

Original Article

Design and Fabrication of a PC-Based 3 Axis CNC Milling Machine

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Abstract - The machine manufacturing industry usually monopolizes CNC-based machine manufacturing technology. These machine tools have world-class manufacturer control systems. Simultaneously, hobbyists, amateurs, and semi-professionals created many solutions for small-scale and low-cost CNC machines. This paper discusses processes for designing and developing a PC-based 3-axis CNC milling machine to meet small-scale and cost-effective machine manufacturing requirements. The following is a review of CNC milling machines built based on the capabilities of similar-sized machines reviewed previously. The milling machine's design is based on a vertical position with a close frame structure. It is assembled with aluminum extrusion profiles to achieve a rigid frame structure. This low cost is achieved by using low-cost off-the-shelf hardware modules that can reduce maintenance costs. The Mach4 software that acts as a PC-based controller communicates G-codes to control the machine. The machining test revealed that the UHMW-PE sample could be cut with different geometric shapes by machining a workpiece under a specific tool path. This machine design shows manufacturing efficiency and flexibility, allowing small facilities to reduce capital costs. Although not intended for mass production or precise machining, this machine can effectively replace expensive commercial CNC machines.

Keywords — PC-Based, CNC, Milling Machine, Small-Scale, Low-Cost.

I. INTRODUCTION

CNC software is a method that uses computer-controlled programs to define the coordinate system. The process commonly used in manufacturing is typically milling, turning, boring, drilling, slotting, etc. CNC is accomplished by pulling the appropriate object into a CAD device and translating the G-code as system coordinate commands [1]. CNC's system configuration consists of many interconnected

sections and modules. It consists of a mixture of mechanical, electrical, and special complementary applications [2]. The software system used is the leading software that can convert G code into its coordinate system. The built machine can store parameters and guide the machine to programmable requirements, including feed rate, cutting depth, cutting speed, and safety features [3]-[5].

Unfortunately, the CNC machine and the current economic conditions make purchasing these machines in large numbers difficult. With this in mind, designing a small-scale desktop CNC milling machine with a close frame structure and using a PC-based controller is necessary. The design is cost-effective, and the machine expansion is easy to use and user-friendly [6], [7]. In addition to the high-tech CNC machine tools used in many industries, the hobbyist and amateur machine tools market has overgrown. Therefore, low production costs are an essential feature of small-scale CNC machine tools [8]. This paper explores how to design and develop small-scale, low-cost desktop CNC milling machines for full operation. Combining standard PC interface features with open source and promoting off-the-shelf hardware components at low manufacturing costs[9]-[11]. In addition, the machine's maintenance costs can be reduced by using off-the-shelf, low-cost parts [12]. Several stages are involved in the design and manufacturing process, including market research, design form, part selection, manufacturing, assembly, and system testing [13], [14]. The manufacturing method begins with a literature review that analyses and reviews existing market machines. Then, the selection of various main components is determined for those that meet the specifications.

At the same time, the procurement of some parts, raw materials, and assembly phases are developed in stages. This milling machine was designed with a 3D detailed model using Solidworks software. Its frame structure is built with an aluminium extrusion profile and an aluminium plate as a primary material. While, the machine system's main



components include a high-speed spindle motor, a PWM inverter, a PMDX-407 speed control, Nema 23 steppers, Gecko G203V stepper drivers, a PMDX-133 board driver, a linear guide, etc. ArtSoft Mach4 Software is motion control software. This software has been upgraded from previous versions and uses the new Windows system to support a USB connector. Three profile shapes were proposed through machining tests and proven the machines can cut high cutting speed and fair accuracy workpieces.

II. RELATED RESEARCH IN CNC MILLING MACHINE DEVELOPMENT

Many semi-professional CNC machines were recently extensively built, as reported by Piotr Boral in 2019. Some researchers have developed a low-cost and small-scale 3-axis CNC milling unit. At the same time, Piotr Boral has developed 4-axis CNC milling with high rigidity and accuracy. A broad cross-section and wall thickness protects the milling machine's design based on a steel segment. This machine is matched with a high-profile track slide to achieve a high-precision machine where linear ball bearings move axial movement. The method has a fourth numerical dimension to lower. The control system used is a powerful SmoothStepper control system with Mach3 software. It enables the motor to rotate rapidly without missing steps [15], [16]. While, in 2010, Kim et al. introduced a compact and easy-to-use 3-axis desktop milling machine. The 3-axis desktop milling machine scale is based on a 200 x 300 x 200 mm³ frame with a cutting volume of 20 x 20 mm³. A rotating motor powers the vertically positioned X and Y stage, while a linear stepper motor is used for the Z-axis. The spindle is fitted with an air-cooled spindle that runs at high speeds at up to 160,000 rpm. Unfortunately, experimental findings show that each control device's efficacy decreases when implemented on 3-axis desktop milling machines [17].

Darvekar et al., 2013, explored machine-milling abilities based on PKM from two machines with a Degree of Freedom (DoF) that measured PKM with a finite element structure. Various conditions have been carefully tested for performance variations such as cutting rate, feed rate, and cutting depth, i.e., surface roughness and material elimination rate. Regression models to predict surface roughness have been created. In the genetic algorithm, attempts have been made to find the optimum machining conditions for PKM. Experimental findings show that the PKM-based method will work on metals like hard aluminium alloys at fixed lengths [18]. However, in 2015, Max et al. researched and implemented a new teaching methodology to design CNC mills at the Department of Machine Design of Pilsen's West Bohemian University. The aim is to create recommendations for students with the following main objectives: easily finding and unifying knowledge in one location and students. In Catia, NX and other software 3D models were developed and later translated into pdf. There is also less hardware and no special programs in this 3D model. Students can rotate, shift, and visibly/invisibly make the model set its components and functions accordingly [19].

MohdHadzley et al., 2015 have clarified the concept of creating a cost-effective CNC 3-axis milling machine during the processes involved. The machine tool consists of standard hardware mounted on three-axis structures, and the air-cooled spindle has a 24,000-rpm maximum spindle speed. This system uses Mach3 software to control device movement with G-codes to enable the CNC axis direction for open-source software. This built machine can handle high-speed metal components with reasonable accuracy. Overall, the machine can provide reliability and versatility to generate goods that minimize capital costs through small installations [20].

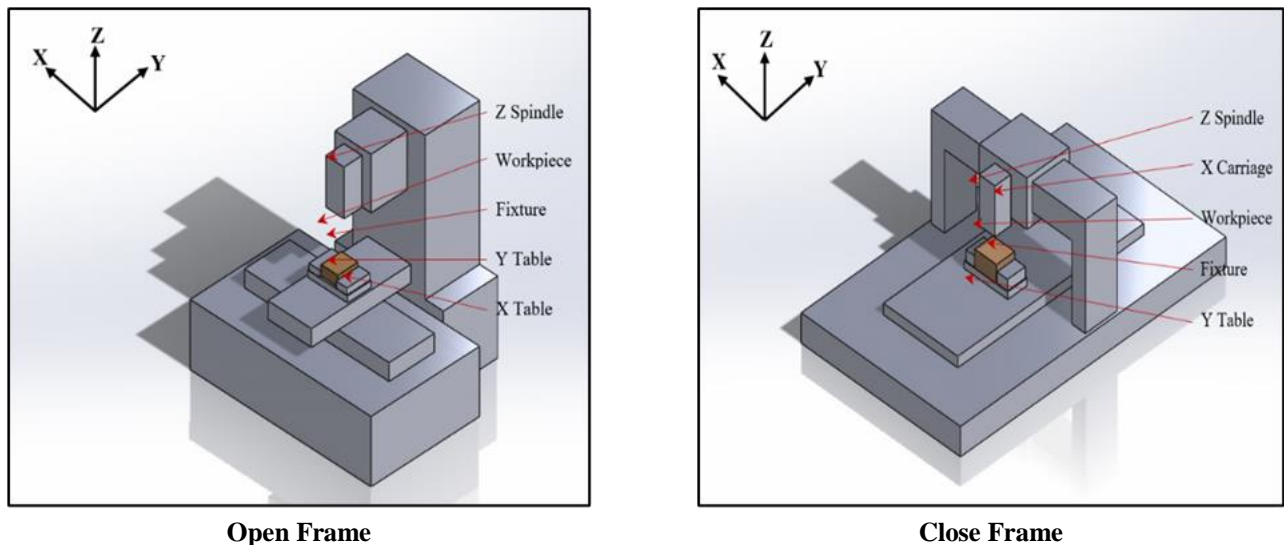


Fig. 1 Type of the frame structure

Nevertheless, in 2012, Basniak&Catapan proposed that CNC milling machines for printed circuit boards be built in their diaries with low production costs for domestic use. Customer requirements are met and processed using a QFD matrix to address product needs through market research. The morphological matrix is used to obtain the conditions for any possibility, and algorithmic principles are best analyzed. The material selection and comprehensive design involve 3D models performed in CAD systems. FMEA review can remove perceived flaws in the final product during product growth [21].

Another researcher, Nikita R. Sahakar and Dhote, 2015, created a small three-axis milling machine. The device structure is analyzed and evaluated during the structural design process. Essential components are picked from different options, including linear guides and the best value pieces chosen to follow rigidity and budget constraints. First, the CAD model was developed and imported into the CAM applications such as PowerMILL using SolidWorks software. Then, storing the input instructions for cutting tool features such as diameter, depth cutting, length cutting, etc. Working costs are reduced with more complex components manufactured automatically and indirectly decrease the overall development time and help see how the item is produced. The software can be made more flexibly and in a shorter period, requiring fewer investment costs. High-speed machining can minimize tool load and costs of production while improving surface finishing [22].

III. STRUCTURE DESIGN

The machine structures are divided into open frames, closed frames, and Truss forms. The most common type of industry structure is open and closed frames, as illustrated in Fig. 1. The open frame structure is often referred to as frame C or G. This configuration is used for most conventional machine tools [23]-[25]. After comparing the two structures and weighing the advantages and disadvantages of each, the close frame structure with a vertical tool position was chosen to construct a small machine. The close frames provide excellent tooling access, while vertical milling machines are far simpler to build in terms of configuration than horizontal milling machines. The component gives convenient access to the workspace and is typically compact and lightweight. The materials needed for this structure are much cheaper and less used than the open frame structure [26]-[28].

IV. DESIGN AND DEVELOPMENT

The product design approach is closely related to a critical mechanism for beginners. Once the design is defined and the selected design drawn using SolidWorks software, the initial design is represented. The final drawing comes out, and some criteria must be determined before the drawing is completed, such as the machine platform size at a distance between the axial lengths. Measures include workspace and machine size restricted. Information on the initial selection and rating of materials or process combinations in the early stage of the new product design should be available to ensure their real design value. This information includes the

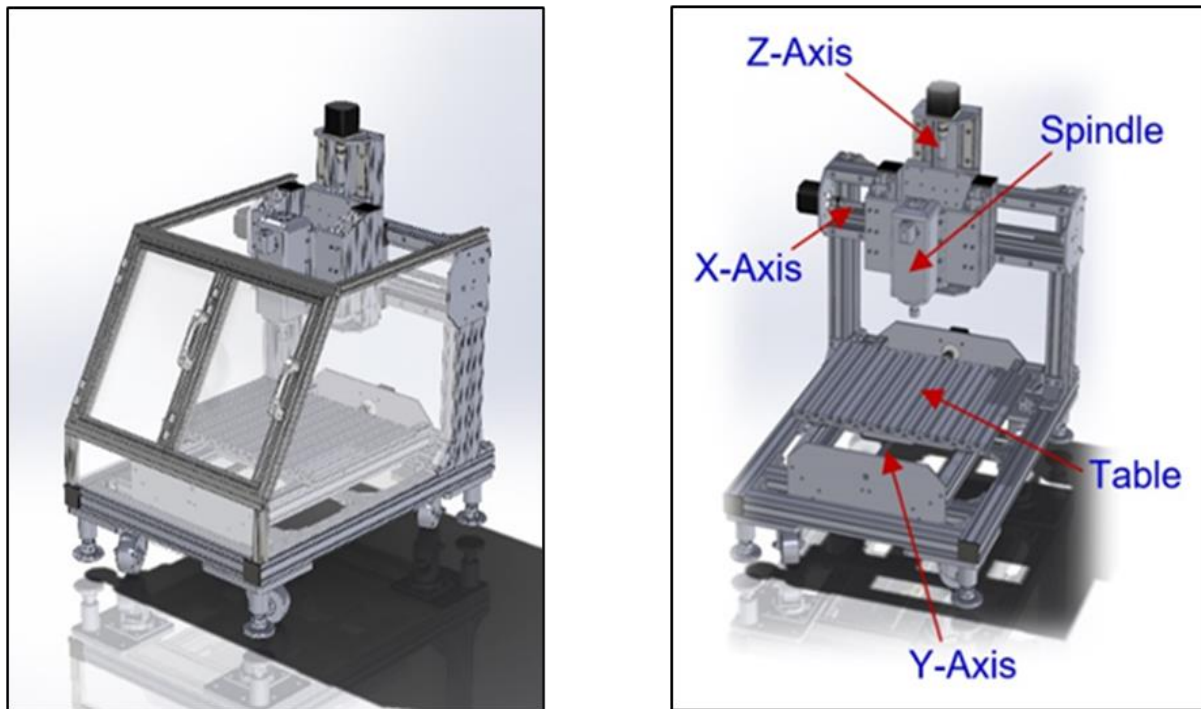


Fig. 2 Drawing concept of milling machine

machining process using the selection of products, parts purchased to meet the specifications, and organizational planning. The detailed manufacturing process of desktop CNC milling machines consists of a mainframe structure, each axis, electronic components, and software.

The selection of different parts and components off-shelf will clarify the thorough manufacturing process. Each component has a standard part, including linear guides, ball screws, stepper drivers, stepper motors, couplings, bearings, spindle, vice, and other electronic components mounted on a three-axis operating system. The developed CNC desktop milling machine can be divided into several components, consisting of 3 axes (x, y, and z), a function panel control system, and CNC control software. These machines are constructed almost entirely of aluminium. The mainframe design structure is aluminium extrusion profile construction. The machine has a built-in 500 mm (length) x 600 mm (width) x 700 mm (height) frame size with a maximum speed of 24,000 RPM. This machine uses a 1.5 kW 220V air-cooled spindle. Each axis specifies that the X-axis travels from left to right, the Y-axis moves from front to back, and the Z-axis is a vertical axis going from bottom to top. This machine's drawing concept, as shown in Fig.2. While Fig. 3-5 depicts the system in 3D drawing design, which includes frame measurements and technical views with complete assembly components for all three axes of x, y, and z.

V. MILLING MACHINE COMPONENT

The machine's main components are selected, which are breakout board, spindle motor, inverter, stepper motor, and stepper driver. The most important device for controlling all components is an interface breakout board, and it is connected to a device through a USB port. This research uses the breakout board the PMDX-424 SmartBOB-IsoUSB. This 5-axis interface board is a motion control pulse engine with an integrated breakout board to connect CNC machines to Mach4 software using a USB port. Mach4 controls every step motor on the axis when the cables are attached correctly to send a signal to each stepper drive board. Since the machine is small-scale, the machine will consider light materials such as wood, plastic, and aluminium that require less machining force. The motor's selection for each axis is carefully made, as the stepper motor directly relates to the driving mechanism and control system. The NEMA 23 bipolar motor stepper is adequate to meet the requirements for the material to be cut. With three Stepper Motor units equipped with stepper control PMDX-133 combined with three Geckodrive G203 units obtained at a reasonable price to complete each available axis. It is available with a High-Speed 1500w Air-Cooled DC Motor Spindle package and 13 ER11 collet sets selected for the main spindle. It will match a Huangyang inverter package that provides sufficient power for both spindle kits and controller sets.

Meanwhile, for spindle speed control, a PMDX-407 module is compared to the PMDX-424 SmartBOB-IsoUSB breakout board. A personal computer system equipped with Artsoft Mach4 Industrial software is available as open-source software. Mach4 is preferred as a PC-based CNC controller and as an open-source CNC controller. Thus, it can operate without relying on specific machine manufacturers and proprietary software vendors[29]-[31]. These PC-based devices are connected to each axial control through a USB connector. The linear motion is given by attaching a threaded ball bearing to a stepper motor and a linear rail slide block for all axis movements. The machine has a magnetic limit transfer sensor to limit the machining axes' direction beyond the operating range and avoid damaging the machine. The unit has one spindle on the z-axis. The spindle was constructed as a shaft to drive a z-axis cutting tool and manually adjusted using particular portable vices. This 3-axis milling machine is designed with a linear guild and lead ball screw for transformation from rotary to linear motion and a lead screw mounted on each axis mounted on the frame body. Table I shows the off-the-shelf technical components for machine requirements.

VI. MACHINE FABRICATION

The frame structure and machine part are custom-made from the aluminum extrusion profile. Aluminum extrusion is suitable for building frame structures because it is easy to mount and assemble and corrosion-resistant or flexible. Because of its lightweight design, aluminium was also chosen for sufficient strength to hold parts without deformation. The orientations x-axis and y-axis are uniform work surfaces, and at the same time, the vertical Z-axis is emphasized as the basis for this unit. The X-axis linear motion components are studied when assembled to the overall of a small-scale milling machine. All electronic components are installed in one set of controls, and a separate set of the controller is placed on the frame's back. The plug-and-play parts consist of several factors, including structural rigidity, an adaptation of ball hinge boards with coupling links, weight reduction, linear axis reduction of linear rail balancing, and minimization of individual component complexity.

In addition to the features discussed, other aspects were also planned during the machine's fabrication and installation process, focusing on all available possibilities. This machine is designed with two main frame parts: a base platform frame and each linear axis traveler. The machine base platform a built-in was 500 mm (length) x 600 mm (width) x 700 mm (height) of frame size. Thus, the size of the machine's working area is 240 mm x 300 mm x 600 mm. Simultaneously, the travel length of the linear x-axis, y-axis, and z-axis dimensions are 250 mm, 210 mm, and 180 mm. The configuration and integration of the machine platform with the linear axis travel system and the completed axial control and installation are illustrated in Fig. 6.

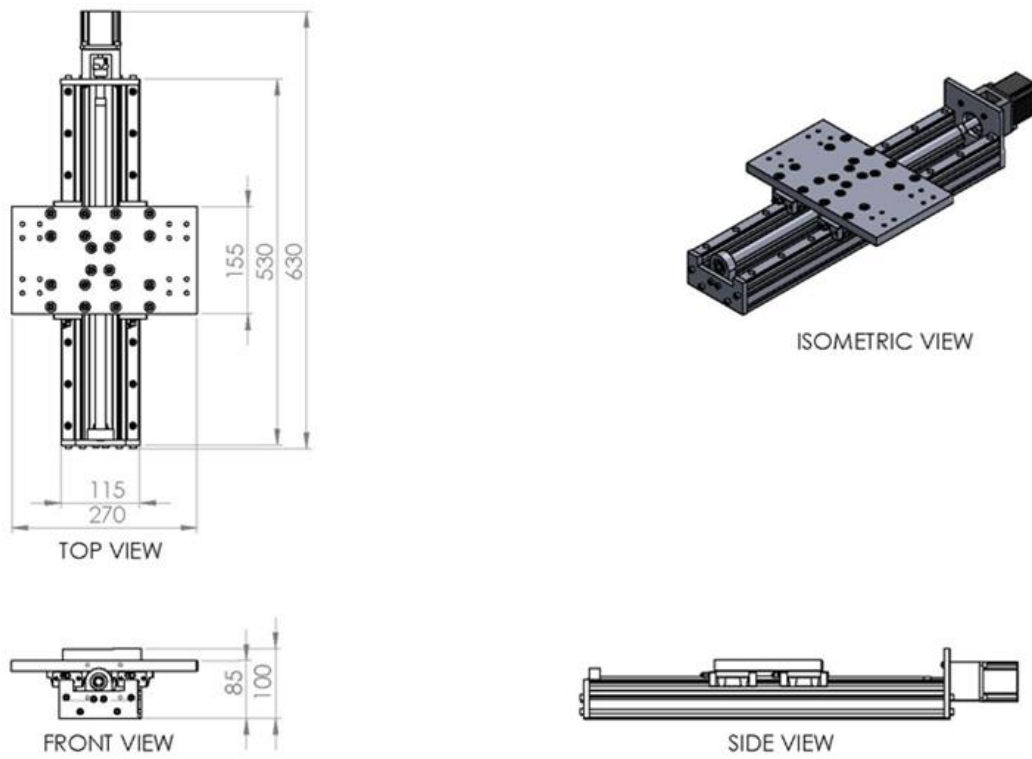


Fig. 3 Technical drawing of X-axis

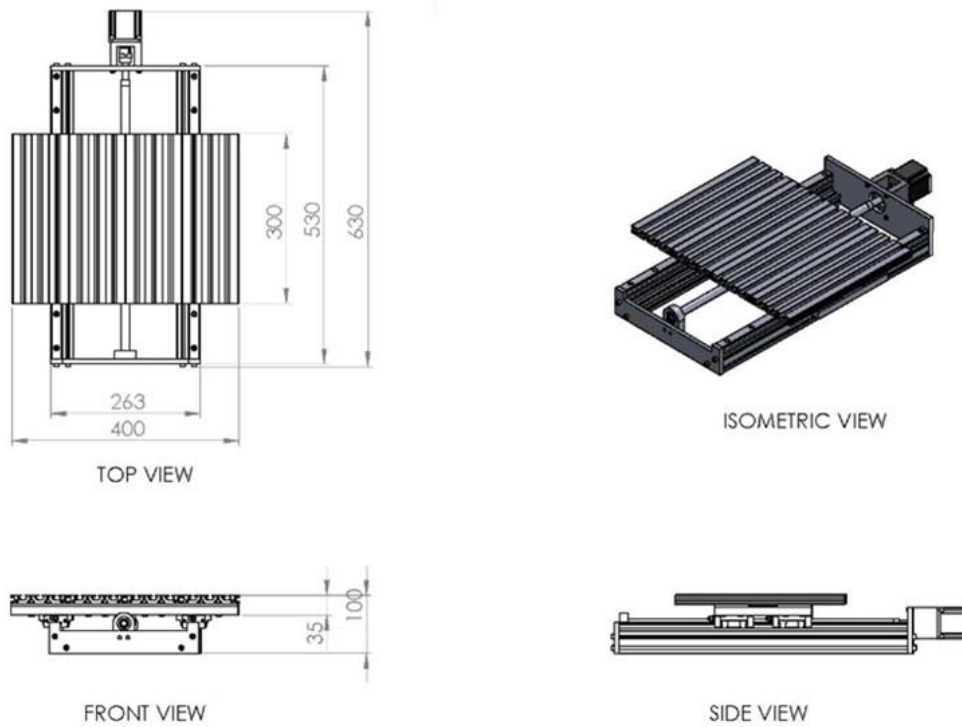


Fig. 4 Technical drawing of Y-axis

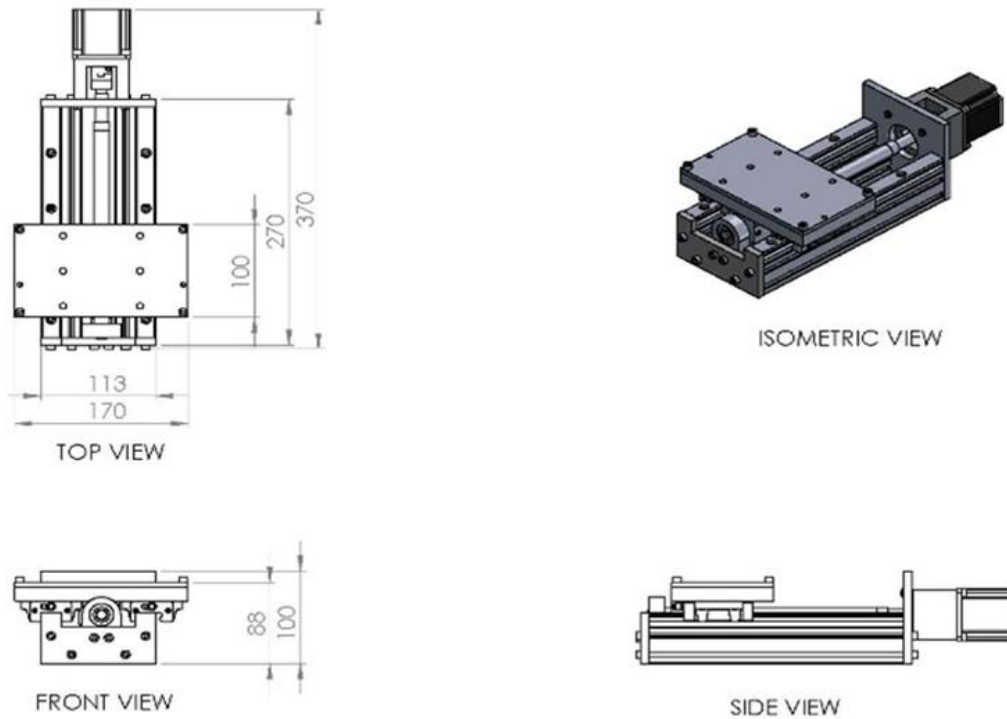


Fig. 5 Technical drawing of Z-axis

VII. MACHINE ASSEMBLING

Machine assembly requires four significant elements: the x-axis, y-axis, z-axis, and controller systems that include specific electronic components. The machine manufacturing method is achieved by step-by-step installation according to the respective components. The parts are assembled and configured after acquiring all appropriate equipment and accessories. All members are configured according to their separate axis parts to complete the machine body, and these include Y-axis assembly and alignment with the machine table. Fig. 7 shows the details for each of these axes. For the machine pole as a structural support system, the gantry type is chosen when the combination between X-axis and Z-axis is installed and aligned. The x-axis and the z-axis are mounted cross-sectionally between them, where the x-axis mounts horizontally while the Z-axis mounts vertically. Combination of the machine table (y-axis) and the configuration of the x-axis and the z-axis, this machine is assembled and carefully inspected as a three-axis CNC machine. Other devices and parts are also mounted, including emergency buttons, spindles, vice, and other accessories. This machine's control system is connected directly to the primary power source and linked to the computer through a USB communication cable. This communication port is mounted on the controller system board's side located at the machine's back.

This control system set includes a power supply, DC converter, breakout board, stepper motor with driver motor for all axes, and other components necessary for assembling this control system. Besides, a series of inputs/outputs power and switch buttons for the inverter's that automatically control the spindle when running the machine. This machine is also equipped with a high-speed spindle that runs automatically with a PWM unit that serves as a spindle speed controller from instructions received through G-code. Finally, as shown in Fig. 8, significant steps have been taken to design the CNC milling machine's electronics and schematic diagram. Table II presents the machine specification are needed to complete the machine design. As illustrated in Fig.9, the controller sets and a complete three-axis desktop milling machine are displayed. There are many advantages to using a lightweight, PC-based machine. This desktop-sized machine with high rigidity and a high strength-to-weight ratio benefit compare to conventional machines available on the market. For a small-scale and a portable machine, the storage area may have an additional benefit. Because this machine needs fewer materials and components, this machine's weight can be decreased indirectly, reducing the energy required to run the machine. It is also possible to minimize vibration and noise, environmental emissions, and faster-operating capacity and improve efficiency and production speed during machining.

TABLE I TECHNICAL REQUIREMENTS OFF-THE-SHELF COMPONENTS

No	Type of Part	Description of Part
1	PC-Based Controller	-ArtSoft Mach4 Industrial
2	Stepper Motor	-NEMA 23 STEP SIZE 1.8 ⁰ -Single Shaft Bipolar step motor
3	Stepper Motor Driver	-Gecko G203V drivers -Stepper Motor Control Type -Native Resolution: 10 uStep (2000 PPR) -Power Rating: 80VDC, 7A maximum
4	Stepper Driver addon	-PMDX-133boards -3-Axis Daisy-Chainable Motherboard for Gecko G203V
5	High-Speed Spindle Motor	-Air-cooled Spindle Motor -Power:1500W -Voltage: 220V -Frequency:0-400Hz -Speed:0-24000rpm -Runout off: less than 0.005mm -Grease Lubrication -Collect Chuck ER11 mm
6	Spindle Speed Control Interface	-PMDX-407 Isolated Basic Speed Control -Analog interfaces 5 volts, 10 volts, or up to 15 volts -Supply a 100 Hz to 1 kHz PWM signal. -PWM input and 5 to 15 VDC power
7	Interface Breakout Board	-PMDX-424 SmartBOB-IsoUSB -Interface Breakout board via USB -Output Stepper motor 5-axis -Interface board adapters -Built-in USB connector -AC mains input of 100 to 240 VAC or an optional version accepts 12 to 36 volts DC -Support Mach3 /Mach4
8	Inverter	-Huanyang Inverter -Input voltage: 220V(+/-15%) -Type:1.5kw -Output Voltage: 220VAC -Input Frequency: 48-63 Hz -Output Frequency: 0-400 Hz -Input Phase: 1 or 3 phase -Output Phase: 3 phase -Auto voltage regulation (AVR) technique -Various control technique -Support manual potentiometer control, 0-5V/0-10V analog control, and Mach4 software G-code
9	Power Supply for Spindle	-Input voltage AC 220 V -Excitation output voltage DC 110 V -Output current 8A
10	Power Supply for driver motor	-3.250W 24V 10A Switching Power Supply -Input current 115 VAC, 5.5A – 230VAC, 3.5A -Output current 24V 10A

TABLE II MACHINE SPECIFICATION

No	Technical Criteria	Value of Selection
1	Machine frame type	Close frame, column, and gantry type
2	Machine configuration	Vertical tool position, three linear axes
3	Structure frame	Aluminum extrusion profile
4	Machine base platform	500 mm (length) × 600 mm (width) × 700 mm (height)
5	Working area	X: 240 mm, Y: 300 mm, Z: 600 mm
6	X, Y & Z travel length	250 mm x 210 mm x 180 mm of the linear axis
7	Spindle motor	High-speed air-cooled motor spindle
8	Spindle speed max	24,000 rpm
9	The motor of each axis	Single shaft bipolar stepper motor
10	Workpiece material	Soft and light material (plastic, wood, etc.)
11	Controller system	PC based Interface breakout board USB connector Mach4
12	Chuck	Collect ER11 mm
13	Power Supply	Input: Single phase ac 110v/ 220v/ 50/ 60hz,
14	Cutting tool diameter	1 mm – 10 mm



Fig. 6 Machine development and frame structure design

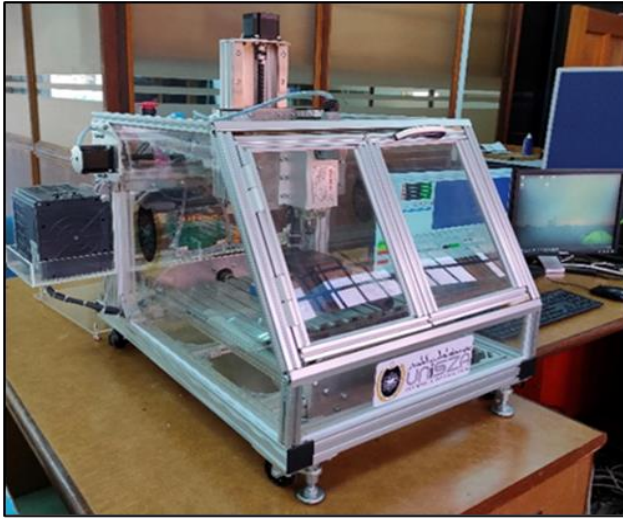
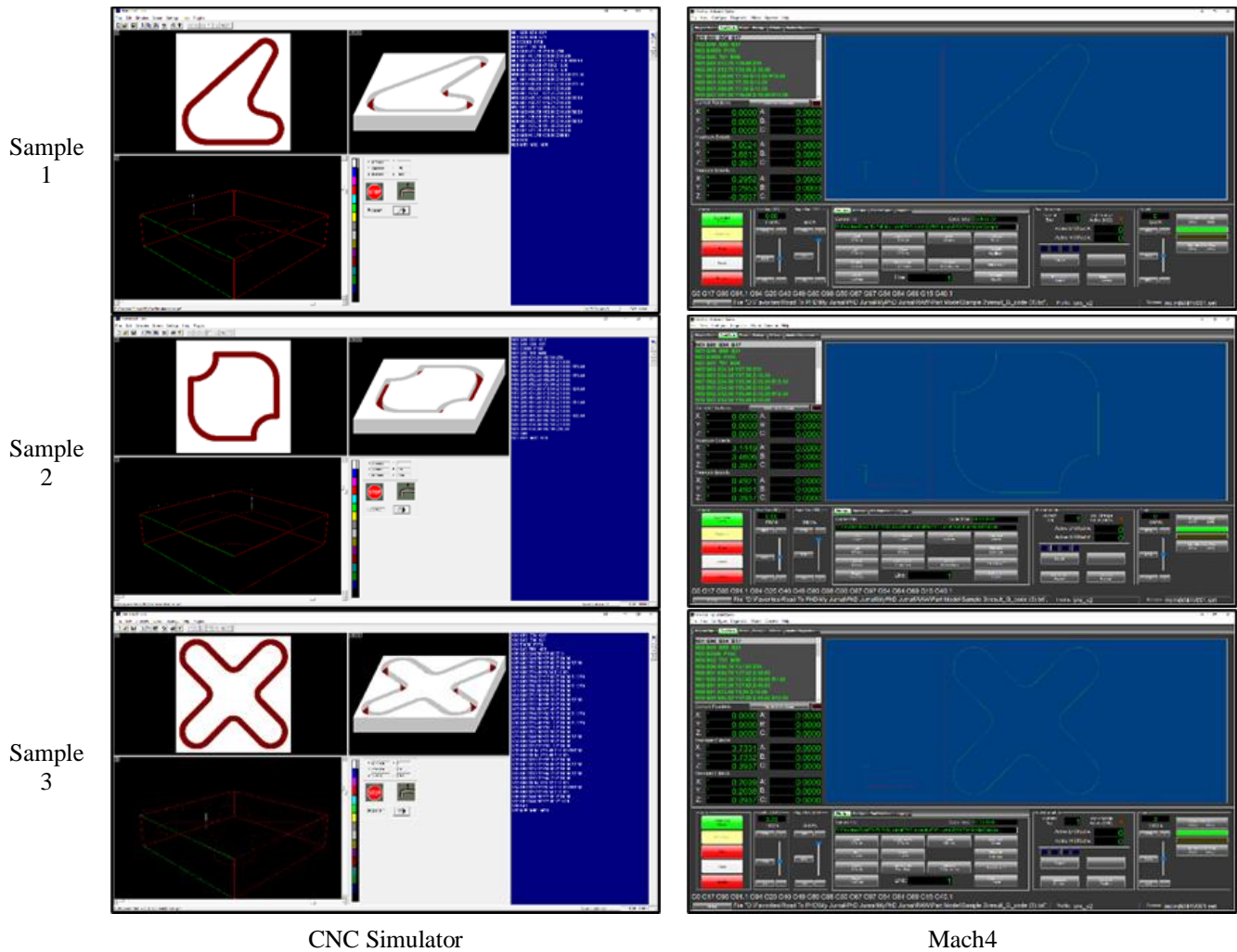


Fig. 9 The 3-axis CNC milling machine and controller system set



CNC Simulator

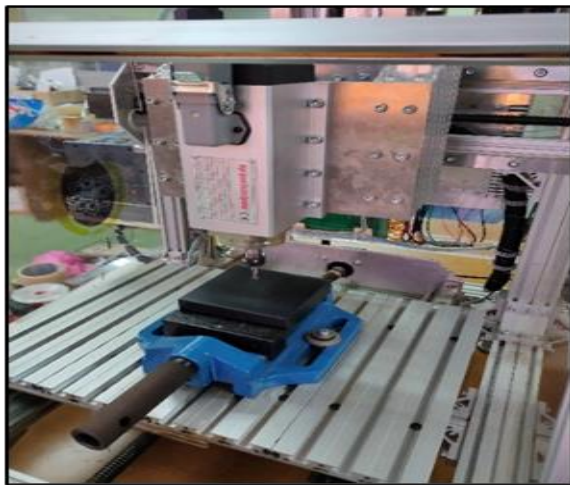
Mach4

Fig. 10 G-code viewer and machining tool path simulation

VIII. MACHINING VALIDATION AND TESTING

This test was performed to evaluate this machine's capabilities compared to existing industrial machines that take up more space than this small-scale machine. This machine is tested by cutting an Ultra High Molecular Weight Polyethylene (UHMW-PE) sample block with dimensions of 100mm x 100mm x 24mm as a machining workpiece and a 5 mm four-flute end mill as a machining cutter. The spindle speed is set to S3000, and the feed rates are set to F500 for the machining test. The first initial tests would determine whether the machines could move up and down, left and right, and front and back along the three axes. At the same time, the CNC Simulator software is used to calibrate or test machines and simulate tool paths before being tested with a Mach4 Industrial. This software is used to view toolpath movements, detect defects, possible code errors, or inefficiencies. However, the Mach4 controller can determine and control the direction of the axes' movement and display

the milling process's tool path during the machine's cutting process of the sample block. Because the text file format is supported by Mach4 and CNC simulators, the notepad was chosen as a G-code encoding medium to be imported into this software. While the G-code was generated using the Integrated Interface System (ISS) as an intermediate platform between CAD and CAM according to the required setting parameters [32]. This application generates the tool path before applying it to the milling process by uploading the 3D CAD design in the wireframe model [33]. The system can automatically generate G-Code for straight lines, circular features, and complete profile shapes. Finally, the sample G-code is imported into the Mach4 program controller to determine the accuracy of the tool path for machining purposes. Fig. 10 illustrates the CNC simulator and Mach4 software used for toolpath simulation and machining.



UHMW-PE Block



Sample 1



Sample 2



Sample 3

Fig. 11 Machining testing

This paper presented three sample parts in different shapes to verify the tool path simulations and machining process. A machining test is performed to determine the tool path accuracy, whether in a straight or curved cut in the workpiece. The features of the simulation results are compared to those of the CAD design and the machining process's end product. This machining test demonstrates the machine's ability to cut parts of varying shapes, and the results are shown in Fig.11.

IX. CONCLUSIONS

This paper describes a small-scale three-axis CNC milling machine, and the most appropriate structure is the close and vertical frame that will be investigated and developed. The machine's platform size is 500 mm in length, 600 mm in width, and 700 mm in height, with a working area of 240 mm in the X-axis, 300 mm on the Y-axis, and 600 mm on the Z-axis maximum spindle speed of 24000 RPM. This manufacturing process begins with selecting main components, followed by the procurement of raw materials, several other certain parts, and the completion of step-by-step installation procedures. The CNC milling machine is controlled by ArtSoft Mach4 software via a PC-based motion controller. These carefully selected and acquired off-the-shelf components and standard parts are used to reduce costs. The cost-effective effect is achieved by integrating standard PC interfaces with an open-source CNC Controller and supporting commercially available hardware components such as stepper driver motors, speed controller spindles, interface boards, etc. Many options are available when choosing critical features such as axis generators, linear guide rails, and breakout boards. These highest-performing components were selected to satisfy rigidity and budget constraints. The NEMA 23 stepper motor with driver and linear guide slide rails controls all axes' motion and configuration. The research manufacturing process begins with product procurement and is followed by assembly and testing. The machine was evaluated using a different shape to determine the machine's efficiency and stability. It was accomplished by machining the workpiece at a specific cutting speed and feed rate. The findings indicated no difference in the machining of UHMW-PE Block material between a desktop and a commercial machine. However, the UHMW-PE block is not ideal for high-precision testing, and aluminium will potentially be the preferable option in the future. These machines, however, are not intended for manufacturing or precise machining. Nonetheless, it is capable of replacing existing high-cost machines. This small-scale machine technology enables manufacturing to expand with greater flexibility and efficiency while also lowering capital costs. Additionally, these machines would replace a commercially available milling machine and require less space to operate. In general, the manufacturing concept demonstrates and is deemed feasible for developing small machine tools such as a CNC milling machine.

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