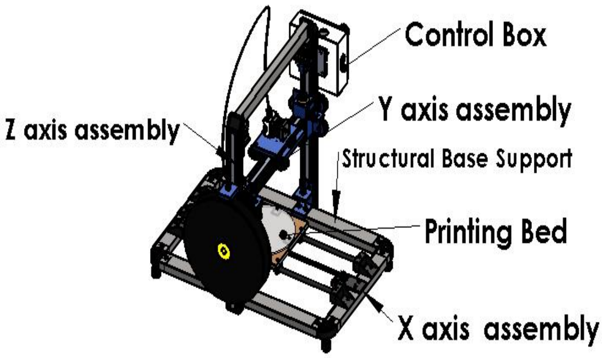

Figure 3: Annotated Isometric View

2.4.1 The Base Support Assembly:

The base of the machine is main supporting structure, upon which the other component of the machine is mounted. The base is a coupled 40 * 20(cm^2) stainless steel with 3D printed plastic edges. This which is shown in the figure 4 below.

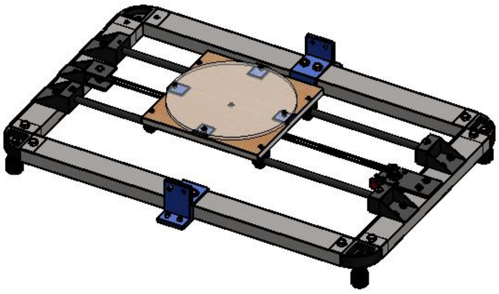

Figure 4: Base support assembly

2.4.2 The X Axis Assembly:

The X axis / linear rail, and the printing bed assembly which is fixed to the base structural support by 3D printed brackets, is comprised of linear rails, and linear bearings sliding through upon which the printing bed is mounted as shown in figure 5 below this which is actuated by a NEMA 17 motor.

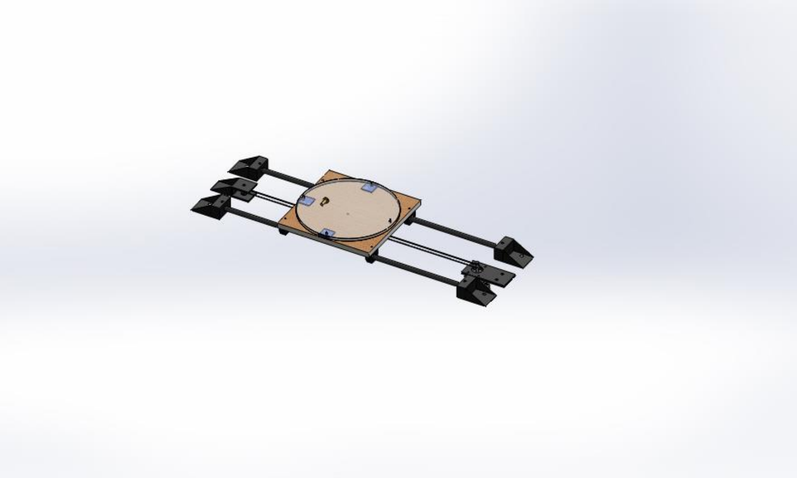

Figure 5 X axis / linear rail and printing bed assembly

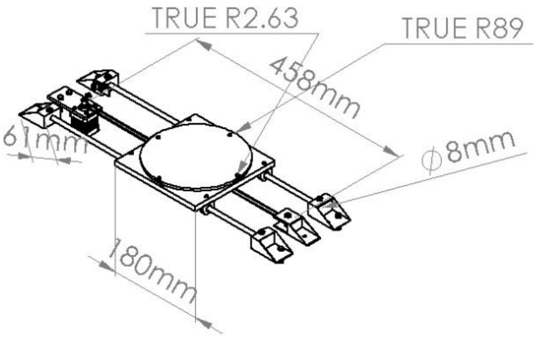

Figure 6 Detailed X axis assembly

2.4.3 The Z Axis Assembly:

The Z axis linear screw rail and aluminium extrusion structural support assembly comprise of linear screw rails, mounted on bearing holder brackets, fixed on aluminium extrusions that is mounted on the structural base support. These linear screw rails is set into a circular motion by 3D printed couplers, interfacing with the NEMA 17 motors, coupled to the aluminium extrusion and thus giving the Y axis assembly an up/down motion. The whole assembly is shown in figure 7 below.

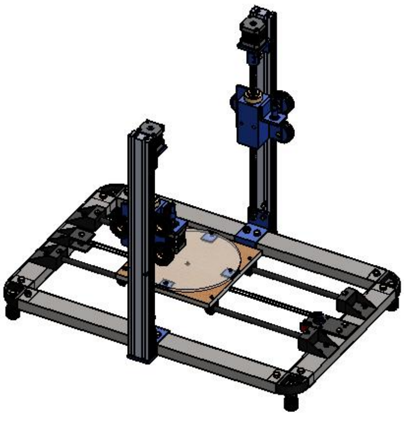

Figure 7 :Z axis linear rails and aluminium extrusion assembly

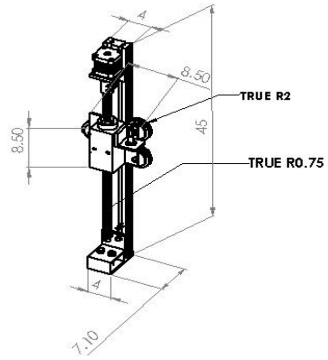

Figure 8: Z axis detailed view

2.4.4 The Y axis assembly:

The Y axis assembly is comprised of and aluminum extrusion mounted on two glider brackets carrying a NEMA 17 motor belted to a return pulley which motions the heater end assembly along the Y + and – axis by a belt coupler screwed by M3 bolts. The assembly is shown in Figure 9.

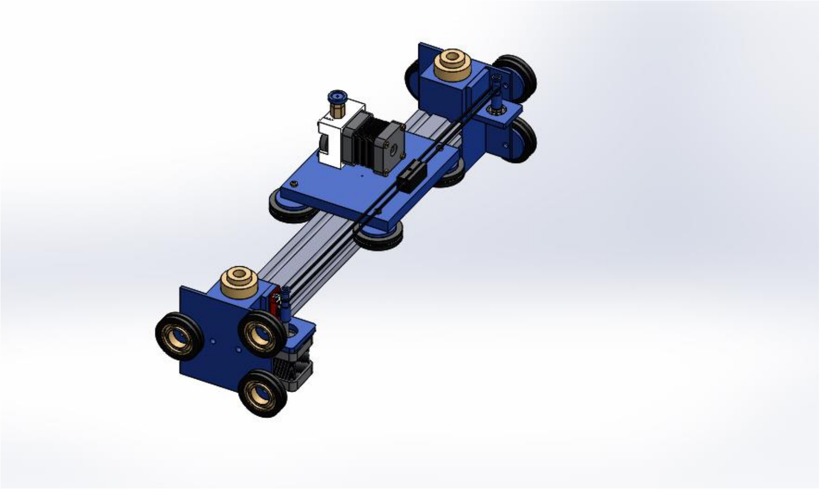

Figure 9: Y axis assembly

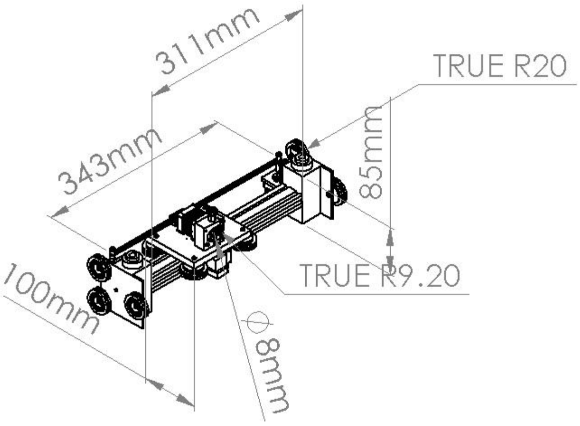

Figure 10: Detailed Y axis view

2.4.5 Heater and Extruder Assembly

The heater end Extruder assembly, which comprises of a heater nozzle, from which the extruded filament comes out is a programed, and the controlled rate coupled with a heater which heats the incoming filament to 200^oC before entering the nozzle, is held by the extruder assembly which includes a NEMA 17 with its pulley pressed side by side with a 608 pulley between which the filament is pulled in to the heater compartment. The assembly is shown in Figure 11.

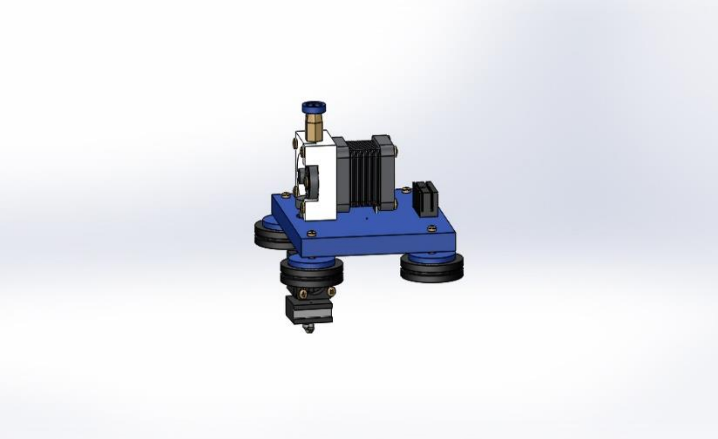

Figure 11: Heater end / extruder assembly

2.5 Design Analysis

Our prototype was designed majorly from parts salvaged from electronic waste as well as off the shelf components, hence much emphasis on design calculation The NEMA 17 motor is a hybrid motor with 1.8 step angles (200 steps/revolution), with a driving voltage-24V, current-1.75-2Amps, maximum speed-200RPM, 1.7 inch by 1.7-inch end face dimension [6]. Heated bed: 12V, 3Amps, power source: AC to DC Adapter: input 220V AC, Output: 12V 10A.

2.5.1 Firmware Calibration Calculation

i. Calculation Parameters

Stepper Motor Resolution = 200 steps per revolution
Total degrees in a revolution = 360
Angle per step = Degrees per revolution / Steps per revolution
= 360 ÷ 200 = 1.8 degrees
Stepper Motor Driver = 1/16 micro steps per full step
1.8 ÷ 16 = 0.1125 degrees per step
200 steps per revolution x 16 = 3200 steps per revolution
Timing Belt Pitch = 2mm

ii. Steps per mm (X and Y axes)

3200 (steps per revolution) x 2mm (Belt Pitch) = 6400
GT2 Timing Pulley - 16 teeth = 6400/16 = 400 steps per millimeter

The calculated values are input into the Marlin firmware to ensure that each of the axes is well calibrated to produce precise prints. To test the degree of calibration of each axis, a 20 x 20 x 20mm cube is printed, and then a digital caliper is used to measure the dimensions of each part along each axis. Any deviation of the length of the printed cube indicates which particular axis has not been well calibrated.

The Z axes and the extruder are also calibrated in the same manner to make the printer be able to produce printed objects with precise dimensions along all axes.

iii. Positioning Accuracy

Positioning accuracy can also be calculated by zeroing the 3D printer nozzle, instructing the 3D printer nozzle to move to a predefined coordinate on the X and Y axis, and then measuring the final position of the nozzle using the calibration software.

Once the actual position has been measured, we subtract the actual position from the expected predefined position. The difference is the accuracy of positioning of the nozzle, and can be adjusted depending on how accurate we want the 3D printer to be.

Positioning Accuracy = Desired position - Actual position

The Positioning Accuracy of the machine depends on the following parameters:

a. Resolution of the stepper motor used (Steps per revolution)
b. Micro steps/revolution on the motor driver (1/16 or 1/32)
c. Pitch of the timing belt and number of teeth on the timing pulley
d. Pitch of the threaded rod for the z axis

2.5.2 Belt Calculation

Our belt was selected from the standard stated in [4, 5, and 6]

2.5.3 Deformation:

GT2-style belts are created expressly to convert rotational action from pulleys into linear motion with the least amount of distortion, slippage, and backlash [5].

i.Belt Stiffness:

$$F(x) = kx \qquad [1]$$

From the above equation 1, x represents the belts deflection, k is the deflection constant. Since the length of the belt is constant i.e. running between two fixed pulleys, modelling the stiffness (k) as a spring with the formula f(x) = kx is possible. Equation 1 demonstrates that the belts stiffness is a function of its deflection under load. Therefore, the belt's nominal design stiffness is its constant-length stiffness [5].

Pitch diameter = number of teeth X tooth spacing /pi [2]

i. Belt parameters:

Belt pitch = 2mm
Pulley teeth = 16
Belt width (b) = 6mm
Belt circumference length = 200mm
Belt height (H) = 1.38mm
Tooth height (h) = 0.75mm
Breaking strength = 124Ib/56kg
Working tension = 6.25Ib/2.8kg
Shape: closed loop
Belt type: nylon cloth
From equation 3 above, the pitch diameter = 16x2/pi =10.2mm~ 10mm
The total belt length is calculated by measurement
Total belt length = 318mm

2.6 Material Selection

The bill of engineering measurement and evaluation (BEME) consists of both the mechanical and electronic components required for the construction of the 3D printer. Most of the components, especially mechanical components like linear rod and bearings were salvaged from electronic waste, while others were designed from easily available local parts.

2.6.1 Bill of Engineering Measurement (BEME) - Electronic Components Table 1

S/N	**Component Description**	**Quantity**
1	E3D Hot-end	1
2	Thermistor	2
3	Nema 17 - Stepper motor	4
4	Ramps 1.4 Control Board	1
5	Graphics LCD controller	1
6	12v Power Supply	1
7	Optical limit Switches	4
8	DRV Stepper Motor Drivers	5
9	12V Cooling fan	2
10	Heated Bed	1
11	Connecting Cables	-

2.6.2 Bill of Engineering Measurement (BEME)-Mechanical Table 2

S/N	Component Description	Quantity
1	Stainless Tubing (20 x 40)	6m
2	Aluminum Extrusion (20 x 40)	2m
3	Linear Rods (8mm) - 500mm	4
4	Linear Bearing (8mm)	12
5	Threaded Rod (500mm)	2
6	GT2 - Timing Belt (2mm pitch)	5m
7	GT2 - Timing Pulley - 5mm (16mm)	5
8	Extruder feed Screw	1
9	608 Roller Bearings	1
10	Glass Plate (250 x 250mm)	1
11	X Axis Support Bracket - Acrylic (250 x 250mm)	1
12	Extruder Support Bracket	1
13	Delrin Wheels/Wheel Bearings (625 bearings)	16
14	Stepper Motor Threaded Rod Adapter (5mm - 8mm)	2
15	Pneumatic Connector (8mm)	2
16	PTFE Tube (8mm)	800mm
17	X Axis Linear Rod Support	8
18	Nuts/Bolts (M3 - M5) Assortment	-

2.7 The Pictorial View of the Development Machine is Shown in Figures 12 -17

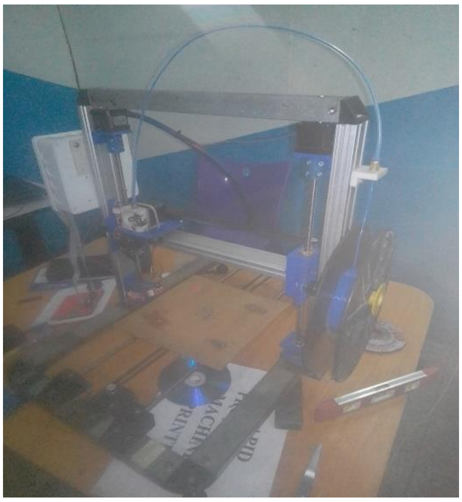

Figure 12: A pictorial view of the printer with installed control box/LCD screen

Figure 13: A pictorial view of the completed printer

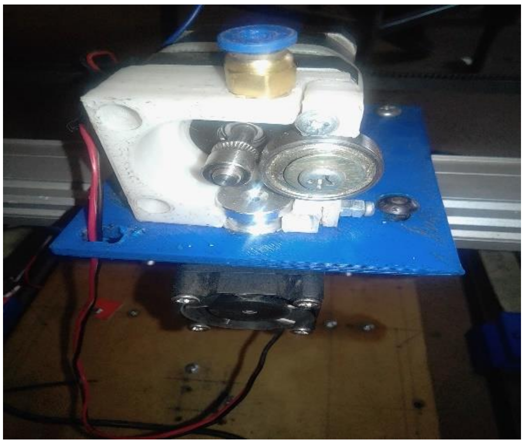

Figure 14: A pictorial view of the heater end and extruder assembly

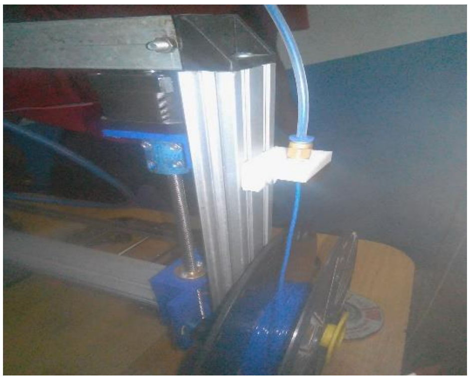

Figure 15: A pictorial view of the z axis aluminum extrusion with installed ABS plastic filament

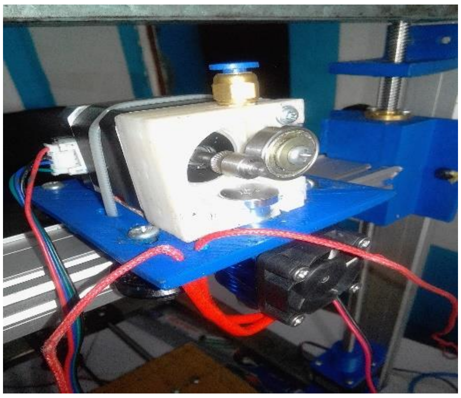

Figure 16: A pictorial view of the installation of the extruder heater assembly

Figure 17: A pictorial view of the graphic LCD controller

3.0 Results and Discussion

In the end, after an exhaustive test performance was done, the printer was found to be capable of printing a wide variety of 3D models with high precision and accuracy which was proven by its ability of replicating some of its 3D printed parts. After calibration, we found out to our pleasant surprise that the print quality was perfect for hobby and even professional work.
The Figure 18 and 19 below shows the pictorial view of objects printed by the prototype.

Figure 18: Pictorial view of 3D printed object

Figure 19: A pictorial view of 3D printed part

4.0 Conclusion

Upon the completion of the construction of our 3D printer, we evaluated the final working design, based on our design objectives and specifications. We observed that the printer was able to meet and surpass most of our design specifications, including low cost of production, modularity and ease of operation and maintenance. Upon calibration, we found out that it was also accurate enough to produce precision parts for future upgrades to the machine, as well as for hobby or professional use.

4.1 Recommendations

However, in the course of printing and evaluating the performance of the 3D printer, we discovered some few drawbacks due to the low precision manufacturing process we used. To achieve better print performance in subsequent models, the following recommendations are made from observation:

1. The glass build plate can be replaced by a flexible spring steel metal printing bed to enable easier removal of printed objects from the build plate.
2. Future designs should also incorporate a build chamber to contain the fumes generated from printing high temperature plastics like ABS
3. The printer can also be tweaked to allow for resumption of failed prints in case of a power outage.
4. To mitigate the problem of epileptic power supply in Nigeria, the power supply unit can also be redesigned to use a dual power supply running on solar, to keep the printer running when the main electricity is not available.

Conflict of Interest

The author's states that they have no competing interests because the work described in this study was carried out without the use of any outside financing. The authors' opinion and findings are the only ones that were considered in this work,

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