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Design and Fabrication of 3-Axes Mini CNC Milling Machine

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Abstract. The main aims of the current work are to explore the theoretical and technical procedures for design, fabricate, assembly, and testing of the electromechanical subsystems for developing a high precision cost-effective mini three-axis vertical CNC milling machine with an easy interface, high speed, less power consumption, safety and durable for rapid prototyping machining, small parts and engraving small features in the electrical and medical industry. The new Mach3mill G-Code CAD/CAM software package runs on a PC and turns it into a very powerful and economical machine controller. The 3Axis CNC driver board type Kit TB6560 was used as a micro-stepping drive for the smooth drive of the selected stepper motors. The fabricated prototype CNC milling machine with an easy interface that can interpret standard G-M codes. The fabricated machine router was tested and calibrated to determine its accuracy in different position modes for surface flatness, axes perpendicularity, and several geometric accuracies such as positioning, straightness under specific tool paths, and feed rate. The results misalignment lay around +0,01 and -0,01 mm. This means that the fabricated prototype machine movements contain 0.13° tilting on X-axis and 0.22° tilting on Y-axis. After comparison and making the required improvements in both electrical and mechanical design, the machine is in a position to milling a complex contour on soft metals with considerable accuracy and speed.
Keywords. 3 Axis CNC mini milling machine, Mach3Mill, G-Code CAD/CAM, ArtCAM software.

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 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 [4-6]. CNC milling machines produce unique precision components, prototyping, and complex parts [7-8]. 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 [7, 9]. Today the CNC is a soft-wired system that makes its flexibility for the different operations. Software control all the function and the programming and the computer is responsible for interprets a language such as G code into the signals that supplied to the controller [10-13]. Today, new functionality and improved performance CNC machines are being developed every day, which will give CNC a leader position in the manufacturing process with an ever-increasing role in the success of our industry. The majority of commercial CNC machines are much expansive due to it complex and not possible to afford for smaller workpieces and laboratories, so the machine with less size, lighter weighted, and budget cost mini CNC machines are affordable. [14-16]. Desktop size CNC milling machines are designed for small and precise measurement exclusively used in classroom, offices, or garages for education, prototyping or making one-off parts [12, 17-18], and has recently joined newer technologies for rapid prototyping for different shapes using different milling strategies [10, 12]. There are several advantages of using small machines to produce small-sized objects, space, and energy saved, less vibration, noise weight of the moving component, more flexible, portable and pollution to the environment and faster operation with lower cost [13, 17], while the main disadvantage is the requirement of skilled labor and the high initial cost. The need for a skilled operator is eliminated by providing a more user-friendly graphical user interface software [1, 19]. These days the CNC machines are 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 [19-21]. The main aims of the current work are to design, analyze, fabricating, and testing 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 durable. A newly motion controller using Arduino and TI MSP430 was also tested and implemented to reduce cost. The fabricated prototype was calibrated and self-testing to meet the industrial standard.

2. Materials and methods

2.1 Design overview of CNC vertical milling machine

The CNC vertical milling machine is consisting of X-Y axes for table movements and a third Z axis for the spindle cutter linear drive movement, base, and frame. The complete control unit of the machine consists of the CNC control card and the computer. The accurate rotations are providing by using stepper motors [8]. The main design requirements are functional and derived requirements. The functional requirements are a set of derived requirements that necessary to complete the design of the machine [17]. The CNC milling machine mainly consists of the mechanical components (includes the structure, i.e., the base, support structure, lead screws, beams, bearing, etc.), the electrical system (consists of the motor, motor control unit, interfacing, and power unit) and the control or computing system to positions the tip of the milling cutter at the required position. The selection of the motion control system and the linear motion components accomplished by linear guideways and drive screws is an important part of the prototype milling machine design. The screws can be driven by some motors using an open or a closed-loop control system. The structure of the CNC machine consists of the mechanical, drive, measuring, and control systems. The kinematic modules for the functional systems (supports, stands, and bearing support system) and the drive systems for leading (sliding and roller guides) and measuring systems for circular and linear movement are built in the structure. The module of the main spindle consists of several essential functional parts (the spindle shaft, the housing, axially spaced roller bearings, electric drive motor, internal cooling system, and system for clamping and releasing tools [9]. The primary design considerations for building a CNC milling machine are:

- The maximum work piece size (maximum travel along the axis) is selected as: X = 350, Y = 400 and Z = 220 mm.

- Different configurations can be considered for the qualities; provides better rigidity, better accuracy, ease of operation, and ease of programming.
- The machine structure (the "backbone" of the machine), integrates all machine components the tool. It is crucial to the performance of the machine since it is directly affecting the static and dynamic stiffness, the damping response. Typically, the closed frame structures are used in precision machines.
- The required screw accuracy = 0.01 mm [8], that can be achieved by using a step of motor = 2°, pitch of lead screw (P = 1.8 mm), then the screw accuracy P x (2°/360°) = 1.8 x (2/360) = 0.01mm. Although the usual accuracy of the movement of the CNC milling machines is 0.001 mm, the precision designed for the machine is sufficient, and accuracy of 0.001 mm can be obtained by using a precision step of motor = 0.2°, that is with a higher price, which increases the price of the machine, and this will be the opposite of the goal of building the machine at the lowest possible price.
- The power required at Y-axis sub-assembly will be maximum. To calculate the power required, take the coefficient of friction, $\mu = \tan\phi = 0.0025$, The screw diameter (d) = 16 mm, the table lead screw angle (α), then [19]:

$$(\tan\alpha = p/(\pi d) = 1.8/(\pi x16) = 0.0358 \tag{1}$$

The maximum workpiece mass on a lead screw in Y-direction, M = 5 kg

$$\text{The external force, } F = M \text{ x } g = 5 \text{ x } 9.81 = 49.05\text{N} \tag{2}$$

$$\text{The frictional force, } F_f = \mu \text{x } M \text{ x } 9.81 = 0.0025 \text{ x } 5 \text{ x } 9.81 = 0.126\text{N} \tag{3}$$

$$\text{The total force, } F_T = F + F_f = 49.05 + 0.126 = 49.18\text{N} \tag{4}$$

The tangential force required at the circumference of the table screw is [19]:

$$F_t = F_T \times [\tan\alpha\tan\phi] \; / \; [1 - \tan\alpha \times \tan\phi] \tag{5}$$

=49.18 x [0.0358+ 0.0025] / [1-0.0358x 0.0025] = 1.884 N

The torque required for the table screw rotation is:

$$T = F_t \times d/2 + m \times F_T \times R \tag{6}$$

= 1.884 x 16/2 + 0.0025 x 49.18 x (16/2) = 16.0537 N-mm = 0. 161 Kgf-cm

The maximum speed of the table lead screw, N= 40 rpm, then the angular speed is:

$$\omega = 2\pi N / 60 = 4.19 \text{ rad/sec} \tag{7}$$

$$\text{The power required, } P = T \times \omega = 0.161 \text{ x } 4.19 = 0.674 \text{ W} \tag{8}$$

3. Fabrication and assembly of CNC milling machine

The structure frame of the machine consumes less amount of material; hence it is less expensive to build. The mechanical system is assembled with the 3-axis movement by using the linear rails with linear bearings. The stepper motors are mounted to each axis of movement and coupled through the shaft couplers to each of the lead screw axes. Each table lead screw was supported by using two bearings [19], one at each end. A total of six 1900 series bearings are selected with a bore diameter of 16 mm, outer diameter = 30 mm, and thickness = 9 mm. The linear motion of each axis is carried away smoothly by the linear rail assembly connected to each axis. The liner sliding blocks consist of the hardened steel linear

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guideway rail and recirculating ball bearing [17]. The speed of the motion in each axis can be directly controlled by controlling the speed of the stepper motor, which is an electromechanical device that converts the required electrical control signals (pulses) into discrete mechanical movements [3]. The selected stepper motors are a brushless, synchronous electric motor that converts digital pulses into some shaft rotation of equal steps. This is an open-loop controller, where the motor's position can be commanded to move and hold at one of these steps without any feedback sensor. A three CNC-Kit-TB6560-Driver-Board-3x-Nema-17 stepper-motors-PSU was chosen to drive the motion of the axes as shown in Figure 1, with about 4.4 KG-cm holding torque, 1.8-degree step angle, 10 A rated current, 12 V supply voltage with a weight of 0.35 Kg each.

Figure 1. The 3Axis-CNC-Kit-TB6560-Driver-Board-3x-Nema-17-Stepper-Motor-PSU.

A smooth anti-corrosion stainless steel linear movement guides rods are used to carry the load without affecting the motion and supports linear movement, as shown in Figure 2. High quality four pieces 16 mm aluminum linear slide bearing with a slide block bushing guide rail of type SCS12UU to provide free motion in a linear direction and reduces friction slides over linear rods shaft was used for mounting the linear rail rods for each coordinate movement, as shown in Figure 3. A four pieces aluminum 16 mm horizontal light linear shaft end support blocks for XYZ table type CNC SHF12 series were used for end or intermittent support to support linear rods /shafts without slip, where light loads are and slight shaft deflection is not a concern, as shown in Figure 4. Six roll bearings with an inner diameter of 15 mm were used to support the lead screws ends of the machine to reduce rotational friction and support radial and axial loads, as shown in Figure 5.

Figure 2. The stainless-steel linear movement guides rods.

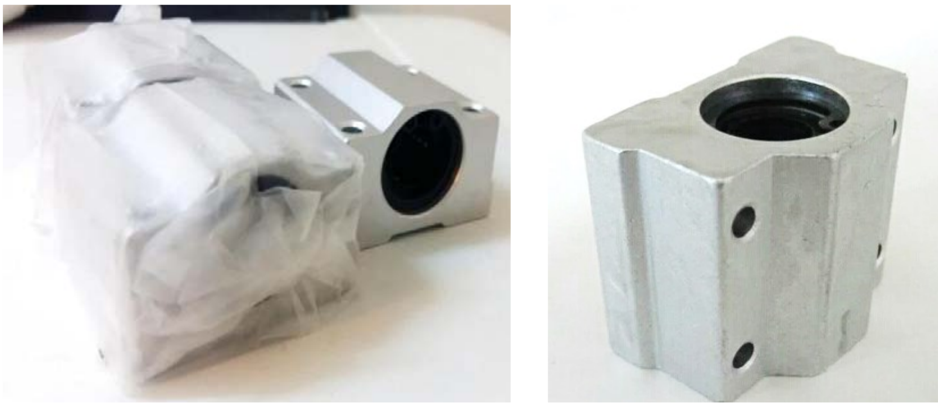

Figure 3. The aluminum linear motion ball bearings.

Figure 4. The aluminum 16 mm horizontal linear shaft support.

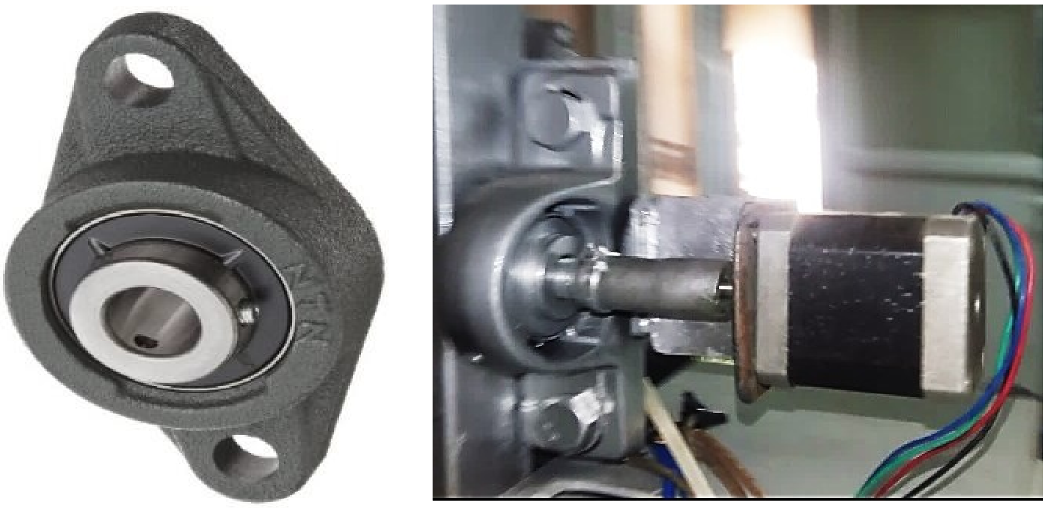

Figure 5. The roll bearings used to support the lead screws ends of the machine with stepper motor connecting coupling.

To transmit the necessary power for the cutting process for each linear movement of the machine, a shaft coupling was used to connect each lead screw end with the stepper motor by using a key [3], as shown in Figure 6. Coupling is used to connect the shaft of the stepper motor with the lead screw.
The spindle for the milling machine motor prototype was selected at a reasonable price [17]. A DC 12-24-36-48V, CNC 300W power, 3000-12000 RPM, 400mN.m torque brush vertical spindle motor, with a mounting bracket, was used for holding the vertical milling cutters as shown in Figure 7. The tool holding collet chuck portion length for arbor parts 43mm, including the nut and sandwich and the part chuck diameter = 16 mm.

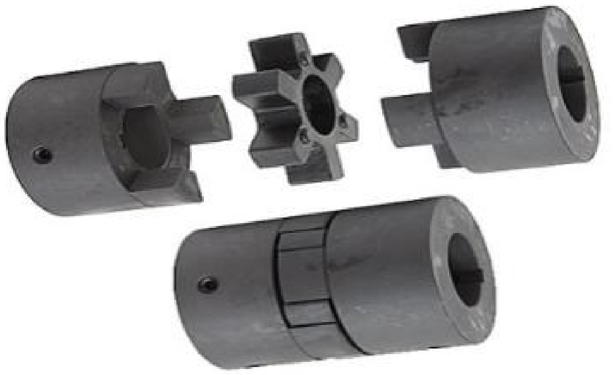

Figure 6. The lead screw end - stepper motor used coupling.

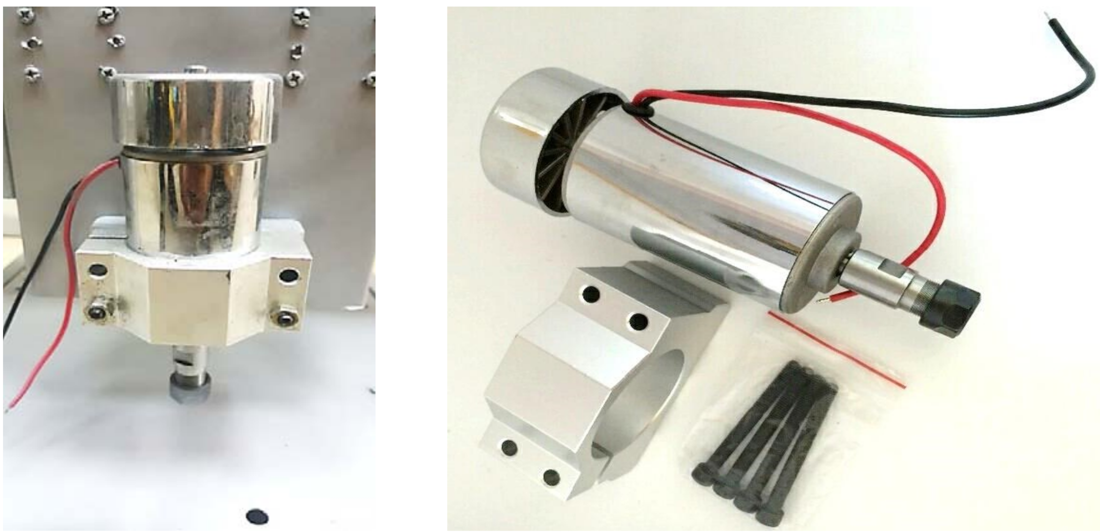

Figure 7. The CNC vertical milling spindle motor.

The work tables are made up of a carbon steel thick plate material used to move the workpiece in an X to Z coordinate system. At the backside of each work table, a ball bearing was fixed through which the guide rods for any axis are sliding. The assembly process for the CNC milling machine was implemented by fitting the machine components. The interlocking parts fit together exactly as planned with the adjustments needed to fit the parts together by clamps. Small tack welds were used to hold the components together, and after all components were fit, the assembly was joined by using the arc welding process. The frame assembly was completed by welding four rectangular cross-section pipes beams together to form the top and bottom part of the frame. The other four beams are bolted vertically to these portions to form the frame structure. Two beams are placed horizontally along X-axis and bolted to the vertical beams to form the guides for the X-axis base. Two bearings are placed on either side of the X-axis screw, as shown in Figure 8. The motor was connected to the lead screw by using the bushing coupling. The Y-axis was assembled in a similar construction of the X-axis sub-assembly. The Z-axis is also similar in construction to the X-axis sub-assembly, where a mid-plate has a provision for the attachment of the milling motor. After frame components were fully assembled, the linear guideways, the lead crews, and other components necessary to attach the Z-axis assembly to the primary frame were installed. Figure 9 shows the final assembly of the fabricated prototype milling machine.

Figure 8. The assembly attachment for X-axes linear movement.

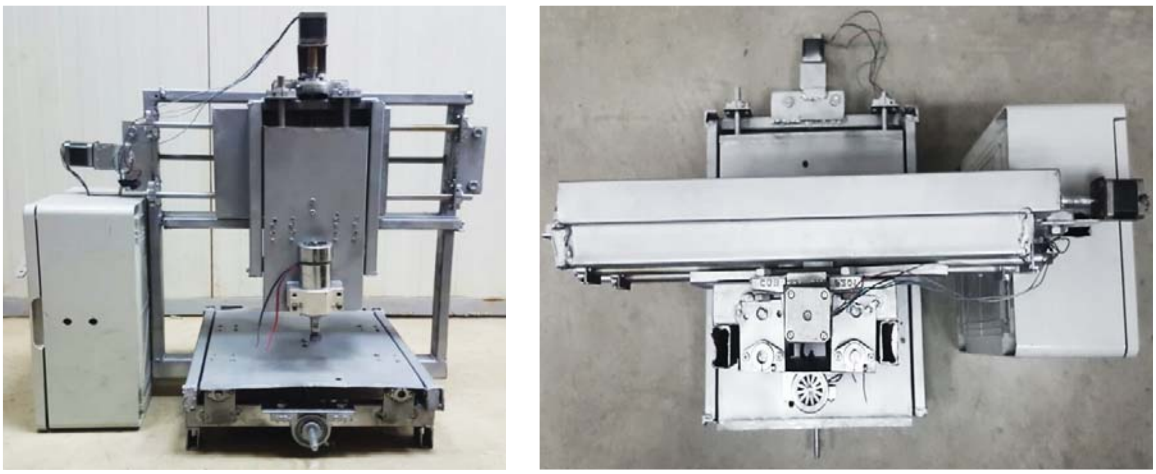

Figure 9. The final fabricated prototype milling machine assembly.

4. The electronics system

The electronics system is responsible for generating a control signal to the stepper motors that guide the motion of the tool path in each axis or direction [10, 19]. The electronics system contains the power supply, the microcontroller board, and the stepper motor driver board. The power supply converts the AC voltage to DC voltage and supplies required voltages to the corresponding devices. The microcontroller board receives 12V, whereas the stepper motor board receives 12-48V. A 48V, 2.5A for switch mode power supply (SMPS) adapters were used for the stepper motors mounted in X and Z directions. A 24V, 2.5A for SMPS adapter used for stepper motor for the machine spindle mounted in the Z direction and a 12V, 1A for SMPS adapter used to drive the microcontroller board. The 3axis 48V/10A connection diagram is shown in Figure 10. The 3-axis CNC driver microcontroller development board type Kit TB6560 is chosen here to control the motion of the system, as shown in Figure 11. It is the brain of the CNC system which receives the commands from the software system from the computer connected through the USB serial port. The Kit TB6560 board is flashed with the GCODE interpreter code which was written in the C language, which is responsible for generating the control signal for the corresponding command signal from the computer system to the stepper motors, which directly controls the motion of the tool path, which is carried away through output pins connected to the stepper motor drives according to the firmware code in the microcontroller. The 3-axis CNC driver board type Kit TB6560 was also used as a micro-stepping drive designed for smooth and quiet operation to drive the selected stepper motors shown in Figure 12. The stepper motor driver board receives the control signal from the microcontroller board to the terminals PULSE and DIR, which generates the corresponding digital pulse signals for four stepper motors to control the rotation of the motor.

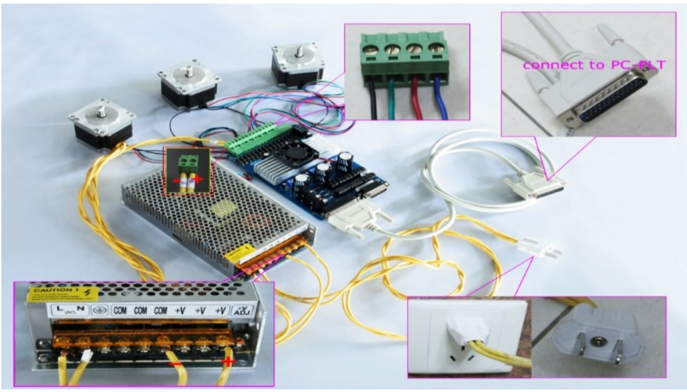

Figure 10. The 3axis 48V/10A connection diagram for switch mode power supply (SMPS) adapters.

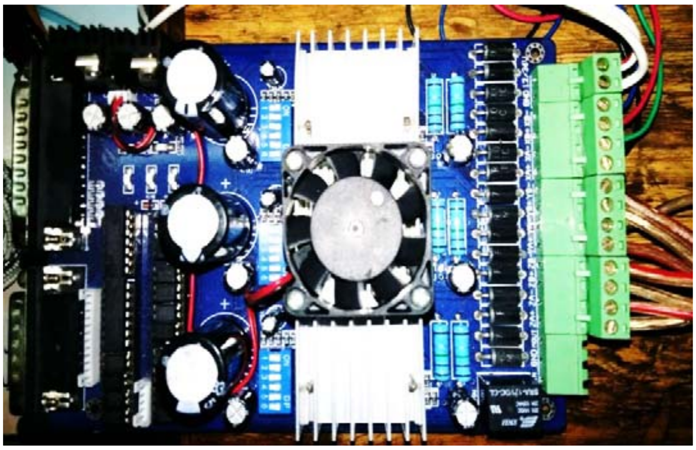

Figure 11. The 3-axis CNC driver microcontroller development board type Kit TB6560.

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Figure 12. The 3axes CNC Kit TB6560 driver board with the stepper motors.

The electronics circuit wiring of the various components of the electronics system is illustrated in Figure 13 below, with the final electronic board components. The microcontroller board is connected to the computer system through the USB serial port. The stepper motor driver board terminals PULSE and DIR of each Board are connected to the microcontroller terminals from 2 to 7 pins (2 terminals for each axis stepper motor driver). Terminals of the stepper motor driver board are connected to the 4-lead stepper motor directly. For the software and coding system, the designer generally uses a CAD/CAM program or programs on a computer. The output of this program, which is a part program and is often in “G-code” is transferred (by a network or perhaps floppy disc) to the machine controller, which is responsible for interpreting the part program to control the tool that will cut the workpiece [1-17]. The signals from the machine controller are amplified by the drives so that they are powerful enough and suitably timed to operate the motors.

The Mach3mill software package runs on a PC and turns it into a very powerful and economical machine controller, as shown in Figure 14. To run Mach3, it needs Windows XP (or Windows 2000), ideally running on a 1 GHz processor with a 1024 x 768-pixel resolution screen. A desktop machine will give much better performance than most laptops and be considerably cheaper.

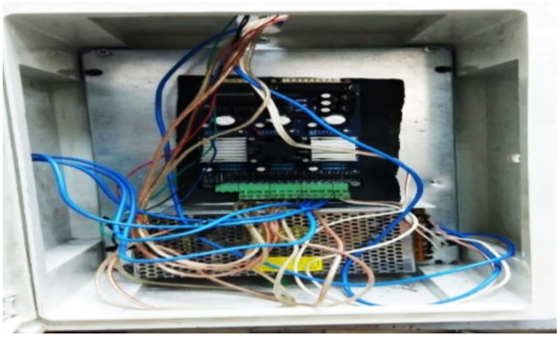

Figure 13. The wiring of the various electronic components board of the electronics system.

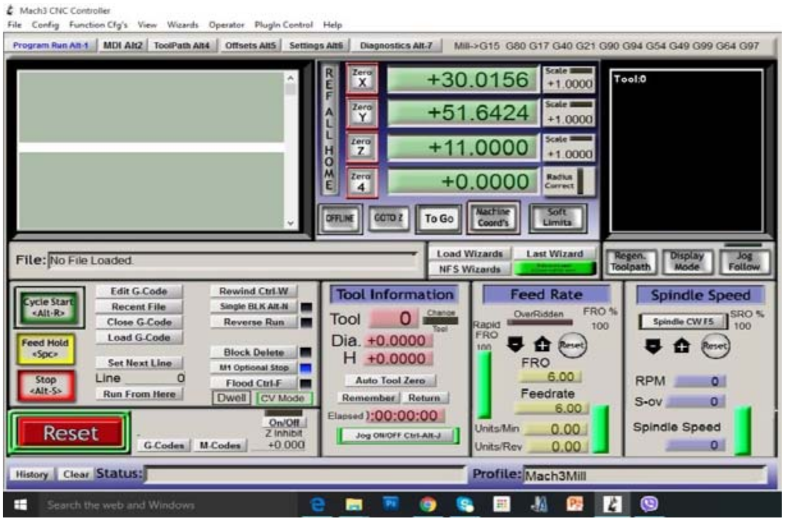

Figure 14. The CNC milling machine computer controller screen window.

5. Results and discussions

The machine is connected to the laptop using a USB cable, and the host software is run using the Mach3Mill G-Code CAD/CAM package, entered into the GUI, and run on the machine. The fabricated CNC router was tested to determine its accuracy in different position modes. The significant tests are the surface flatness test, axes perpendicularity test, and several geometric accuracies such as positioning, straightness by machining a workpiece under a specific tool path, and feed rate, as shown in Figure 15. The machine was verified using a testing marker attached to the vertical spindle of the test m achine.Several G-code commands were executed repeatedly, and the path of the machine was recorded by the marker traveling across the workpiece. Specifically, the command "G 01,02 and 03" was run many times, causing the drawing pen to move in a clockwise circle over the same path each time. A 0.01 mm accuracy dial gauge was attached to the machine to test the linear movements of each axis, and the test was repeated ten times for each axis in different locations. The validation of test results showed an exactable accuracy in alignment, and this indicated a good fabrication and assembling approach implemented the prototype milling machine. The misalignment results lied around +0.01 and -0.01 mm. This means that the fabricated prototype machine movements contain 0.13° tilting on X-axis and 0.22° tilting on Y-axis. These angles of tilting for the machine table sliding were calculated as the cotangent of the dial gauge deflection to the working length of the table in the longitudinal or transverse axis. Finally, the fabrication of the low-cost 3-axis CNC milling machine considerably gives greater affordability in low budget with minimum accuracy errors. The ArtCAM software was used for designing and machining the university logos shown in Figure 16. The ArtCAM software is an interface to import 3D files to make more complex 3D reliefs with high-quality decorative engineering work.

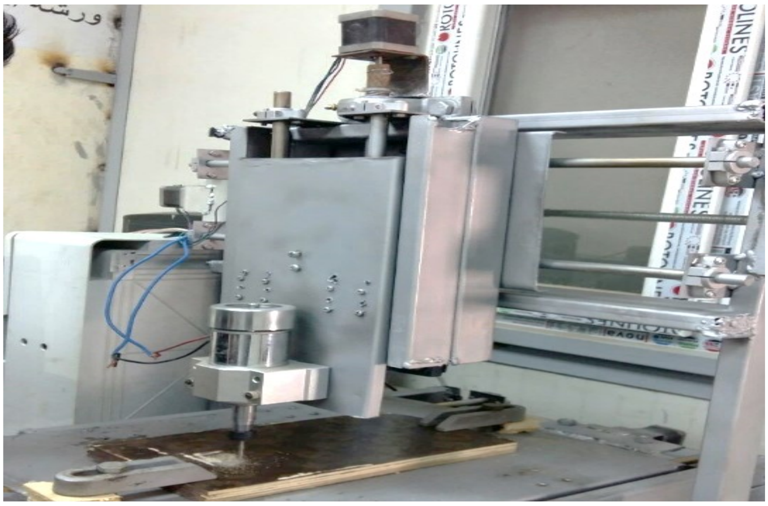

Figure 15. The testing of the fabricated CNC milling machine.

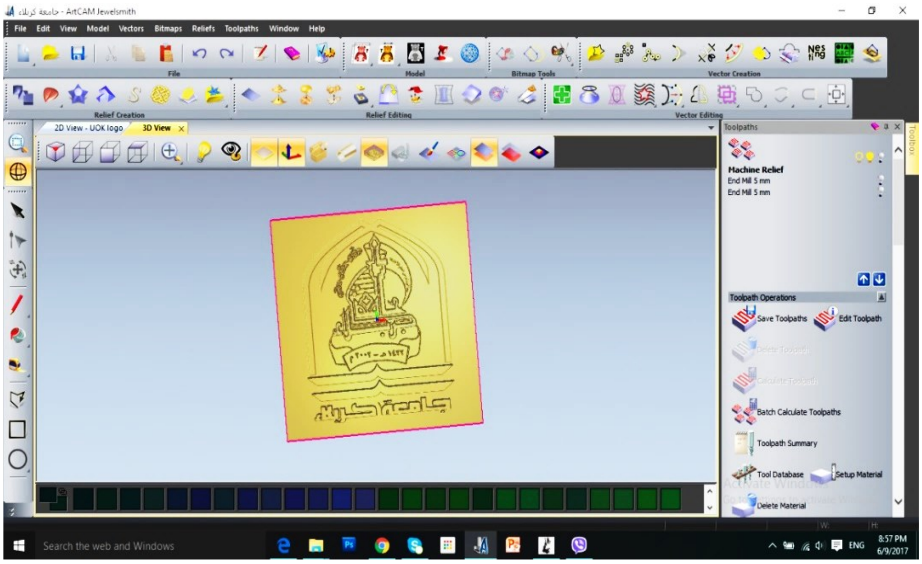

Figure 16. Complete the university logo design by using ArtCAM software.

Safe operation regulations, rules, and procedures that workers must follow when operating CNC milling machine have been prepared, including the safety technical knowledge and precautions, the operation steps and procedures, correct use of personal safety protection equipment, the emergency measures to prevent accidents, the safety inspection systems and requirements, the maintenance of production equipment and safety facilities, The switches and handles are designed in the specified position, and the speed change operation is not allowed during the operating processes and the used CNC programming software not allowed to modify or delete machine parameters arbitrarily.

6. Conclusions

- In the current work, the design, fabrication, assembly, and testing of the electromechanical subsystems of a low-cost three-axis vertical CNC mill suitable for adoption in undergraduate mechanical engineering laboratory setting with an easy interface, easily programmable, easily operable, high speed, high flexibility less power consumption, safe and durable for rapid prototyping machining was achieved.

- The 3-axis CNC driver board type Kit TB6560 was used as a micro-stepping drive designed for smooth and quiet operation to drive the selected stepper motors.
- The Mach3mill G-Code CAD/CAM software package runs on a PC and turns it into a very powerful and economical machine controller was used.
- The fabricated prototype CNC milling machine with an easy interface can interpret standard G-M codes, calibrated, and self-testing to meet the industrial standard.
- The fabricated CNC router was tested to determine its accuracy in different position modes for surface flatness, axes perpendicularity, and several geometric accuracies such as positioning, straightness by machining a workpiece under a specific tool path and feed rate.
- The misalignment results lied around +0,01 and -0,01 mm. This means that the fabricated prototype machine movements contain 0.13° tilting on X-axis and 0.22° tilting on Y-axis.
- The validation of test results showed an exactable accuracy in alignment, and this indicated a good fabrication, and assembling implemented the prototype milling machine.
- After comparison and making the required improvements in both electrical and mechanical design, the machine is in a position to milling a complex contour on soft metals with considerable accuracy and speed.
- The exploring of the new ArtCAM software used for designing and machining the university logo as software with better capabilities was helped in achieving the project goals.

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