



An interactive approach towards the development of an additive manufacturing technology for railcar manufacturing

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Abstract

An interactive approach towards product development enables the creation of products which combine optimal performance with effective users' interaction. In this work, an additive manufacturing technology which is suitable for manufacturing internal and external accessories of a railcar was developed using an interactive approach. The mechanical design of the body kit, which consists of the frame vertex triangle, front threaded and smooth rods, NEMA 17 stepper motor, micro-switch and extruder, was done using the Autodesk Inventor[®] 2016 while the finite element analysis of its extruder was done using the Commercial Abaqus software 2018. Also, the electronics board which controls the 3D printing process comprises of the MELZI V2.0, a DIY shield board, USB to serial converter and Arduino micro controller. A software program using process G-code instruction in the Arduino micro controller in conjunction with MELZI board and additional circuit was employed to control the sensors used as input. During the performance evaluation, the 3D printing technology was used to produce the circular and non-circular gears. The results obtained indicate that an increase in the feed rate and nozzle diameter results in an increase in the speed of printing but with a reduction in the print quality and vice versa. Hence, the developed 3D printing technology offers the realistic possibility for easy and quick, production of products on demand, thus, enabling product development and customization which has the potential to boost innovation and foster more efficient use of resources.

Keywords 3D printer · Additive manufacturing · Micro controller · Railcar

1 Introduction

The 3D printing technology is one of the various forms of additive manufacturing technology whereby a 3D object is created by depositing materials in successive layers [1–3]. It is also known as rapid prototyping in which 3D objects are made quickly in a mechanized method on a reasonably sized machine that is connected to a computer containing the blueprints (model) for the object. Typically, the common additive technologies are the Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), stereolithography

etc. For the SLS, a powder source known as the laser is often used for the sintering of the powdered materials such as the polyamide or nylon to create a solid structure based on the developed 3D model. The SLM technique employs a laser of high power density to melt and create fusion of the metallic powders. In the FDM technique, the component parts are fabricated by material deposition in successive layers followed by selective curing while the FFF technique involves the continuous extrusion and deposition of a filament from a heated nozzle. The stereolithography process involves the production of component parts in a layer by layer manner via the cross linking of monomers and oligomers to form polymers in a photochemical process for [4–6]. The additive manufacturing technology is suitable for product visualization and fabrication of component parts most especially the “difficult to machine parts” offering the realistic possibility for easy and quick, production of any object on demand [7–9]. Hence, resulting in significant reduction in the manufacturing steps, time and cost as well as in the level of human involvement in the manufacturing process. The additive technology also enables product customization with the potential

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to boost innovation, foster more efficient use of resources and transform the way products are manufactured [9–12]. With the technology, a whole component part can be built, thereby, eliminating the time and cost of assembly when compared to the conventional way of manufacturing. Going by the huge demand for end products by consumers, the rapid prototyping industry needs to move faster towards the development of cost-effective technologies that are easily accessible by consumers [13, 14]. Prototyping is often the costliest and time-consuming stage of the product-development life cycle, it is therefore desirable for manufacturers to reduce the manufacturing cost and cycle time of product development, hence, the need for the development of additive manufacturing technology which offer a realistic possibility in this regard [15, 16]. This will increase the cost effectiveness of the manufacturing process via proper scheduling and keeping the manufacturing activities within a realistic forecast. The 3D printing technology finds application in the development of specialized parts, components or products, medical equipment, teaching aids and sensors [17, 18]. In the automobile and railcar manufacturing, it is suitable for developing complex components, tools and other parts that enhances the overall developmental phase [19–21]. This has resulted in the development of automobile and rail vehicles component parts with improved cost and environmental sustainability, which has helped in addressing the climate changes and unwanted emissions. The technology can significantly improve the life cycle of engineering products from the initial stage (design phase). During the sub assembly and final assembly stage, it can also reduce the number of key players in the supply chain thereby closing in on the supply chain gaps and activities [22, 23]. Typically, the use of additive technologies such as the selective laser sintering, fused deposition modelling (FDM), stereolithography, ink jet printing, fused filament fabrication (FFF) etc. have brought about the development of products with excellent mechanical properties including high strength to weight ratio and aesthetics [24–26]. For instance, the ink jet printing technology allows the addition of colours to the object during manufacturing so that the object with the desired final appearance is obtained sometimes without the need for post processing. Furthermore, the deployment of 3D printing technology for manufacturing activities will boost the human capital development for individual entrepreneurs. This is because the technology has the potential to promote product innovation, direct manufacturing, energy efficiency and increased product performance [19, 20, 27]. The use of additive manufacturing technology can improve the degree of freedom for the design of products with complex and intricate shapes by allowing easy translation of the conceptual design into the desired product design [28, 29]. It also has the tendency to promote product development with adequate integrated and technical functionalities, thus, eliminating the need for expensive tooling and machin-

ing [30–32]. This contributes to the overall cost effectiveness of the process coupled with the fact that the conversion rate of raw materials to finished products is very fast when compared with conventional manufacturing [21, 33, 34]. In contrast with the conventional manufacturing, the additive manufacturing offers feasible solution in the development of specialized composite materials aimed at improving the overall mechanical properties of the product or exploring some material's specific features [35–37]. The challenges of the additive manufacturing technology being the effective control of process conditions and the development of the right concept for its repeatability in order to keep product variations within the permissible tolerance limit. Many works have been reported involving the deployment of additive manufacturing technologies for product development. For instance, Laplume et al. [38] developed an open source self-replicating 3D printing technology for small-scale manufacturing. The successful development and performance evaluation of the cost effective prototype shows that the proposed 3D printing technology is viable for product development ranging from small to medium and large-scale manufacturing. Also, Cheng-Hai et al. [30], Brant and Sundaram [39] as well as Gao and Qui [40] designed a conceptual model for a 3D printing technology which encompasses the cloud manufacturing technology. The works conform to the green, agile, collaborative and intelligent manufacturing mode providing high degree of freedoms in design and innovation. The 3D printing technology encompasses product and service evaluation, cloud manufacturing platforms, service architecture and control as well as configuration mechanisms. In addition, Whyman et al. [41] developed an extrusion system for the 3D printing of biopolymer pellets incorporating robust mechatronics design which results in the development of a lightweight extruder unit. The only challenge being its limitation to a single nozzle extrusion. This increases the set up time during manufacturing in a bid to clean up a nozzle for different colour operations. Ali et al. [42] developed a multi nozzle extrusion system with control mechanism in order to address the limitation of a single nozzle extrusion system. The application of the 3D printing technology ranges from its intrinsic applications to low speed of operation. Many interactive design approaches geared towards the additive manufacturing technology have been carried out. Savio et al. [43] interactively design the homogenization of lightweight structures for additive manufacturing while Liverani et al. [44] performed the interactive design for six sigma for additive manufacturing applied to an innovative multifunctional fan. Similarly, Morretton et al. [45] discussed the impacts of the settings in a design for additive manufacturing process based on topological optimization and Quinsat et al. [46] characterized the surface topography of 3D printed parts by multi-scale analysis. In addition, Fuwen et al. [47] performed the interactive design for additive manufactur-

ing: a creative case of synchronous belt drive. The findings from these works showed that the interactive approach is highly feasible for effective product development in order to enhance the creation of products which combine optimal performance with effective users' interaction. In line with the deployment of the fourth industrial revolution technologies to improve railcar manufacturing, this research work considers the development and application of 3D printing technology in the railcar manufacturing using an interactive approach. The major drawbacks of existing systems however include lack of real time monitoring during the manufacturing process and the effective tracking of process parameters using the mobile or web applications. The interactive design objective of the automated 3D printing technology is to achieve real time monitoring and automation, hence, the novelty of this work however lies in the fact the system can operate remotely via SMS command from mobile device and sends or receive feedbacks via SMS to the authorized user, thus, promoting effective interaction between the user and the system.

2 Materials and method

The mechanical and electrical component parts employed for the developed of the additive manufacturing technology and their specifications are presented in Table 1.

2.1 The interactive design approach

An interactive approach towards product development was deployed in order to enhance the creation of products which combine optimal performance with effective users' interaction. It will assist the manufacturer in the rapid transformation of the conceptualized or virtual model into a physical product. It comprises of information acquisition, processing and exchange between the users and the system with the input, processing and output elements for effective communication [43, 44]. The interactive design approach encompasses its aesthetics, visual representation in terms of the 3D representation, product behaviour in service, manufacturing cycle time, error tracking and mitigation modules, as well as adequate feedback mechanisms following an execution of a specific task. The interactive approach is significant in studying and correlating the individual and cross effects of the process parameters on the quality of the printed parts. This will assist in predicting and keeping the range of process parameters such as the temperature, thickness of layers, sprint speed and feed rate within the optimum range for optimum and quality production of the component parts. Furthermore, the interactive design approach also assist in proper system configuration which will promote optimum production and effective communication between the user and the product. It also incorporates the users' requirements during

each of the manufacturing phases that will assist the manufacturer develop virtual and computer aided design models of the component parts in order to investigate the service requirements and the performance of the system before the actual manufacturing phase. The interactive features of the Autodesk Inventor 2016, the Commercial Abaqus software 2018 and the repetier host were explored in this work. One of the merits of the additive manufacturing technology is the degree of freedom in product design and visualization. Hence, the combination of the interactive features of the software assisted in the product development and its topological optimization in relation to the service requirements. The lattice structure was controlled virtually to bring about the development of a light weight product. Figure 1 shows the interactive development framework for the additive manufacturing technology and product development which integrates the elements of the Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) as well as the Computer Integrated Manufacturing and the Flexible Computer Integrated Manufacturing (FCIM).

A software program in the Arduino micro controller in conjunction with MELZI board and additional circuit controls the sensors used as input. With this input, the main board set the references while the outputs are the stepper motor, actuator and repetier software.

The system's architecture is shown in Fig. 2.

Basically, the entire work is divided into three phases, which are the design and interaction, fabrication, performance evaluation and the analysis phase.

The system can be categorized into three parts as follow; mechanical part, hardware part and simulations, as well as the software part (Repetier host).

2.2 Phase I: mechanical part design

The body kit is used to provide support for the system and to protect the electronic circuit from liquid that may cause the electronic circuit to malfunction. The design of 3D printer body kit is based on the functions the designer intended, the position of the internal components necessary to make the 3D printer operational, reduction in the weight of load to be carried by the system in order to reduce its power consumption, and enhance reduction in the gravity centre. The microcontroller validates the software and then perform specific prints on the device. This stationary 3D printer consists of the frame, five stepper motors, print plate and the extruder. Figure 3 shows the Computer Aided Design (CAD) of additive manufacturing system using Autodesk Inventor[®] 2016.

Figures 4, 5 and 6 shows the design of a 3D printer body kit in different angle designed by Autodesk Inventor[®] 2016 software. It consists of the frame, Y-axis and bushings, Z-axis and Y-axis, extruder, X-carriage, print plate, electronics, stepper motors, stepper motor controllers and end stops.

Table 1 The list of mechanical and electrical component parts employed

S/N	Part name	Specification	Qty.	Remarks
<i>List of mechanical component parts</i>				
1	X threaded stud	M8 × 420 mm	6	Machined
2	Y threaded stud	M8 × 463 mm	4	Machined
3	Y plain stud	Ø8 × 345 mm	2	Machined
4	Z plain stud 1	Ø8 × 325 mm	4	Machined
5	Z plain stud 2	Ø8 × 376 mm	4	Machined
6	Z threaded stud	M8 × 300 mm	2	Machined
7	Extruder block		1	Machined
8	Print plate	225 mm × 225mm	1	Machined
9	Frame end support A		1	3D Printed
10	Frame end support A_MIR		1	3D Printed
11	Frame end support AA		1	3D Printed
12	Frame end support AA_MIR		1	3D Printed
13	Frame end support b		2	3D Printed
14	Frame end support B MIR		2	3D Printed
15	Z-rod holder		2	3D Printed
16	Z stepper motor housing		2	3D Printed
17	Bar clamp		4	3D Printed
18	Y-brace		1	3D Printed
19	Left idler		1	3D Printed
20	Right idler		1	3D Printed
21	Filament clip A		1	3D Printed
22	Filament clip B		1	3D Printed
23	Belt holder		4	3D Printed
24	Print glass	300 × 300 × 5 mm	1	Bought out
25	Linear bearing housing	SCS 8UU	6	Bought out
26	Hot-end insulator		1	Bought out
27	Pulley	Ø26	2	Bought out
28	Washer	Ø8	60	Bought out
29	Nut	M8	60	Bought out
30	Bolt	M4	20	Bought out
31	Bolt	M3	50	Bought out
32	Nut	M3	50	Bought out
33	Flanged bearing	8 × 12 × 6	6	Bought out
34	Z motor nut	M8 × 15 mm	2	Bought out
35	Linear coupler	Ø18 × 25 mm	2	Bought out
36	Linear bearing	LM 8UU	10	Bought out
37	Extrusion gear	Ø12 × 13 mm	1	Bought out
38	Bed spring	Ø8	10	Bought out
39	Extruder spring	Ø8	5	Bought out
40	Timing belt	GT2	2	Bought out
41	File clip		4	Bought out
<i>List of electronic component parts</i>				
1	Control board	MELZI	1	Bought out
2	Stepper motor	NEMA 17	5	Bought out
3	Hot end	J-head	1	Bought out
4	Cooling fan	40 mm × 40 mm	1	Bought out
5	Limit switch		3	Bought out

Table 1 continued

S/N	Part name	Specification	Qty.	Remarks
6	Heat bed		1	Bought out
7	Cable tie		1 (roll)	Bought out
8	Led strip		1	Bought out
9	Control switch		2	Bought out
10	Power pack	12 V, 30A	1	Bought out
11	USB cable		1	Bought out
12	Memory card (microSD)	1G	1	Bought out
13	Memory card reader		1	Bought out
14	Wires		1 (roll)	Bought out
15	Ac plug	3 pins	1	Bought out
16	Print filament	1 kg	1	Bought out

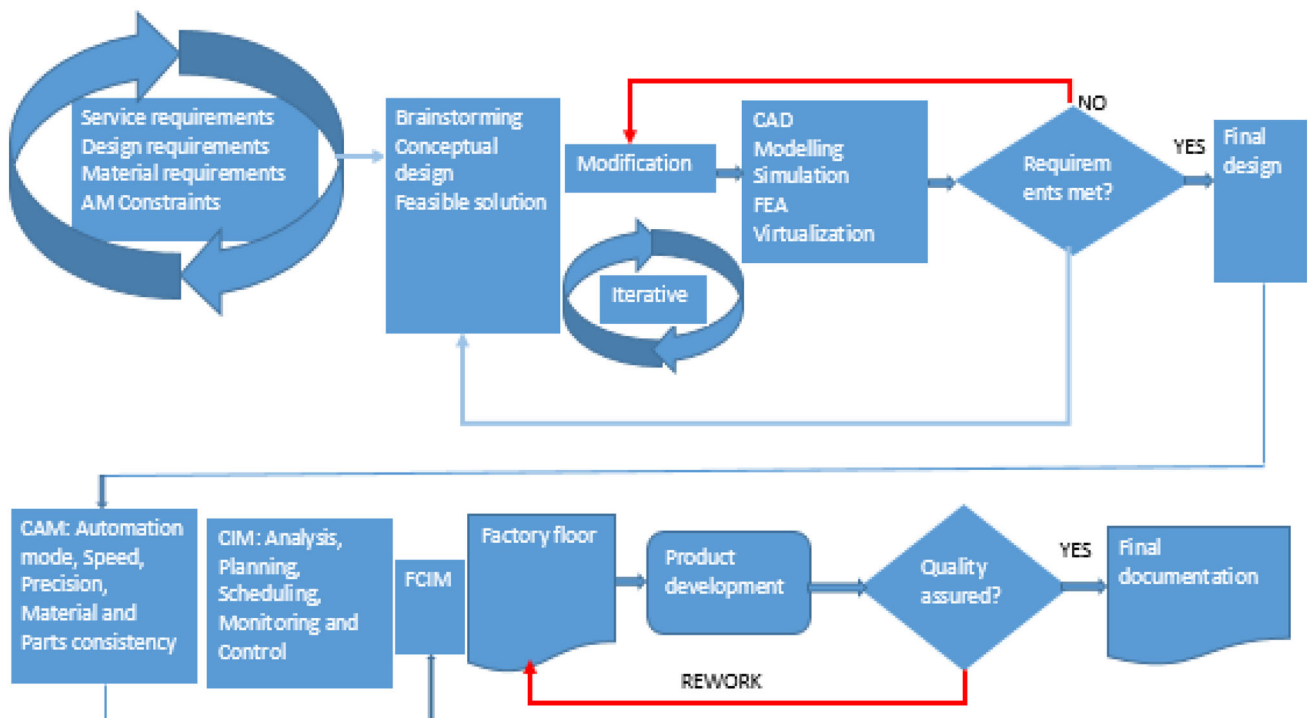


Fig. 1 The interactive design framework for the additive manufacturing technology

Fig. 2 System architecture of 3D printing technology for FFF

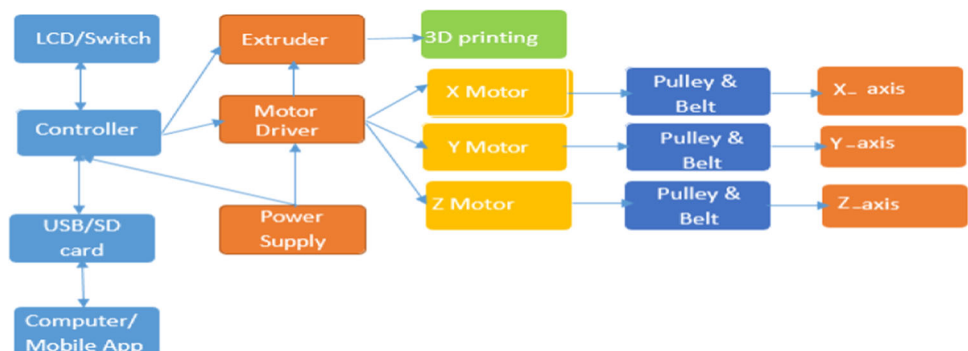


Fig. 3 The CAD of the additive manufacturing system (3D printer)

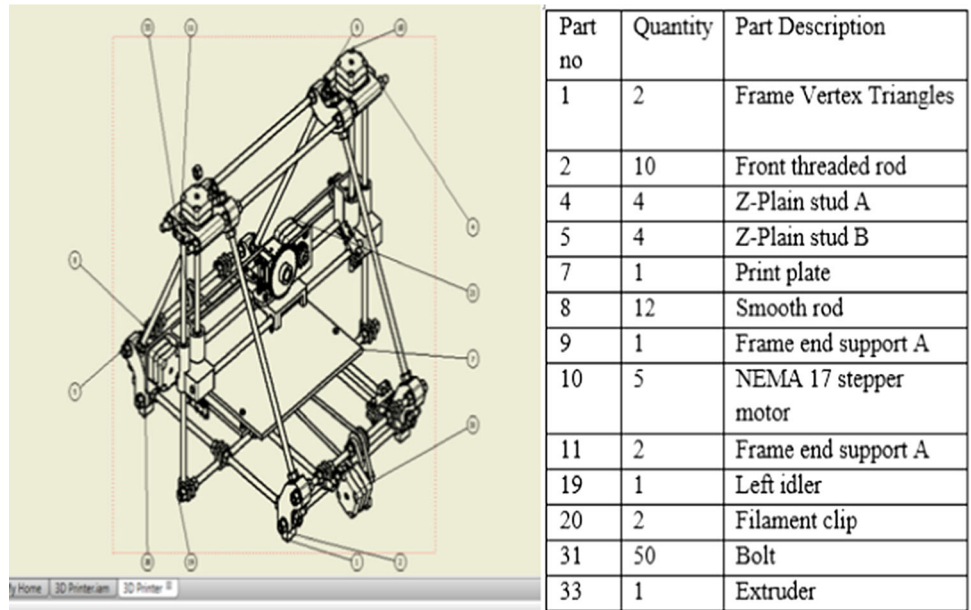


Fig. 4 Isometric view of additive manufacturing system (3D printer)

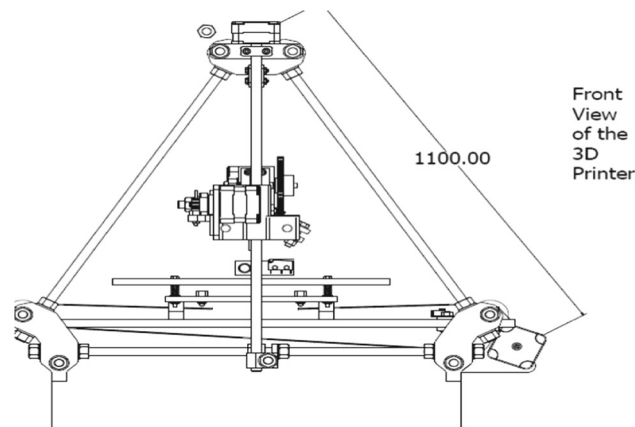
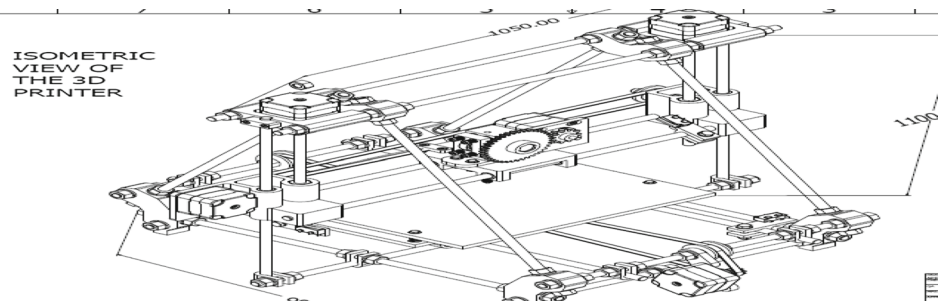


Fig. 5 Front view of the 3D printer

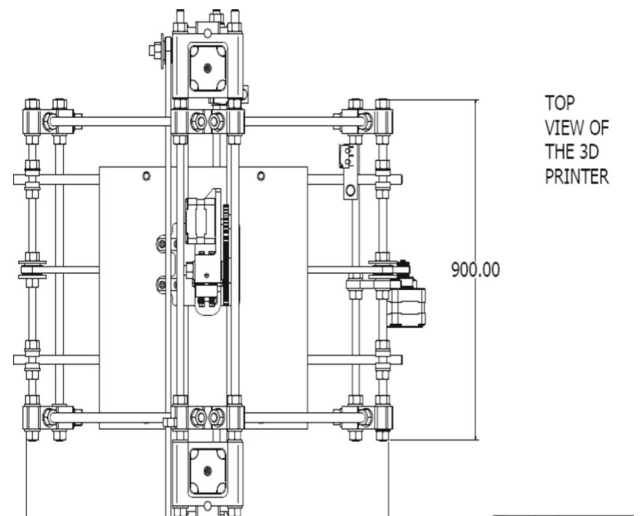


Fig. 6 Top view of the 3D printer

2.2.1 Frame

The frame, which gives the printer its stiffness comprises of three axes and threaded rods connected together with printed parts, called the vertices.

2.2.2 Y-axis and bushings

The print bottom plate is assembled on the Y-axis smooth rod and has one degree of freedom (it can move between

the front and the back of the frame). A belt is attached to a stepper motor with a pulley for viewing the image above which controls the Y-axis. The print bottom plate has four bushings attached to the print bottom plate. The axes moves over the smooth rods with two bushings or more having linear bearings. The bushings are actually plain bearings, which slide over the smooth rods providing almost no friction when moving up and down the rods. Usually they are employed to turn around the cylinder (or to have the cylinder turn inside). On the 3D printer, the bushings does not turn, instead they linearly move up and down the smooth rods following an imaginary line on the rods.

2.2.3 Z-axis and Y-axis

The Z-axis moves the X-axis in the upward direction and downward the frame while the X-axis moves the extruder in the left and right directions within the frame. The Z-and-X axis construction consists of two printed parts called the X-end idler and X-end motor. The X-end idler comprises of two vertical sections: a square open box where two bushings are glued and a hexagon structure where two M8 bolts and a spring are mounted. A stepper motor is also employed to turn a threaded rod connected to it on the top of the frame around the rod axis, which will in turn make the X-end idler move up and down.

2.2.4 Extruder

The process of extrusion begins with the application of heat to the extruder, which brings about the plastic deformation of the polymeric material (filament) at a predetermined temperature. The single screw extruder with a screw diameter of 3 mm essentially consists of the drip feeder, which controls the amount of input raw material into the hopper, an aluminium heater core as well as a heating barrel of 120 mm length made from stainless steel. The screw extruder driven by a stepper motor pushes the plastic filament into the hot-end (usually a brass bolt with a hole drilled down its vertical axis) where melting takes place called the heating barrel. There are two sizes of filament available: 3 mm wide and 1.75 mm wide. The hole drilled in the heating barrel was designed to match the size of the filament. A hot-end has three more crucial components; a thermistor to measure the temperature, a heat barrier to separate the hot-end from the cold-end (without this the cold-end would melt) and the nozzle through which the deformed plastic flows out of the heating barrel. The thermistor is connected to the electronics board which allow the electronics to measure and regulate the temperature of the heating barrel. The heating barrel operates at a configurable temperature, hence, the thermistor assists in keeping the temperature constant with the aid of the heat barrier. This prevents heat from the heating barrel to rise to the cold part,

which consists of the printed parts in order to prevent plastic deformation.

The change in temperature of the screw extruder during feeding is expressed as a function of the pressure gradient $\left(\frac{\partial P}{\partial Z}\right)$ and the screw length (L) as expressed by Eq. 1.

$$\Delta P = \frac{\partial P}{\partial Z} L \quad (1)$$

The design and modelling of the extruder in order to obtain the thermal characteristics was done using the Commercial Abaqus software 2018 (Fig. 7). The geometrical composition of the model comprises of mainly three regions; the flow channel consisting of the die and the preform, the heating barrel as well as the nozzle and exit. Since the thin surfaces of the extruder are not symmetrical including combinations of complex geometries of the extruder sub components, it is suitable to choose a 3D FE models for its modelling. A simplified modelling and simulation of the thermo mechanical behaviour of the extruder under the designed conditions was carried out using the scientific, general-purpose, the Commercial Abaqus software 2018 designed for advanced linear and non-linear analysis. This approach was used to investigate both the thermal and transient non-linear dynamic response of the extruder to thermal loading. A combination of coupled thermal-displacement and static general steps for thermal heat transfer analysis were employed in the Abaqus implicit module. This is because the implicit dynamic simulations can be applied to structural analysis with non-linear analysis. Due to the complexity associated with the contact analysis of the sub components of the extruder, the implicit analysis procedure ensures ease of convergence via iterations of the temperature matrix equations. The thermal zone was loaded with as-is heat flux corresponding to the operating temperature of 200 °C in the thermal step within a step time of 20 ms. The thermal boundary conditions were imposed on the positive and negative z-axis of the model, with the nodes on the sides constrained in all translational and rotational directions and the temperature constrained to the ambient (25 °C). The 200 °C thermal loading temperature was selected to capture the melting temperature range of the filament. A structured 8-node hexahedral mesh element type with linear displacement and temperature advancing front was selected to mesh the assembly into finite elements and thereafter subjected to convergence simulation runs with mesh refinement feature employed for the ease of convergence. Progressive variations in mesh sizes were imposed until the results obtained were unaffected by the changing size of the mesh. An average mesh size of 0.8 mm which falls within the seed size stability convergence zone was used, taking into account the balancing of computational costs, efficiency and accuracy in contrast with other mesh sizes within the convergence band.

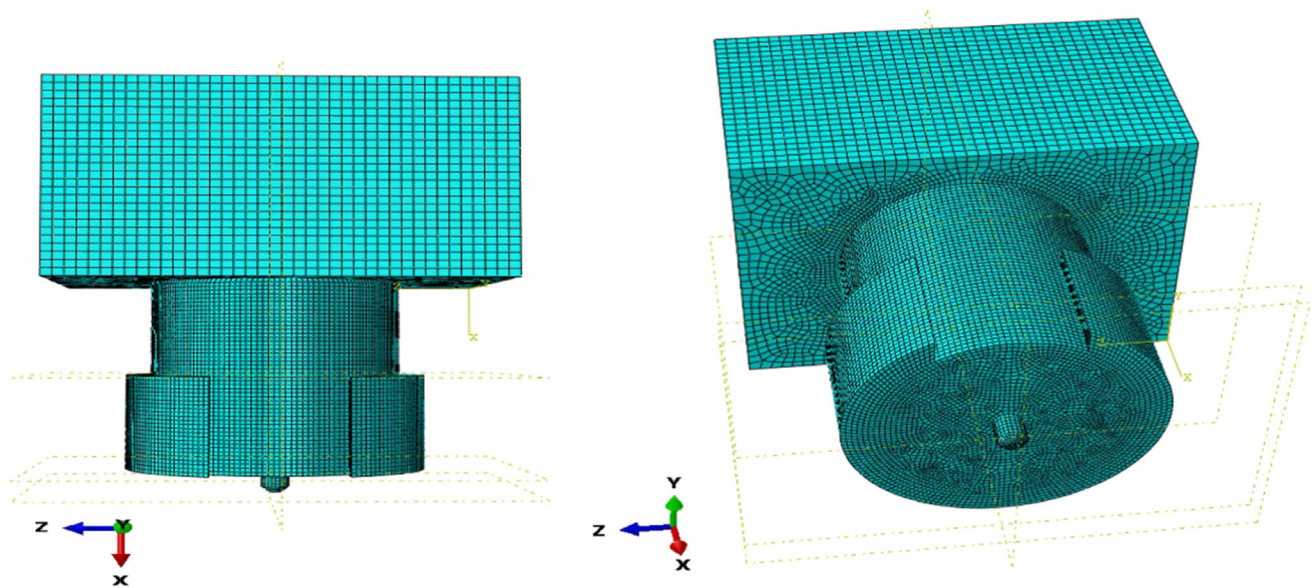


Fig. 7 Design and modelling of the extruder

Using the interactive design approach, the numerical Finite Element Analysis (FEA) of the extruder obtained from the CAD software (Abaqus) was integrated into the design framework which comprises of the CAM and CIM features for easy decision making and automated component manufacturing. This is because the FEA can determine the suitability or otherwise of the material employed for component part in relation to the required service condition. Once it is suitable, the FCIM which incorporate the elements of CAM and CIM in terms of the process planning, automation, monitoring and control can be implemented for the product manufacturing.

For instance, the temperature of the extruder is one of the key process parameters which determines the rate of plastic deformation and the overall success of the fused filament fabrication. As such there is need for the analysis of the heat flux and temperature distribution in order to determine the optimum range of temperature. This will foster effective process monitoring and control by keeping the temperature within the optimal range in order to enhance the development of products of high quality. Hence, the incorporation of the FEA module into the development framework will permit an iterative process for the determination of the optimum range of temperature based on the required service requirements and the material's properties.

The heat flux q_o is the quantity of heat across the surface per unit time per unit area, which is a function of the rate of heat energy transferred across the given surface. The heat flux conducted into the pelletized polymeric material is only

a proportion of the total heat flux q_a . Hence, this proportion X is obtained from Eq. 2.

$$q_o = q_a X \quad (2)$$

The total heat flux q_a varies as a function of the position in the contact zone. This is expressed as Eq. 3.

$$q_a(y) = q_b(y) X \quad (3)$$

2.2.5 X-carriage

The assembled extruder, comprising of the cold-end, heat barrier and hot-end, is mounted on the X-axis carriage controlled by one stepper motor and a belt.

2.2.6 Print plate

The developed parts are printed on the print plate. The three axes move together so that the nozzle can move above the print plate within the designed area. The print plate actually consists of two plates: the print bottom plate that is mounted on the X-axis smooth rods with bushings and the print top plate that is mounted on the bottom plate, which forms the print surface.

2.3 Electronics

The electronics board controls the printing process. The Arduino was used with the MELZI board with a built-in converter. The MELZI is a shield board that is connected to an Arduino MEGA 1280P having the additional features:

one extra heater/thermistor channel (three in total) and an optional SD card reader.

The electronics board performs the following functions: process G-code instructions, control the four stepper motor controllers (there are five stepper motors on the 3D printer but both Z-axis motors are connected to the same stepper motor controller), control the temperature of the hot-end, monitor the hot-end thermistor, monitor the end-stops (end-stops are used for homing the three axes, this was discussed further in the later section), controls the temperature of the heated bed and monitors the heated bed thermistor.

The USB-to-serial converter was employed to connect the electronics board to the PC.

2.3.1 Control board

The control board, which uses MELZI V2.0, is regarded as the central processing unit of the 3D printer. It is such that it supports only one extruder. Its plug and play features contributes to its performance as to making it less time consuming which plays an important role for the development and installation phases. It also has a good stability as it is based on Arduino, which is more accurate in temperature detection. The features of MELZI V2.0 are as follow; the operating voltage is 12 V while the main control IC is the ATMEGA 1284P. It allows for effective integration of the 3 MOSFET driver for the hotbed, fan and extruder and also provides space for the memory card which integrates the G code files. It was integrated with a stepper motor driver and has a weight of 70 g.

2.3.2 Stepper motors

There are five stepper motors on the 3D printer: one controls the Y-axis, another controls the X-axis, while two controls the Z-axis and the last one controls the extruder.

The motors on the 3D printer are the same in specification except for the two motors that control the Z-axis. There are two stepper motors on Z-axis in order to ensure force balancing. The 3D printer was designed to use bipolar NEMA17 motors, which determines some of the dimensions of the stepper motor. However, the amount of torque the motor supplies is also determined by the stepper controller board. The MELZI electronics board controls the stepper through micro stepping mode in which the percentage of current is gradually changed per phase to make the shaft rotate in small incremental steps.

2.3.3 End stops

At the start of a print job, all three axes have to be moved to their starting position, which is the zero position on the Cartesian robot. The axes cannot move any further than zero

(since they cannot move to a negative position). To achieve this, three end stops were installed; one for each axis and each end stop was installed at the boundary position of the robot. For the X-axis, it is positioned where the nozzle reaches the left-hand side of the print plate while another is positioned on the backside of the axis for the Y-axis. On the Z-axis, the third end stop is positioned where the nozzle barely touches the print plate. When printing, it was ensured that the Z-axis is lifted a little before printing the first layer.

2.4 Axes movement calculations

The firmware used for this Fused Filament Fabrication technique is based on the custom-built Repetier firmware editor and was further re-edited using the Arduino IDE, to obtain optimum performance and calibration of the system. The stepper motors used in the fabrication of this additive manufacturing technology have the following specifications which was used in the calculation of the axes movement.

Stepper motor name (NEMA 17), step angle (1.8°), micro stepping ($\frac{1}{16}$), timing-belt pitch (2 mm), motor pulley teeth (20), threaded screw pitch (1.25 mm) and pinch wheel diameter (7.5 mm).

$$X\text{-axis} = (\text{motor steps per revolution} \times (1/\text{driver micro stepping})) / (\text{belt pitch} \times \text{motor pulley teeth}) \quad (4)$$

$$Y\text{-axis} = (\text{motor steps per revolution} \times (1/\text{driver micro stepping})) / (\text{belt pitch} \times \text{motor pulley teeth}) \quad (5)$$

$$Z\text{-axis} = (\text{motor steps per revolution} \times (1/\text{driver micro stepping})) / (\text{leadscrew pitch}) \times (\text{gear ratio}) \quad (6)$$

$$E = (\text{motor steps per revolution} \times (1/\text{driver micro stepping}) \times (\text{gear ratio})) / (\text{pinch wheel diameter} \times \pi) \quad (7)$$

$$\text{Motor step/rev} = \frac{360}{1.8} = 200$$

$$X\text{-axis} = \frac{200 \times 16}{2 \times 20} = 80 \text{ steps/mm}$$

$$Y\text{-axis} = \frac{200 \times 16}{2 \times 20} = 80 \text{ steps/mm}$$

$$Z\text{-axis} = \frac{200 \times 16}{1.25 \times 1} = 2560 \text{ steps/mm}$$

$$E = \frac{200 \times 16 \times 1}{7.5 \times 3.14} = 135.88 \text{ steps/mm}$$

2.5 Electrical power requirement calculations

In order to select the adequate power pack needed to power the 3D printer for fused filament fabrication, the electrical power consumption for the entire standard electrical components parts were calculated using Eqs. 8–10.

$$P = IV \quad (8)$$

$$P = \frac{V^2}{R} \quad (9)$$

$$P = I^2R \quad (10)$$

where P is the required power (watt); I is the input current (Ampere), V is the applied voltage (Volts) and R is the resistance in Ohms

2.5.1 Power required by the extruder

The extruder consists of a NEMA 17 with a rated voltage of 4.7 V and current of 1.7 A, a 12 V DC cartridge heater rated 40 W and a 12 V DC fan with a current of 0.5 A.

From Eq. 8, the power required by NEMA 17-stepper motor is calculated thus;

$$P = 1.7 \times 4.7 = 7.99 \text{ W}$$

Also the power required by the fan is calculated from Eq. 8 as follow;

$$P = 0.06 \times 12 = 0.72 \text{ W}$$

Hence, the total power required by the extruder is obtained thus;

$$P = 7.99 + 0.72 + 40 = 48.71 \text{ W}$$

2.5.2 Power required by the drive axes

The 3D printer consist of three drive axes with four stepper motors with a rated voltage of 4.7 V and current of 1.7 A each.

Total power required by the stepper motors is calculated thus;

$$P = 7.99 \times 4 = 31.96 \text{ W}$$

2.5.3 Power required by the heat bed

The heat bed used on the 3D printer is rated as 12 V DC with a resistance of 1.4 Ω and the power required by the heat bed from Eq. 9 is calculated thus;

$$P = \frac{12^2}{1.4} = 102.86 \text{ W}$$

2.5.4 Power required by the control board

A MELZI V2 board powered from 12 V DC, which is thereafter regulated to 5 V by a 7805 linear regulator, controls the 3D printer.

The power required by the control board from Eq. 8 is calculated thus;

$$P = 12 \times 1.2 = 14.4 \text{ W}$$

From the above power calculations, the total power required by the 3D machine is 197.93 W.

A 12 V DC ATX power supply with a current rating of 30 A (360 W) was chosen to power the 3D printer with enough tolerance for future expansion.

2.6 Phase II: hardware and circuit design

To operate the 3D printer and for successful print to be achieved, it requires an electronic circuit combination. The MELZI board used for the development of the 3D printer is shown in Fig. 8.

For effective tracking of the manufacturing process, the control system incorporates the control features of the Flexible Computer Integrated Manufacturing (FCIM) system into a USB serial adapter and two wireless RS232 module as well as a GSM/GPRS cellular module for sending and receiving SMS with the micro controller. This enables authorized users to send commands and query the system in real time. This will also assist in tracking manufacturing errors and changes in order to compensate for such in real time. The control system also incorporates the repetier host software for process control and manufacturing. The repetier host is the software employed in the control of the axes of the 3D printer and slicing of the stereo lithography (stl) CAD files. It is a 3D printing application software with different slicers. The interactive features of the application enabled a good object placement which permits loading of different 3D models which fits appropriately on the build plate with simultaneous printing. This will promote the optimal use of the build plate with significant reduction in the printing time. The icon also permits the placement, scaling, rotation and duplication of the models in a virtual environment. Furthermore, with the use of the repetier host, the printing plate was sliced in order to pave way for an optimal setting in order to get the desired result. The components to be produced were first previewed in different layers before the printing. One of the interesting feature of the repetier host is the user's friendly interface with which the printing can be done interactively and directly from it via the USB connection or the SD card.

Fig. 8 MELZI board used for the 3D printer

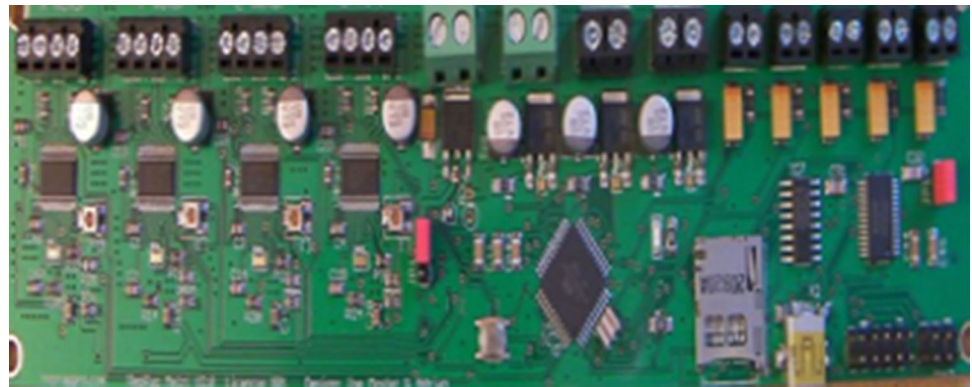


Fig. 9 Illustration of the configuration of repetier host software

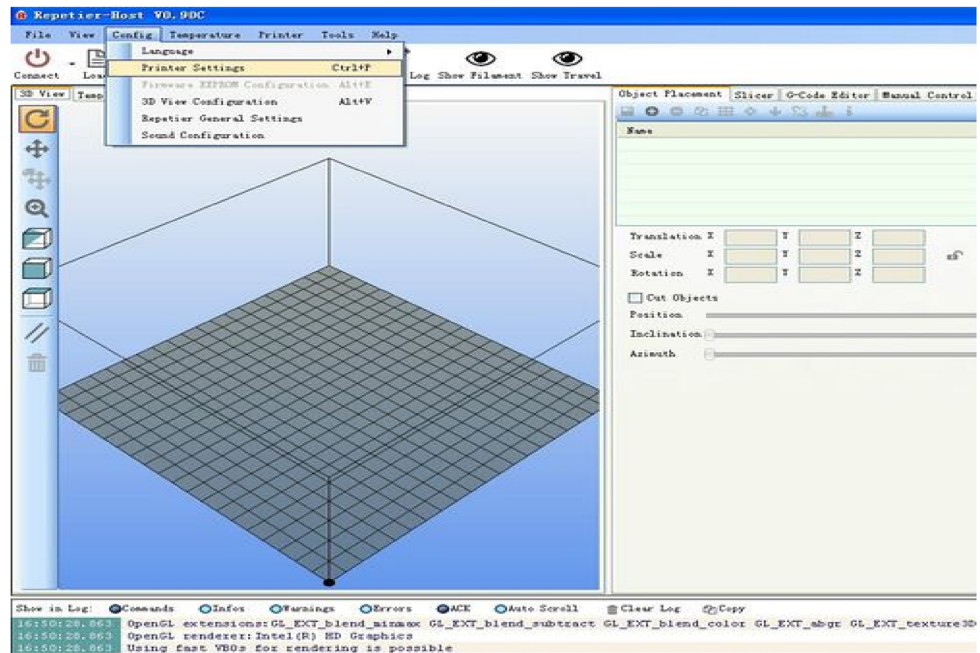
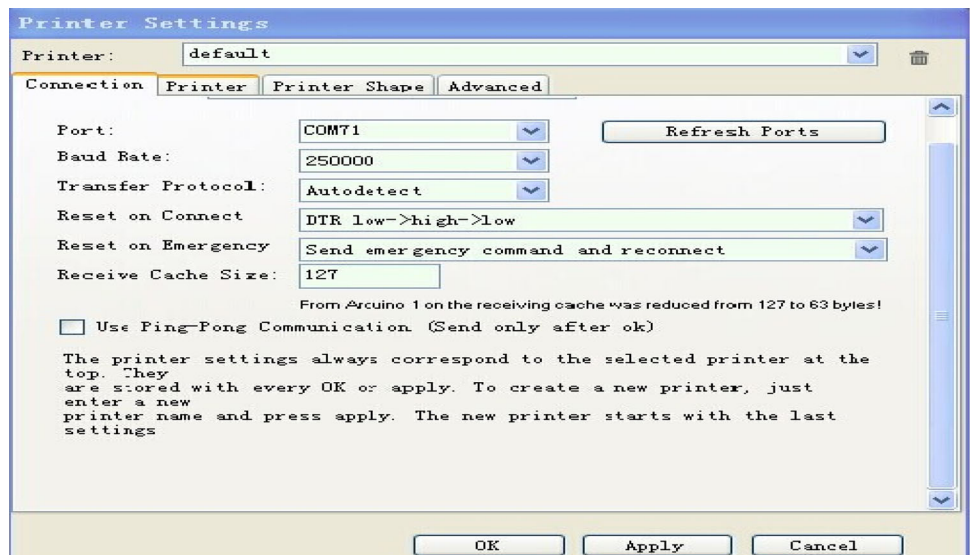


Fig. 10 Illustration of the baud rate for the MELZI V2.0 board



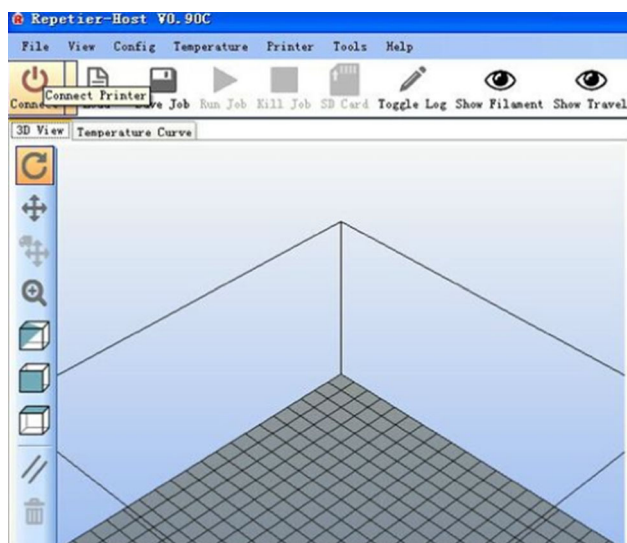


Fig. 11 Illustration of the 3D printer connection

Following the creation of the 3D model of the object via a CAD software, the geometric conversion of the object involving the discretization of the solid model into different shapes using the stl extension was performed. The created stl files are sent into the system for additive manufacturing where they are converted into the G-codes. With the repetier host, the G-codes are generated which was employed to start the system. The G-code is generated so as to describe movements that will make a part, including dimensions such as extrusion width and speed. At this point, it is possible to analyse, simulate and optimize the different geometry or configurations of the models that will meet the users and functional requirements without sacrificing the quality. The product is built by the extrusion of filament from the heated nozzle, deposition layers by layers as well as subsequent removal for cooling and post processing. Figures 9, 10 and 11 present the users friendly interface of the repetier host.

The interface shown in Fig. 9 represent the setting up the repetier host software. From the Figure, the configurations and setting in terms of language, printer, views, object placement, slicers etc. can be performed iteratively.

Figure 10 illustrates the process of printer setting as well as the communication port for MELZI V2.0 board and the baud rate. With the interface, the printer and its shape can be selected.

Figure 11 illustrates the connection of the printer and the selection of the G-code file in preparation for printing.

2.7 Fabrication and assembly of the additive manufacturing technology

Some of the mechanical component parts presented in Table 1 were machined while some were manufactured with the aid of the 3 D printing technology and others were bought out.

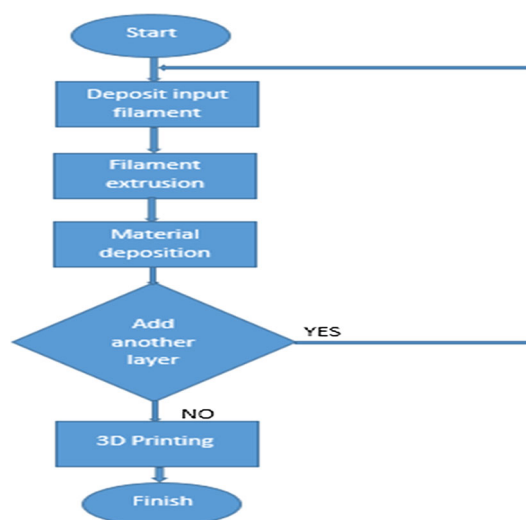


Fig. 12 Flow chart of the 3D printing technology (Fused Filament Fabrication)

The electrical components parts were bought out and both the mechanical and electrical component parts were integrated a single system.

2.8 Performance evaluation

The developed 3D printing technology employs the Fused Filament Fabrication (FFF) technique in which a plastic filament; is fed a hot extruder which creates the 3D product layer by layer via the extrusion of the thermoplastic filament. In this case, the acrylonitrile–butadiene–styrene (ABS) was used and colour was added to each layer deposited with the aid of the ink jet head. A heated nozzle extrudes the molten filament, which is deposited in thin layers, over one another, and onto a print bed thereby forming the 3D printed parts. Before the printing, the slicing features of the repetier host software was used to break the 3D model into layers that the printer is capable of printing. This brings about the production of a near-net-shape preform that can be subjected to post processing in order to meet the finish requirements. This method uses a computer controlled deposition nozzle and print bed to create different patterns, impressions as well as 3D objects.

Figure 12 shows the flowchart for the implementation of the 3D printing technology. This process is iterative and interactive until the product specification is met.

3 Results and discussion

Figure 13a, b shows the heat flux and the cross section of temperature distribution for the extruder. The heat flux of the extruder is the rate of heat transfer which represents the ther-

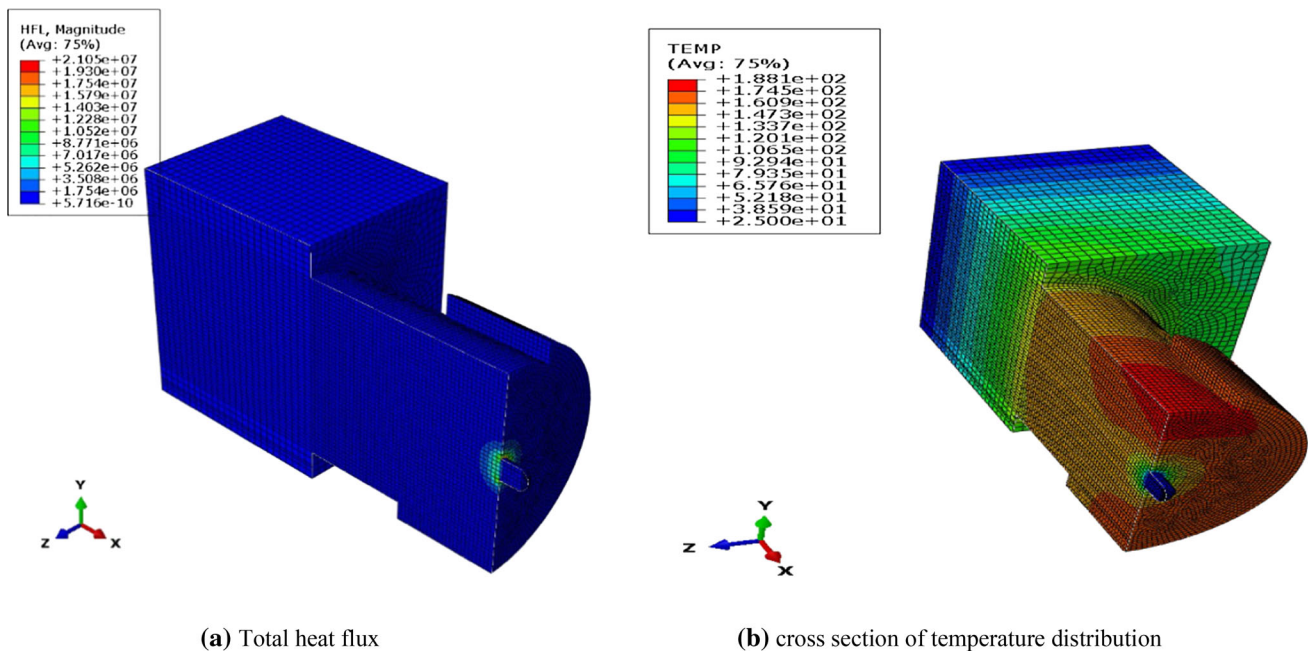


Fig. 13 Total heat flux and cross section of temperature distribution of the extruder

mal energy per unit area per unit time. It is a function of the change in temperature, thermal conductivity as well as the direction of the heat transfer. It also depends on the type of the work piece material, contact length and specific energy. From Fig. 13a, the maximum and minimum value of the total heat flux was $2.105 \times 10^7 \text{ W/m}^2$ and $5.716 \times 10^{-10} \text{ W/m}^2$. The result show that there is an increase in the value of the heat flux around the region occupied by the heating barrel where plastic deformation of material takes place as a result of heating. Figure 13b shows the temperature distribution across the cross section of the extruder which ranges from the room temperature to a maximum value of $188.1 \text{ }^\circ\text{C}$. The presence of the insulating material was observed to significantly reduce the rate of heat transfer however, the heat flux input is sufficient to plastically deform the polymeric material.

Figure 14 shows the temperature distribution over the extruder. The effect of insulation as well as temperature measurement and control via the use of thermistor around the heating barrel significantly reduced the effect of temperature when compared to the nozzle inlet and exit region. The thermistor connected to the electronics board allows measurement and regulation of the temperature of the heating barrel. Hence, the distribution of heat around the heating barrel was significantly controlled to prevent fluctuations in the viscosity of the molten material. This prevents the heat transfer from the heating barrel to the cold part, which consists of printed parts in order to prevent further plastic deformation of already printed materials. From the Finite Element Analysis (FEA) carried out, the values of the maximum and minimum temperature was $188.1 \text{ }^\circ\text{C}$ and $25 \text{ }^\circ\text{C}$. Since the melting temperature

of the filament employed (ABS) was $175 \text{ }^\circ\text{C}$, the result indicates that plastic deformation will occur. However, increase in temperature beyond the maximum may no longer be desirable leading to increase in the energy requirement of the process with less economic and environmental sustainability.

Figure 15 shows the developed 3D printer which is aimed at the manufacturing the internal and external accessories of a railcar most especially the components with complex or intricate shapes. The developed 3D printing technology can as well be employed for other applications other than railcar applications but the advantages of the manufacturing technology such as high degree of freedom in design creation and customization, fast production, cost effectiveness, product virtualization, creation of several shapes and geometry (both simple and complex) will be highly beneficial to the rail manufacturing industry in the development of the component parts for the internal and external accessories of the railcar. With the emerging materials the 3D manufacturing technology can easily be employed for the development of lightweight products from such materials most especially the ones that are difficult to machine conventionally. The use of such products will promote both the economic and environmental sustainability. Figure 16 shows the packaging of the developed 3D printing technology. The packaging was done to support the parts of the system, and to protect it from exposure to liquid which can cause corrosion of its parts.

Figures 17 and 18 show the circular and non-circular gears manufactured with the 3D manufacturing technology. The non-circular gear can be used to achieve the variation of transmission ratio, axle displacement oscillation, generation of

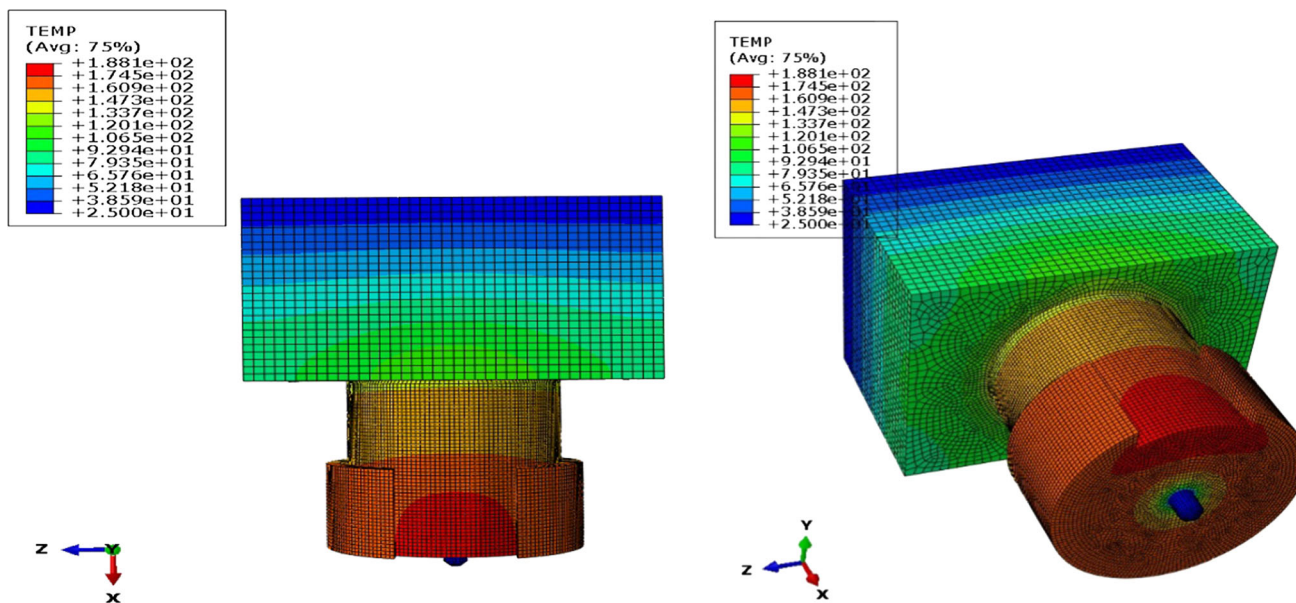


Fig. 14 Temperature distribution of the extruder

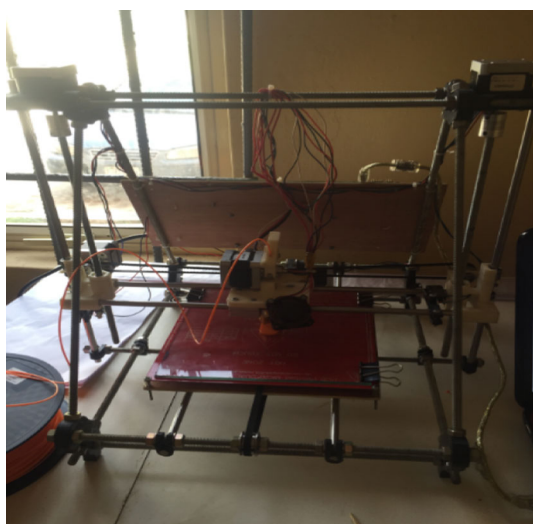


Fig. 15 The developed 3D printing technology

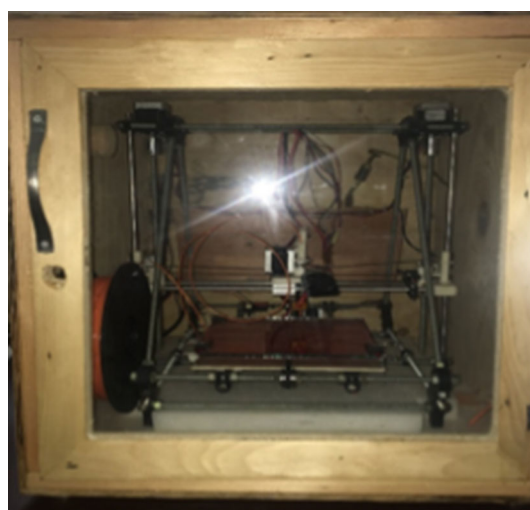


Fig. 16 The packaged 3D printing technology

non-uniform torque and speed amongst others. On the other hand, the plastic circular gear can be employed for constant torque and speed transmission for shaft drive balancing with the merits of reduced noise, wear and high operational efficiency. The development process of the plastic gears is quick, cost and time effective and can provide constant, adjustable or customized motion transfer. Though the surface finish and durability are traded off for these advantages when compared to the ones manufactured conventionally but the products can sufficiently provide ideal and efficient solutions in railcar and automobile applications.

The quality of the materials depends on the print quality and the feed rate specified before slicing. The print quality is a

function of the deposition rate and the diameter of the nozzle. The lower the deposition and feed rate, the higher the print quality and vice versa. For instance, at the rate of 0.1 mm, the surface finish of the printed materials were observed to be finer and probably stronger than that of 0.2 mm. This is because the extruder deposits the plastic at an interval of 0.1 mm making the printed materials to be more compact and stronger. It was noted that the rate at which the material run off the nozzle is inversely proportional to the diameter of the nozzle, as the diameter of the nozzle where the molten plastic passes out is 0.4 mm. The print quality of the final material obtained from utilizing different nozzle diameters are analysed below.



Fig. 17 Non circular gear



Fig. 18 Circular gear

- a. When 0.1 mm nozzle diameter was used, the surface roughness of the printed material which is a function of the print quality was observed to be $1.33 \mu\text{m}$, while the rate at which the material was printed was slow. On the other hand, when 0.2 mm diameter was used, the print quality in terms of the surface roughness of the printed material was observed to increase ($2.46 \mu\text{m}$) even though the speed of printing was observed to increase.
- b. For 0.3 mm diameter, there was further increase in the magnitude of the surface roughness ($3.89 \mu\text{m}$) of the printed component part with an increase in the speed of printing.

From these observations gotten from using different nozzle diameters (0.1 mm, 0.2 mm, 0.3 mm), it can be implied that the print quality of the printed materials is inversely proportional to the nozzle diameter and speed of printing. From this assertion, based on the application and service requirements of the final printed material, a manufacturer has the choice of sacrificing the speed of printing for the print quality or vice versa.

4 Conclusion

A 3D manufacturing technology aimed at the manufacturing of railcar internal and external component parts and accessories was developed. A suitable product development framework which integrates the features of the CAD, CAM, CIM and FCIM was also developed for its implementation. An increase in the feed rate and nozzle diameter brings about an increase the speed of printing but with reduction in the surface quality of the printed products and vice versa. The lightweight, print quality, and ease of operation are special attractions to the 3D printing technology. The system has the capacity to interface with mobile device, thus, enabling the micro controller to sends or receive feedbacks via SMS to the authorized user. Hence, it offers the realistic possibility for easy and quick production of objects on demand thus enabling product development and customization that promises to boost innovation, and foster more efficient use of resources as well as transform the way products are developed.

The following recommendations are hereby made based on the performance of the fabricated machine:

1. The machine should be optimized to use lead screw as the motion transmission mechanism on all the axes, to improve the print accuracy of the machine.
2. The mechanical, thermal and surface roughness properties of printed materials should be improved.
3. The machine should be improved to print different mix of materials in a single print operation.

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