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DESIGN OF A DUAL FUSED DEPOSITION MODELLING 3D PRINTER FOR STUDIO CERAMICS PRODUCTION IN NIGERIA

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Abstract
A Fused Deposition Modelling (FDM) Delta-type 3D printer was designed and fabricated using locally sourced materials for several components. The design was based on the open-source Replicating Rapid Prototyper (RepRap) platform. The printer features a build volume of 288 mm × 288 mm × 910 mm and utilises a control system comprising a RE-ARM board and a RAMPS 1.6 interface, operating with Marlin firmware. The structure incorporates plain hollow rods, plywood frames, 3D-printed parts, and various electronic components. Finite Element Method (FEM) analysis was conducted on critical 3D-printed parts to assess their structural integrity under operational conditions. The results showed that the von Mises stress values were well below the material's yield strength, while the displacements remained within acceptable limits for high-precision applications. These findings confirm that the components are capable of maintaining both structural integrity and dimensional accuracy during use. Moreover, the total power requirement of the 3D printer was estimated to be 130.32 W, which fits within a moderate energy consumption range when compared with typical desktop FDM 3D printers. The fabricated printer was tested in producing models for clay-cast moulds, though further improvements are recommended.

Keywords: *Fused deposition modelling, low-cost 3D printer, polylactic acid filament, finite element analysis, ceramic 3D printing*

Introduction

Technology has always been a viable tool for man to improve his life and his environment, dating back to primordial times. Computers are a recent technological achievement that have evolved into a flexible instrument for solving problems and improving processes in virtually every aspect of human endeavour. The use of computer-aided technologies has had a significant impact on the execution of technological advancements in all sectors of human endeavour, including industrial design (Adelabu and Kashim, 2011). The evolution of technology in the ceramic industry has been very interesting over the years, from traditional modelling methods using the pinching method from a lump of clay to making wares using throwing wheels and other innovative ideas like the jigger and jolly machine, etc.

The introduction of three dimensional (3D) printing into manufacturing ceramic wares offers entirely new possibilities for creating wares with highly complex and precise structures that are difficult to achieve with traditional forming techniques (Chen *et al*., 2019). These wares are built from a 3D CAD model that is digitally sliced into two-dimensional (2D) cross sections and built layer-by-layer until the final object is achieved. This phase of industrialisation of 3D printing is unlike the common paper printers that are used to print graphics on a flat surface (2D printing). Objects are printed in three dimensions (x, y, z) using a 3D printer (Simons *et al*., 2019). However, despite the increasing interest in the development and application of additive manufacturing (AM) technologies globally due to their flexibility and potential uses in various fields, their practical adoption in Nigeria is still rather at a slow pace (Inoma *et al*., 2020a).

In the past decade, studies on the development of AM technologies have been documented in Nigeria, though they remain very few. Most of the empirical studies are focused on Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) 3D printing technology (Farayibi *et al*., 2019a;

Oluwajobi and Kolawole, 2021, 2022; Oluwajobi and Osunkoya, 2020). A study on the awareness of additive manufacturing (AM) technology in southwestern Nigeria found that few professionals are familiar with 3D printing, reflecting its very low adoption in the country's light manufacturing sector (Farayibi and Abioye, 2017a). Conversely, a survey in the educational sector showed that around 93% of engineering professionals are aware of these technologies (Klenam *et al*., 2022). While it is promising that these professionals have some knowledge of 3D printing, a comprehensive understanding of its functionality is lacking. This indicates a need to incorporate 3D printing into the manufacturing industry and academic curricula for both undergraduate and postgraduate programs. Similar research among design students and professionals in Nigeria is still needed.

The exploration of creative applications for low-cost AM systems and improvements in shaping technologies for ceramic products are of special interest to this study. This study hopes to contribute to capacity building towards advancing clay-forming technologies, particularly for ceramic studio practices and education in Nigeria. The study recognises the need to ramp up efforts in the development of low-cost 3D printing technologies that will have the ability to form complex-shaped ceramic structures within the ceramic studio. According to Zhou *et al*. (2024), there are various typologies of AM, which include Vat Photopolymerisation, Powder Bed Fusion, Binder Jetting, Material Jetting, Sheet Lamination, Material Extrusion, and Directed Energy Deposition. However, this study is focused on exploring digital prototyping for indirect ceramic forming on the Fused Deposition Modelling (FDM) technique. The FDM is a Material Extrusion method that presents the opportunity for a relatively low-cost build and an easy-to-adopt AM option (Dhinakaran *et al*., 2020; Farayibi *et al*., 2019b). It has been shown in recent studies on awareness of 3D Printing technologies that many aspects of AM remain underexploited in Nigeria, and more concerted effort will be required to build capacity for applications in educational and industrial sectors (Farayibi & Abioye, 2017b; Inoma *et al*., 2020b).

The Fundamentals of FDM 3D Printing

The FDM 3D printer requires a 3D model with the desired shape, created using 3D CAD (computer-aided drawing) tools like SolidWorks, Autodesk Inventor, Autodesk Fusion 360, Rhinoceros 3D, Blender, etc. The CAD file is then converted to an STL (Standard Tessellation Language) file. Next, the STL file is further sliced into thin layers and converted to G-codes using suitable slicer software. This G-codes file would then be uploaded to the 3D printer, for printing (Steuben *et al*., 2015). The FDM 3D printer builds objects using an extrusion process. A clay material or a plastic filament is extruded from a nozzle while the machine prints out 3D objects, layer by layer. As one layer of material is laid on top of another, they fuse to form a solid object. As illustrated in Figure 1, the process flow of 3D printing comprises key stages, including 3D CAD modelling, slicing the model into a series of 2D layers, and subsequently constructing the 3D solid model by sequentially printing the 2D layers.

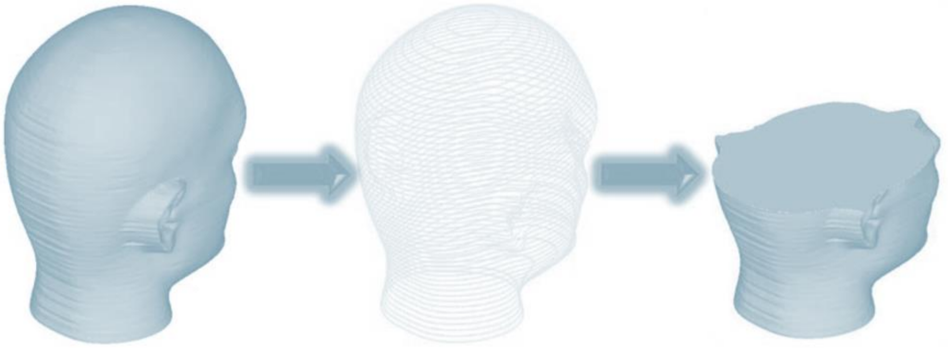

Figure 1: Basic processes of 3D printing (Song, 2016)

Delta Kinematics

The Delta-type FDM 3D printer uses inverse kinematics to calculate the position of the effector (Equations 1–3). The position of the print head is determined by the relative lengths of the three arms. Each of the three arms moves independently, but together they control the X, Y, and Z coordinates of the print head (see Figure 2).

$$X = \frac{L}{2}\left(\cos(\Theta_1)\right) + \left(\cos(\Theta_2)\right) + \left(\cos(\Theta_3)\right)$$

$$Y = \frac{L}{2}\left(\sin(\Theta_1)\right) + \left(\sin(\Theta_2)\right) + \left(\sin(\Theta_3)\right)$$

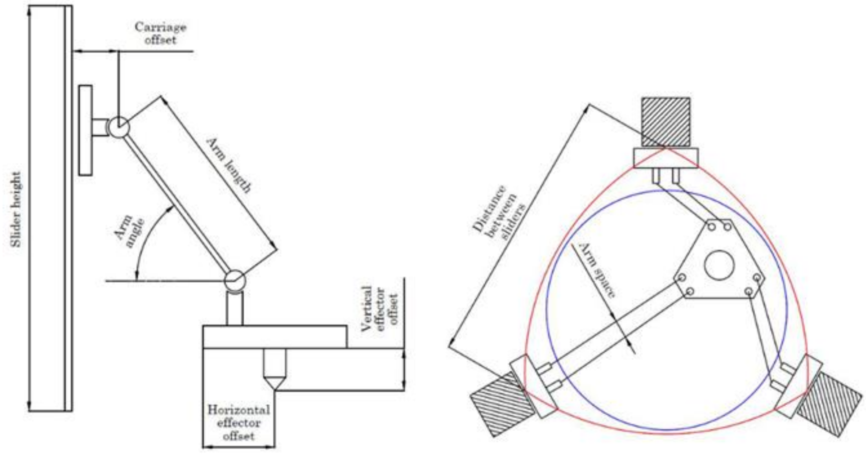

Figure 2: Delta Kinematics (Gonz, 2017)

$$Z = h - \frac{L}{2}\left(1 - \cos(\Theta_1 + \Theta_2 + \Theta_2)\right)$$

where: L is the length of the arms; $\Theta_1, \Theta_2, \Theta_3$ are the angles of the arms controlled by the stepper motors; h is the height of the arms.

Method

The Delta-type FDM 3D printer was selected as a foundational platform for the development of a studio-size ceramics 3D printer due to its unique advantages. Delta 3D printers provide high-speed, precise, and efficient printing on a fixed bed, making them ideal for prototyping intricate ceramic designs and the smooth manufacturing of cylindrical objects. The printer has three axes hollow rods that serve as linear rails and a support structure for the base and top plates. However, it features a complex bearing carriage assembly that requires four pairs of bearings per carriage (Simons *et al*., 2019b). Furthermore, the Delta configuration maintains high precision and speed over a larger build volume, making it particularly suitable for the scale and complexity of ceramic pieces.

The model design for the printer was created using Autodesk Inventor 3D CAD software, where models with exact dimensions were developed for the 3D printed parts. The structural development of the printer predominantly utilised locally sourced plywood sheet and PLA-based components

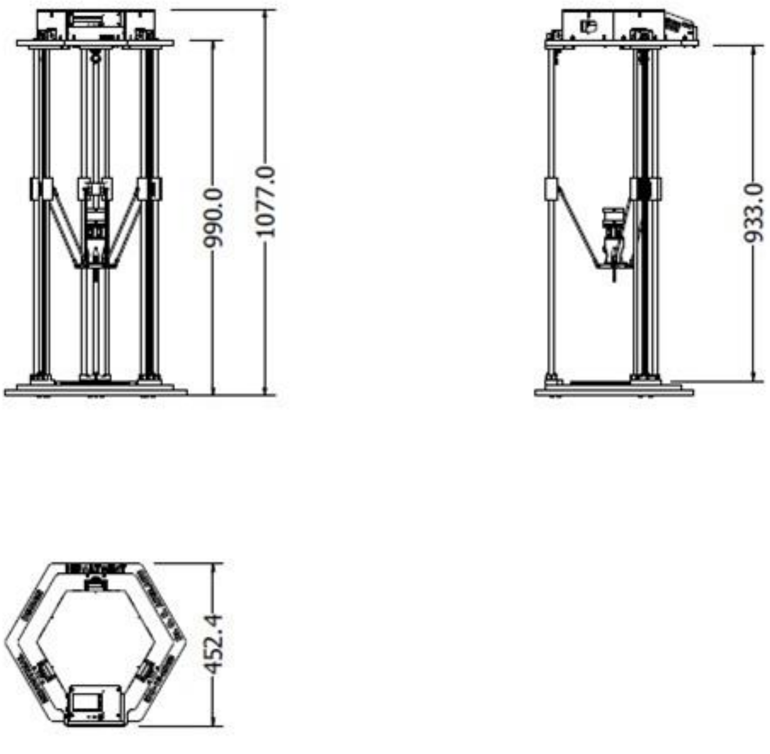

Figure 3: Orthographic Drawing of the Delta 3D Printer

(including idler, motor holder, carriage, and effector), which were printed using a RepRap Cartesian-type FDM 3D printer. Core electronic components, as listed in Table 1, were sourced from a Chinese e-commerce platform, AliExpress.

Design Considerations

For this project, a build volume of 288 mm × 288 mm × 910 mm was considered for the construction of the studio-size printer, which is regarded as the fundamental parameter for fabrication. As shown in Figure 2, the base of the printer was designed with a hexagonal shape to enhance more stability, unlike the more common triangular-based delta printer. The hexagonal base provides a larger surface area and improved weight distribution, thereby increasing the overall stability of the printer. This design choice helps to minimise vibrations and wobble during printing, resulting in improved print quality and precision.

The print head and effector were designed in such a way that the Delta printer can adopt both the hot-end filament extrusion and the cold-end extrusion interchangeably. In addition, the electronic components of this printer was designed to stay at the top of the printer to prevent water ingress in the case of cold extrusion, unlike some other Delta printers whose components are at the base of the printer. For the frame of the printer, plywood was used to construct the frame of the printer, including the top cover and the base. The choice of plywood was based on its relative strength along the longitudinal direction and its low cost relative to

Table 1: 3D Printer Imported Part List

S/N	Items	Specifications	Material	Quantity
1	Power Switch	15 A 250 V power switch AC power	Composite	1
2	Power Pack	12 V 20 A AC power pack	Composite	1
3	Linear Bearing	LM16UU	Aluminium	12pcs
4	Stepper Motor	NEMA 17, 42 x 48 mm	Composite	5
5	Belt Idler	GT2-20T ID5 OD18 W6	Aluminium	5pcs
6	Pulley	GT2-20T ID 5 OD18 W6	Aluminium	3
7	Stepper Driver	DRV8825 Motor Driver	Composite	5
8	Timing Belt	GT2 Timing Belt	Reinforced rubber	10M/Lot
9	Thermistors Sensors	100k NTC Thermistors Sensors	Composite	5pcs
10	Diagonal Rods	310 mm Delta Diagonal Arms	Stainless steel	6pcs
11	Pneumatic Hose	12x 8-3M	Polyurethane	3M
12	Pneumatic Connector	Connector Fitting PC	Brass	5
13	Nozzle	1.5, 2 mm Print Nozzle	Brass	2
14	Limit Switches	Mechanical Limit Switches	Composite	5pcs
15	Control Board	RE-ARM 32bit + RAMP 1.5	Copper	1
16	LCD Display	LCD12864 LCD Controller	Composite	1

Table 2: Locally Sourced Part List

S/N	Item	Specification	Material	Quantity
1	Tower Rods	16 mm Diameter Hollow Plain Rod	Stainless steel	6
2	Top and Bottom cover	Plywood	Plywood	
3	Bolts, Nuts, and Washers	M4, M5	Stainless steel	4 dozen
4	Electric Cable	220V AC Cable	Copper	1
5	USB Cable	Connectivity Cable	copper	1M

other materials such as aluminium, Perspex, or iron. The printer has three major motion axes (X, Y, and Z). The X, Y, and Z axes each consist of two 12 mm hollow stainless-steel rods, 960 mm in length, and carriages equipped with four LM12UU linear bearings, with two on each rod, to reduce arm vibration during vertical movement. Additionally, each axis includes three printed idlers, a stepper motor pulley system, belt pulleys, and a 3D-printed housing for the stepper motors.

However, this Delta printer was designed to have a complex bearing carriage assembly, which requires four bearings per carriage to ease the movement of the arms and ensure less vibration during printing. The bearing pair stack assembly was adopted which uses two bearings per hollow rod. A simple carriage support structure was developed for the adopted bearing stack design.

Frame Design

The frame is the printer's main component, on which all axes, stepper motors, the extruder, and other parts of the printer are mounted to provide rigidity and balance during the printing process. The electronic components are also housed at the topmost part of the frame to prevent contact with water. The frame was made of plain hollow rods, plywood, and 3D-printed plastic parts. The frame structure provides the rigidity and support needed during the printing process. Half-inch thick 4 × 8 feet plywood was machined with a router into a hexagonal shape to enhance stability. The project name and other important details were engraved on it.

Arm Length and Positioning

Each arm length (L) must be sufficient to allow the effector to move across the entire build volume. The arm position depends on the tower angles and the length of the rods. Each arm forms a triangle with the build plate. Using inverse kinematics (Siciliano & Khatib, 2008), the position of each arm must satisfy the following:

$$L^2 = \mathrm{x} - \mathrm{r}\cos\theta_1{}^2 + (\mathrm{y} - \mathrm{r}\sin\theta_1)^2 + z^2$$

Where r is the distance from the centre of the effector to the arms attachment points.

Thus, to calculate the arm positions at any point (X, Y, and Z) of the effector, the three arms' positions can be determined using:

$$Z_1 = \sqrt{L^2 - (x^2 + (y + d)^2) - h_1}$$
$$Z_2 = \sqrt{L^2 - ((x + r)^2 + y^2) - h_2}$$
$$\mathrm{Z}_3 = \sqrt{L^2 - (x^2 + (y - d)^2) - h_3}$$

where: h_1, h_2, h_3 are the heights of the respective arms; x, y and z are the coordinates of the effector; θ_1, θ_2, θ_3 are the angles of the three arms relative to the vertical axis; L be the length of the arm; d - horizontal distance from the centre of the effector to the connection point of the arm.

Stepper Motor Selection

The key mechanical component in a Delta printer is the stepper motor torque that drives the arms. Torque determines the speed and precision of movement, especially under the weight of the effector.

To calculate the torque required for the stepper motors:

$$T = F\ x\ r$$

where: F is the force needed to move the effector; r is the radius of the pulley connected to the stepper motor.

The required force is:

$$\mathrm{F = m\ x\ g}$$

$$\mathrm{F = 0.34\ x\ 9.81 = 3.34\ N}$$

where: g is gravitational acceleration (9.81 m^2); m is effector weight; Pulley radius is 0.0064 m

Torque required for each motor would be = 3.34 x 0.0064 = 0.0214 Nm

Printer Control and Electronics

The electronics used in the control of the 3D printer are standard modular components, comprising the microcontroller, main board, motor drivers, stepper motors, hot end, print bed, limit switches, and temperature sensors.

The Control Board and Firmware

The control board of the Delta 3D printer is a combination of the RE-ARM board and the RAMPS 1.6 interface board. The RE-ARM board is a 32-bit plug-in replacement for the Arduino Mega, which only has an 8-bit processor. It runs at 100 MHz, significantly faster than the 16 MHz Arduino Mega boards. The RE-ARM board is compatible with Marlin, Smoothieware, and possibly other popular 3D printer firmware. It uses the widely adopted NXP ARM Cortex-M3 processor (LPC1768). The RAMPS 1.6 board serves as an interface between the RE-ARM board and the rest of the system, integrating all the necessary electronics required for controlling the 3D printer. (Arduino, 2019).

Power Consumption Calculation

According to Oluwajobi & Kolawole, (2021), to select an adequate power pack for the 3D printer, the electrical power consumption for all the standard electrical parts was calculated using the following equations:

$$P = IV \quad (9)$$

$$P = \frac{V^2}{R} \quad (10)$$

$$P = I^2 R \quad (11)$$

Power Required by the Extruder

The extruder consists of a NEMA 17 stepper motor with a rated voltage of 12 V and a current of 2 A and a 12 V DC fan with a current of 0.16 A.

Power required by NEMA 17 stepper motor:

$$P = 2 \text{ x } 12 = 24 \text{ W}$$

Power required by the Fan:

$$P = 0.16 \text{ x } 12 = 1.92 \text{ W}$$

Power required by the hot end nozzle:

$$P = 2.5 \text{ x } 12 = 30 \text{ W}$$

Total power required by the extruder

$$= 12 + 1.92 + 30$$

$$= 43.92 \text{ W}$$

Power Required by the Drive Axes

The 3D printer consists of three drive axes, each with a rated voltage of 12 V and a current of 2 A.

Total power required by the Stepper motors

$$= 24 \text{ x } 3 = 72 \text{ W}$$

Power Required by the Control Board

The 3D printer is controlled by a 32-bit RE-ARM board and RAMPS 1.6 interface board, powered by a 12 V DC supply.

Power required by the Control Board

$$= 12 \text{ x } 1.2 = 14.4 \text{ W}$$

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 = 130.32 W

Axes Movement Calculations

According to Simons *et al*. (2019), the general formula for steps per mm in a pulley-driven system is:

$$Steps\ per\ mm = \frac{\text{Motor steps per rev. x Microstepping factor}}{\text{Pulley circumference}}$$

Step Angle = 1.8°,

Micro Stepping = 1/16,

Timing-belt Pitch = 2 mm,

Motor Pulley Teeth = 20

$$\text{Steps per revolution (full step)} = \frac{360^\circ}{1.8^\circ}$$

Steps per revolution (micro stepped) = Full steps × Micro stepping factor

$$= 200 \times 16$$

$$= 3200 \text{ steps per revolution}$$

Pulley circumference = π x d

$$= \pi \text{ x } 12 \text{ mm} = 37.7 \text{ mm}$$

Therefore:

$$\text{Steps per mm} = \frac{3200}{37.7}$$

$$= 84.9 \text{ steps per mm}$$

Materials Selection and Consideration

The materials selected for the various parts, along with their specifications, have been documented in Tables 1 and 2. Our primary considerations during the selection process included ensuring an overall low cost, prioritising the availability of some local materials, and the feasibility of 3D printing multiple components. It is worth noting that a significant number of parts were imported from China while other parts were obtained from the local market.

3D Printed Parts

Polylactic Acid (PLA) filament material was used to 3D print several critical components, including the idler, motor holder, carriage, and effector. Finite Element Analysis (FEA) was conducted on these components, specifically the idler, carriage, stepper motor holder, and effector, using Autodesk Simulation Mechanical (ASM) software. These parts were selected for analysis due to their structural importance within the assembly. The analysis considered the force and the moment generated by the extruder sub-assembly, the stepper motor weight, and the holding torque. Table 3

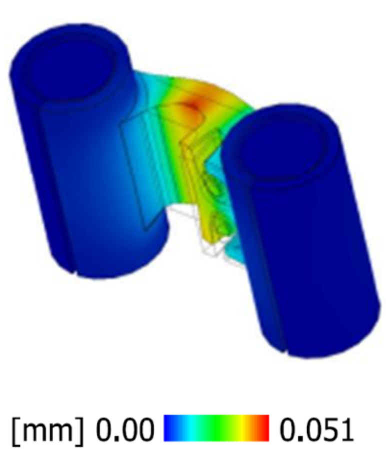

Figure 5: FEA displacement analysis of the carriage of the idler

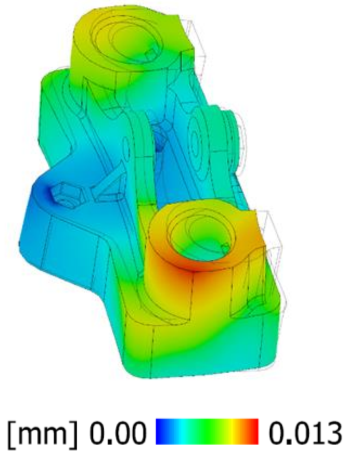

Figure 6: FEA displacement analysis of the idler

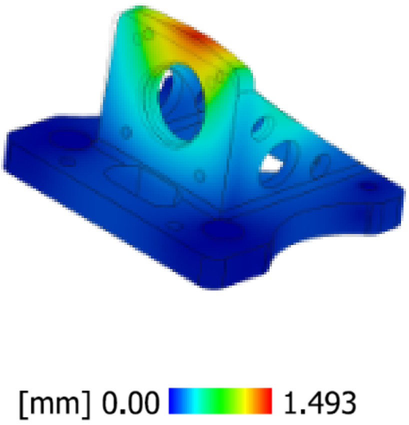

Figure 7: FEA displacement analysis of the stepper motor holder

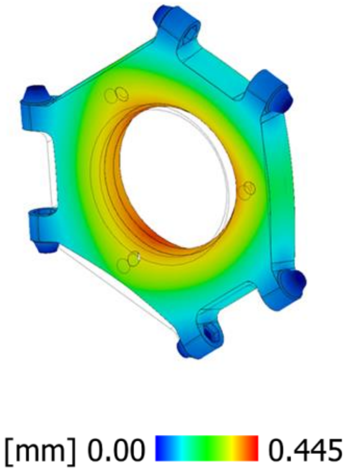

Figure 8: FEA displacement analysis of the effector

Table 3: Plastic properties assigned for the structural simulation

S/N	Properties	Values
1.	Density	1.290×10^{-6} kg/mm^3
2.	Young's Modulus	709.00 MPa
3.	Poisson's Ratio	0.40
4.	Yield Strength	30.00 MPa
5.	Ultimate Tensile Strength	40.00 MPa
6.	Thermal Conductivity	2.500×10^{-4} W/(mm·°C)
7.	Thermal Expansion Coefficient	4.190×10^{-5} /°C
8.	Specific Heat	1750.00 J/(kg·°C)

highlights the properties assigned to the PLA materials used for the structural simulation.

Idler / Carriage

The idler serves as the major player for the stepper motor pulley system. It was designed to fit in two hollow cylindrical rods and connects the GT2 timing belt to transmit rotary motion from the stepper motor pulley to the linear motion of the extruder sub-assembly. The carriage houses the linear bearings that facilitate the movement of the extruder along the axis. Four linear bearings are assembled within a single carriage to ensure smooth motion along the hollow rods. Finite Element Analysis (FEA) was conducted on the 3D-printed carriage, and Figure 5 shows the displacement results. The maximum stress and displacement obtained from the FEA are 3.447 MPa and 0.051 mm, respectively.

Figure 6 shows the displacement results of the FEA for the idler. The maximum stress and displacement obtained from the FEA analysis are 0.759 MPa and 0.013 mm, respectively.

Motor Holders

The motor holders are of similar shapes coupled with limit switches on the three axes of the 3D printer. These motor holders were 3d printed with PLA and were designed to house the stepper motors. Four M3 bolts holds the stepper motor to the motor holder, three M3 bolts holds the limit switches to the base of the motor holder and four M4 bolts and nuts hold the motor holder to the printer ply-wood frame. The motor pulley system runs vertically between the two hollow rods attached to the motor holder. It is also fitted to the plywood frame on all axes keeping the hollow rod in alignment with the hole on the lower idler pulley system. Figure 7 shows the displacement results for the motor holder. The maximum stress and displacement obtained from the FEA analysis are 12.50 MPa and 1.493 mm, respectively.

Effector

The effector serves as the base component for the extruder on which other components of the extruder are assembled. This effector carries the extruder and a cooling fan and also connects the carriage for the linear bearings with two arms on the three axes. Three M3 bolts and nuts hold the extruder to the effector and six M3 bolts and nuts hold the six arms that connect to the carriage. Figure 8 shows the displacement results for the effector. The maximum stress and displacement obtained from the FEA analysis are 11.522 MPa and 0.445 mm, respectively.

Results and Discussion

Finite Element Method (FEM) analyses were carried out on several critical 3D-printed components to assess their structural integrity under expected operational loads. The components analysed included the effector, carriage, motor holder, and idler; all fabricated using polylactic acid (PLA) filament. The simulations were performed using Autodesk Simulation Mechanical (ASM) software.

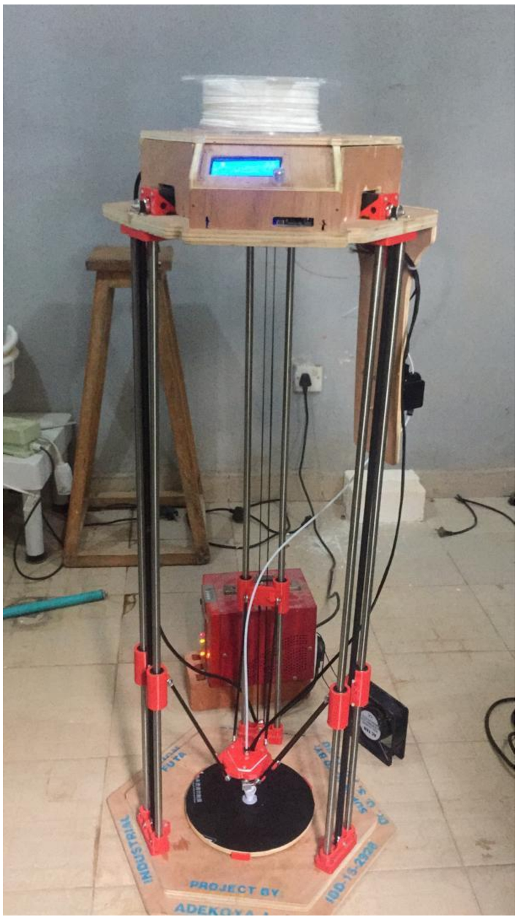

Figure 9: A functional prototype of the Delta-type FDM 3D Printer

Figure 9: Outputs from the indirect approach to 3D printing ceramics

The results showed that the effector experienced a maximum von Mises stress of 11.522 MPa with a displacement of 0.445 mm. The carriage recorded a stress of 3.447 MPa and a displacement of 0.051 mm, while the motor holder exhibited a stress of 12.500 MPa and a displacement of 1.493 mm. The idler, being less mechanically loaded, had the lowest values, with a stress of 0.759 MPa and a displacement of 0.013 mm.

All the stress values obtained from the simulations are well below the yield strength of the PLA material, which is 30.00 MPa, and significantly lower than its ultimate tensile strength of 40.00 MPa. This indicates that none of the components is likely to undergo plastic deformation or structural failure under normal usage. Furthermore, the displacement values fall within acceptable limits for high-precision applications, ensuring that the components will retain their dimensional accuracy and contribute to the reliable functioning of the assembled system.

Figure 9 presents a functional proof-of-concept of the Delta-type FDM 3D printer configured for indirect ceramic prototyping. A significant outcome was achieved using the 3D printer to generate a plastic model from a digital design. This model serves as an intermediate mould or pattern for developing a Plaster of Paris (POP) mould, which is subsequently used in the slip-casting of ceramic forms. Figure 10 shows the outcome of this approach where on the left side is the clay-based result of the process while on the right side is the PLA model printed directly through FDM. The pores observed on the clay cast were caused by trapped air bubbles during the slip casting process. This defect may also be attributed to inadequate slip deflocculation, imbalance water-clay mix ratio, overly rapid pouring or draining, insufficient vibration or agitation during casting, or contamination with foreign particles. The printer's extrusion capabilities were evaluated, revealing an extrusion speed of 70 mm/s, a maximum extrudable filament diameter of 0.4 mm, and an extrusion temperature of 220°C. The printer is capable of printing with PLA filament and utilises a flexible, removable build surface as its printing base. To achieve fine print quality, the integration of a cooling system during the printing process was found to be essential.

The total power requirement of 130.32 W indicates that the printer operates within a moderate energy consumption range, aligning with typical desktop FDM 3D printers, which generally consume between 50 and 150 watts during operation. This reflects an energy-efficient design, making the printer suitable for use in power-constrained environments.

Essentially, the fabricated printer demonstrated commendable accuracy and precision in producing models for clay-cast moulds, with a satisfactory surface finish. Nevertheless, further improvements in calibration and material selection are necessary to enhance performance and ensure optimal results for more demanding applications at both studio and industrial levels.

Conclusion

This study aimed to design and develop a ceramic 3D printer using Autodesk Inventor software for CAD modelling. The study succeeded in developing a working 3D printer that can operate as a hot-end extrusion and can further be adapted for a cold-end extrusion. The indirect approach of 3D printing ceramics was adopted for producing prototypes of different designs and a POP mould was made for the mass production of the prototype.

The conducted tests have shown that providing a cooling system results in a finer surface finish and prevents warping during printing. Therefore, printing is considered optimal as long as the technical specifications of the most critical components are maintained, namely: a printing nozzle with a 0.4 mm diameter; a plastic filament with a 1.75 mm diameter; a metallic extruder equipped with a cooling fan; a print bed; and high-speed printing of up to 60 mm/s.

The primary challenge faced was securing sufficient funding for the project, which hindered the smooth fabrication process. Looking ahead, future work will focus on investigating the direct 3D printing of ceramics using a specially formulated paste.

Declaration of Competing Interest

The authors confirm that there are no known conflicts of interest associated with this publication.

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