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Design and Implementation of Computer Numerical Controlled Milling Machine for Printed Circuit Board Fabrication

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تصميم وتنفيذ آلة تفريز متحكم بها رقميا حاسوبيا لتصنيع لوحات الدوائر المطبوعة

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Abstract:
For several years, printed circuit board fabrication manufacturing has been using acid etching to build electronic boards. However, the evolution of technology required more delicate and precise board schematic diagrams, at the same time Computer Numerical Control (CNC) machines were also improving over the years and proved their accuracy and preciseness. Therefore, the combination of the CNC machine and milling head can achieve precise engraving for the printed circuit board diagram with promising results. This project introduces the basic steps to building a CNC milling machine for a printed circuit board.
Building a CNC machine requires a combination of mechanical, electrical, and computer-controlled systems. In this project, a frame of the machine is designed using aluminum and 3D printed parts, and stress analysis for the machine frame is proposed. Mechanical motors, bearings, and other parts are selected to meet the machine's requirements. Open-source software programs are used to operate the machine based on the computer-designed diagram model. Then, milling was performed on the single-sided copper-clad sheet to construct an electronic circuit to evaluate the machine's performance. Test results confirmed that the machine operated smoothly and consistently as required.

Keywords: CNC machine, printed circuit board, milling machine, Arduino, stepper motor.

الملخص
لعدة سنوات، كان تصنيع لوحات الدوائر المطبوعة يستخدم الحفر الحمضي لبناء اللوحات الإلكترونية، ولكن نتيجة التطور التكنولوجيا مما تطلب الحاجة لمخططات أكثر حساسية ودقة للوحات الإلكترونية، وفي الوقت نفسه كانت ماكينات التحكم العددي بالكمبيوتر تتحسن أيضًا على مر السنين وأثبتت فعاليتها ودقتها. ولذلك، فإن الجمع بين ماكينة التحكم الرقمي باستخدام الحاسب الآلي ورأس التفريز يمكن أن يحقق نقشًا دقيقًا لمخطط لوحات الدوائر المطبوعة. ولهذا يقدم هذا المشروع الخطوات الأساسية لبناء ماكينة تفريز باستخدام الحاسب الآلي للوحة الدوائر المطبوعة.
يتطلب بناء ماكينة التحكم العددي بالكمبيوتر مزيجًا من الأنظمة الميكانيكية والكهربائية وأنظمة التحكم بالكمبيوتر. في هذا المشروع، صُمم إطار الماكينة باستخدام الألومنيوم والأجزاء المطبوعة ثلاثية الأبعاد، وتحليل الإجهاد لإطار الماكينة. كما تم اختيار المحركات والمحامل والأجزاء الأخرى لتلبية متطلبات الماكينة. استخدمت برمجيات مفتوحة المصدر لتشغيل الآلة، استنادا إلى نموذج تخطيطي مصمم حاسوبيا لتفريز صفائح النحاس المغلفة أحادية الجانب، وصممت دائرة إلكترونية لتقييم أداء الآلة. وأكدت نتائج الاختبارات أن الآلة تعمل بسلاسة وثبات كما هو مطلوب.

الكلمات المفتاحية: ماكينة التحكم الرقمي باستخدام الحاسب الآلي، لوحة الدوائر المطبوعة، ماكينة التفريز، أردوينو، محرك الخطوة.

1. Introduction

Milling machines were first developed to mass-produce parts by Eli Whitney in 1818, during the Industrial Revolution. They can be used for slotting, boring, circular milling, dividing, drilling, cutting keyways, racks, and gears [1]. Computer Numerical Control (CNC) machines are machine tools that perform the desired product shape and are operated by a computer-controlled program using specific alphanumeric codes with command data code numbers, letters, and symbols [2, 3]. In CNC systems, the product design is made with computer-aided design (CAD) and is created by computer-aided manufacturing (CAM) programs [4, 5]. CNC milling machines produce unique precision components, prototyping, and complex parts [6]. In modern CNC systems, the end-to-end component design is highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. CNC machine tools are controlled using a control unit that can be saved, modified, and upgraded. Programming of the CNC machine tool can be performed directly using the keyboard and screen through a computer network or transferred with a USB storage device. Today the CNC is a soft-wired system that makes it flexible for different operations. Software controls all the functions and the programming and the computer is responsible for interpreting a language such as G code into the signals that are supplied to the controller [7]. Today, new functionality and improved performance CNC machines are being developed every day, which will give CNC a leadership position in the manufacturing process with an ever-increasing role in the success of our industry. The majority of commercial CNC machines are much more expensive due to their complexity and it is not possible to afford smaller work-pieces and laboratories, so the machines with less size, lighter weight, and budget cost mini CNC machines are affordable [8]. Desktop-size CNC milling machines are designed for small and precise measurement exclusively used in classrooms, offices, or garages for education, prototyping, or making one-off parts [9], and have recently joined newer technologies for rapid prototyping for different shapes using different milling strategies. The utilization of compact machinery for the fabrication of diminutive-sized goods offers a myriad of distinct advantages. These include a significant reduction in the consumption of both space and energy, a marked decrease in vibration and noise levels, and a lighter weight for the moving components. Furthermore, these small-scale machines provide enhanced flexibility, improved portability, and a lesser environmental impact in the form of reduced pollution. Notably, they also enable faster operation at a lower cost. However, the primary drawback associated with this approach lies in the prerequisite for skilled labor and the elevated initial investment. Remarkably, the need for a seasoned operator can be effectively mitigated by the provision of a more user-friendly, graphical user interface software. These days CNC machines have found extensive applications in almost all industries, for machining metal, wood, fabric, foam, acrylic, glass, and plastics, mostly using a laser, milling cutter, or drill as cutting media [10]. The main aims of the current work are to design, analyze, fabricate, and test a low-cost, easily operable, flexible, small prototype 3-axis vertical CNC laboratory educational milling machine developed for purposes of student experiments in CNC and CAD/CAM programming areas. The produced machine should have an easy interface that can interpret standard G-M codes, low power consumption, safety, and durability; The Fabricated prototype was calibrated and self-tested.

The main motive of this work is the lack of local manufacturing of a printed circuit board (PCB) in locally; therefore, designing a CNC machine that would print any desired design needed for various types of PCBs could be the solution to this problem. The majority of commercial CNC machines are very expensive due to them being complex and not possible to afford for smaller work-pieces and laboratories, Therefore, designing a small CNC machine would be more cost-efficient. In addition, one of the important motives is the knowledge obtained through this project, especially in the fields of computer programming, electronics, and mechanical components selection and assembly, eventually combining these three fields of engineering in what is known as Mechatronics engineering.

The project objectives are to design and construct a CNC machine with the materials and components available in the local market. And accomplish the required design in a low-cost and affordable way that makes it constructible and easy to use. The paper is organised as follows. The system Components are presented in section 2. The system testing and project results are discussed in section 3. The conclusion and its potential future improvements are given in section 4.

2. System Components

The mechanical and electrical system components and software in the proposed design of 3D printed parts to achieve the objective are as follows:

A) Mechanical system components:

- Linear bearings (see table 1), LM type is the linear motion system with unlimited stroke by applying with LM shaft. Because of the point contact between the Balls and the LM shaft, minimum friction can be acquired, giving high-precision motion.

- Ball bearings with seals are particularly versatile, have low friction, and are optimized, for low noise and low vibration.

- Cutting tools are typically made from a solid carbide composite, a material typically composed of tungsten carbide and cobalt. Its high hardness and corrosion resistance, making it suitable for prolonged use and withstanding harsh conditions, characterize this material.

Table 1: Mechanical system parts.

Part	Dimension (mm)
Linear bearings dimensions	inner diameter 8 x outer diameter 15 x length 24
Deep groove ball bearing dimensions	inner diameter 8 x outer diameter 22
Chrome shaft	diameter 8 x length 400
Lead screw	diameter 8 x pitch 2 x length 400
Split nut	inner diameter 8 x outer diameter 22

- Chrome-plated induction shafts are mechanical components used in many applications requiring high rigidity and durability. The chromium-plating layer mainly increases the resistance to corrosion and chemical corrosion. Chromium is naturally resistant to corrosion, so chrome plating reduces the likelihood of damage to the connecting rod from exposure to harsh environments or oxidizing chemicals. The chrome shaft material C45 high carbon steel, hardness 57-62 HRC, cross-section diameter 8mm (tolerance -0.005 to 0.03mm) and length 400mm (tolerance 0 to 0.5mm)

- GT2 Timing Belt and Pulley, the GT2 pulley with 20 teeth is one of the popular choices for 3D Printer construction, Laser Engraving, Precision Positioning, Assembly Line, and other transmissions, etc.

- GT2 pulley 6mm belt 20 teeth inner diameter 5mm, for precise motion control, this pulley is designed for use with GT2 belts that are only 6mm wide.

- Lead Screw & Split nut, the power screws (also known as translation screws) are used to convert rotary motion into translator motion.

-Rigid coupling aluminum, it acts as a connector between the stepper motor shaft and the trapezoidal screw. The coupling has the form of a solid block of Aluminum with two mounting holes: with a diameter of 5 mm for installation on the stepper motor shaft and 8 mm for the trapezoidal screw. Additionally, there are holes with pressure screws in the body. The total height of the product is 25 mm, and the outer diameter of the whole block is 14 m.

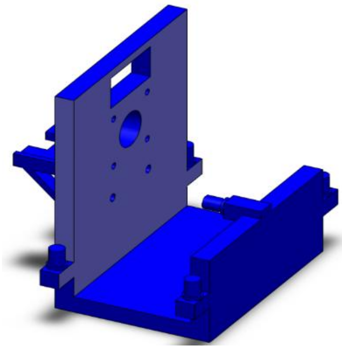
-Main Frame**,** it consists of Three Aluminum hollow beams of 2 cm in width, 4 cm in height, 45.5 cm in length, and 1.5 mm in thickness. In addition, a wooden beam is added at the base to increase rigidity. To transmit the rotary movement of the motors into linear movement at the CNC machine axis, customized parts are required to mount the motors and the other parts on them, therefore, two designs were proposed to accomplish this task, as shown in Figure 1 and Figure 2. The two designs were compared based on stress and failure to select the optimum one of them.

Using SolidWorks CAD software, a stress analysis is performed on the CNC machine frame and 3D printed parts of the two introduced designs, Figure 1 and Figure 2 demonstrates the result of the stress analysis. The stress analysis shows that the maximum stress is below the yield stress of the material but the maximum deflection is 0.14mm for the first 3D model, which is a bit high for this application. The stress analysis shows that the maximum stress is below the yield stress of the material also the maximum deflection is 0.002mm for the second 3D model, which is suitable for this application. Eventually, the selected model is the second model for its lower deflection.

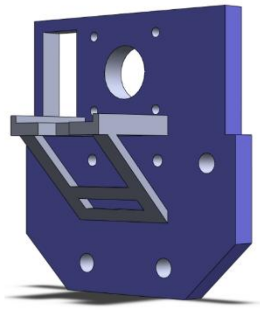
B) Electronic System Components:

This section covers all the electronic and electrical components of a CNC mill machine for PCB and helps understand how they work with other components to form a functional machine.

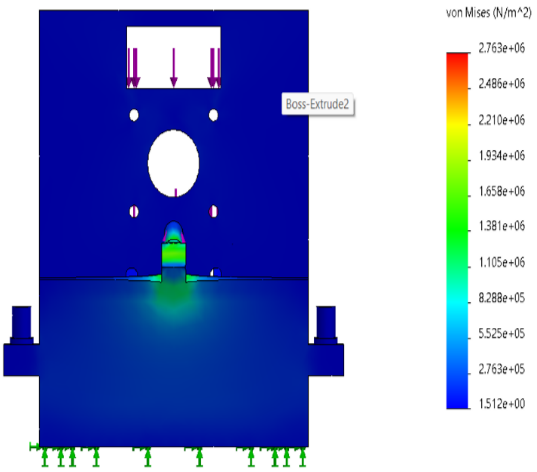
This machine consists of three main electronic components with different power ratings. They are a microcontroller board, a small portable drill, and a CNC shield. The microcontroller board is typically powered via a USB port or an external power supply (5V). The power required to drive the CNC shield and the drill is around 12V/DC. Therefore, there is a need for a power converter to convert the normal 220V/AC to the required DC value. The power supply consists of two inlets of 110/220V AC converted to four output channels of DC voltage; two channels of +12V and two of 12V. It also contains a potentiometer that allows the voltage to be adjusted to about ±15% of the voltage value. The maximum power of each channel can reach 120W and the Total output current of these channels is 10A.



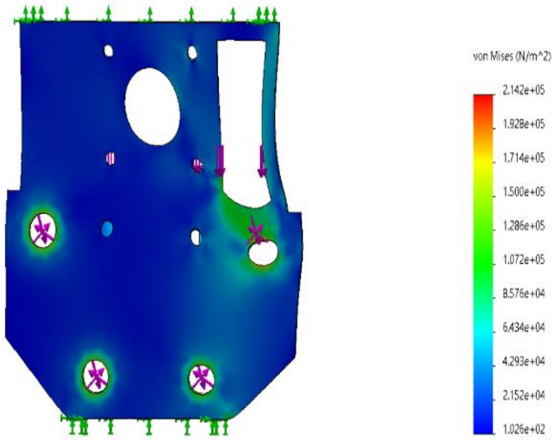
First 3D model



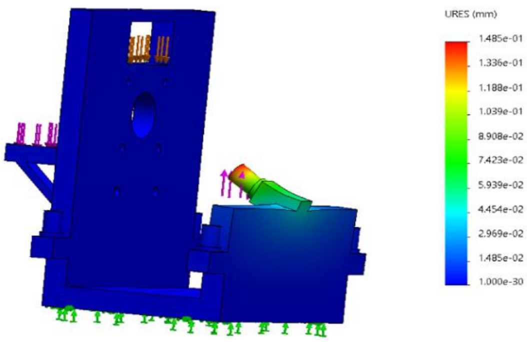
Second 3D model



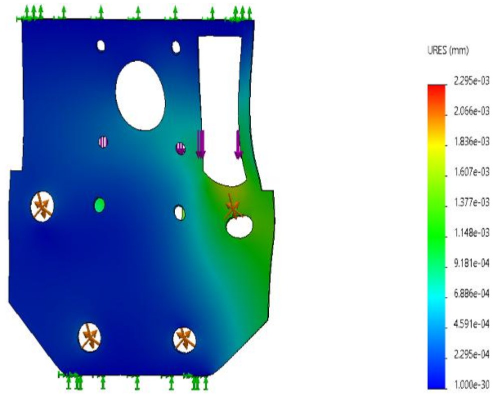
First 3D model stress distribution.



Second 3D model stress distribution.



First 3D model displacement profile.



Second 3D model Displacement profiled

Figure 1: Main machine shoulder design no. 1.

Figure 2: Main machine shoulder design no. 2.

-The microcontroller board (Arduino Uno) is the brain of this CNC. It contains an ATmega328p chip, where the programs can be stored, which tells the microcontroller what to do.

- Stepper motors: The X, Y, and Z axes are all independently controlled stepper motors stepper motors are bipolar, meaning there is only one winding per phase. A full 360º degree circle divided by the step angle gives the number of steps per revolution, 1.8 degrees per full step, which equals 200 steps per revolution. Its specifications are shown in Table 2.

- The Mini DC Drill (see Figure 8) has a high rotation speed of up to 20,000 RPM. It can be used in several precision applications such as drilling holes in thin metals, wood, and plastic. It can also be used for wood carving and segmenting thin copper and small stones.

Table 2: The specifications of the stepper motor.

Name	Nema17 Stepper Motor
Model	17HS4401
Step angle	1.8º
Motor length	40 mm
Rated voltage	12VDC
Rated current	1.7 A
Phase inductance	1.5 mH
Holding torque	40 N.cm
Motor weight	280 g

C) SOFTWARE:

The following section introduces the used software for circuit CAD designing, CAM G-code generation, and CNC machine commands for the microcontroller.

- Easy EDA is an open-source software that enables the user to draw and design their PCB board to print it or use it in other software. Figure 3 shows the generated circuit from this software was used in another software to generate the required path to engrave the PCB.

- FLAT CAM is an open-source program for preparing CNC jobs for the stepper motor of a CNC router. It requires the Gerber file generated by the previous CAD program and then creates a G-Code for isolation routing. Figure 4 shows The generated circuit using the Flat CAM program. For this application, the user is capable of specifying the dimensions of the grooves, the type of cutting tool, cutting depth, drilling speed, and cutting speed. Finally, the user can export a G-code file to other software to run the CNC.

- Universal G-code Sender: It is a free and full-featured G-code platform used for interfacing with advanced CNC, which sends the G-code to the microcontroller to actuate the motor of the CNC. Figure 5 shows the generated G-code to run the CNC.

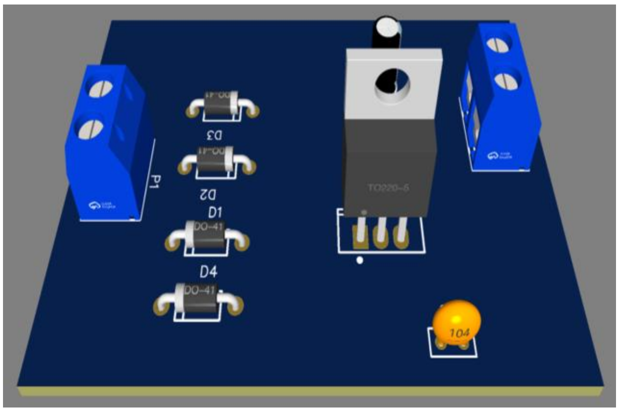


Figure 3: The generated circuit using Easy EDA software for a voltage regulator circuit board.

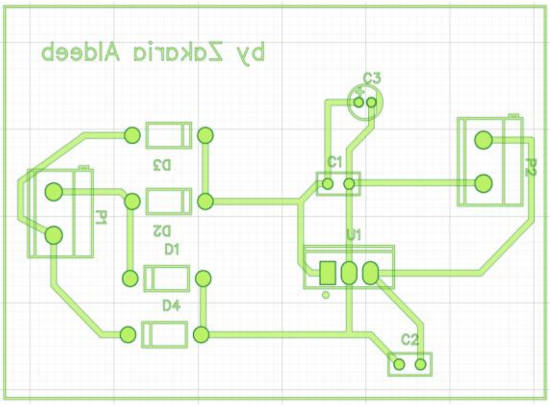


Figure 4: The generated circuit using the Flat CAM program for a voltage regulator circuit board.

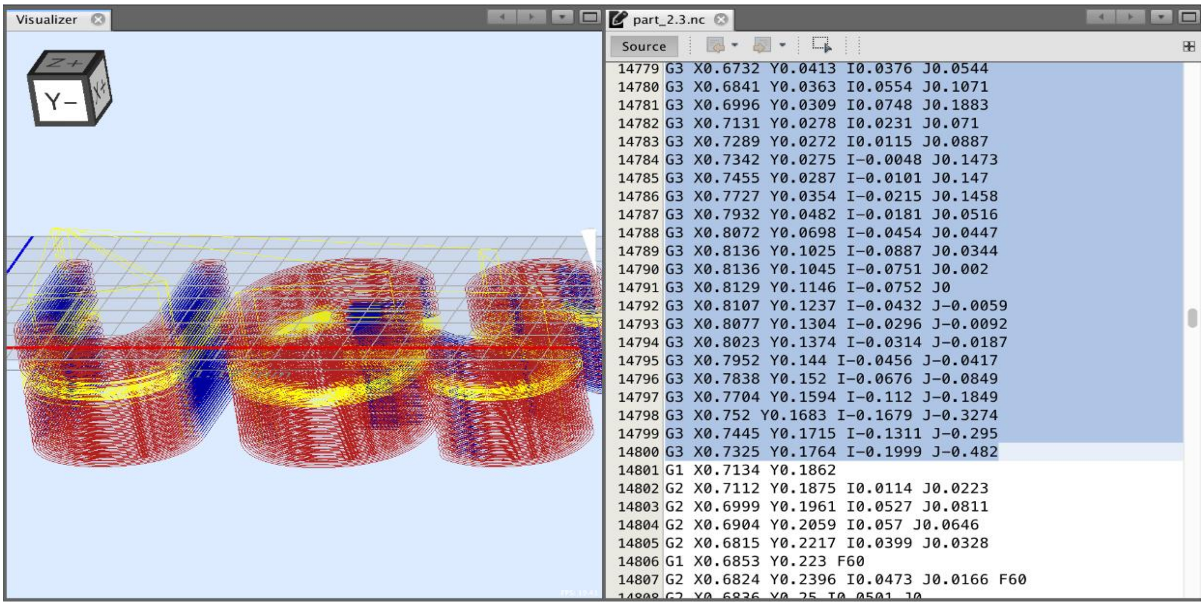


Figure 5: The generated G-code to run the CNC.

3. Evaluation results

In this project, there is more than one system and component, so there is a need to ensure they work together properly. The next sections show the results and the tests of these components.

3.1 CNC operating error:

To measure machine carving error, geometrical shapes with defined dimensions were used to compare them to the actual carved shapes that were measured using a Caliper and multiple points. Table 3 contains the actual dimensions and the measured dimensions of the square shape, the circle shape and the crossed lines. The error results in the tables show that tolerances are very small and they are within the acceptable range for the PCB applications in the general cases (No special high-resolution specifications are required).

3.2 Depth Error Compensation:

To perform a leveled cut on the workpiece the bottom surface of the CNC machine and the workpiece, had to be leveled, however physically it was quite difficult to perfectly flat the surface. To compensate for this problem, CNC software is used to measure how far is the surface from the milling bite, and then a depth map is reconstructed, therefore the machine itself is based on the depth map, Figures 6, and Figure 7 show the depth map and the compensated path.

Table 3: Tolerances between the defined and the engraving of shapes using the CNC milling machine PCB.

Test no.	Shape	Defined (cm)	Actual (cm)	Tolerances (cm)
1	square (length x width)	5x5	5x4.990	0x0.01
2	square (length x width)	5x5	4.995x4.992	0.005x0.008
3	square (length x width)	5x5	5x5	0x0
4	circle diameter	3	2.99	0.01
5	circle diameter	3	2.98	0.02
6	circle diameter	3	2.945	0.055
7	angle((intersecting lines)	45°	44.8°	0.2°

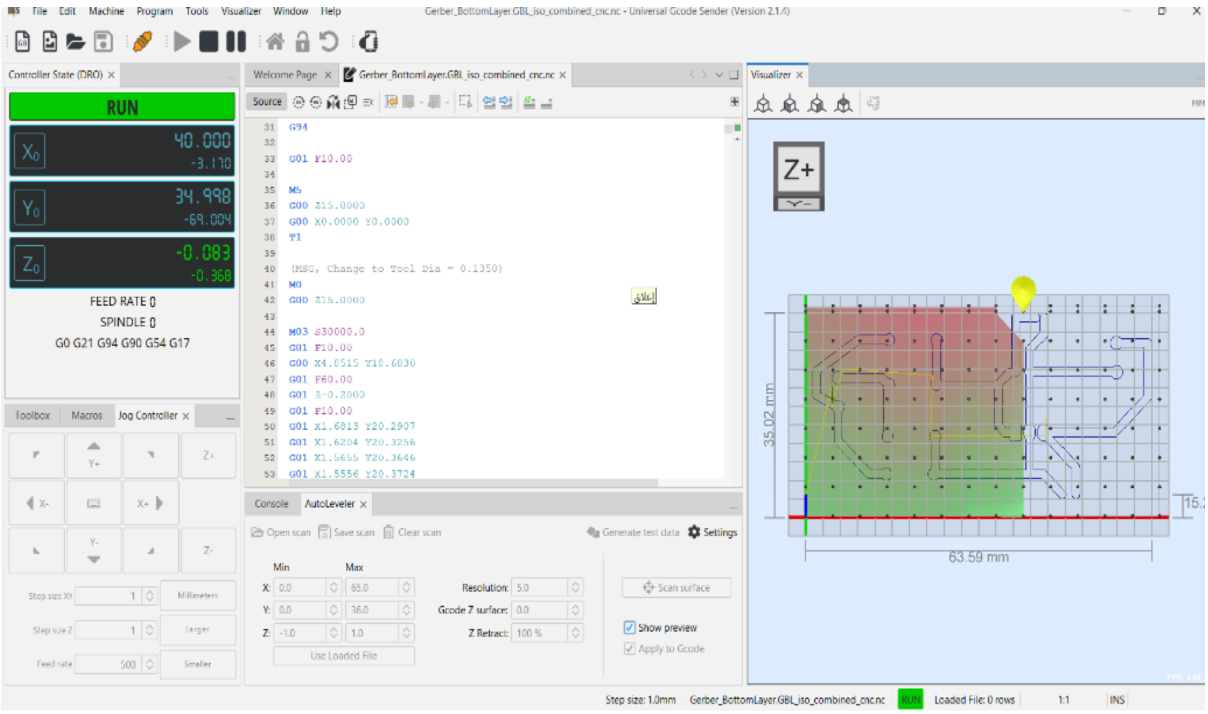


Figure 6: The machine depth map.

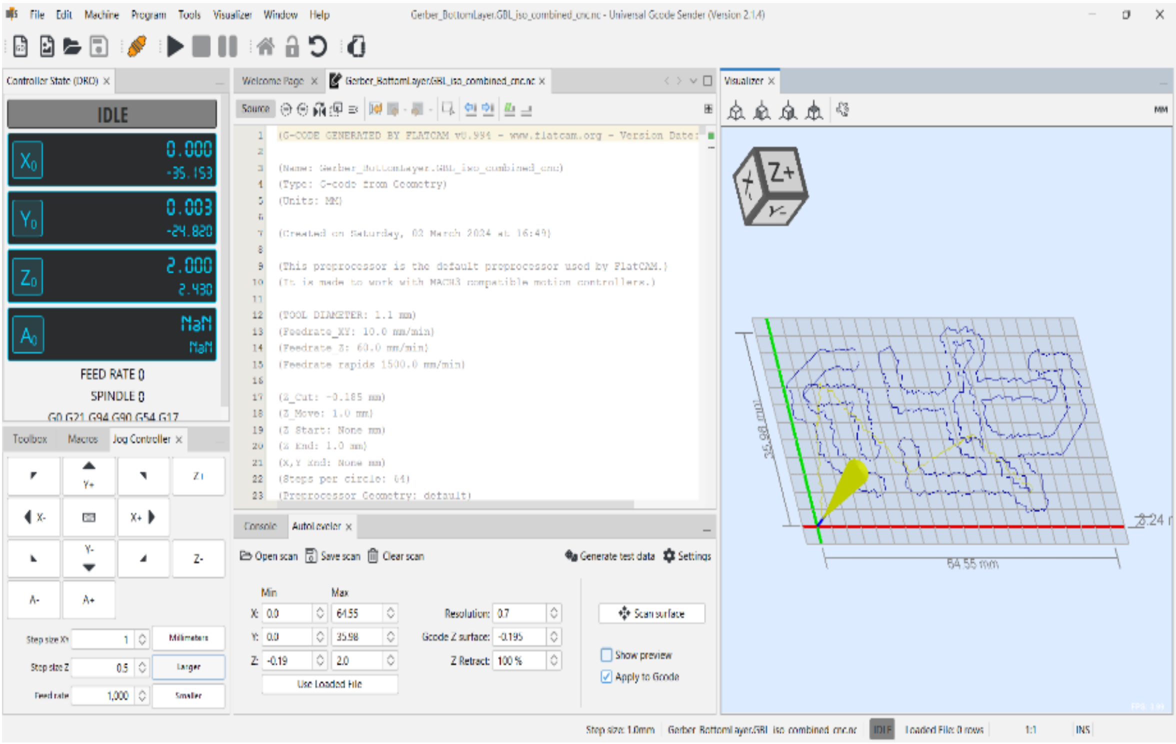


Figure 7: The compensated path.

3.3 Milling a PCB circuit diagram:

The image in Figure 8 shows the final assembly of the CNC machine, including the DC micro-drill and the main machine shoulders. Figures (9, 10) show the result of the CNC machine after milling a voltage regulator circuit board on a PCB sheet. Figure 9 shows that the mid-run of the engraving process was smooth and straight before it abraded all the copper; there wasn't fluctuation in the grooves or any misalignment, which is a good indication of successful progress in the milling process. Figure 10 shows the final result after the bit abraded all the surface copper, reaching the plastic underneath.

As shown, the grooves are clear and have no copper left, indicating a successful milling process. In addition, there is no current flow in the grooves, which is the main required feature in any circuit board. Finally, the results were remarkably decent considering the machine's accuracy and capability.

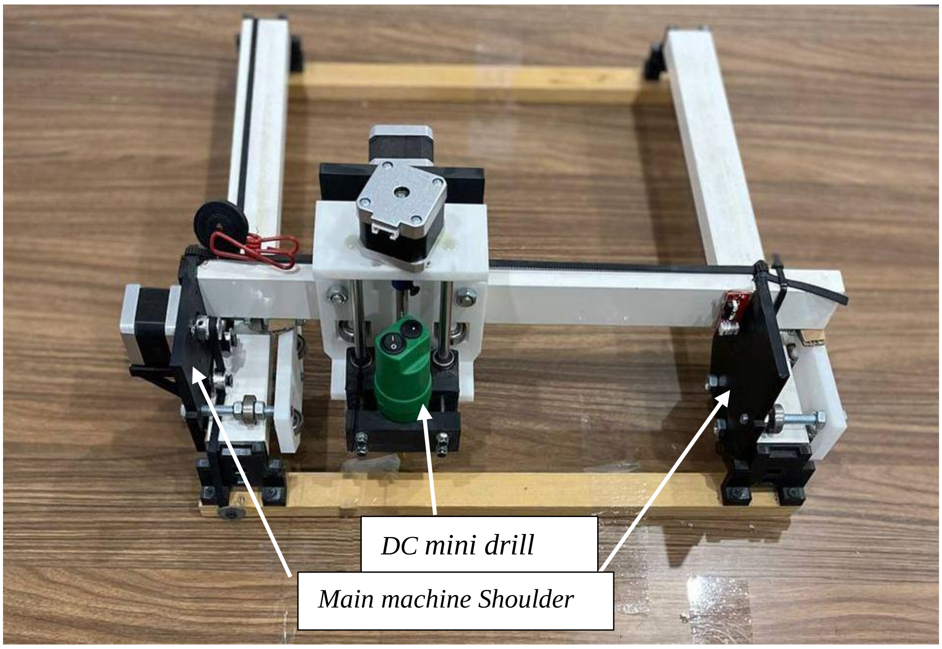


Figure 8: Assembled computer numerical controlled milling machine for printed circuit board Fabrication.

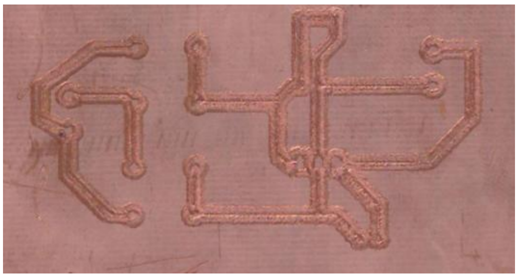


Figure 9: Circuit Board half-depth milled using single-sided copper-clad laminate.

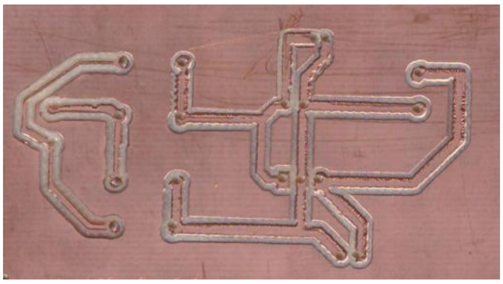


Figure 10: Circuit board full-depth milled using single-sided copper-clad laminate.

3.4 Comparing Computer Numerical Controlled machines for Printed Circuit Board

Table 4 compares the differences between the CNC for PCB and the two previously designed CNC plotter and milling machines regarding the type and number of motors and the software used. Refers to [11] “the CNC milling machine is made to engrave and cut shapes and data on a rectangular coordinate system. The machine contains 4 stepper motors that control the 3 axes X, Y, and Z (Y-axis requiring 2 steppers) held in place with a combination of a wooden frame and 3 Dimension printed parts that were designed, a printed circuit board was designed and used with a microcontroller to move the stepper motors after interpreting the g-code that was streamed from a USB and the cutting tool as a variable speed spindle. The prototype CNC worked well, and some designs and models were made successfully”. It is noted that the Y-axis requires 2 steppers; it needs a greater driving force that can be compensated for by using a larger motor and placing it in the appropriate place to maintain the balance of movement in the Y-axis.
Building a mechanical prototype of a CNC plotter machine can draw any image or text on a given solid surface as described in [12]. “It is made with easily available components and spare parts. The machine is designed with a very simple construction scheme and can be carried anywhere without much effort. The algorithm used is simple. The pen can be replaced with a pinhead laser head or any other tool for different purposes of use. Software that has been used is open source”. It is noted that a servomotor is used in movement in the Z-axis because the required movement is limited between two positions.

Table 4: compares the differences between the CNC PCB, CNC plotter and milling machines.

Machine	CNC plotter machine	CNC milling machine	CNC PCB
Motor	3 full-step stepper motors 1 servo motor	4 Stepper Motors	3 Stepper Motors
Driver	H-Bridges	IC (DRV8825)	IC (DRV8825)
Microcontroller	Arduino Uno		
Software	Inkscape software is used to draw the image. Grbl controller software is used to stream the G-code to the Arduino.	SolidWorks or AutoCAD is used to draw. Grbl controller software is used to control the motion of machines. OpenBuilds CAM is a web-based application for converting SVG, DXF, and Bitmap drawings to GCODE for use with your CNC, Laser, or Plasma.	Easy EDA or KiCad is used to draw and design PCB boards to print them. FLAT CAM is an open-source program for preparing CNC jobs for the stepper motor of a CNC router. Universal G-code Sender: It is used for interfacing with advanced CNC, which sends the G-code to the microcontroller to actuate the motor of the CNC.

4. Conclusion

In this project, a CNC milling machine was constructed and programmed to make a PCB board. The construction process started by building a frame for the machine, selecting the required motors, parts, and material, and then using open-source software to operate the machine through an Arduino Uno microcontroller and CNC shields.
A stress analysis for the frame of the machine and the 3D-printed parts had been done to ensure the reliability and strength of the machine. In addition, the electrical components had been tested and calibrated to work within the rated range. Correspondingly, the variables of the software had been tweaked to meet the required feed rate and speed for milling. In the end, the machine is evaluated the cutting was acceptable within the requirement with an average error of (0.08%) for Square Shape, (0.94%), and (0.4%) for Circle Shape and 45º Angle Line Shapes, respectively. As shown, in Figures 9 and 10, the grooves are clear and have no copper left, indicating a successful milling process. Moreover, there is no current flow in the grooves, which is the main required feature in any circuit board. Consequently, the machine worked smoothly and harmoniously as required. Furthermore, all components were inexpensive and locally manufactured, and assembled, and could be improved in the future with more precise components and higher-quality copper plates.

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