

Implementation of CNC Machine Prototype Targeted for Lesotho Industrial Manufacturing Applications

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Abstract – In the modern days of living, CNC technology has become one of the evolutionary technologies, which motivates high efficiency, quality, and complexity in the manufacturing areas. However, in Lesotho, not many people in manufacturing areas and individuals acknowledge and use this technology. Some of the causes of this behavior could be high costs incurred when importing such technology from other countries. In this paper, a mini CNC plotter machine is implemented and used to sketch any given custom CAD design; various forms of shapes, text, and complex images. The machine was also built with careful consideration of the portability factor, cost of production, and capability for mass production of the machines. The success of this paper is assumed to become an attractive force to the future development of CNC machines in Lesotho.

Key Words: CNC, Servo Motor, Arduino Board, Drivers, G-Code.

1. INTRODUCTION

The term Computer Numeric Control (CNC) machining is normally used in manufacturing processes and it is a widely successful technology that is used to manufacture parts [1]. This is a subtractive process, which is controlled by computers to process a given workpiece into user custom design parts. CNC machining process can operate on various workpiece material types such as wood, metals, and plastic; thus CNC machines exist in various types and have various applications in production industries [2]. However, the fundamental principles of CNC machining remain the same, in all these machine types.

The process of CNC machining starts from a design of a 2D or 3D vector template in the computer using a Computer-Aided Design Software (CAD) [1]. A CAD design file is then passed through another manufacturing software called Computer-Aided Manufacturing (CAM), which is responsible for generating highly optimized tool paths to be followed by CNC machines [2]. The G-code file is an output from the CAM software and contains the instructions to be used by CNC machines. The CAM and

CAD software can be used independently, but a CAM program usually exists as an add-on to CAD software. Some examples of CAD software are FreeCAD, TinkerCAD, Sketchup, and Blender, while those of CAM software are CAMWorks, NX CAM, MasterCAM, Fusion 360, and Solidworks CAM.

The concept of CNC machining outgrows from Numerical Control (NC) machining. These precursors of CNC machining technology were first introduced between the 1940s and 1950s by John Parsons, shortly after world war II, and the whole idea was to modify some of the manually controlled machine tools to facilitate reliable, repeatable, and accurate manufacturing of complex aircraft parts [1]. John had successfully manufactured the templates of helicopter rotary blades from data encoded in punched cards, using the Swiss jig borer to process data generated by the IBM 602A multiplier to determine the aerofoil coordinates. The NC machines used punched tapes and later punched cards as the form of instructions storage technology or NC programming language, which was later replaced by analog processing technology [3]. **Error! Reference source not found.** below depicts an example of the punched tape and a punched tape reader/decoder machine.



Figure 1: Creed model 6S/2 5-hole paper tape reader [4]

The holes on the punched tape encoded the instructions to be used by the NC machines in the process of NC machining. Even though the punched tapes were

considered the best approach to manufacture parts throughout the 19th century, several challenges remained; which include the production of tapes being expensive, tapes being fragile, and difficult to pair. Nowadays, digital processing technology is used instead. This type of technology uses computers to store, generate and stream the machine control instructions onto CNC machines. The CNC technology uses Geometric Code (G-Code) and Miscellaneous Code (M-code) as their programming language instead of punched cards. [5]. Figure 2 shows an example of a CNC milling machine, reading instructions from a G-Code file to reproduce a custom design on a piece of aluminum.



Figure 2: G-Codes and M-codes from a computer used as instructions to a milling machine [6]

Before the invention of NC technology, machine tools were manually controlled by the machinists, as a result, the industrial and commercial manufacturing processes were often slow and inefficient, and of low quality due to the fallibility nature of humans [1]. The advent of CNC machines was the state of the art in production industries. It brought about improved production accuracy, and efficiency, simplicity, flexibility, reduced costs [1]. It also led to high-quality products, reduced production time, reduced chances of product damages, etc. These were all achieved from the fact that CNC machines used computers, and their operation was automatic i.e. CNC machines required minimal assistance from humans.

CNC machines were normally known to be industrial machines because they were very expensive [7]. However, nowadays this technology is becoming increasingly more popular and is extending to small-scale manufacturing processes in some developed countries. CNC machines currently take different forms and sizes and are sold at relatively affordable costs in some countries. This makes it possible for some individuals to own CNC machines i.e. the DIY CNC'ers are currently able to manufacture the CNC machines for their personal use [8]. The most common CNC machine types are CNC plotters, CNC laser cutting machines, CNC lathe machines, CNC milling machines, CNC

plasma cutting machines, 5-axis machines, 3-D printers, pick and place machines, etc. [1].

This paper focuses on CNC plotter machines. Plotter machines are the type of CNC machines that are commonly known to produce vector graphic sketches on paper using a pen, but in some applications, they are used as cutting machines, replacing a pen with a cutting knife i.e. in vinyl and lather cutting process[9]. This type of plotters, which possess the cutting capabilities are called cutting plotters, while those used to produce sketches are called pen plotters [9]. The plotter machines were commonly used before the advent of laser printer machines around the 1980s, and they were a perfect alternative over conventional printers since they relatively produced line sketches much faster and at a much higher accuracy [9]. Even though the birth of laser printers eliminated most of the roles commonly performed by plotters, they are still useful in many manufacturing industries [9].

The rest of this paper is organized as follows. Section 2 outlines some literature on CNC technology basics. Section 3 gives a detailed account of the design and implementation of the mini CNC machine prototype. In section 4 the image vector and different shapes produced by the plotter will be observed and compared with their respective input templates. Section 5 concludes this paper by outlining some major findings drawn from this work as well as the remarks on future developments.

2. CNC TECHNOLOGY BACKGROUND

While the CNC machines use graphical codes (G-Codes) and miscellaneous codes (M-Codes) as their programming language, the first step in CNC machining is to create a custom 2D or 3D vector design using the CAD software installed in a computer. The finished CAD design is then saved in the file format that corresponds to CNC machining, which is predominantly Exchange of Product Data Files (STEP files) and Initial Graphics Exchange Specifications Files (IGES files). The concept of file formats has become handier in the competitive and ever-changing software space, in the parts manufacturing process, to enable sharing of CAD information between programs without the use of any tedious conversion processes.

CAD software is a platform used to create 2-3D vector blueprint designs within a computer [1]. A CAD design file is then passed through another important manufacturing software called Computer-Aided Manufacturing (CAM), which is responsible for generating highly optimized tool paths to be followed by the CNC machine [2]. The CAM

software outputs a G-Code file, which is a language of CNC machines. The CAM and CAD software can be used independently, but a CAM program usually exists as an add-on to CAD software [10]. Some examples of CAD software are FreeCAD, TinkerCAD, Sketchup, and Blender, while those of CAM software are CAMWorks, NX CAM, MasterCAM, Fusion 360, and Solidworks CAM [10].

IGES and STEP file formats are the popular file formats created from CAD programs to facilitate sharing of CAD designs to work across various design systems [11]. The IGES file format was created by the U.S. Government around the 1970s with a realization that more money and time are being wasted in the process of converting shared data files across various software systems [11]. The use of IGES file format made it through to 2D and 3D CAD file sharing across major CAD software systems, and thus became a standard across various fields such as aerospace, military, etc. At around the 1980s, the STEP file format came into being [11]. This format came along with some improvements upon IGES and became widely accessible around the 90s. The STEP format is continually gaining popularity with continuous improvements in its functionalities across an increasingly growing number of CAD systems [12]. Figure 3 shows the workflow of CAD/CAM for subtractive (Mill, Lathe, etc.) and additive (3D printer) CNC machining.

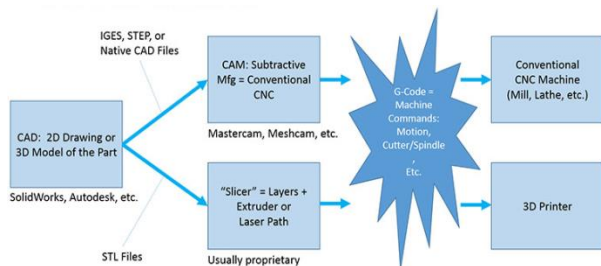


Figure 3: The workflow of CAD/CAM [10]

Figure 3 shows the workflow of the CAD/CAM process in CNC machining. The first step, shows the creation of a 2D or 3D model of a part, using CAD software, such as SolidWorks, Autodesk, etc. The CAD file design is then saved as an IGES, STEP, or Native CAD File in the case of a 2D model, and saved as an STL file for 3D models. An STL (stereolithography) file format is a standard for 3D systems. These CAD files are then transferred to CAM software and converted to G-code, which will later be used by CNC machines to manufacture parts. The information flow chart shown in **Error! Reference source not found.** depicts clearly, the compositions of each file in the manufacturing CAD/CAM workflow.

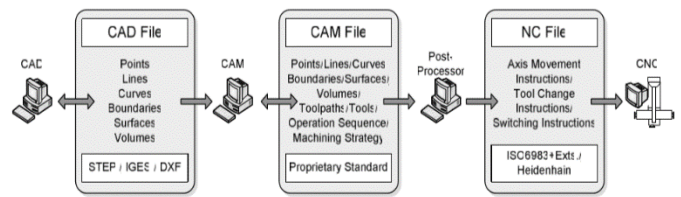


Figure 4: Manufacturing information flow from CAD to CNC [13]

2.1 Software Subsystem

The CNC program file contains the instructions which control the motion and state of the system [16]. Since the program is normally in the higher-level languages i.e. G-Code, there has to be a mechanism inside the system to translate/decode the instructions from the higher language into the language that can be understood by the machine, and usually, this mechanism is implemented inside the system's controller. The controller's program interpreter will receive the instructions set from the CNC program file in the form of a text and will process and convert the textual instructions into electrical pulse signals which are in the form of 0's and 1's whereby 0 represents the absence of a signal while 1 represents the presence of the electrical signal. The electrical signals are later converted into either mechanical motion or mechanical state control instructions.

The motion along x, y, and z dimensions are normally described as shapes in the graphic vector space using the Cartesian plane, but when dealing with computer graphics, the approach of normal Cartesian plane description fails. The solution to this failure requires a transformation algorithm from the graphic vector space to the raster space, and the process is called Rasterization [17]. Figure 727 below depicts an example of the rasterization of a straight line graphic vector into a computer graphic format.

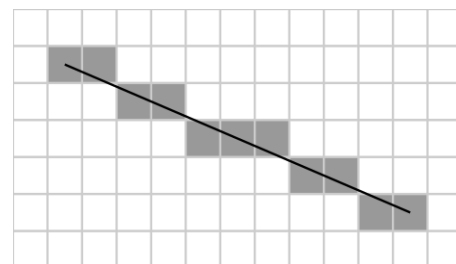


Figure 72: Rasterization of a straight line graphic vector [17].

In Figure 727 a black straight line is shown; which is normally represented by a line equation (1). The

corresponding representation of the line in the Raster plane is shown using the grey boxes in the grid, and it is conspicuous how complex, simple vector graphic shapes, could be represented in this space.

$$y = f(x) = mx + b \quad (1)$$

Interpolation algorithms (linear [18] or circular [19]) are typically used to estimate the intermediate (and fractional) pixel positions over which the line (or curve) crosses.

2.1 Mechanical Subsystem

The concept of CNC machining is mainly to automate the conventional manual toolsets such as hand-saw, drilling machine, and grinding machine. This automatic feature is achieved by using the motors to drive the CNC tool i.e., spindle along the paths declared in the CNC program. In the CNC machining process, precision is of higher priority, thus the motors to be used to establish these motion sets have to be very special motors, whose rotary motions can precisely be controlled. The commonly used motor types in CNC machines are stepper motors and servo motors.

2.1.1 Stepper motor

A stepper motor is an electromechanical device that is sometimes referred to as a special DC brushless synchronous motor, whose rotation is of discretized equal steps as opposed to normal brush DC motors, with continuous rotation[20]. It functions by converting the pulses of electrical signals into mechanical rotary motion[20]. A type of motion used by stepper motors, where a full rotation is divided into an equal expansive number of steps makes it easier to control. The position of the motor can precisely be controlled by the pulse signals which are made to generate unit step of a specific size, thus stepper motors can be successfully employed in open looped precision control systems, operating without any feedback mechanism or position sensor in as long as the motor sizing in respect to torque and speed are adequately selected for an application. In the situation whereby the motor is not properly sized for an application, the stepper motor is likely to miss some step without any compensation mechanism and would result in errors in the construction of the programmed paths. **Error! Reference source not found.**8 shows an example of a real-life stepper motor.



Figure 83: A stepper motor

2.1.2 Servo Motor

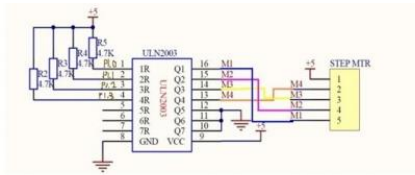
A servo motor is an electromechanical system that converts electrical signals into mechanical motion. This type of motor is normally used in precision control applications such as CNC machines, military robots with bomb detection, and other applications of position control. Even though servo motors and stepper motors are both meant for position precision control applications, the two are quite different, and in some cases, one motor type is preferred over the other. The stepper motors are commonly preferred in open looped control applications whereas servo motors are normally used in closed-loop control applications because of their unique positioning feedback mechanism.

Servo motors exist in various sizes and forms, which can be operated either by AC or DC. The AC servo motors are normally used in heavy-duty machines, due to their capability to handle heavy currents, while the DC servo motors are used in smaller applications that involve precision control. The frequency of the input voltage signal and the number of magnetic poles are the key features that determine the speed of the motor. There are three basic types of servo motors which include positional rotation, linear, and continuous rotation.

2.1.3 Motor Driver

In CNC machining, the motion of the precision motors (i.e., stepper and servo motors) is controlled via the CNC controller, which generates the PWM control signal patterns to rotate the motor back and forth in discrete steps [21]. However, the motors are usually not connected directly to the controller pins due to their high current requirements, and a dedicated precision motor driver board is always used [21]. The motor drivers are the interfacing circuit boards between the CNC controller and precision motors. They are used to translate low currents from the controller board into high currents required by the motors [22]. Figure 949 shows an example of the most common unipolar stepper motor (28BYJ-48), and its

circuit connection to the controller together with their corresponding table of the motor control signal patterns.



The following picture is the control signal to drive a 28BYJ48 stepper to rotate 1/4096 circle.

line	1	2	3	4	5	6	7	8
red	1	1	1	1	1	1	1	1
orange	1	1	0	0	0	0	0	1
yellow	0	1	1	1	0	0	0	0
pink	0	0	0	1	1	1	0	0
blue	0	0	0	0	0	0	1	1

Figure 94: The ULN2003a stepper motor controller circuit with the control signal patterns table [22].

The UNL2003a stepper drivers are dedicated to the 28BYJ-stepper motors, and an example of their kit is shown in Figure 10510.



Figure 105: ULN2003 Driver Board and 5 wire 5v 4 phase 28BYJ-48 unipolar stepper motor [23].

2.1.4 CNC Controller

The CNC controller is a digital circuit that acts as the brain of the CNC machine [24]. It is the source of all the intelligence of the CNC machines and in control of the operation of CNC machining processes. The CNC machine controllers are programmed to decode the g-code instructions from the computer and translate them into precise motor rotary steps, which are then sent to the stepper motor drivers to obtain the mechanical movements [24]. There are various types of CNC controllers, and these include [24]:

- Industrial OEM CNC Controller
- CNC Retrofit Controller
- PCB Based CNC Controller
- Microcontroller Based CNC Controller
- Breakout Board CNC Controller
- etc.

The use of Microcontroller Based CNC controllers is gaining popularity, and this is due to the accessibility and low prices of microcontroller boards [25]. One example of the microcontroller board is shown in Figure 11611 and is called the Arduino Uno microcontroller board.

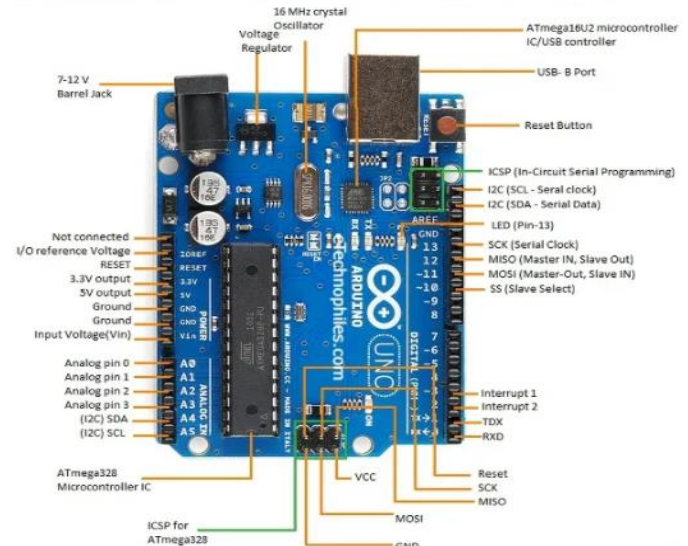


Figure 116: Arduino Uno Microcontroller board [25].

3. DESIGN AND IMPLEMENTATION

In this section, the focus is on the design and implementation of the NC plotter, which would be subdivided into three major compartments; being NC frame design and implementation, NC circuit design, and NC software.

3.1 Frame Design and Implementation

3.1.1 Hardware requirements:

- Aluminium angle iron 1.5 x 19 mm & 1.5 x 25 mm
- RM3ZZ 12mm V-Groove Guide Bearing Shielded (x8)
- Eccentric Nut Spacers (x12)
- Socket Screws and Washer kit
- M6 75 mm hex (nuts and bolts) (x4)
- M5 30 mm Machine screws (bolts & nuts) (x10)
- GT2 pulley head
- 25 mm Nylon Bearing Pulley idler
- Clear Plastic Sheet (e.g., Drawing board) 3mm
- CD/DVD Drives Rail System
- 28byj-48 Stepper Motors (x2)
- Plastic furniture corner bracket 27.5 x 26.5 mm (LxW) Mounting Hole:M3 (x2)
- Arduino Positional servo motor (x1)
- Ball-bearing 16 mm out diameter & 2 mm in diameter (x1)
- Ballpoint Pen Spring

3.1.2 Tools:

- Hand Saw
- Drilling machine and drill bit set
- Wood-working file (i.e., flat and or triangular file)
- Allen key Set

3.1.3 Estimated Cost:

Table 1: Table of NC frame quotation prices.

Material	Unit Cost	Total Cost
Aluminium angle iron 1.5 x 19 mm	M 96.00	M 96.00
Aluminium angle iron 1.5 x 25 mm	M 109.99	M 109.99
RM3ZZ 12mm V-Groove Guide Bearing Shielded (12 pcs)	US\$ 9.65	M 134.71
Eccentric Nut Spacer (10 pcs)	US\$ 7.84	M 210.88
M2CH2 M2 Carbon Steel Allen Bolt 4-16 mm Hex Socket Cap Screw Metric Assortment Kit (180 pcs)	US\$ 7.99	M 111.54
Metric Flat Washers (180 pcs)	US\$ 8.39	M 117.12
M6 75 mm hex (nuts and bolts) (4 pcs)	M 21.50	M 21.50
M5 30 mm Machine screws (bolts & nuts)	M0.5	M 5.00
GT2 Pulley Head	US\$3.23	M 90.18
Nylon Bearing Pulley idler 25 mm	US\$1.18	M 32.94
Clear Plastic Sheet (e.g., Drawing board) 4ft x 8ft x 3mm	US\$ 23.72	M 331.12
CD/DVD Drives Rail System		
28byj-48 Stepper Motors (2 pcs)	US\$ 5.77	M 80.55
Plastic furniture corner bracket 27.5 x 26.5 mm (LxW) Mounting Hole:M3 (2 pcs)	M 18.40	M 18.40

Arduino Positional servo motor	US\$ 5.73	M 80.00
Ball bearing 16 mm out diameter & 2 mm in diameter	M 1.40	M 1.40
Ballpoint Pen Spring	M 4.99	M 4.99
Contact Glue	M 20.00	M 20.00
M 1,465.44		

Most of the materials found on the table can be salvaged from old equipment at home for someone interested in implementing a similar plotter design at home to reduce the manufacturing costs e.g., an old engineering drawing board was used instead of buying M 331.12 PVC sheets, CD/DVD Drives Rail System salvaged from old CD/DVD player, etc. Delivery and transport costs have not been included in Table 1.

1.1.1 Frame Design:

The NC frame is designed using the 3D CAD software called Sketchup. This software is preferred because it is very user-friendly and open source. The sketch design in this paper is mainly used to visualize the plotter frame in 3D to access the feasibility of the design before the actual implementation. The advantages of the sketching process are that it facilitates the reasonable choice of the type of materials to be used, easy dimensioning of a product, easy costs estimation process and to easily access whether the design is practical. **Error! Reference source not found.** show the design process of the NC frame.

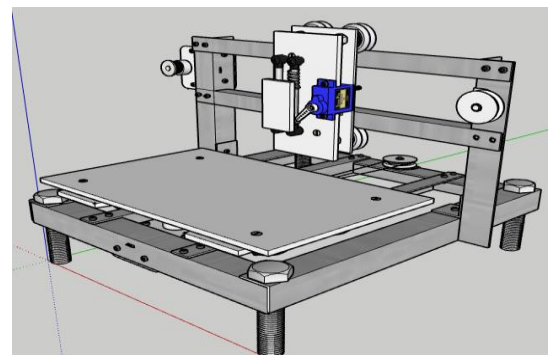


Figure 12: Isometric view of an NC frame Design

1.1.2 Implementation

Error! Reference source not found. shows the frame design made from aluminum angle profiles and plastic

plain sheets. The aluminum and plastic were preferred in this paper because of their lighter weight which would result in a portable and lightweight frame structure. Apart from that, the aluminum materials are easy to process and do not require expensive and complicated tools to process i.e., a metal cutting hand saw can still be used effectively to nicely cut aluminum angles instead of a cutting grinder machine, a manual hand drilling machine instead of an electric hand drilling machine to make holes and again the high-quality drill bits are not necessary to effectively get the best results. All the qualities just mentioned about the aluminum and plastic materials ultimately address the issue of production cost and portability of the NC machine.

The design structure mainly uses bolts and nuts to fasten the angle irons together. This facilitates simpler and flexible product which can easily be assembled and disassembled to make the system mobile and easy to maintain. The type of screws used was also carefully selected. The socket screws were found to be the perfect selection for this application since they offer more clamping force than other standard screws such as machine screws and other formats of small fasteners. The frame legs are also made from 6 x 75 mm hex screws to enable the structure legs to be fastened to eliminate any mechanical vibrations that may affect the accuracy of the system.

The type of stepper motors used in the design is 28byj-48 stepper motors. These motors provide high torque at reasonable speeds (around 500rpm), and this calls for more accuracy of the plotter machine. The plotter rail system is made from v-slot wheels which were made specifically for precision machine rail systems. The wheels go hand-in-hand with the adjustable spacers, to control the creep on the metal rails.

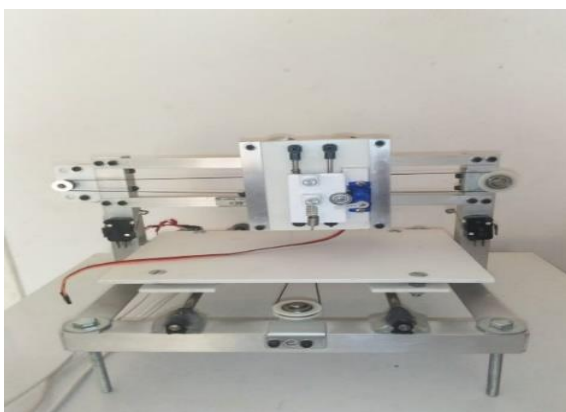


Figure 7: Design Implementation of the NC Plotter Machine

The pen holder mechanism was made from plastic pair of campus and was glued onto the plastic sheet using contact glue. The rail system is made from the CD/DVD drive system shafts using the ballpoint pen spring to always push the pen holder mechanism downward. The reason why the spring was used was to facilitate a smoother pen movement. The spring would absorb any machine paper_base surface imbalances and roughness by allowing the pen holder to stretch with the surface geometry and roughness. The eccentric nut spacers between the wheel gentry plate and the rail plate offer an allowance for the servo motor to slide into the Z-Axis system. The ball bearing on the pen holder plate also facilitates the smoother jerking of the pen holder plate, by the servo arm by simply sliding on the arm without gripping.

1.2 NC Circuit Design

1.2.1 Hardware requirements:

- ULN2003A stepper drivers (x2)
- HC-06 Bluetooth module
- 10k potentiometer
- LED Screen (2x16)
- ON/OFF LED
- 220k, 1k, 2k resistors
- Power Jack
- Buttons (x2)
- Arduino Uno
- Buzzer
- 470uF capacitor
- Male and female PCB connector strips
- PCB Jumper wires
- Heat shrink 3mm

1.2.2 Tools:

- Soldering iron & wire
- Wood-working flat file
- Drilling machine & drill bit set
- Allen key Set
- Copy saw
- Lighter

1.2.3 Estimated Cost:

Table 2: The estimated cost of all the electronics required.

Material	Unit Cost	Total Cost
ULN2003a Stepper Motor Driver	US\$ 2.15	M 60.03
HC-06 Bluetooth module	US\$ 4.31	M 60.17

10k potentiometer	US\$ 2.88	M 40.20
LED Screen (2x16)	US\$ 3.69	M 51.51
ON/OFF LED	M 1.00	M 1.00
220k, 1k, 2k resistors	M 1.50	M 4.50
Power Jack (50 pcs)	US\$ 4.31	M 60.17
Buttons (10 pcs)	US\$ 3.73	M 52.07
Arduino Uno	US\$ 5.29	M 73.84
Buzzer (5 pcs)	US\$ 1.59	M 22.20
470uF capacitor	M 1.20	M 1.20
Male Female PCB connector Strip	US\$ 2.26	M 31.55
PCB Jumper wires	US\$ 1.23	M 17.17
Heat shrink 3mm	US\$ 2.12	M 29.59

M
505.20

It is also important to note that it is usually wise to have 2-3 extra components as the backup to the components that may accidentally get damaged in the manufacturing process.

1.2.4 Circuit Design:

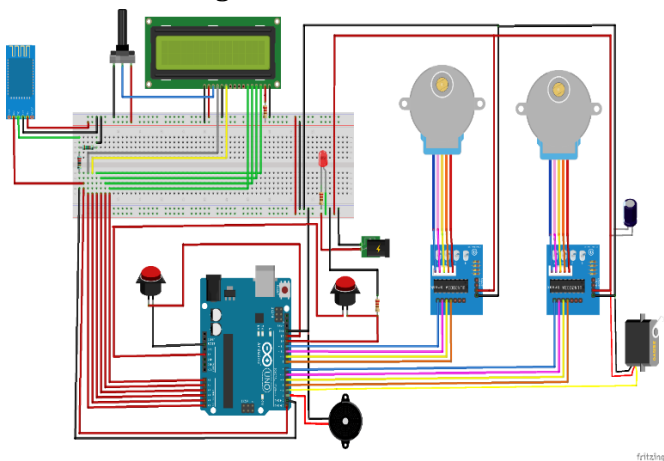


Figure 18: The circuit design of the NC plotter.

The type of microcontroller used for this design paper is Arduino Uno. The board was preferred over many others due to its moderately lower costs and the number of pins it offers i.e., the paper required about 14 input-output pins which the exact number of pins in Arduino Uno. Otherwise, any other microcontroller with an adequate number of pins (e.g. Arduino Mega) would still be ok, even though they are a bit costlier than Arduino Uno.

The type of stepper motors and stepper drivers used in the design are 28BYJ-48 stepper motors and ULN2003a stepper drivers respectively. Usually, the selection of motors and driver to be used in the design of the CNC machine is a very critical and long process and helps optimize the performance of the machine in terms of torque, and maximum speed to improve the production process quality. However, in this proposed design, not special attention was given to the process of stepper and driver selection because the gentry systems of the machine were made to be very light (used aluminum and plastic) apart from the fact that the machine is also very small. The 28BYJ-48 stepper motors are geared to have very high torque and reasonable speed, so it was very obvious that they should be adequate for this application. The drivers and motors are usually sold as a kit, and a cheaper one for that matter, hence why they were both selected for this application.

The servo motor type that was selected for this application was the 180° positional servo motors. This type of motor was also preferred simply because it is cheaper and easily accessible i.e., they are usually present in the starter Arduino kits. Another important reason, for the selection of this motor, is that they have a relatively very high torque which would be more than enough for this application, not leaving behind the fact that they were could easily be integrated with the proposed z-axis design.

There is nothing special for the selection of the HC-06 Bluetooth module type used in the design. Any other Bluetooth module (e.g. HC-05) would still be fine, and the HC-06 just happened to be the one accessible. The LCD screen is used to display the g-code, and other important technical messages such as errors and the potentiometer are used to adjust the brightness of the screen. The buzzer is used to indicate the booting process of the machine, and the two buttons are the emergency stop and tool change buttons. The capacitor connected to the servo motor is used to improve the servo motor's operation, to ensure stable motion.

1.2.5 Implementation:

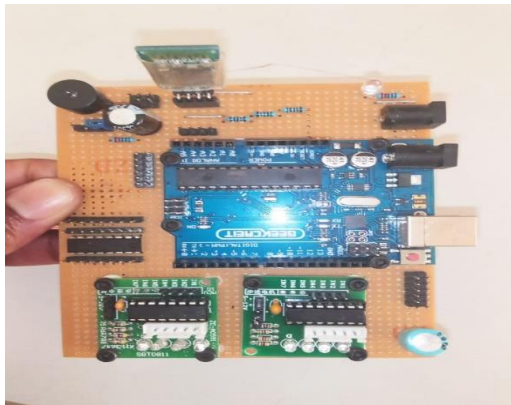


Figure 15: The NC plotter PCD.

The electronic components and modules were bought together on a single solder type PCB, and the connections were made using the PCB male and female connector strips.

1.2.6 LCD Screen Connection PCB:

To ensure clean packaging, the LCD screen, due to its numerous pins had also called for the screen connection PCB, which is shown in Figure 169.

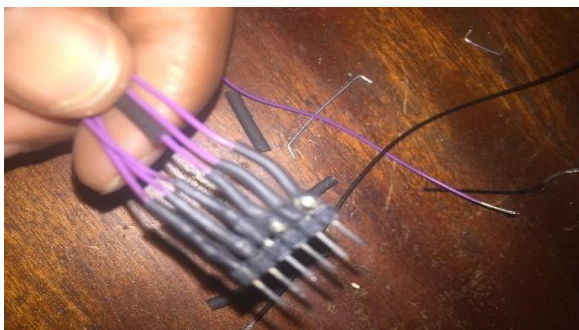


Figure 169: The NC plotter LCD screen connection PCB.

1.3 Electronics Enclosure

1.3.1 Hardware requirements:

- ATX desktop power supply case
- Clear Plastic sheet (e.g., drawing board) 3mm
- 2mm metal sheet
- Machine screws (bolts & nuts) 3.5mm (x4)
- Socket screws and washers
- GX 5-way connectors
- Heat shrink 3mm
- Insulation tape
- Potentiometer Knob cap

1.3.2 Tools:

- Copy saw

- Wood-working file
- Drilling machine & Drill bits Set
- Flat type Screw Drivers Set

Error! Reference source not found.17 shows the implemented design of an electronics enclosure for the NC machine.

1.3.3 Estimated Cost:

Table 3: Estimated cost of an electronics enclosure

Material	Unit Cost	Total Cost
Machine screws (bolts & nuts) 3.5mm (50 pcs)	M 15.00	M 15.00
GX 5-way connectors	US\$ 5.99	M 250.86
Heat shrink 3mm (length 2.5 m)	US\$ 2.51	M 35.04
Insulation tape	M 34.50	M 34.50
Potentiometer Knob cap (10 pcs)	US\$ 4.31	M 60.17
M 395.57		

1.3.4 Implementation:



Figure 1710: A complete electronics enclosure.

1.4 NC Power Supply

There are various options for powering the plotter machine in this paper since most of the electronics used require a 5v supply. To cater for the coolant fan powering, an extra 12v voltage was required and the closest option was to reuse a PC power supply.

1.4.2 Hardware requirements:

- Banana plugs (x6) (3 black, 3 red)
- Switch
- LEDs (x2)
- 330ohm resistors
- 10-ohm 10w Power resistor
- 1-Amp fuse
- Laminated front panel design
- Zero PCB
- ATX PC Power Supply Case

1.4.3 Tools:

- Drilling Machine & Drill bits Set
- Hear shrink & Lighter
- Soldering iron
- Wood-working file
- Screw Drivers Set

1.4.4 Cost Estimate:

Table 4: Estimated cost of building a power supply.

Material	Unit Cost	Total Cost
Banana plug (2xBlack & 2xRed)	M 3.50	M 21.00
Switch	M 17.99	M 17.99
LED (Redx1, Green x1, Blue x1)	M 1.00	M 2.00
330ohm resistors	M 0.50	M 1.00
10-ohm 10w Power resistor	M 15.00	M 15.00
Laminated front panel design (printing + laminating)	M 12.00	M 12.00
Zero PCB (3 cm x 3 cm)	M 7.50	M 7.50
M 76.49		

1.4.5 Implementation:



Figure 1811: NC bench power supply from the PC power supply.

The power supply enclosure front panel was designed using Inkscape CAD software colored-printed and laminated to protect the printed paper. It was then glued at the front side of the case as shown in Figure 181118.

1.5 NC Software

1.5.2 Interpreter

The function of an interpreter in CNC programming still retains its meaning as in any other programming language. The NC interpreter converts the G-code instructions text into machine language instructions to control the NC motions and other miscellaneous features.

Table 5: g-code commands for the CNC plotter design.

COMMAND	MEANING
G00 & G01 G01 [X(n1)] [Y(n2)] [F(n3)]	Move to position XY at the federate F
G04 G04 P(n)	Wait/Pause for n milliseconds
G21	Metric Scale selection command
G90	Absolute mode
G92 G92[X(n1)] [Y(n2)] [Z(n3)]	Relative mode
M01	Pen change command
M114	Position reporting command
M300 M300 S50.00	M300 S50.00: Pen up
M300 S30.00	M300 S30.00: Pen down

M300 S30.00	
M18	Drivers Off

Figure 211321 shows a portion of the generated g-code file opened in a notepad text editor.

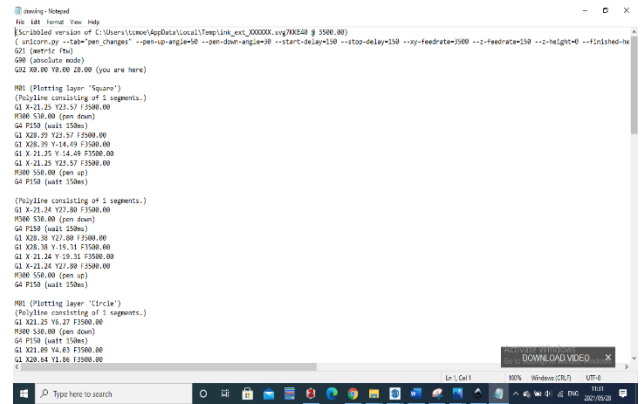


Figure 2113: A portion of a generated g-code file.

The g-code file was then sent to the CNC plotter machine, line by line (you, to reproduce a custom design encoded in g-code data in Figure 211321.

1.5.4 G-code Streaming:

The generated g-code would ultimately be sent line by line to the NC plotter machine via the USB or Bluetooth serial port, and this called for the development of a very simple g-code sender software called Moeti CNC Machines G-Code Sender. This software offers a very straightforward GUI with limited functionalities since it was mainly dedicated to sending the g-code instructions from the file in the PC to the NC machine. This G-Code sender was implemented using java programming language confined in processing sketchbook. The interface for the g-code streamer was developed using the controlP5 and G4P GUI processing libraries.

The streaming process will continue with the previously generated g-code file, and show in steps how to stream the g-code file to the NC machine using Moeti CNC Machines software. The first step is to connect the software to the correct com port depending on the means of communication used i.e., the com port used in USB Serial communication would differ from the one used in Bluetooth Serial Communication. The com ports can be validated in the PC device manager. Figure 221422 shows the process of selecting the com port in Moeti CNC Machines software.

1.5.3 Generating the G-Code

The custom design was generated using Inkscape software, and the G-code Unicorn Master Inkscape extension was used to generate the corresponding g-code for the custom design. The default units used in the document were in millimeters, and the document size was set to 100 x 100 mm which is a perfect fit in the machine plotting range of 250 x 250 mm. The graphic object was designed in 3-layers named (star, circle, and square) shown at the right-side panel of the document to enable a pen change functionality at every layer change. A successful design of the graphic object was then followed by the conversion of the object design into design line paths as shown in Figure 1912.

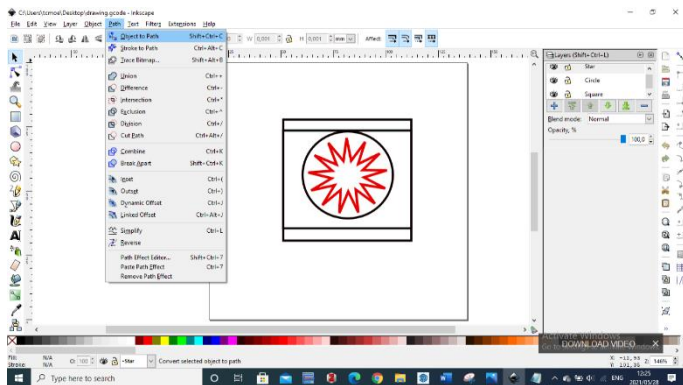


Figure 1912: Converting a graphic object into line paths.

The conversion of an object into line paths format is followed by saving a design with a .gcode file extension made possible by the MakerBot Unicorn Gcode Inkscape extension.

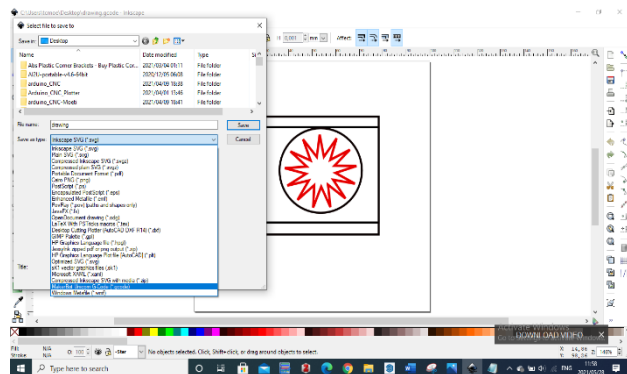


Figure 20: Saving a design in a .gcode file extension.

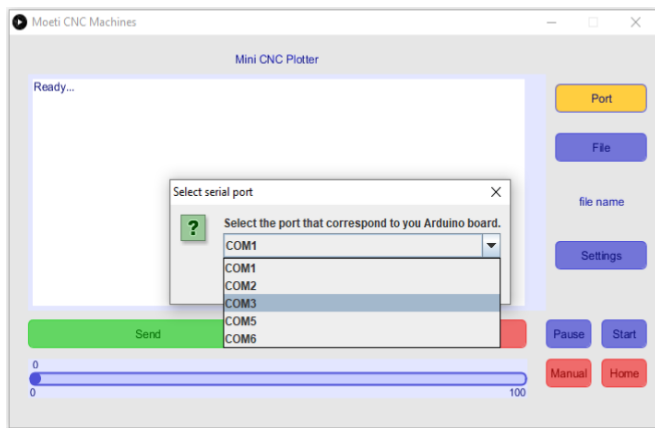


Figure 2214: Selecting the Com Port in Moeti CNC Machines software.

When the software is successfully connected to an appropriate com port, the g-code file can then be browsed from the PC in an appropriate directory by clicking on the file button on the left side of the GUI. The g-code file is selected and opened, and to stream the file, the send button is clicked. This process is demonstrated in Figure 2315, and Figure 2416 shows the streaming process of the g-code file.

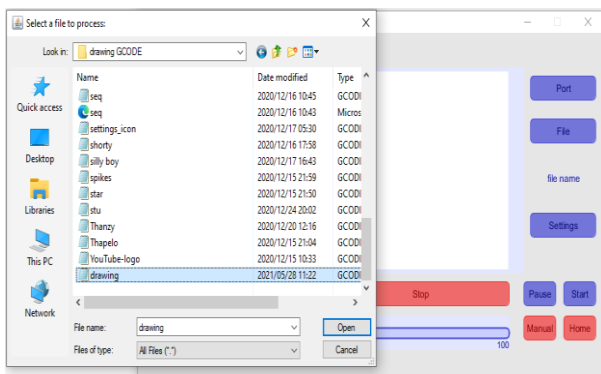


Figure 2315: Importing the g-code file into Moeti CNC Machines software.

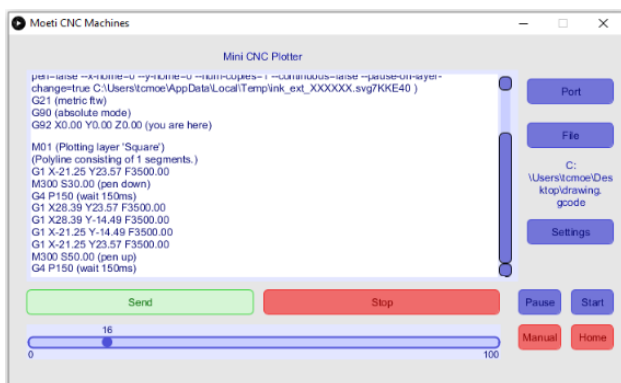


Figure 2416: The generated g-code streaming process to the NC plotter using Moeti CNC Machine g-code sender.

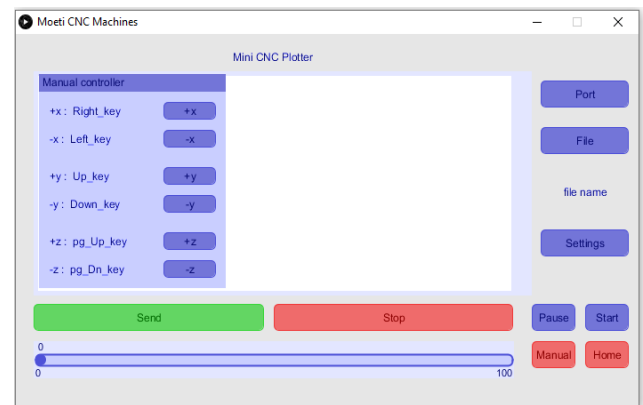


Figure 2517: Manual control context menu showing the motion buttons and the keyboard hotkeys.

The g-code sender in Figure 241624 displays some g-code commands received from the file on the PC from a directory shown below the file button on the left side of the interface. It also shows the progress bar which displays the plotting progress as a percentage determined by (current line number/total number of lines in the file) x 100%. The keyboard keys are also supported to manually move the machine axis, and the hotkeys are the navigation keys, page up and page down, etc. By pressing the manual button, the manual control context menu is displayed as shown in Figure 251725.

4. TEST RESULTS & DISCUSSION

This section is designed to determine whether the machine works and adheres to the following objectives,

- Mass Production Capability
- Portability (i.e., lighter structure)
- Cost-Effectiveness
- Ability to write text
- Draw any form of shape (Regular and Irregular)

4.1 Complete Product

When the product is complete, it would be composed of the NC plotter machine structure, electronics box, power supply, and Moeti CNC Machines software installed on the PC. Figure 261826 shows an overview of the complete NC plotter machine.



Figure 2618: Complete NC plotter overview.

The NC frame of the complete CNC plotter was found to be very firm, light, and stable. In design, it was mostly made from nuts and bolts and this had made the end product to be very flexible, repeatable, and mobile, thus the structure could easily be maintained through a quick disassembling process. With the quality for repeatability in the building of the CNC plotter, it would imply the potential of the machines to be mass-produced.

4.2 Estimated Production Cost

Table 6: NC Plotter Manufacturing Total Estimated Cost

Type	Cost
Hardware Design	M 1, 465.44
Electronics	M 505.20
Power Supply	M 76.49
Enclosure	M 395.57
Total Cost	M 2, 442.70

The total estimated cost of building the NC plotter for commercial and mass production purposes was found to be around M 2, 442.77. Although the estimated cost looked a little high, intuitively, it was still reasonable. Looking closely at Table 6, most of the bought components were bought in bulk, which means that similar expenses would be exclusive in the preceding building of several NC machines. With this thought, the cost price for the unit NC plotter machine production would immensely be reduced i.e, a single 6m 25mm M109.99 angle iron can produce about 3 NC plotter machines, which renders the total cost

of the angle profile per unit NC Plotter to about $M109.99/3 = M36.66$. The costs of the NC machines found in AliExpress range between US\$ 120.00 – US\$ 700.00 with an exception to delivery costs, thus the mass production of the custom design introduced in this paper could relatively be cheaper than importing the depicted NC machines in Lesotho.

4.3 Product Testing

This section deals with the testing of the NC plotter capabilities, to observe whether the final product gives the results which were expected as per the goals and objectives of the paper. Figure 271927 shows the plotter output of the g-code generated in the previous sections.

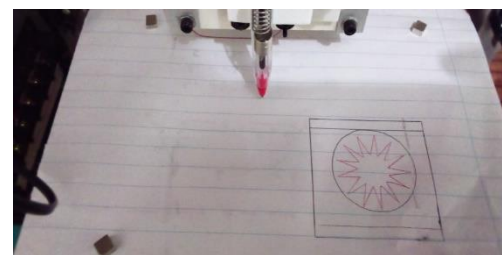


Figure 2719: The CNC plotter machine results from the generated g-code.

The NC machine plotter output result shown in Figure 271927 seems to match with the custom CAD design object in Figure 191219.

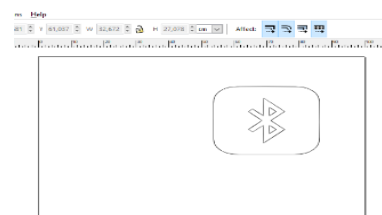


Figure 2820: CAD Design of the Bluetooth icon.

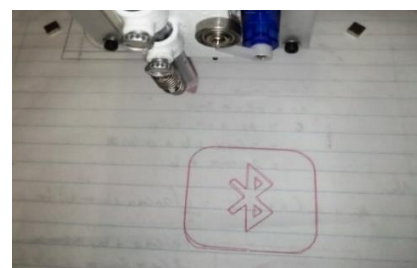


Figure 2921: The Plotter results of the Bluetooth icon.

The NC Plotter machine was also expected to be able to reproduce any given text, and plotter results are shown in Figure 302230.



Figure 3022: Inkscape text design.

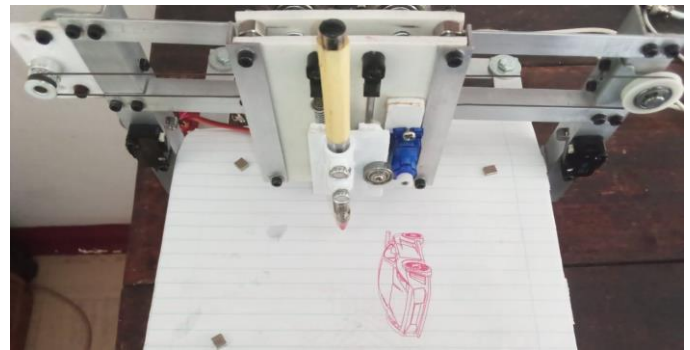


Figure 33: The Lamborghini NC plotter results.

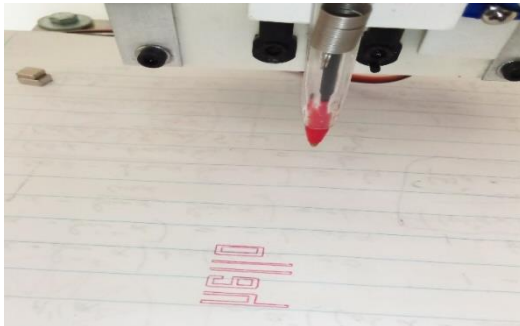


Figure 3123: The plotter text results

Figure 302231 shows the success of the plotter to reconstruct the Inkscape text 'hello' onto the piece of paper. The reproduced is double lines, but this property can be changed from the design by editing the line paths from double to single line path, otherwise the results satisfactory

The NC plotter was also tested on very complicated designs to observe its performance, and most of the results obtained were satisfactory. One instance of the tested designs is shown in Figure 2432, and the NC plotter results are shown in Figure33.

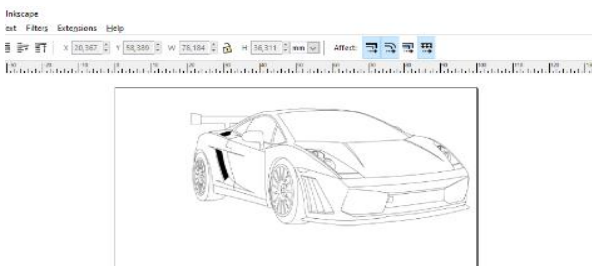


Figure 242: The Lamborghini Inkscape graphic vector design.

The design and implementation of the mini CNC plotter were a success, and the results obtained were quite impressive. However, the major challenge encountered in the implementation of the machine was that most materials used in the paper were ordered from outside the country. That ultimately increased the manufacturing costs for this particular startup machine because most of the materials were bought in bulk as a backup for anything that might go wrong in the middle of the manufacturing process.

The machines to be designed in the future would be made in such a way to minimize the number of imported materials i.e., the linear guide v-wheels will be substituted with the normal ball bearings, and the driver boards be redesigned to make use of the electronic components already found in the country. Another challenge was to find a regulated power supply with adequate power to offering both the 5v and 12v for the electronics coolant, and the power supply design used in this paper made the overall paper to be a little bulky, and in the future, a smaller power supply, which would fit inside the electronics box will be redesigned.

5. CONCLUSIONS

The motive behind these papers came from an observation that not many people acknowledge and take advantage of the CNC technology in Lesotho. The success of this paper could work as a wake-up call and an introduction to CNC machine manufacturing companies in Lesotho for quality productions. It was found in the results of this paper, that it could be quite expensive to import CNC machines from other countries as compared to when produced in Lesotho. Another advantage of developing these machines in Lesotho is that it would be easier to maintain them, and can be easily accessible to anyone in the country hence improve their livelihood.

In this paper, the mini CNC plotter (250 mm x 250 mm) was designed and implemented. The structural design was developed using a free and open-source 3D vector design software called SketchUp, and the frame was designed to be rigid, light, and stable to facilitate mobility, and improved the operation process. The machine was mostly implemented using fasteners for easy maintenance and repeatability and made gave a design a capability of mass production. The CNC design implementation costs were also estimated to be at around M 2, 442.70 with the materials capable of producing at least three machines, thus reducing the unit cost of the machine. In comparison with other CNC plotters already in the market, the production of these CNC machines was found to be reasonably cheaper as opposed to their import in Lesotho from other countries, not leaving fact that it would motivate the machines to be maintained locally.

As already highlighted earlier that the fundamental principles remain the same in all types of CNC machines, the success of this paper would attract a variety of CNC machine types. For example, one of the future improvements to this paper would be to alter the plotter into a laser CNC machine and use the laser to draw sketches and cut soft materials. The bigger papers would then follow, whereby machines like CNC routers, plasma cutters, bigger laser machines would be developed for industrial purposes.

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