Design of a Computer Numerical Control Router for Producing Printed Circuit Boards*

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Abstract

Printed Circuit Boards (PCBs) are indispensable in electrical and electronic engineering. Making PCBs can be chemically messy and hazardous, especially chemical etching. Manual etching, on the other hand, is time-consuming. PCB milling, as an alternative to etching, is initially expensive and not accessible to students and makers in developing countries like Ghana. This paper presents a cheaper PCB milling machine prototype as an alternative to chemical etching. The prototyped PCB milling machine is made of locally sourced materials, acrylic sheets and 3D printed parts. Solidworks 3D modelling software was used to model the prototyped Computer Numerical Control (CNC) PCB milling machine to ascertain design feasibility. Galvanized steel square pipes were welded into a rigid frame to form the CNC PCB milling machine. The Arduino Uno CNC shield control board was used to control all the parts of the machine, coupled with the aid of the Universal G-code sender software, the G-code of any circuit can be sent from the user's personal computer into the machine for drilling and milling. The merits and demerits of the prototyped CNC PCB milling machine compared with conventional ones were evaluated. Finally, a comparison between the prototyped PCB milling technique for prototyping circuit boards and chemical etching was done to validate whether it is a viable alternative. It was realised that it was cost-competitive, produced for $123.14, to the chemical etching technique with an added advantage of being environmentally and humanly benign.

Keywords: Computer Numerical Control (CNC), Printed Circuit Board (PCB), Milling Machines, E-Waste

1 Introduction

Printed Circuit Boards (PCBs) are indispensable in electrical and electronic engineering as they aid in prototyping and test-running a circuit before the actual circuit is deployed in production.

A PCB, in simple terms, is a drilled insulator with traces of copper, which serves as electrical connections on one side, both sides or in advanced levels, multiple internal layers. PCBs, mechanically support and electrically connect electronic components using conductive tracks, pads and other features etched from copper sheets laminated onto a non-conductive substrate. Components, such as capacitors, resistors, inductors, etc. and active devices are generally soldered onto the PCB. Currently, there are advanced PCBs that may contain components embedded in the substrate.

Concerning prototyping circuits on printed circuit boards, many techniques are available for use. These techniques include photo-sensitive chemical etching, heat-toner transfer chemical etching, manual etching using a blade and PCB milling using a CNC milling machine.

The technique common to students and developers in most developing countries, especially Ghana, is the heat-toner transfer method. Unfortunately, the heat toner transfer method of making PCBs has several challenges enumerated below:

(i) Due to the manual application of heat, the toner is not transferred uniformly unto the copper cladding board;
(ii) It requires a lot of time to transfer the toner;
(iii) Chemicals used in etching the PCB are harmful to human health;
(iv) Due to the exposure of copper boards to chemicals, the copper sheets peel off easily when exposed to heat; and
(v) The proper disposal of the by-products of the chemical reaction is an issue since it is not environmentally benign.

Alternatives available in Ghana to heat toner transfer etching technique is manual etching and PCB milling. Unfortunately, the manual etching results in non-uniform depth and shape of signal and power paths leading to overheating and consequent power losses and damage to PCB boards. PCB milling machines, however, are expensive and not accessible to students and developers in developing countries like Ghana. This paper elaborates the design and construction of a cheaper Computer Numerical Control (CNC) PCB milling machine prototype to create printed circuit boards using locally available parts and other components salvaged from e-waste.

PCB prototyping is a key step in the development of electronic and electrical products. Often after the simulation step, the developer prototypes a circuit for trials and fault detection. There are several techniques used in the development of circuit prototypes. These techniques are categorized into

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two main groups - chemical etching and non-chemical etching.

Chemical etching overlays the copper cladding board with a protective film in the pattern of the desired circuit. The board is then placed in a chemical bath, which dissolves the unprotected surfaces leaving the desired circuit on the board. There are two methods for depositing the protective film on the copper cladding board - photo-resistant media etching and the heat toner transfer etching.

Various chemicals can be used as an etchant to remove the copper. Nitric acid (HNO_3) and ammonium persulfate $(NH_4)_2S_2O_8$ can be used but Ferric Chloride ($FeCl_3$) is the most commonly used. The reaction of copper with $FeCl_3$ is a two-step redox reaction:

$$FeCl_3 + Cu \rightarrow FeCl_2 + CuCl \qquad (1)$$
$$FeCl_3 + CuCl \rightarrow FeCl_2 + CuCl_2 \qquad (2)$$

Non-chemical etching is environmentally friendly and involves no chemicals. This technique rather involves the removal of strips of copper from the surface of a copper-cladding board. This isolates some sections of the board from other sections, and therefore creating signal and power tracks. This technique can be very efficient. There are two techniques under this category – manual etching using an etching knife and PCB milling using a CNC milling machine. The former is less efficient as compared to the latter. Fig. 1 is a manually etched PCB board. This is idle to small simple circuits.

Fig. 1 Manually Etched PCB

PCB milling with CNC machines involves the removal of copper strips from the surface of a copper-cladding board based on the CAD design fed into a CNC machine. This technique requires the use of a PCB designing CAD software like Eagle CAD or Proteus.

The added advantage of PCB milling with CNC machines is that the CNC machine can drill the holes for the through-hole components and save time in the process. Fig. 2 (Maskinen, 2011) shows a PCB being milled with a PCB milling CNC machine.

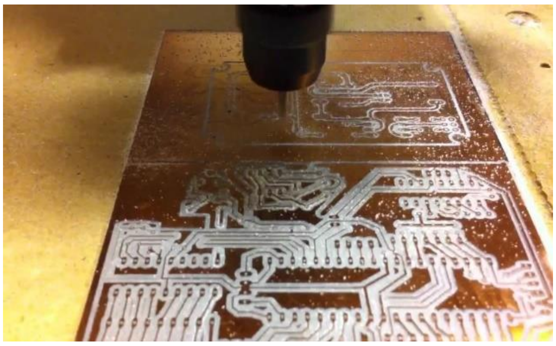

Fig. 2 PCB Milling Using a CNC Machine

PCB milling using a CNC machine gives a higher resolution output and can handle more complex circuits. It can also automate the process of drilling holes, hence, saving the designer time during prototyping. However, CNC milling machines are expensive and not readily available in Ghana.

Several authors, also faced with the dilemma of an expensive PCB milling machine, sought to develop their PCB milling machine. Kumpf (2003), Basniak (2012) and Anon. (2013) designed PCB milling machines that have high-performance accuracy and is less expensive. Their motivation for designing the machines was to provide less expensive alternatives to the PCB CNC milling machines in the market.

Raut *et al.* (2019), Rajan *et al.* (2019) and Hossain (2019) also worked on DIY PCB milling CNC machines. However, their design is impractical in developing country settings as most components are not readily available. Aluminum extrusions, smooth rods and linear bearings are difficult to come by. This makes developing machines here in Ghana relatively expensive. This project develops a PCB CNC milling machine with components readily available in Ghana.

2 Resources and Methods Used

2.1 Materials Used

A PCB milling machine will yield optimum output when it has a rigid structure. The rigid structure reduces vibrations and results in finer outputs. This design tries to reduce vibrations to a minimum. This machine is made of several materials such as metals, plastics, wood and some electrical and electronic components.

2.1.1 Metallic Materials

Galvanized steel square pipes

The framework (chassis) of the PCB milling machine comprises of a welded frame of galvanized steel square pipes. The galvanized steel square pipes have cross-sectional dimensions of 18.0 mm by 18.0

mm with a thickness of 1.0 mm. This piece produces a strong, rigid framework for the CNC machine.

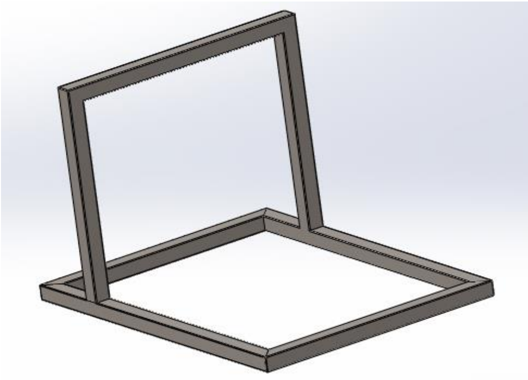

Fig. 3 Galvanized Steel Frame

The frame provides mechanical support directly or indirectly to all the components of the CNC machine. The frame is coated to protect the steel because the galvanized steel found was of inferior quality. Fig. 3 shows the SolidWorks model of the galvanized steel square pipe frame.

Galvanized square pipe rails

The rails of the machine are made of galvanized steel square pipes. The dimensions of the square pipe are 18 mm for the x- and y-axes rail. Fig. 4 shows a SolidWorks 3D model of the galvanized steel square pipe.

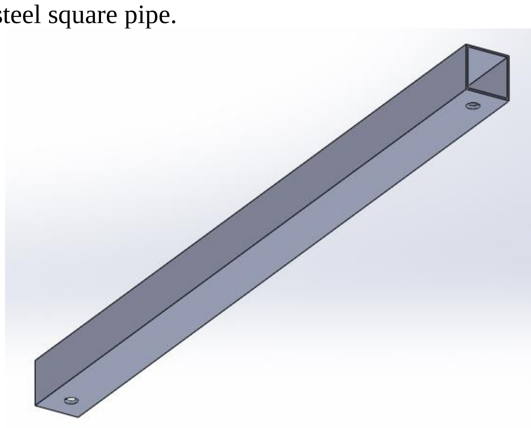

Fig. 4 Galvanized Steel Square Pipe

A 2 mm galvanized steel sheet metal

In the design of the CNC milling machine, galvanized steel sheet metal of thickness 2 mm was used as support material for the x-axis and y-axis carriage systems. The steel metals due to their thickness are stiff enough to help in the establishment of the linear rail mechanisms.

2.1.2 Plastic Materials

Acrylic sheets

The body of the CNC machine is made of acrylic sheets of thickness 6 mm. The 6 mm is achieved by stacking two 3 mm sheets together. This provides sufficient rigidity and mechanical support for the attachment of rails and motors.

PLA 3D printed parts

Polylactic acid (PLA) is a plastic material used in 3D printing to fabricate designs. With the use of the KLAKS 3D printer, some parts of the CNC machine were printed. Some of the printed parts are shown in Fig. 5.

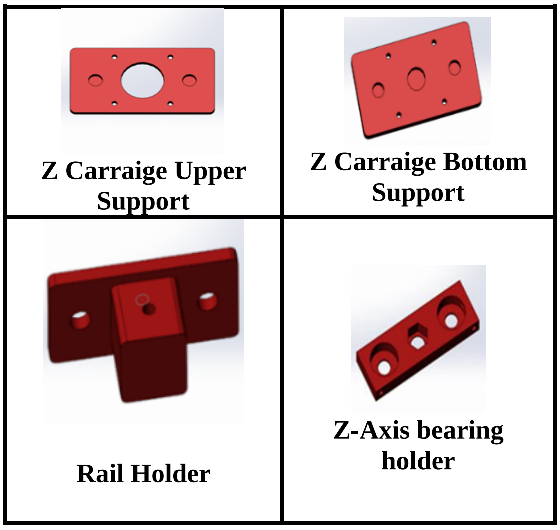

Fig. 5 Model of 3D Printed Parts

2.1.3 Wooden Material

The base of the machine is made of 19.05 mm plywood. Plywood used to allow for easy fastening of the components onto the board. The bolts countersunk into the plywood gives the machine a flat base.

2.1.4 Other Materials Used

Arduino Uno CNC shield

The Arduino Uno CNC shield serves as the brain or the control board of the CNC machine. It runs on the ATmega 328p microcontroller, which reads data from its input pins and sends corresponding data to its output pins to drive the stepper motors and the spindles. Its input pins receive data from the user computer, the control switches and the limit switches. The features of the Arduino Uno CNC shield are:

(i) 4-axes stepper motor driver (x-, y-, z-axes and drill motor);

(ii) Two-phase four-wire stepper motor with a maximum current of 2 A;
(iii) Has male header pins extensions for interfacing other modules such as the limit switches;
(iv) Supports I2C interfacing (can be interfaced with LCD using I2C);
(v) Acceptable input voltage is 7.5 V to 12 V.
(vi) Logic level voltage is 5 V;
(vii) Compatible with GRBL;
(viii) Supports interfacing with a PC via USB cable; and
(ix) Detachable motor driver IC interface.

These features influenced the selection of this board. As this project uses some salvaged stepper motors, the current drawn by the three motors would not be the same hence the motor driver ICs are equipped with potentiometers that can adjust the current flow. In the case where the IC is damaged, it can easily be detached from the control board.

NEMA 17 stepper motor

The NEMA 17 stepper motor is a hybrid stepper motor that runs on 12 V. It provides the rotational motion to the various carriages, which is then converted into linear motion by the use of threaded rods. The shaft of the NEMA 17 stepper motor is coupled to the threaded rod using vinyl tubing and horse clips, which are locally sourced.

Pololu A4988 stepper driver

The Pololu A4988 stepper driver interfaces the stepper motors with Arduino Uno CNC shield. The control board runs on 5 V while the stepper motor runs on 12 V. The stepper motor driver isolates these two circuitries to prevent any over-voltage faults. Also, it allows for open-loop bi-directional control of the stepper motors. The Pololu A4988 stepper driver has several features and these features outlined below influenced the selection of this stepper motor driver:
(i) Automatic current decay mode detection/selection;
(ii) Mixed and Slow current decay modes;
(iii) Synchronous rectification for low power dissipation;
(iv) Internal under-voltage lockout (UVLO) circuitry;
(v) Crossover-current protection;
(vi) 3.3 V and 5 V compatible logic supply;
(vii) Thermal shutdown circuitry;
(viii) Short-to-ground protection;
(ix) Shorted load protection; and
(x) Five selectable step modes: full, 1/2, 1/4, 1/8, and 1/16.

Metal clips

To hold the wooden working area platform onto the metal plate that forms the y-axis linear rail, metal clips are used. These clips hold the board firmly to the metal plate and prevent it from moving when operational.

Bearings

To reduce friction while increasing rigidity, roller element bearings were used. Two types were used namely 625zz and 608zz. The 625zz bearings were used in collaboration with square pipes to form the linear rails while the 608zz were used to aid the free rotation of the M8 threaded rods.

Endstops or limit switches

To prevent over-travel and moving mechanisms smashing into stationary parts, limit switches were used. Mechanical limit switches were used to stop the various carriages from over-travel when activated.

M8 threaded rod

Conventionally, lead screw sets are used to convert rotational motion into linear motion. To achieve the project objectives, M8 threaded rods in addition to M8 nuts were used. These are locally sourced and serves as a substitute for the lead screw set.

2.2 Methods Employed

2.2.1 Design Concept

The proposed CNC machine consists of an ATmega328p microcontroller-based control board, which serves as the brain of the system. The controller controls the cartesian motors (X, Y and Z axis stepper motors) through the A4988 motor driver IC. This motor driver IC allows for the interfacing of the stepper motors with the microcontroller. That is, the motor driver IC circuitry isolates the 12 V supply for the motor from the 5 V supply for the microcontroller. Connecting them directly together would lead to the destruction of the microcontroller since 12 V is too high for the microcontroller to handle. Besides, the motor driver IC allows for the reversal of the motor direction and the selection of the running mode of the motor, that is, whether full step mode, micro-stepping mode, eighth step mode or sixteenth step mode.

The limit switches (X, Y and Z-axis limit switches) prevents the stepper motor from sliding the various carriages beyond the rail limits hence the name limit switches. The control switches consist of the power switch, the emergency stop switch, the pause switch and the resume switch. These switches allow for the easy control of the CNC machine.

The CNC spindle is a motor with drilling or cutting or a milling bit. In this design, the Dremel 3000 drilling is employed. Based on the signal from the microcontroller, the spindle is either activated or deactivated. The bit of the spindle is changed accordingly based on the mode of operation of the CNC machine; milling, cutting or drilling. Fig. 6 shows a block diagram that summarizes the components of the CNC machine and how they are connected.

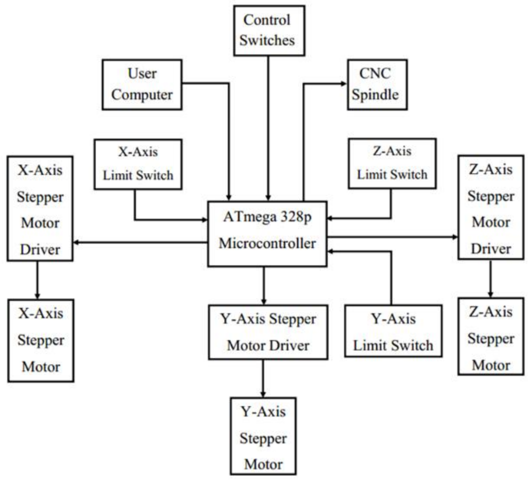

Fig. 6 Block Diagram of a PCB CNC Milling Machine

From Fig. 6, the user computer feeds the microcontroller with data. The working procedure for sending data to the microcontroller is quite simple. Once the Printed Circuit Board (PCB) model of the desired circuit is ready, the user must export it as G-code. This G-code is imported into a G-code sender application, which is the user interface software for the CNC PCB milling machine. The controller (ATmega 328p) runs a firmware called grbl. Grbl uses G-code commands to control the stepper motor, the spindle and any other accessories of the CNC PCB milling machine.

The CNC PCB milling machine is configured such that it moves to the home position or origin (x = 0, y = 0, z = 0) before any other process can begin. This is completed when all the limit switches are closed. After homing is achieved, based on the sequence adapted by the user, the drilling, milling and cutting processes can be initiated. Fig. 7 is a flow chart for the CNC PCB milling machine algorithm.

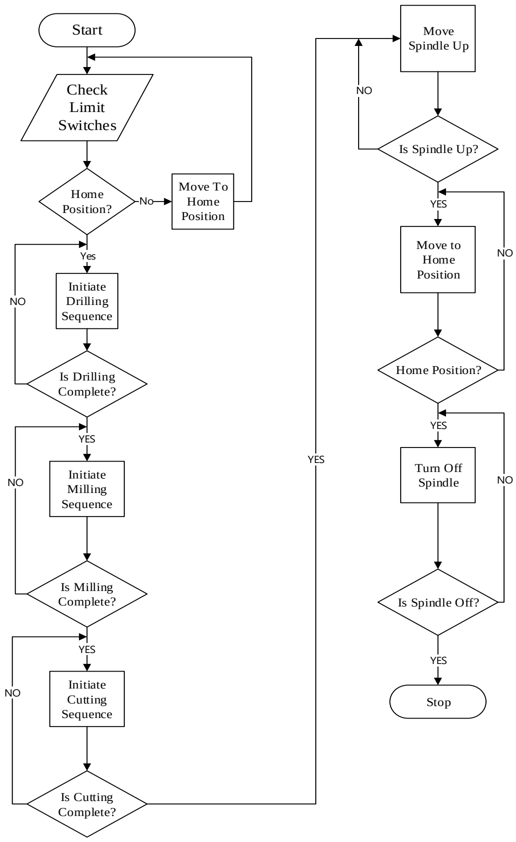

Fig. 7 Flow Chart for CNC PCB Milling Algorithm

2.2.2 System Design

In the design of the CNC milling machine, some already existing designs were considered. This was as a result of the method adopted for this machine design (Adoptive Machine Design). From these considerations, some key features were adapted. The adaption was based on the rigidity of that feature, how feasible the feature is in achieving the desired work area (16 mm × 20 mm), and how easily the feature can be adapted based on the available local resources. Discussed below are some of the open-source DIY CNC machines considered in this research.

Cyclone PCB Factory

The Cyclone PCB Factory is a 3D printable PCB milling machine. It is open-source and easy to reproduce if a 3D printer is easily accessible. It is relatively cheap compared with the other open-source CNC machine. Some features of this CNC milling machine were adapted. The y-axis motor-gear assemble was adapted into the design. This feature was adapted because it limits the overall length of the machine. As the y-axis motor mount is internally mounted, the overall y-axis length reduces. This mounting technique uses indirect motor-gear meshing instead of the direct motor shaft and rod coupling. Although the feature uses a motor-gear mechanism, the gear ratio is 1:1 hence it is the same as the direct motor shaft and rod coupling. Fig. 8a shows a 3D model of the Cyclone PCB Factory and Fig. 8b shows the y-axis motor-gear assembly that was adapted into the design.

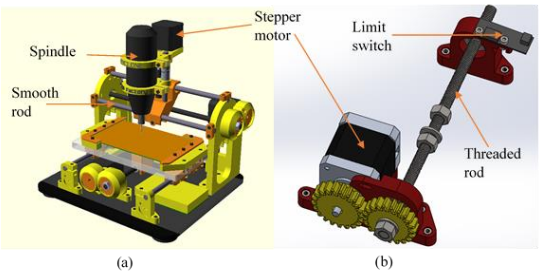

Fig. 8 (a) Cyclone PCB Factory and (b) the Y-axis Motor Gear Assembly

KLAKS 3D printer

The KLAKS 3D printer is an e-waste 3D printer manufactured in Ghana. This 3D printer, as a type of CNC machine, consists of 3D printed and locally sourced materials like galvanized steel square pipes, threaded rods, bearings, etc. One fascinating feature of the KLAKS 3D printer is its type of linear rail system. Its linear rails consist of galvanized steel square pipes with a pair of 625zz bearings running along its edge. This feature was adapted into the design of the CNC PCB milling machine mainly because it is in line with the project objective of building a CNC PCB milling machine using locally sourced materials. It also makes our system affordable and easy to repair as parts are locally sourced.

The 625zz bearing is a rolling element type of bearing that makes our linear rail system rigid (Simons, 2017). Fig. 9a shows the KLAKS 3D printer and Fig. 9b shows the x-axis linear rail mechanism of the KLAKS 3D printer.

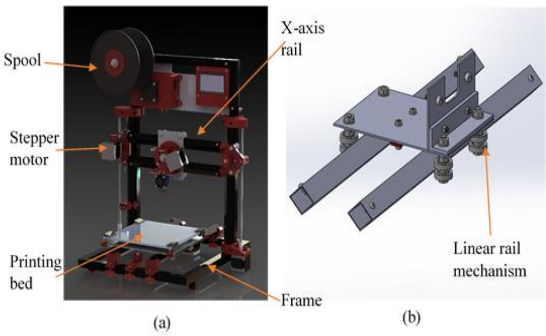

Fig. 9 (a) KLAKS 3D Printer and (b) its X-axis Linear Rail Mechanism

The DIY CNC PCB milling machine

This is a DIY CNC milling machine designed by Lirtex. This CNC machine consists of steel square pipes welded together to form a rigid frame. Thick acrylic sheets are used in securing most of the components of the machine. A feature was adapted from this CNC machine. The motor-frame attachment mechanism was adapted and improved by introducing a 3D printed spacer. This mechanism uses bolts and nuts in securing the motor to the frame. Bolts and nuts are locally sourced parts, very affordable and with the help of the 3D printed spacer ensure rigidity hence the reason for adopting this mechanism. The demerit observed was the stress effect on the acrylic in the long term, which leads to cracks. This design was modified to resolve the demerit. A 3D printed spacer is used to spread the force over a wider area to prevent any cracks in the long term as the motor vibrates. Fig. 10a is an image of the CNC machine by Lirtex and Fig. 10b (Anon., 2011) shows the motor-frame attachment mechanism.

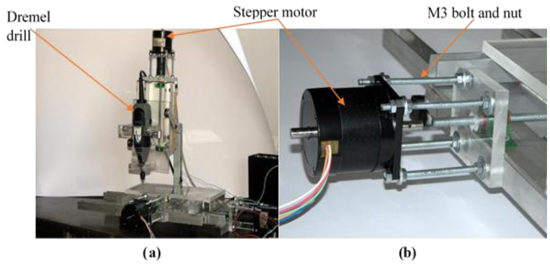

Fig. 10 (a) DIY CNC Machine and (b) Motor-Frame Attachment Mechanism

From the critical consideration of the already existing CNC milling machine, SolidWorks 3D modelling software was used to model a design that meets the design objective.

2.2.3 Final Solidworks Design

In the design of the CNC PCB milling machine, Solidworks 3D modelling software was used. This software was used in designing the various parts of the machine as shown in Fig. 3 to Fig. 9. These parts were then assembled to form the CNC PCB milling machine. The complete Solidworks design is as observed in Fig. 11.

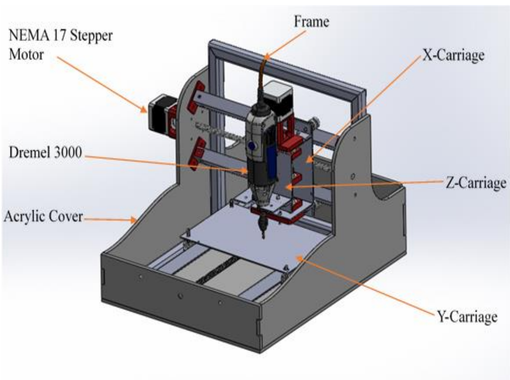

Fig. 11 Complete SolidWorks 3D Model

3 Results and Discussion

3.1 Designed CNC Machine

As the objectives of the project were to design a CNC machine that is rigid, affordable and made from locally available materials Fig. 12 shows the designed CNC PCB milling machine.

Fig. 12 Completed PCB CNC Milling Machine

3.2 PCB CNC Milling Machine Operation (Test Run)

There are three main operating modes of the CNC milling machine. These three operation modes are drilling, milling and cutting. In the quest to prototype a printed circuit board, eagle CAD software was used to design the desired circuitry. With the aid of the PCB G-code add-on, the desired circuit was converted from the eagle CAD files to gcode files. The PCB G-code add-on software outputs two files, one being the milling and cutting G-code file while the other is the drilling G-code file.

3.2.1 Drilling Operation

After obtaining the G-code files of the desired circuit, a copper-cladding board was fixed onto the working area (bed) of the CNC machine. Using the universal G-code sender, that is the graphical user interface (GUI), the axes are moved to the home position and the spindle turned on. Based on the G-code file for the desired circuit, the axes moved accordingly to drill out all the holes in the circuit.

3.2.2 Milling and Cutting Operation

After drilling, the milling G-code file was uploaded into the universal G-code sender. Once again, the axes move to the home position and the spindle was turned on. Based on the G-code file, the axes coordinated with each other and moved the spindle to initiate milling. The milling depth adapted for this machine was 0.1 mm. After all the traces were milled, the spindle continued to the cutting process. The cutting depth used was 1.5 mm. This is solely dependent on the thickness of the copper-cladding board.

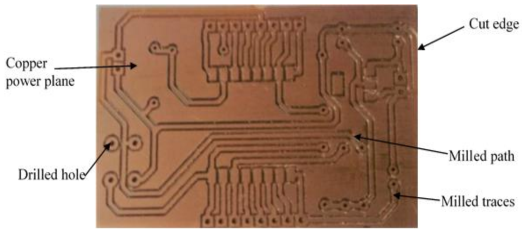

Fig. 13 A Completed Printed Circuit Board

3.3 Cost Analysis

In the design and manufacture of the CNC PCB milling machine, some components were purchased while others cladding from discarded photocopier machines and scanners. Table 1 shows the cost of the components purchased in building the machine.

As one of the objectives of the project was to build a relatively cheaper CNC milling machine, a cost comparison of some conventional PCB milling machine was conducted and Table 2 shows the cost comparisons of some common PCB milling machines on the market. Also, one of the objectives of this project was to provide an alternative method to PCB manufacturing during prototyping, hence comparison between chemical etching of PCBs and milling of PCBs was conducted. Table 3 shows a comparison between the chemical etching of PCBs and milling of PCBs.

Table 1 Total Cost of Producing the CNC PCB Milling Machine

Item	Quantity	Unit Cost ($)	Total Cost ($)
NEMA 17 Motors	5	5.20	25.98
Power Supply	1	13.85	13.85
Arduino Nano CNC Shield	1	17.32	17.32
Limit Switch	3	0.87	2.60
Square Tubing	1	1.90	1.90
Vinyl Tubing	1 yard	0.52	0.52
Horse Clips	6	0.087	0.52
608zz Bearing	6	0.52	3.12
625zz Bearing	16	1.21	19.40
M8 threaded rod	1	2.60	2.60
M5 bolt	20	0.035	0.69
Screws and Washers	-	-	1.73
Spray Paint Can (white)	1	1.73	1.73
Transparent Acrylic Sheet	3 sheets	5.20	15.59
Laser Cutting Service	3 cuts	5.20	15.59
TOTAL			**123.14**

Table 2 PCB Milling Machine Cost Comparisons

SN	CNC PCB Router	Cost (USD)
1.	Prometheus PCB Milling Machine	2,299.00
2.	Mysweety CNC Router	283.23
3.	Othermill Pro	3,199.00
4.	Cirqoid	2,134.98
5.	Millit PCB Milling Machine	126.51

Table 3 Comparison between PCB Milling and Chemical Etching

Parameters	PCB Milling	Chemical Etching
Duration	Shorter duration	Longer duration
Resolution	Quite good resolution	Relatively better resolution
For Prototyping	Best for prototyping	Not ideal for prototyping
Hazardous	Not chemically hazardous	Very hazardous (HCl & $FeCl_3$)
Environmental Effect	No adverse effect	Can lead to massive pollution
Initial Cost	The relatively high initial cost	Lower initial cost
Running Cost	Cheaper running cost	Higher running cost

3.4 Summary of Findings

A summary of findings is indicated below:

(i) Environmentally benign CNC PCB milling machine can be successfully built using locally sourced materials and e-waste.

(ii) The durability and cost-effectiveness of the CNC PCB milling machine are dependent on the state of the locally sourced materials and e-waste deployed in its construction.

(iii) The accuracy of drilling and milling depends on the material being worked on and the drill bit and/or cutting tool used.

(iv) The cost of production of the CNC PCB milling machine was USD 123.14.

4 Conclusions

Based on the findings of the study, the following conclusions were drawn:

(i) It is possible to build a CNC PCB milling machine from locally sourced materials;

(ii) The constructed CNC PCB milling machine is cost-competitive to chemical etching with the added advantage of being environmentally benign;

(iii) The constructed CNC PCB milling machine drilled, milled and cut printed circuit boards with much accuracy and speed; and

(iv) The use of locally sourced materials and e-waste to produce CNC PCB machines can serve as the panacea to managing wastes in the country.

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