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Design and Development of 3-Axis Benchtop CNC Milling Machine for Educational Purpose

Zammeri Abd Rahman[1], Saiful Bahri Mohamed[1*], Mohammad Minhat[2], Zulkifli Abd Rahman[3]

[1]Faculty of Innovative Design and Technology,
Universiti Sultan Zainal Abidin (UniSZA), Terengganu, 21300, MALAYSIA

[2]Faculty of Manufacturing Engineering,
Universiti Teknikal Malaysia Melaka (UTeM), Melaka,76100, MALAYSIA

[3]Faculty of Engineering Technology,
University College TATI (UC TATI), Terengganu, 24000, MALAYSIA

*Corresponding Author

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Abstract: The main factor in improving learning skills is providing students with hands-on laboratory experience, and the small-scale machine can accomplish academic programs requiring students to learn machining skills. This paper aims to design and develop a 3-axis CNC milling machine with a PC-based open architecture controller in a vertical position open frame structure. Some technical specifications were randomly selected based on the capabilities of similarly sized machines reviewed in previous work. The designed machine consisted of inexpensive off-the-shelf hardware components capable of machining the sample block with high cutting speed and reasonable precision. The accepted percentage error of circular and straightness test readings is below the set requirements. This machine is not intended for series production and precise machining. It can still effectively replace the high cost of commercial CNC machines and be used in any higher education institution offering technical courses.

Keywords: Milling machine, CNC, PC-based, open frame, G-Codes.

1. Introduction

CNC software is a computational tool that performs movement by specifying the coordinate system using computer-controlled programs. Milling, turning, boring, drilling, and multitask slotting are the main applications in the manufacturing sector, and this method is widely used [1-2]. The appropriate objects are drawn into any CAD system in CNC application and translated into system coordinate commands, commonly known as G-codes. The configuration of CNC computers consists of several systems, such as mechanical, electrical, and a combination of highly complex software. Mechanical systems are the most important for developing CNC machines, such as frame, drive, and guidance [3-5]. Conversely, the electrical system includes several main components, such as handhelds, control panels, and electronic motor-driven devices. Furthermore, software systems are essential applications that can translate G code into coordinate systems to instruct parameters to cut according to program requirements such as feed rate, cutting depth, cutting speed, and safety features [6-8].

Recently, most higher education institutions are planning to offer some new technology programs related to manufacturing technology. Therefore, using a CNC machine fulfills the students' learning and research activities [9-10]. Unfortunately, the CNC machine's expenses and today's economic climate make it difficult to buy them in large numbers [11-12]. Because of these factors, developing a low-cost CNC milling machine is essential so that the machine's

*Corresponding author: saifulbahri@unisza.edu.my

construction and development are clear and understandable to the student. Hence, this paper aims to develop the CNC machine and design and fully manageable CNC milling machines. Maintenance costs of machines are reduced by using inexpensive and off-the-shelf components to construct the machines. The lower cost is achieved by integrating standard PC-based interfaces with open-source software and supporting off-the-shelf hardware components [13-14]. The manufacturing and analysis process includes selecting the correct parts, the manufacturing process, and the specific experiment based on the machine test [15]. This process involves selecting components in the main part, purchasing raw materials, and completing step-by-step installation procedures. The detailed 3D model designs of the milling machines were designed using Solidworks software. The primary material used for this machine tool design is an aluminum alloy 1060 involving welding, drilling, cutting, and milling in this manufacturing process. This system's essential component consists of the spindle motor, linear guide, ball screw, bearing, stepper motor, driver motor, PWM speed control, inverter, breakout board, etc. [16-18]. The ArtSoft Mach3 Software is used as the motion controller for this machine. All related machine accuracy processes and procedures from literature reviews are used as reference or guidance to determine workflow and predict operation. This test is the machining process and a specific cutting speed and feed rate [19-22]. It was conducted to determine the position and geometric accuracy by developing a new computational imaging technique for measuring circularity and straightness using a CMM machine [23-24].

2. Previous Work on CNC Milling Machine

Max et al. [25] studied and introduced a new teaching approach to designing CNC milling machines at the Department of Machine Design at the University of West Bohemia in Pilsen. The aim is to define students' guidelines to discover and unify knowledge in one place and learn clearly. The parts and functions are established, and students can still rotate and move the models and make them visible or invisible. The 3D models are constructed in Catia, NX, and converted to a 3D pdf that supports lower hardware requirements and uses specific software for the machine controller. At the same time, Mohd Hadzley et al. [26] propose to develop a cost-effective 3-axis CNC milling machine. The designed machine tool consisted of off-the-shelf hardware mounted in three-axis operating systems. The machine has a small design and uses two coil bipolar stepper moto for the XY axis and a linear motor for the Z-axis with a maximum air-cooled spindle speed of 24,000 RPM. Open-source software was used to control machine movement using G-Codes to assign CNC axis movement. As a result, the machine could cut high-precision metalworking parts using high-speed cutting. The developed machine provides productivity and versatility in manufacturing products, allowing small facilities to minimize capital costs.

Sahakar and Dhote [27] designed, analyzed, and developed a small-scale 3-axis milling machine. The system structure is examined and evaluated during the structural design stage. The main parts, including linear guides, are selected from various possibilities. The best and cheapest components are chosen to meet rigidity and budget constraints requirements. The CAD model was designed using SolidWorks software, and then the model is imported into PowerMILL as a CAM application. Input commands for cutting tool characteristics such as tool diameter, cutting depth, cutting duration, etc., are applied to determine machine accuracy. A more precise work part can produce, which automatically reduces human labor costs. It reduces total production lead times and lets users see how the product is produced. Machine programming can be generated as soon as possible, is more flexible, and requires fewer investment costs. This high-speed machining provides better surface finishing and reduces production costs and tool loads.

Basniak and Catapan [28] suggested developing the CNC milling machine for printed circuit boards with low domestic production costs. Through market analysis, product requirements are satisfied and processed using the QFD matrix to fulfill product needs. A morphology matrix is used to get some solution for each condition, and an algorithm analyses the best idea for this product. Detailed design includes a 3D model and material selection of the CAD system before completing machine design. FMEA allows for analyzing potential defects in the finished product that can be removed during product development. Some tests were performed with a functional prototype to ensure those customer requirements were fulfilled. Ultimately, the mathematical models used during the development process can be validated. Another researcher, Boral [29], also developed several semi-professional CNC machine tool solutions, where the researcher builds a 4-axis CNC milling machine with sufficient rigidity and precision. The milling machine's design is based on structural steel closed with a large cross-section and wall thickness, which allowed a rigid frame structure to be obtained. The high precision of the profiled slide rail and the pre-stressed linear ball movement were used as high precision axis movement. The machine tool has four controlled axes that can be disassembled and demounted. The machine's control system with the Mach3 software and SmoothStepper is very efficient, achieving a high motor rotational speed without missing steps.

Darvekar et al. [30] explored a PKM-based milling machine's machining capability from two degrees of freedom (DoF), and the PKM rigidity was measured using finite elements. Different working conditions, such as cutting rate, feed rate, and cutting depth, were extensively tested to study performance measurement variations, such as surface roughness and material elimination rate. Regression models to forecast surface roughness were established, and attempts were made in the genetic algorithm to find optimal machining conditions for PKM. The experimental results show that the PKM machine tool can machine metals such as hard aluminum alloys in fixed lengths. However, Kim et al. [31] introduce a 3-axis mini desktop milling machine that can be serviced. The machine's size is 200 x 300 x 200 mm3, and its cutting volume is 20 x 20 x 20 mm3. Voice-coil motors control the vertically mounted X,Y axis, the axis travel uses a preloaded air bearing and a linear motor, and the air spindle speed operates at 160,000 RPM. Experimental results show each control system's effectiveness and limitations for these 3-axis desktop milling machines.

3. Machine Design and Development

CNC benchtop machines are defined in detailed manufacturing processes as having six major components, including the mainframe structure, each axis, electronic components, software, and testing. Most mechanical research is conducted on the primary structure of the frame. The detailed manufacturing process can start with identifying suitable off-the-shelf parts and components [32-33]. Information about the initial material selection and process combination should be available early in the new product's development to ensure that the design has true meaning. This information may include the machining method used in the material selection process, the designs obtained to meet the requirements, and operation planning. This process is important because it is a starting point for product design. After identifying the procedure, the initial design is sketched, and the design is then drawn using SolidWorks software. Before finalizing the drawing, criteria such as machine platform size and axis length distance were established.

Additionally, it has requirements for workspace and the machine's small scale. This CNC milling machine is composed of four major components: the X, Y, and Z axes, as well as the controller system. Each axis has its specification, with the X-axis moving left to the right, the Y-axis moving front to back, and the Z-axis moving vertically from top to bottom. The X-axis traveled 560 mm, the Y-axis traveled 420 mm, and the Z-axis traveled 420 mm. The machine platform dimensions are 680mm x 670mm x 660mm. It is equipped with a 600-watt air-cooled spindle with a maximum spindle speed of 13000 RPM. The machine frame is constructed entirely of aluminum 1020 alloy, and the machine tool is assembled entirely of off-the-shelf hardware. Each component has standard parts, including ball screws, stepper motors, linear guides, bearings, couplings, electronic components, and three-axis operation systems. Other components, including an emergency stop button, spindle, and vice, were also assembled, as shown in Fig. 1, and the technical drawing for the machine design is shown in Fig. 2.

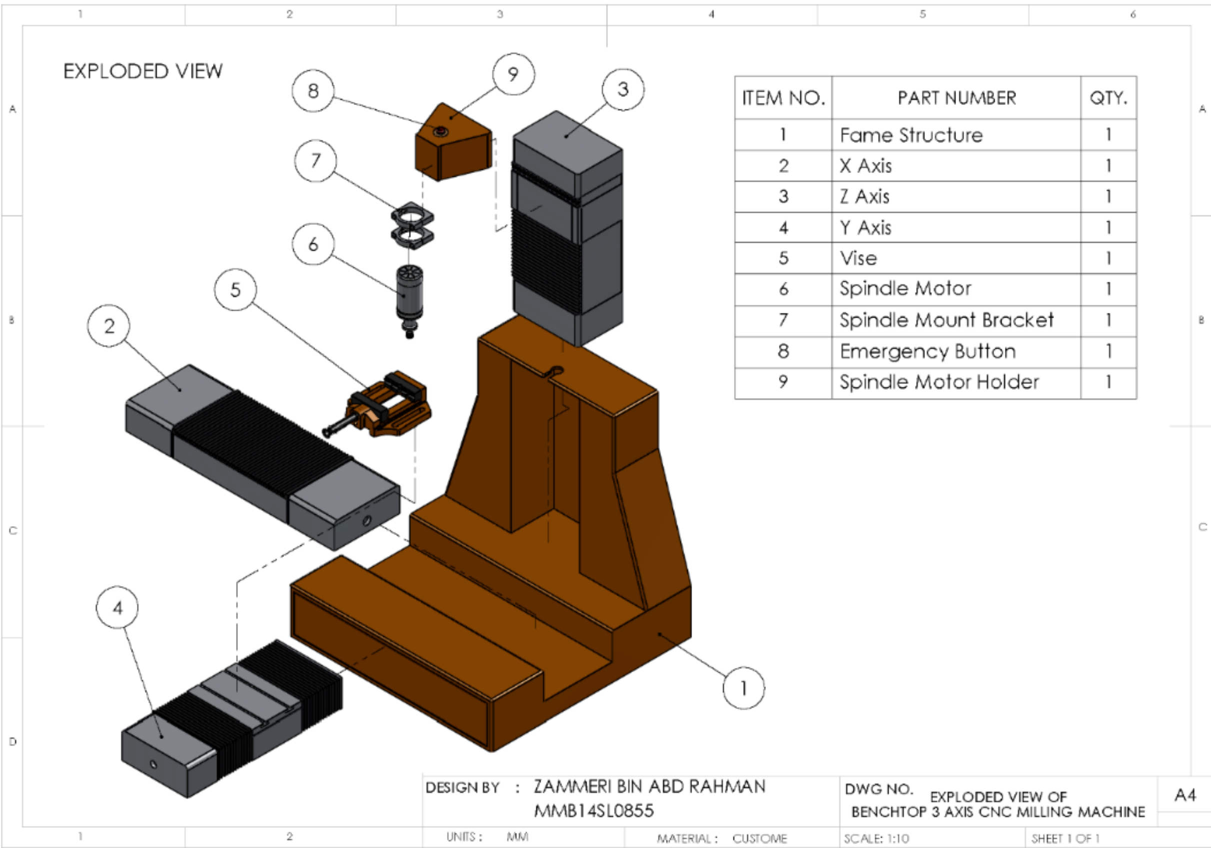


Fig. 1 - Details view of the machine

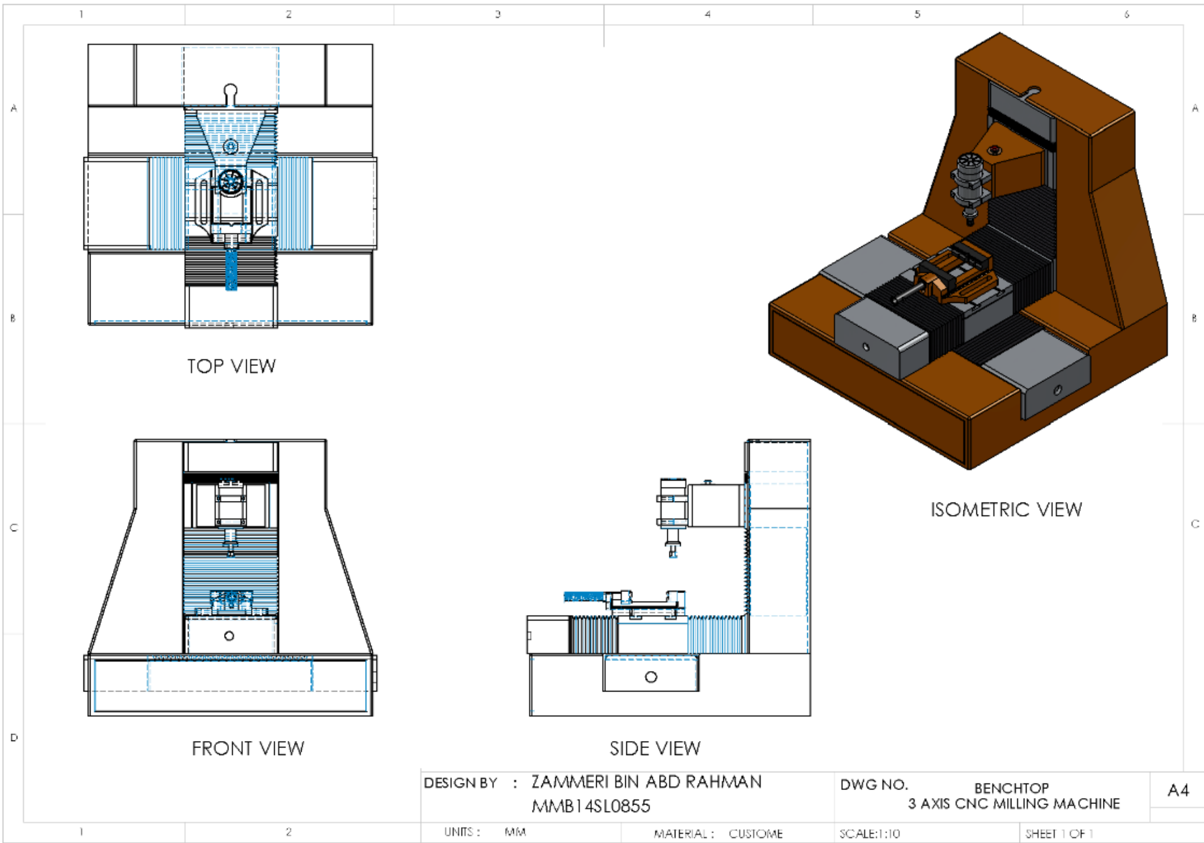


Fig. 2 - Technical drawing of the machine design

6.1 Component of the Milling Machine

The spindle motor, inverter, breakout board, stepper motor, and stepper driver are all chosen as the machine's primary components. Due to the machine's educational purpose, particularly for students learning CNC programming, considers light materials for cutting processes, such as wood, plastic, and aluminum, which require less machining energy. The NEMA 23 bipolar stepper motor and driver are chosen because they are affordable for the type of material to be cut. This low cost is achieved by selecting a basic main spindle, standard cutting tools, and a personal computer running Mach3 software as an open-source PC-based controller. Through the DB 25 male connector, the machine and the PC-based controller are connected to each axis control. The travel movement is generated for each axis by coupling a threaded ball bearing to a stepper motor and linear rail slide block. The machine is equipped with a magnetic limit switch sensor to prevent operating outside its range and causing damage.

Meanwhile, Table 1 illustrates a commercially available technical component for a three-axis CNC milling machine. This milling machine utilizes a linear guild and lead ball screw to transform rotary motion to linear motion, and each axis on the frame body is equipped with a lead screw. Each axis' motor selection is carefully defined about the stepper motor's driving mechanism and control method. On the z-axis, the machine features a spindle configured as a shaft for manually changing the z-axis cutting tool.

6.2 Machine Fabrication

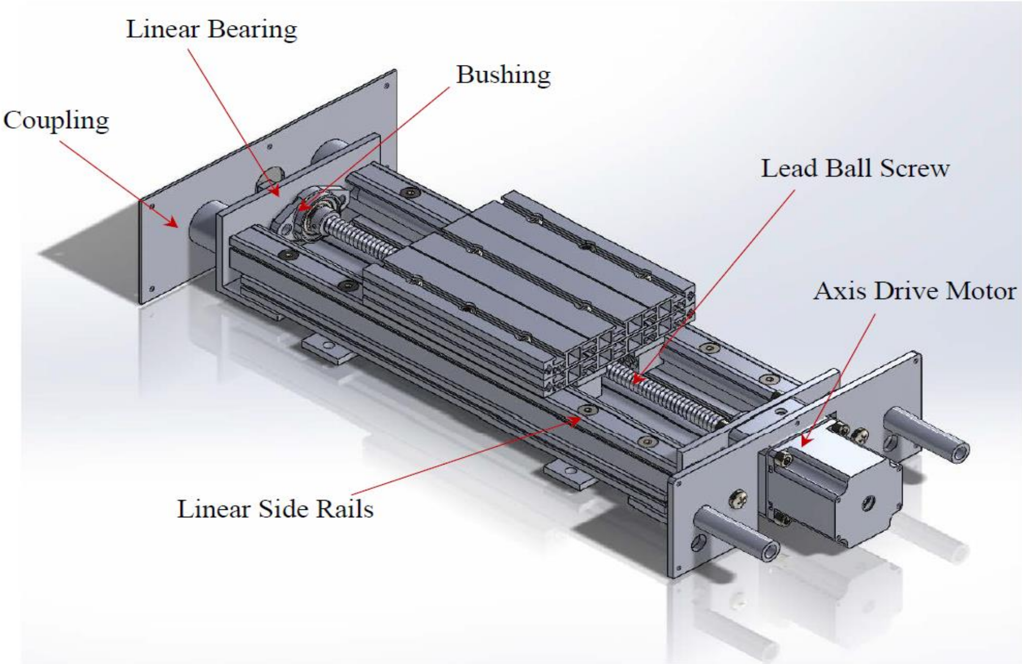
The frame structure and machine component are constructed entirely of a 5 mm aluminum 1060 plate. Aluminum alloys are well-suited for frame structures with thin-walled structures typically used to provide corrosion resistance or flexibility. Aluminum was chosen due to its high weight-to-cost ratio and sufficient strength to retain components without deforming. The X and Y axes' orientation, the uniformity of the work surface, and the Z vertical axis all served as the basis for developing this machine. A separate set of guards is mounted behind or at the frame base during assembly, and each axis's linear motion component is analyzed. As illustrated in Fig. 3, each component is contained within its volume. The design objective determines the final assembled product, including structural rigidity, lead ball screw, coupling set adjustment, weight reduction, offset linear rails for each axis, and depreciation of part complexity.

Table 1 - Technical specification of off-the-shelf components

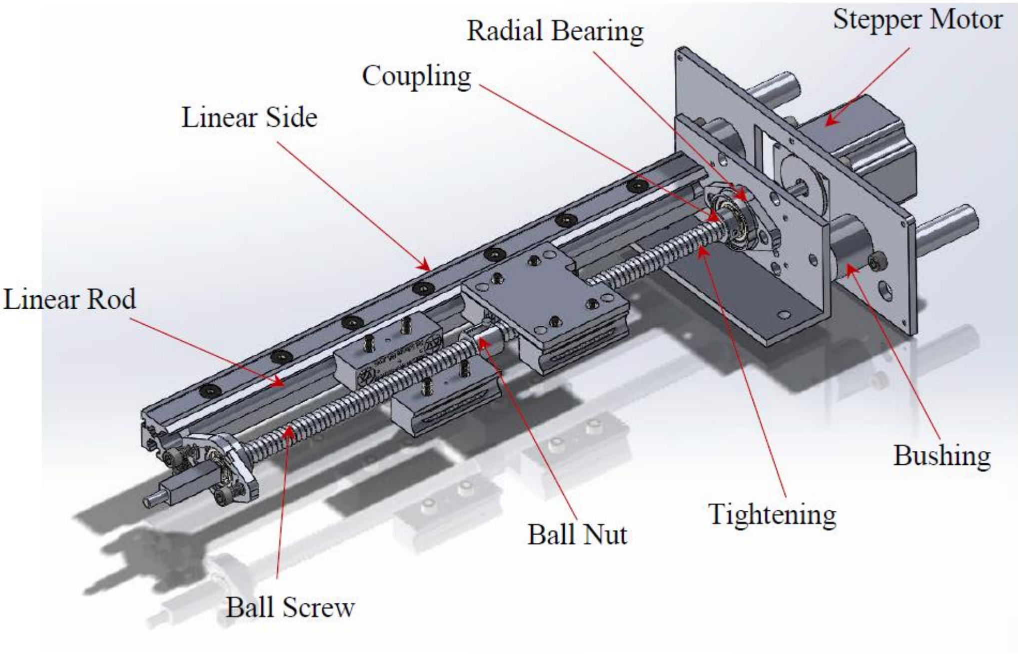
No	Type of Components	Description
1	Controller	ArtSoft Mach3
2	Stepper Motor	NEMA 23 STEP SIZE 1.80 Single Shaft Bipolar step motor
3	Stepper Motor Driver	HY-DIV 168N-3.5A Input voltage DC 12-36V Input current 1A-4A Output current 0.5A-3.5A
4	High-Speed Spindle Motor	Air-cooled LD57GF 600W DC 24V-110VDC 3000 - 13000 RPM Torque 600 mN.m 6A 400V Runout off: 0.01-0.02 mm Collect Chuck ER11 mm
5	Interface Breakout Board	CNC USB Interface Breakout Board CNC Stepper motor 6-axis interface board adapters Built-in DB25 male connector DB25 output pin: P1, P2, P3, P4, P5, P6, P7, P8, P9, P14, P16, P17 DB25 input pin: P10, P11, P12, P13, P15 DB25 GND pin: P18-P25 Power voltage is 5DC and supports Mach3 USB input
6	Power Supply for Spindle	Input voltage AC 220 V, DC 0 – 110 V Armature voltage output DC 0 – 110 V Excitation output voltage DC 110 V Output current 6A
7	Power Supply for driver motor	2-250-24 3.250W 24V 10A Switching Power Supply Input current 115 VAC, 5. 5A – 230VAC, 3.5A Output current 24V 10A

Fig. 3 - The frame structure and part of the machine

As shown in Fig. 4 (a) and 4 (b), the assembly drawings used to redefine production parts are proportional to the size of each axis. All axes utilize the same systems, including the drive system, linear guides, and the enclosing structure frame, depending on the size of the working area of each axis. The following sections fully assemble the axis drive system and all linear axis travel, as shown in Fig. 5. The two primary body frame components are the machine's base platform and linear travel axis. The machine platform dimension is 680 mm in length, 670 mm in width, and 660 mm in height. The X linear travel axis dimensions are 700 mm, the Y linear travel axis is 530 mm, and the Z linear travel axis is 500 mm.



Assembly of the axis components



The axis drive system

Fig. 4 - Technical drawing of the linear axis

X - axis Y - axis Z - axis

Fig. 5 - The frame structure and part of the machine

6.3 Machine Assembling

Ground assembly, screwing, and pinning are just a few methods to install machines. The assembly mechanism comprises several major components, including a control system that supplies specific electronic components and an x, y, and z-axis travel system. Each machine axis is mounted in a specific orientation, with the Y-axis spanning the X-axis and the Z-axis mounted vertically. Each axial travel direction was assigned a positive or negative value. It is important to protect the linear guide and lead screws from metal chips during the milling process, as the precision component may be harmed if the chips accumulate. The accordion-style folding cover protects the screws and exposed linear lead from damage. Otherwise, as illustrated in Fig. 6, the XY table-mounted configuration requires numerous screws to be secured upside down. A power and parallel communication cable connect the controller system to the machines.

In contrast, communication ports are conveniently located behind the machine on the side of the controller system frame. Each electrical component is connected to the spindle control mechanism through the spindle's motor wiring control. Significant electronic components, such as the DC converter, breakout board, stepper motor axis, and power supply, are grouped in control system sets, as presented in Fig. 7. An additional spindle power button is mounted on the controller system's side, and the controller automatically controls the spindle speed using CNC programming instructions. The travel axis, assembly components and accessories are all configured in a specific manner. The working table surface is meticulously assembled and inspected for flatness, as is the Z-axis in the body structure. Fig. 8 depicts a control diagram illustrating the critical steps in developing electronic components for CNC milling machine components.

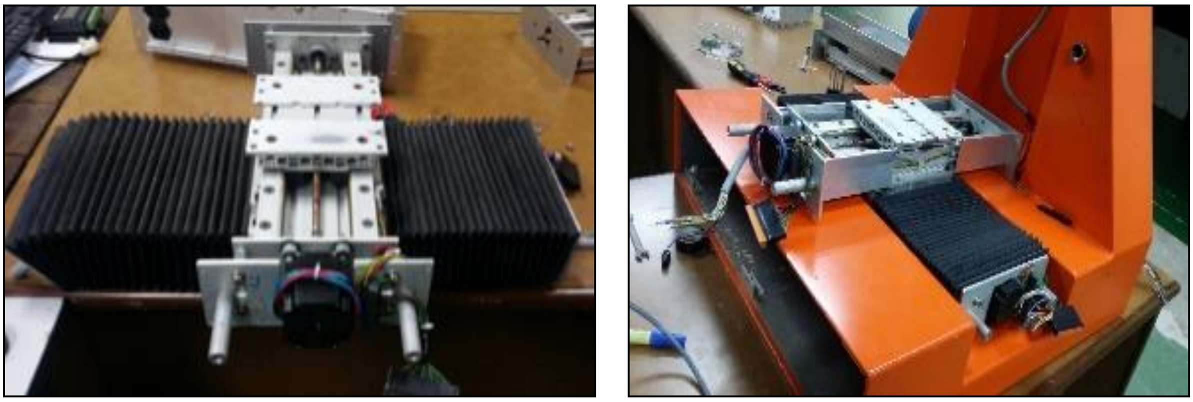


Fig. 6 - The X and Y-Axis assembling

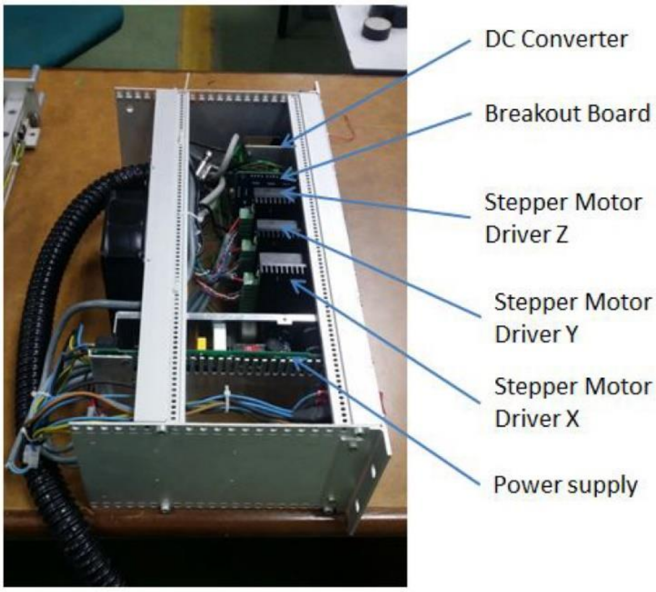


Fig. 7 - The controller system sets

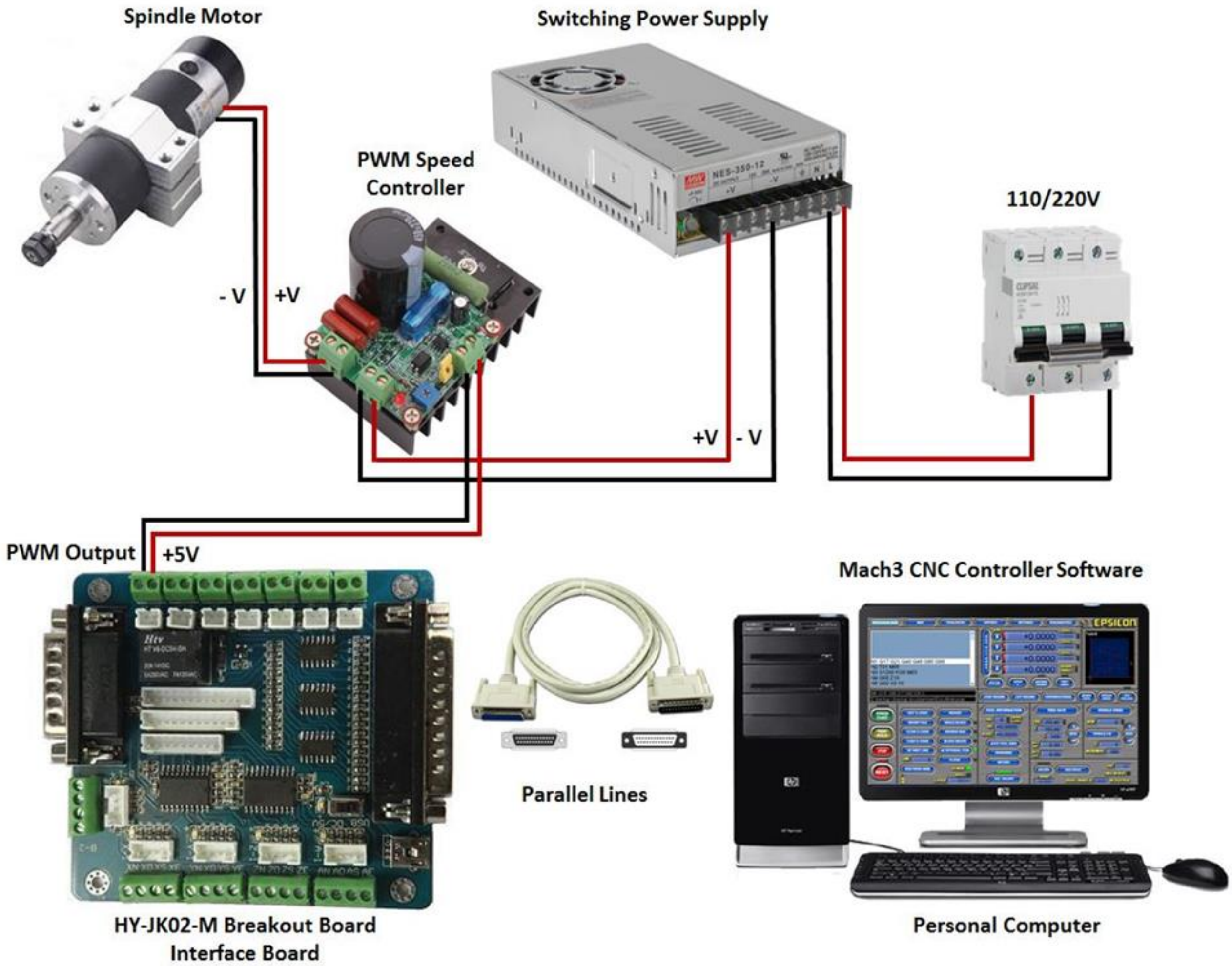


Fig. 8 - The Spindle control wiring diagram

Table 2 summarizes the machine specifications and requirements for completing the machine design and the condition of the completed machine. Whereas Table 3 contains a list of derivation requirements for machine design. Small-scale machines offer numerous advantages over conventional tools, including reduced size, more available space, portability, increased stiffness, and a higher strength-to-weight ratio. Because the machine requires fewer materials and parts, the weight of the moving components can be reduced, lowering the machine's power consumption. Additionally, it can help minimize vibration, noise, and environmental emissions while machining. These advantages allow for faster operation and increased output and productivity.

Table 2 - Milling machine specification

No	Technical requirement	Selection Value
1	Machine frame type	Open frame construction, column, and knee type, vertical spindle
2	Machine configuration	Vertical tool position, three linear axes
3	Structure frame construction	Welded 1060 aluminum composted of 2D CNC cut components
4	Machine platform size	X x Y x Z: (680 mm x 670 mm x 660 mm)
5	Working area size	X: 10 mm min – 400 mm max Y: 10 mm min – 300 mm max Z: 10 mm min – 200 mm max
6	X, Y & Z axis linear travel	(700 mm x 530 mm x 500 mm) max
7	Spindle motor	Air-cooled motor spindle
8	Spindle speed max	13,000 rpm
9	Motor	Stepper motor
10	Workpiece material	20kg
11	Controller system	PC based step/direction/Interface breakout board DB25 male connector/Mach3 software
12	Chuck	ER11
13	Weight	80kg maximum
14	Electrical	Input:ac110v/ 220v ± 10%50/60hz, 1 phase
15	End mill diameter	1 mm – 8 mm

Table 3 - Derived requirements

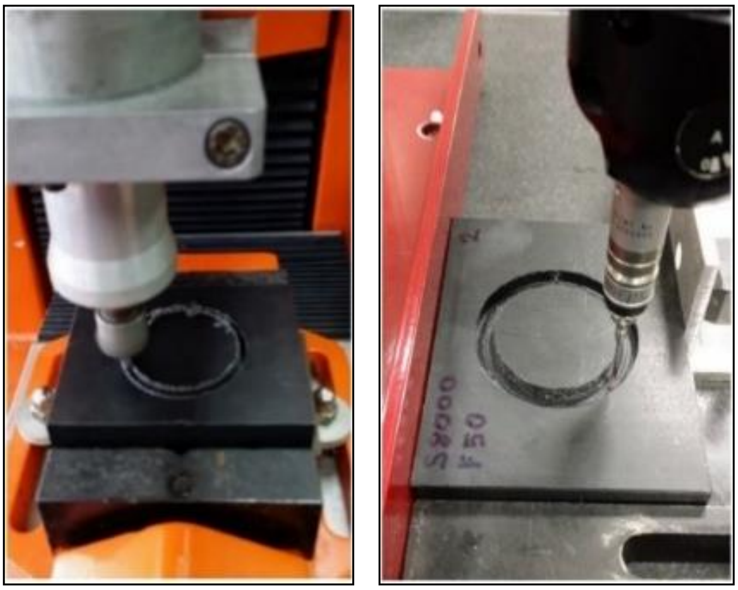
No	Requirement	Value	Selection criteria
1	Spindle speed	1000 RPM minimum	Theoretical maximum spindle speed
2	Accuracy	0.05" or 1 mm	Selected to achieve the objective
3	Body frame structural analysis	10% maximum for margin of the total error	Validate the dynamic analysis.
4	Positioning	0.1 mm maximum for full travel of each axis	Positional accuracy analysis
5	X and Y axis circular & straightness error	10% error maximum over the full travel	Allocated from requirement 17
6	Z-axis straightness error	10% error maximum over the full travel	Allocated from requirement 17

7. Machining Test and Validation

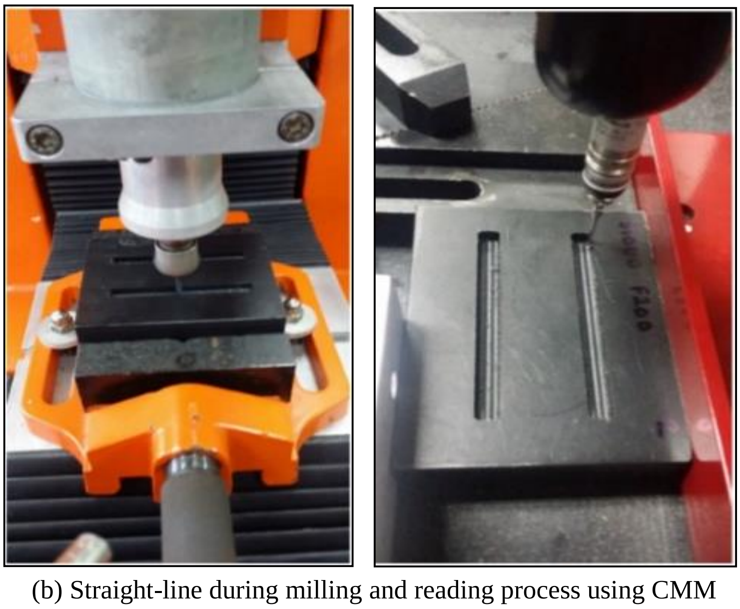
This test was conducted to determine the machine's capabilities compared to larger, more space-consuming machines. This machine is evaluated using a 5 mm end mill cutter to mill an Ultra High Molecular Weight Polyethylene (UHMW-PE) block. A 25-pin male-to-male cable is used to connect the computer to the breakout board. The initial tests would determine whether the machines could move up-down, left-right, and front-back, as well as the linear travel of each axis. The critical step is to control the axes' movements to monitor the UHMW-PE block's cutting process. The simulation software tests and calibrates machines and simulates tool paths. Eventually, the required coding is evaluated to determine whether the simulation software's fundamental knowledge is sufficient to model the CNC programming to identify defects, potential collisions, or inefficiencies. This study's coding testing requires a straight line and circular motion cutting profile. Mach3 software supported text files, which could be imported and used to read and edit g-code programming.

7.1 Circular Test

A circular test quantifies and diagnoses CNC machining tool motion errors. Four UHMW-PE block samples are prepared and analyzed to determine different parameters. Following the verification of measurement accuracy, the experimental result was identified using four CMM machine reference points. An average CMM machine result was obtained by analyzing four repeated sample tests. The machine generates a circular workpiece to conduct a circular test at predetermined spindle speeds and feed rates. The circular feature generated the CMM-measured profile of the surface contouring. The machine's circular test moves the spindle in a circle and detects deviations from the ideal process. These tests provide information about the machine's control, such as the effects of speed and interpolation when performed at different feed rates. Linear axis movement, axes that are not perpendicular, and movement that is not straight are all examples of fundamental geometrical errors that affect the test. Fig. 9 (a) illustrates the experimental procedure for performing the circular test in the milling process and reading with CMM machines. A UHMW-PE sample block creates a circular profile with a radius of 40mm, a cut depth of 5mm, and specified test parameters. At the same time, Fig. 10 (a) depicts the finished UHMW-PE block sample in the circular test experiment. The experimental parameters for four circularity tests are shown in Table 4. Spindle speed is set between 1000 and 8000 revolutions per minute, with a cut depth of 5mm and specific feed rates of F50 and F200.



(a) Circular profile during milling and reading process using CMM



(b) Straight-line during milling and reading process using CMM

Fig. 9 - The machine test experimental

(a) Circular test (b) Straightness test

Fig. 10 - The complete test of sample UHMW-PE block

For this research, a default diameter of 40 mm is used for each circle to be measured using a circle test. Circularity and expected deviations from the UHMW-PE reference circle are depicted graphically in Fig. 11. The best circularity test result is 0.61, and the parameter S8000 F50 DOC 5mm has 0.88%. The worst circularity test result is 0.64. Although the percentage error for the parameter S1000 F200 DOC 5 mm is 4.6%, it is still less than the derived requirements and thus acceptable. The results show that the surface along the circle part with a low spindle speed is significantly rougher than the surface along the circle part with a high spindle speed.

Table 4 - The circularity test parameters of the UHMW-PE block

Part	Std. Dev.*4	Actual R (mm)	Circle Ø (mm)	Circularity	Error (%) [Ø]
		S1000 F50 DOC 5mm			
1	2.27	21.97	43.94	0.64	
2	1.38	19.93	39.87	0.41	(40.88 - 40)
3	2.28	19.89	39.78	0.59	40
4	1.99	19.96	39.93	0.51	X 100%
Avg	1.98	20.44	40.88	0.54	2.2
		S1000 F200 DOC 5mm			
1	1.99	19.96	39.93	0.51	
2	2.84	20.06	40.12	0.73	(39.65 – 40)
3	2.47	21.83	43.65	0.65	40
4	2.65	21.82	43.65	0.68	X 100%
Avg	2.49	20.92	41.84	0.64	4.6
		S8000 F50 DOC 5mm			
1	2.37	19.81	39.62	0.64	
2	2.48	19.80	39.60	0.65	(39.65 – 40)
3	1.65	19.83	39.65	0.45	40
4	2.58	19.86	39.72	0.70	X 100%
Avg	2.27	19.83	39.65	0.61	0.88
		S8000 F200 DOC 5mm			
1	2.51	19.85	39.69	0.67	
2	0.86	19.80	39.59	0.26	(40.64 – 40)
3	2.39	21.82	43.64	0.63	40
4	2.19	19.83	39.65	0.57	X 100%
Avg	1.99	20.33	40.64	0.53	1.6

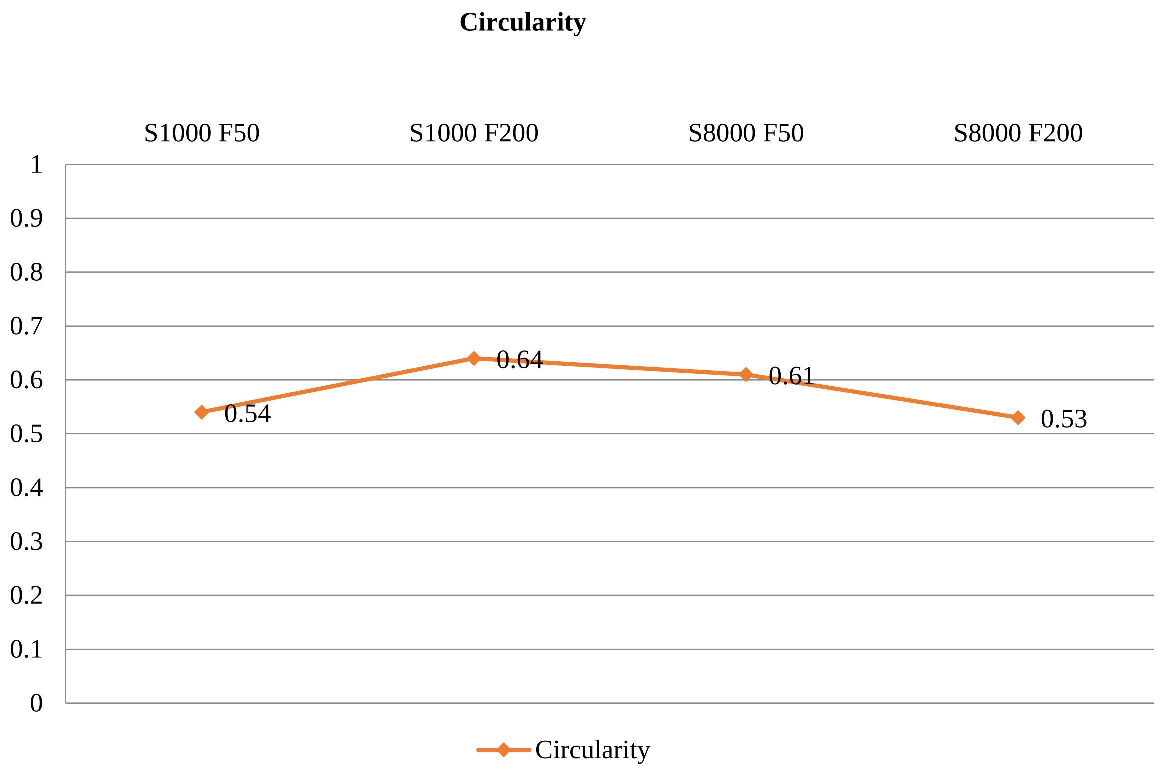


Fig. 11 - Circularity and predicted deflections from the reference circle

7.1 Straightness Test

The straight line represents all linear dimensions' directions since the shortest distance between two points is along a line. Straightness, a fundamental concept in linear measurements, is also necessary for the functional integrity of many engineering products [8]. A flat surface was machined on a UHMW-PE block using a 5 mm end mill cutter to determine straightness. The flatness test determines whether the X and Y axes are horizontal or vertical and whether the working table is vibrating, inclining, or tilted. Three steps comprise the experimental procedure: prepare and evaluate two UHMW-PE block samples for various test parameters and create two straight lines for each surface. Following verification of measurement accuracy, the experimental result is defined using four reference points along the linear tool path of the CMM machine. Four repeated tests per sample are measured using a high-precision CMM machine to obtain an average value. For instance, a straight-line test required the machine to construct a straight line within a workpiece using linear interpolation at various spindle speeds and feed rates. The CMM can be used to determine the straight-line surface profile, and two straight lines are drawn on the flat surface of the UHMW-PE sample block, as shown in Fig.9 (b).

Fig. 10 (b) illustrates the finished sample block for the straightness test in the milling process. On the profile, four data paths are measured for each straight line created with a CMM machine. All paths should have a constant height in the Z direction. Each straight line is set to a value of 1mm in all tests, and the straightness test's four distinct parameters are assigned to a depth of 5mm. The S1000 with F50, S1000 with F200, S8000 with F50, and S8000 with F200 have straight-line measuring parameters listed in Table 5. While Fig. 12 illustrated the straightness and predicted UHMW-PE reference line deviations graphically. The best straightness test result is the S8000 F50 DOC 5 mm parameter with a two-percentage error. However, these values are still less than the derive-requirement value and are acceptable. The highest straightness test results were rejected, with a straightness test of 0.15 and a parameter S1000 F50 DOC 5 mm with a 15% error over the derived requirements of 10%.

Table 5 - The straightness test parameters of the UHMW-PE block

Part	Std. Dev. * 4	Straight Line	Straightness	Error (%) [Ø]
		S1000 F50 DOC5mm		
1	0.38	0.82	0.18	(0.85 – 1) / 1 X 100%
2	0.13	0.94	0.06	
3	0.32	0.85	0.15	
4	0.44	0.80	0.20	
Avg	0.32	0.85	0.15	15
		S1000 F200 DOC5mm		
1	0.18	0.92	0.08	(0.92 – 1) / 1 X 100%
2	0.11	0.95	0.05	
3	0.22	0.9	0.10	
4	0.19	0.91	0.09	
Avg	0.18	0.92	0.08	8
		S8000 F50 DOC5mm		
1	0.06	0.97	0.03	(0.98 – 1) / 1 X 100%
2	0.05	0.98	0.02	
3	0.02	0.99	0.01	
4	0.09	0.97	0.03	
Avg	0.06	0.98	0.02	2
		S8000 F200 DOC5mm		
1	0.04	0.98	0.02	(0.97 – 1) / 1 X 100%
2	0.04	0.98	0.02	
3	0.03	0.98	0.02	
4	0.12	0.94	0.06	
Avg	0.06	0.97	0.03	3

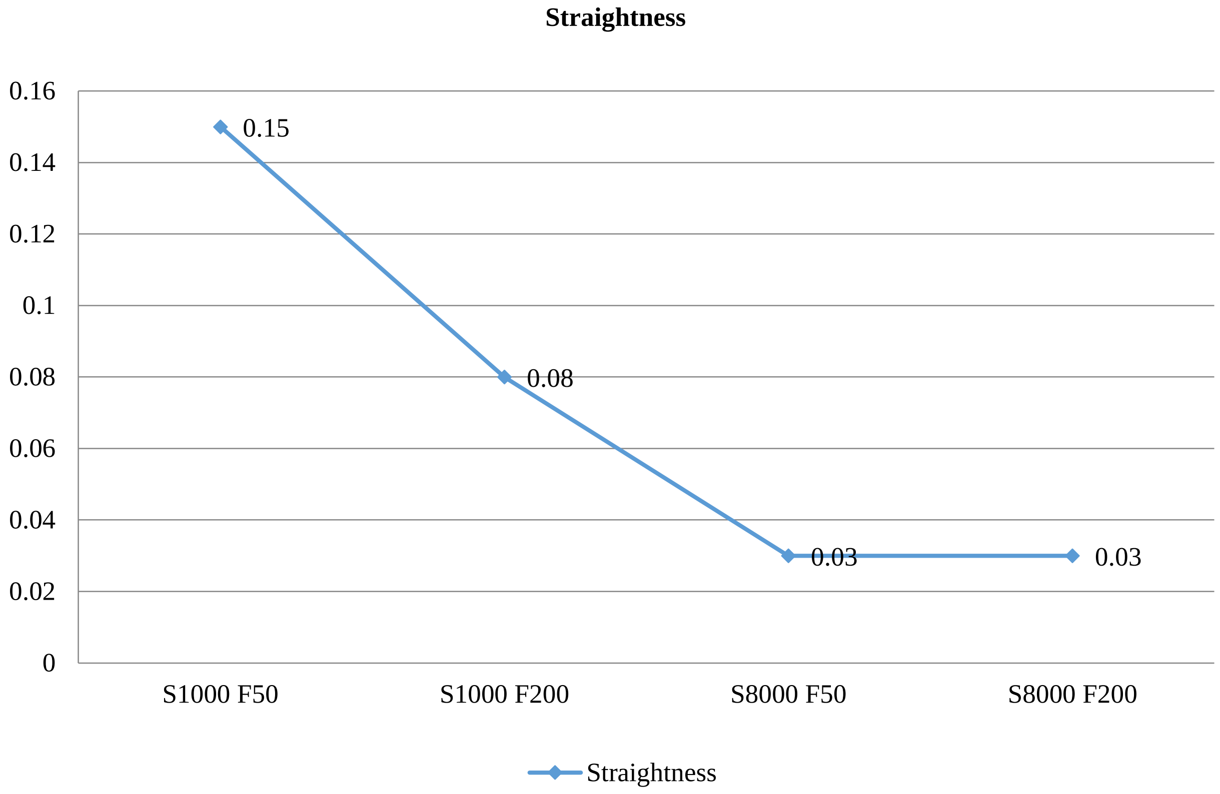
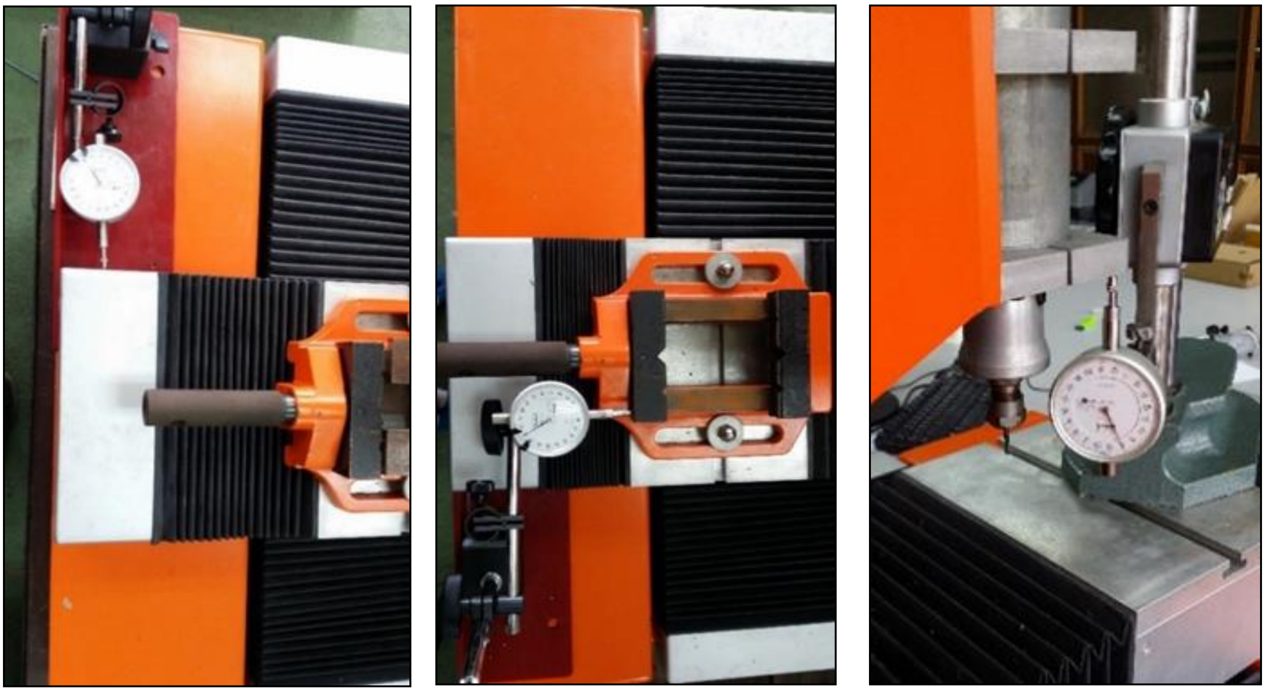


Fig. 12 - Straightness and predicted deflections from the reference line

7.2 Positional Test

Several tests are conducted to determine the CNC machine's efficiency, but positional accuracy is critical. Vertical machining accuracy and repeatability tests were conducted, and measurements on all axes, as shown in Fig. 13. Experiments were conducted using instrumentation, including a dial test indicator with a magnetic base, a height gauge, and a steel angle plate. Accuracy and repeatability are best defined as the machine's ability to position itself, and this test is conducted both before and after tuning a new machine. Experiments are conducted to determine the accuracy and repeatability of the developed technique and evaluate the technique's accuracy. The test procedure is efficient and can produce significantly better results when a dial indicator is used.

Nonetheless, the result eliminated a 0.001 mm error in most readings, as the dial test device sticks a little when attempting to use the maximum 1 mm range. Noonan [34] suggested that the accuracy and repeatability test data for each X, Y, and Z-axis consisted of ten readings. On each axis, X, Y, and Z, samples were taken around the entire axis, resulting in the highest average of 0.083 mm for accurate testing and 0.060 mm for repeatability testing. As this value approaches 0.1, the accuracy of this instrument approaches 0.1 mm, and data were reported as shown in Table 6.



X-Axis Y-Axis Z-Axis

Fig. 13 - The measurement positioning of the X, Y, and Z axes

Table 5 - The positional machining test parameters of sample UHMW-PE

No of Test	1	2	3	4	5	6	7	8	9	10	Avg
X-Axis Accuracy Test (mm)											
Reading	0.063	0.000	0.073	0.000	0.073	0.076	0.080	0.013	0.071	0.014	0.046
X-Axis Repeatability Test (mm)											
Reading	0.024	0.000	0.001	0.002	0.003	0.001	0.002	0.002	0.001	0.001	0.004
Y-Axis Accuracy Test (mm)											
Reading	0.079	0.082	0.080	0.081	0.082	0.081	0.080	0.088	0.083	0.095	0.083
Y-Axis Repeatability Test (mm)											
Reading	0.001	0.000	0.006	0.007	0.004	0.005	0.006	0.006	0.005	0.009	0.005
Z-Axis Accuracy Test (mm)											
Reading	0.061	0.000	0.046	0.000	0.059	0.000	0.076	0.000	0.082	0.000	0.032
Z-Axis Repeatability Test (mm)											
Reading	0.011	0.051	0.069	0.063	0.075	0.080	0.047	0.057	0.077	0.079	0.060

8. Conclusion

This paper introduces a three-axis CNC milling machine, with the most appropriate application for this machine being the development of vertical open frame structures. The machine's platform measures 680 mm in length, 670 mm in width, and 660 mm in height and features a work area of 400 mm on the X-axis, 300 mm on the Y-axis, and 200 mm on the Z-axis. It also features a maximum spindle speed of 13000 RPM. This manufacturing process entails component selection for the main portion, raw material procurement, and the completion of step-by-step installation procedures. Proper component selection can help to reduce costs and allow the appropriate determination or purchase of commercially available components, standard parts, and commercially available items. The low-cost product is made possible by combining standard PC interface features with the open-source ArtSoft Mach3 CNC Controller and utilizing commercially available hardware components such as stepper driver motors, a spindle speed controller, and interface boards. Procurement and product manufacturing are the first steps in the manufacturing and testing process for research, followed by assembly and testing. Critical components such as axis motors, linear guide rails, and breakout boards are selected from various configurations. The NEMA 23 stepper motor with driver and linear guide slide rails is an axis motion and configuration that allows selecting the highest performing components while adhering to rigidity and budget constraints.

Machines' efficiency and stability are assessed using positional accuracy, repeatability, circularity, and straightness techniques. It is completed to ascertain the feasibility of the design concept and the structure's form. A method for implementing a methodology for measuring circularity and straightness was developed for computational image analysis. The circular test demonstrates that increasing the feed rate reduces the machine's accuracy and flatness of the surface. The best circularity result is 0.61, and the parameter S8000 F50 DOC 5 mm has an error of 0.88%. However, the best results for the straightness test are the 5mm S8000 F50 DOC and 5mm S8000 F200 DOC parameters with a 2% error. 10% of the accuracy requirement chosen to accomplish the research objective is assigned an acceptance error. The completed machine is tested using various methods, the most critical is the positional accuracy test, and the machine's accuracy is typically around 0.1 mm. Due to their small-scale nature, these machines allow for more excellent manufacturing flexibility and efficiency while lowering capital costs. However, it is not designed for manufacturing or precise machining. Besides, it can easily replace high-cost conventional machines and enhance learning by increasing access to and understanding CNC mill operation and use. This machine can be used in a training institution based on programming machine tools, and the development system benefits students' teaching and learning processes. This machine would be a cost-effective alternative to a commercially available milling machine and require less installation space. The manufacturing concept proved feasible for designing small machine tools such as a CNC milling machine.

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