STUDY ON THE IMPROVEMENT OF A 4-AXIS MINI CNC MILLING MACHINE

NGHIÊN CỨU CẢI TIẾN MÁY PHAY CNC MINI 4 TRỤC

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Abstract - This study presents the process of improving a mini CNC milling machine from a 3-axis configuration to a 4-axis configuration to improve the ability to process parts with complex shapes. The improvement process includes improving the mechanical system with high-precision ball screws, adding an A-axis, and improving the control system using Mach3 communicating via USB with drivers and step motors. The experimental process was carried out by machining a number of aluminum alloy parts under different cutting conditions with the evaluation of geometric accuracy and surface quality using 3D scanning. The results show that, the average geometric deviation reaches 0.027 mm and the surface roughness reaches R_a = 1.2–1.5 µm. This research result provides a model for improving low-cost CNC systems for training and small-scale production.

Key words - Mini CNC milling machine; 4-axis machining; Mach3 control; Scan 3D

Tóm tắt - Nghiên cứu này trình bày tiến trình cải tiến máy phay CNC mini từ cấu hình 3 trục lên 4 trục nhằm cải thiện khả năng gia công các chi tiết có biên dạng phức tạp. Quá trình cải tiến bao gồm việc cải tiến hệ thống cơ khí với vitme bi chính xác cao, bổ sung trục quay A và cải tiến hệ thống điều khiển bằng Mach3 giao tiếp qua USB cùng bộ driver với step motor. Quá trình thực nghiệm được thực hiện thông qua gia công một số chi tiết từ hợp kim nhôm dưới nhiều điều kiện cắt khác nhau với việc đánh giá độ chính xác hình học và chất lượng bề mặt bằng công nghệ quét 3D. Kết quả cho thấy, độ lệch hình học trung bình đạt 0,027 mm và độ nhám bề mặt đạt R_a = 1,2–1,5 µm. Kết quả nghiên cứu cung cấp một mô hình cải tiến các hệ thống CNC chi phí thấp trong nhằm phục vụ cho đào tạo và kết hợp sản xuất quy mô nhỏ.

Từ khóa - Máy phay CNC mini; Gia công 4 trục; Mach3; quét 3D

1. Introduction

CNC (Computer Numerical Control) machining technology is increasingly playing a crucial role in industrial manufacturing and technical education. CNC milling machines, especially small-sized CNC machines, have become valuable tools in education, research, and manufacturing due to their compact size, low cost, and flexible customization capabilities [1], [2]. However, most commercial small CNC machines currently feature only three axes (X, Y, Z), which limits their ability to machine parts with complex geometries. In the field of precision mechanical machining, upgrading CNC milling machines from three axes to four axes has become an important trend to meet the demand for machining complex mechanical parts, such as engraving curved profiles, spiral machining, or manufacturing cylindrical components. The addition of the A-axis not only expands machining capabilities but also improves performance and product quality [3].

In recent years, several studies have focused on improving small CNC machines and applying CAD/CAM/CNC technology in production and training. Nei Paz and Marcus Americano da Costa developed a specialized 4-axis CNC machine for dental machining, enabling the production of high-precision dental prostheses [4]. Rastvorova and Klyucherev proposed a design model for a multifunctional CNC machine with integrated control algorithms to enhance machining efficiency [5]. Lin and Lee developed a remote servo control system for multi-axis CNC machines based on virtual machine tool simulation, which improves processing speed and machining accuracy [6]. S. Hatefi et al. proposed a new CNC controller that increases machining speed and reduces errors in mini CNC systems [7]. Many studies have focused on improving the accuracy of CNC machines through various methods. For example, M. S. Adivarekar used a Gaussian map to calculate the rotary axes for 4-axis CNC milling machines, optimizing the machining process [8]. Meanwhile, L. Cai et al. proposed an optimal design method to maintain machining accuracy for multi-axis NC machines, which can limit geometric errors and specify accuracy levels [9].

Upgrading the control system also plays a vital role in enhancing machine performance. R. Ward et al. conducted research on accurately predicting machining speed by modeling the kinematics and toolpath generation of modern CNC machine tools. Accurate prediction of feed rate and cycle time through dynamic modeling of the interpolator can improve production efficiency [10]. Additionally, Z. Wang and H. Yuan's research group proposed a generalized accuracy allocation method to improve CNC machining performance based on specific design requirements, with optimization results showing that this method is effective and can reliably optimize machining accuracy [11].

The integration between programming software and the control system is also of interest. The use of Fusion 360 in combination with Mach3 has been discussed in many forums and studies, demonstrating the compatibility of G-code generation and post-processing for multi-axis CNC machine control [12-14]. However, developing post-processing requires building specific methods to determine error compensation parameters, which is quite complex for machines with more than three axes, as mentioned in M. S. Adivarekar's research [8].

Overall, significant advances have been made in optimizing control systems, improving accuracy, and expanding the applications of mini CNC machines. However, most of these studies still focus on industrial CNC systems, while upgrading mini CNC machines to suit educational and scientific research environments remains uncommon.

This paper aims to describe the process of upgrading a mini CNC milling machine from three axes to four axes by surveying the machine status, improving mechanical components and the control system, reconfiguring machine parameters, and conducting specific machining experiments to provide a feasible model for laboratories and educational institutions. Experimental results after the upgrade show machining accuracy, with the lowest recorded average geometric deviation at 0.027 mm and surface roughness in the range of R_a = 1.2–1.5 µm. The research results can be applied to machining small-sized parts with complex geometries and are suitable for teaching, research, and training purposes.

2. Machine Condition Assessment

2.1. CNC milling machine before improvement

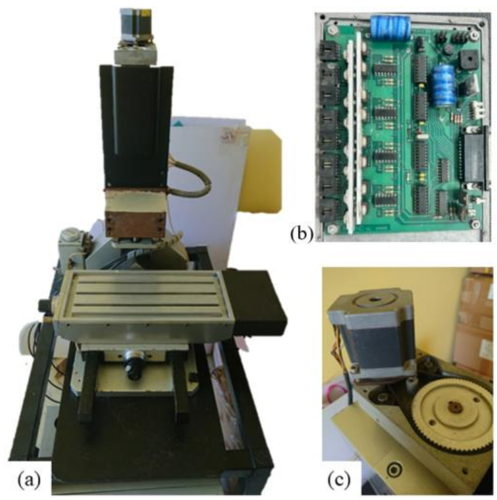

Figure 1. *CNC milling machine before improvement; a) 3-axis CNC milling machine frame; b) Controller; c) Z-axis transmission*

The initial CNC milling machine used in the study featured three axes with a machining space of 300 × 300 × 300 mm, as shown in Figure 1. The machine used NEMA 23 stepper motors combined with a ball screw transmission system. The surface of the ball screw shaft showed signs of rust due to mechanical corrosion. The drive belts were stretched, resulting in inaccurate transmission. The cooling system was no longer operational, the mechanical limit switches were damaged, and internal mechanical components exhibited wear due to friction, leading to positional deviations and reduced machining accuracy when detecting travel limits, which posed safety risks and positional errors during operation. The machine was controlled by a MAXNC-10108C controller, with onboard stepper motor drivers that were not fully compatible with current software and were susceptible to electromagnetic interference, resulting in unstable operation as shown in Figure 1b. The MS2-107 inverter from Adlee Powertronic installed on the CNC machine no longer met modern requirements for performance, features, and connectivity. These limitations highlight the need for a comprehensive upgrade of the system to meet the demands of teaching, research, and machining.

2.2. Mechanical system improvement

The upgrade process focused on improving accuracy and expanding the machining capabilities of the mini CNC machine. The protective frame was redesigned to safeguard mechanical systems, enhance operational safety, and minimize risks from chips during machining. The T16 ball screw with a lead t=5 mm was replaced to improve the travel accuracy of the X, Y, and Z axes and reduce errors caused by vibrations during operation [15], [16]. To ensure stable operation even when machining hard materials such as aluminum, higher-power stepper motors were used. The 2M57-80A-0830 stepper motor, with a step angle of 1.8°, was used to drive the X, Y, Z, and A axes, improving machining accuracy. Additionally, the upgraded CNC milling machine was equipped with an oil pump system for lubricating the linear rails and ball screws to ensure smooth operation. Limit sensors were replaced with ones meeting IP65 or higher protection standards, preventing coolant and dust ingress and accurately controlling the movement of the axes, ensuring stable, reliable, and safe machining.

The lead of the X, Y, Z axes was calculated using the following formula (1):

$$\textit{Axis lead} = \frac{\frac{\text{number of pulses}}{\text{1 motor revolution}} \times \text{transmission ratio}}{\text{ball screw lead}}\ (\text{mm}) \quad (1)$$

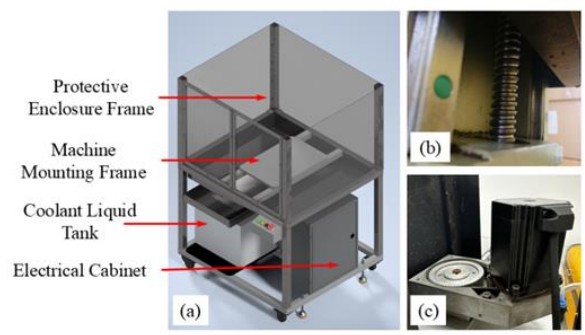

Figure 2. *Mechanical system after improvement; a) Milling machine protective frame; b) Ball screw transmission; c) Stepper motor*

The A-axis mechanism was installed to machine parts with complex geometries, such as curved surfaces, helical profiles, or cylindrical shapes [17], [18]. The worm gear transmission with a ratio of 1:80 increases torque, ensuring stable movement suitable for machining parts requiring high precision. The worm shaft uses a single-head design, with precisely manufactured helical grooves to ensure proper engagement with the worm wheel. The rotation angle of the A-axis is calculated using formula (2):

$$\textit{Axis rotation angle} = \frac{\frac{\text{number of pulses}}{\text{1 motor revolution}} \times \text{transmission ratio}}{360}\ \textit{(degrees)} \quad (2)$$

Table 1. *Mechanical system specifications before and after improvement*

Item	Specification	
	Before improvement	After improvement
Overall dimensions	1300×900×900 (mm)	
Machining space	300×300×300 (mm)	
X, Y, Z axis motor	NEMA 23	2M57-80A-0830
A axis	Not available	2M57; transmission ratio 1:80
Spindle motor	Not available	0~24.000 rpm, 0,8kw
Ball screw	Damaged	T16; t=5mm

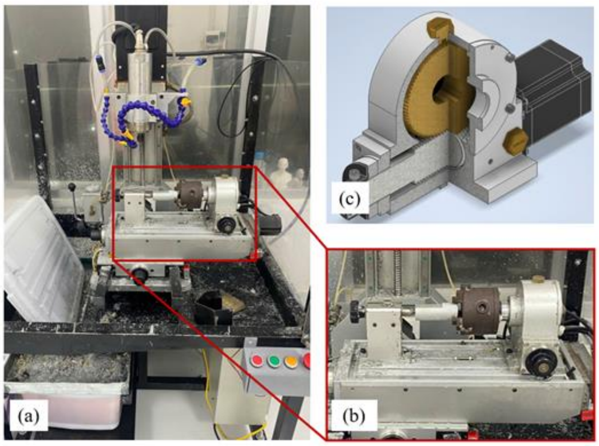

Figure 3. *CNC milling machine after upgraded; a) CNC machine frame; b) A-axis; c) A-axis transmission*

2.3. Control system improvement

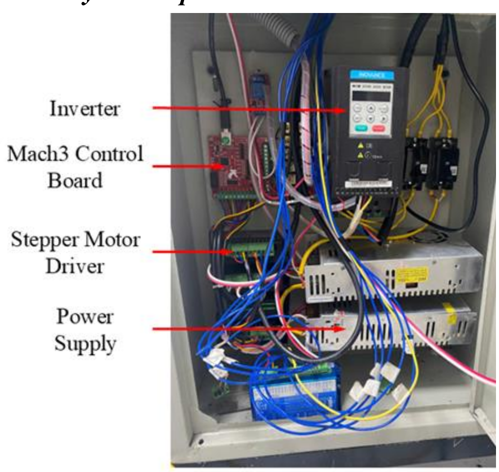

Figure 4. *CNC milling machine control system*

The control system upgrade aimed to ensure compatibility with modern machining support software and replace independent drivers to facilitate easier adjustment and maintenance. In this study, the Mach3 BOB USB controller was selected to replace the MAXNC-10108C controller. Mach3 software is installed and directly controls the machine from a computer. The BT6600 driver was chosen to control the 2-phase stepper motors (Model 2M57-80A-0830), helping to reduce electromagnetic interference and enhance system reliability, especially in machining environments with many disturbances and electrical noise [17]. The Inovance 0.8 kW inverter was used to control the spindle motor speed, supporting a wide speed range from 100 to 24,000 rpm. The spindle speed can be adjusted to suit machining requirements for materials such as aluminum, copper, and plastics. Additionally, the control system is connected to the computer via USB and Ethernet interfaces, increasing data transmission speed and enabling simulation of the machining process on the computer screen. Proper arrangement of the electrical system also helps reduce electromagnetic interference, ensuring more accurate control signals.

Table 2. *Electrical system specifications before and after improvement*

Item	Specification	
	Before improvement	**After improvement**
Control circuit	MAXNC-10108C	BOB Mach3 USB
Inverter	MS2-107	MD200S; 0,75b-int
Driver	Onboard	BT6600, 9~42 VDC
Power supply	110V ~ 220V ±15%	

3. Experimental operation

3.1. Machining parameters

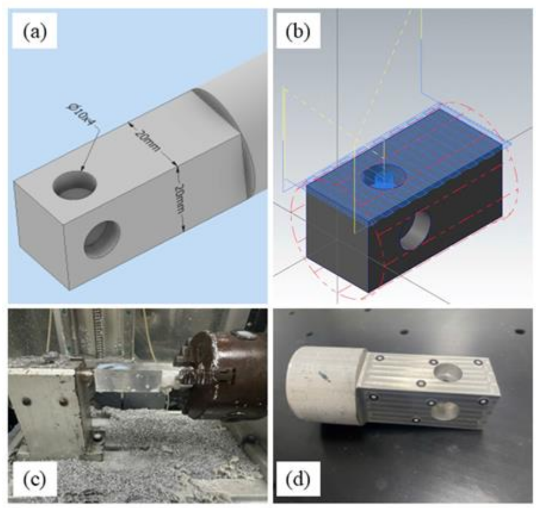

Figure 5. *Sample machining and inspection process; a) CAD sample dimensions; b) Machining programming; c) Machining process; d) Inspection process*

To evaluate the performance of the CNC milling machine after improvement, the research team conducted machining tests using aluminum as the workpiece material. The input parameters considered included feed rate, cutting speed, and depth of cut, with three levels of cutting speed V = 500, 700, and 900 (mm/min), three levels of feed rate f = 0.02, 0.04, and 0.06 (mm/rev), and three levels of depth of cut d = 0.2, 0.4, and 0.6 (mm). The output factors included surface roughness and geometric accuracy of the machined parts. A total of nine samples were programmed and simulated for machining using integrated CAD/CAM software directly connected to the Mach3 control system, as applied in this study. Each sample was machined with different combinations of cutting parameters to assess machine stability under various operating conditions. The machining and inspection process is shown in Figure 5. The machining parameters are presented in Table 3. After machining, the parts were inspected for geometric accuracy using a GOM 3D scanner. The scanned data were processed and compared between the CAD model and the measurement results from GOM Inspect software. The measurement results for the samples using the scanner and GOM Inspect software are shown in Figure 6. Indicators such as maximum deviation, average deviation, and error distribution by region were used to evaluate machining accuracy.

Table 3. *Machining parameters in the experiment*

Level	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)
1	500	0.02	0.2
2	700	0.04	0.4
3	900	0.06	0.6

3.2. Results and discussion

The inspection results of the machined samples show that the improved small CNC system can machine aluminum with high accuracy and significantly better surface quality compared to before the upgrade. Across nine combinations of cutting parameters, the geometric error measured by GOM Inspect software ranged from ±0.025 mm to ±0.065 mm. Notably, the combination with a cutting speed of 900 mm/min, feed rate of 0.04 mm/rev, and depth of cut of 0.4 mm yielded the lowest error, with an average deviation of approximately 0.027 mm. The measurement results for the samples after machining are presented in Table 4.

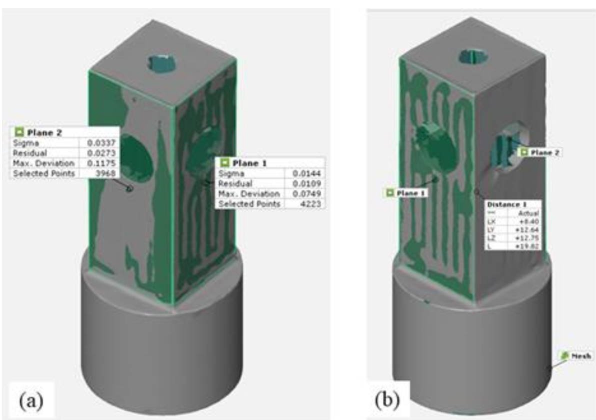

Figure 6. *Samples measured and processed by GOM Inspect software*

Table 4. *Results after inspection of machined samples*

No.	Cutting speed (mm/min)	Feed rate (mm/rev)	Depth of cut (mm)	Average deviation (mm)	Maximum deviation (mm)
1	500	0.02	0.2	0.042	0.058
2	700	0.04	0.4	0.036	0.052
3	900	0.06	0.6	0.031	0.050
4	500	0.04	0.6	0.039	0.061
5	700	0.06	0.2	0.033	0.047
6	900	0.02	0.4	0.027	0.041
7	500	0.06	0.6	0.045	0.065
8	700	0.02	0.6	0.040	0.056
9	900	0.06	0.4	0.030	0.048

Figure 7 shows the deviation map based on the average geometric deviation measured after machining the samples. The map was constructed from nine different combinations of cutting parameters, including cutting speed = 500, 700, 900 (mm/min) and feed rate = 0.02, 0.04, 0.06 (mm/rev). The color distribution on the map clearly indicates that the lowest average error (0.027 mm) occurs with a cutting speed of 900 mm/min and a feed rate of 0.02 mm/rev. Conversely, higher errors are recorded at combinations with low cutting speeds and high feed rates, particularly at 500 mm/min and 0.06 mm/rev, where the error reaches up to 0.045 mm. The results show that high cutting speed combined with low feed rate helps improve geometric accuracy. The feed rate significantly affects surface error; increasing the feed rate can increase tool deflection and vibration, leading to greater errors. The upgraded system demonstrates stable and reliable operation, with deviation ranging narrowly from ±0.03 mm to ±0.05 mm, suitable for training and prototyping applications. Overall, the deviation map confirms that upgrading the mechanical and control systems has significantly improved the accuracy and stability of the mini CNC milling machine.

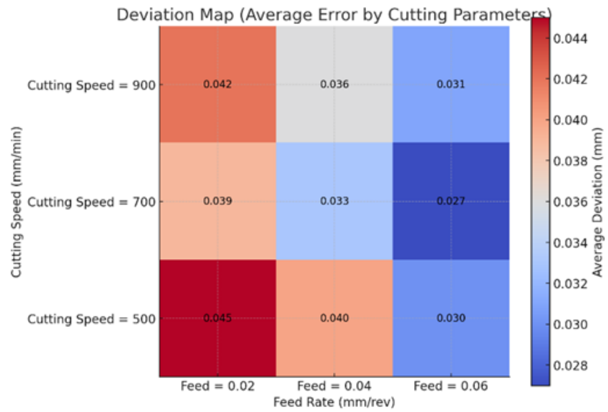

Figure 7. *Error chart, average deviation by cutting combination*

The deviation map from GOM Inspect shows that error regions are mainly concentrated at the edges and positions with large tool direction changes, while most of the remaining surface has deviations below 0.03 mm. Measurement results indicate that the CNC machine upgraded from three axes to four axes ensures stable machining. The measured surface roughness reaches Ra values of approximately 1.2–1.5 µm, which meets the requirements for many standard engineering applications.

4. Conclusion

This paper presents the process of upgrading a mini 3-axis CNC milling machine to a 4-axis configuration, focusing on improving the mechanical system and upgrading the control system. The mechanical improvements, including replacing the ball screw and stepper motors, contributed to enhancing the rigidity and accuracy of the system. Simultaneously, the integration of Mach3 control software via USB interface along with the drivers was completed. The results show that after the upgrade, the machine achieves geometric accuracy and surface quality, with the lowest average deviation recorded at around 0.027 mm and surface roughness ranging from Ra = 1.2–1.5 µm, suitable for training and prototyping applications. Error map analysis shows that the system operates stably under various cutting conditions and can machine complex profiles with small, evenly distributed errors. This CNC milling machine can be used for training and small-scale production of aluminum materials.

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