



Research article

Development of Control System for TU-2A CNC Machine*Ariawan Bayu Wicaksono^{1a*}, Lewi^{2a}, Muh. Abdillah^{3a}, Ishak, Nurhidayanti^{4a}**^aDepartment of Mechanical Engineering, Politeknik Negeri Ujung Pandang, Makassar, Indonesia*

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This study aims to design and develop an electronic control system for the TU-2A CNC machine to improve performance, simplify programming, and facilitate machine maintenance and repair. The method is to retrofit the EMCO TU-2A CNC machine by replacing its old electronic components with more modern, affordable components, without compromising its precision. Calibration is performed to ensure the machine's movement is accurate, while machine testing is conducted by machining workpieces made of Teflon (PTFE) and aluminum. The results of the study indicate that after the development and maintenance, the CNC TU-2A machine showed improvements in precision and ease of use. The machine's error remains within the tolerance limit, approximately 0.01 to 0.02 mm, indicating that the calibration was successful. This study concludes that the development of the new electronic control system has made the CNC TU-2A machine more efficient and easier to maintain, making it more suitable for use in vocational education.

1. INTRODUCTION

Modern manufacturing industries heavily rely on automated machine tools to produce high-precision products at high speeds. One key innovation in manufacturing is the CNC (Computer Numerical Control) machine, which allows the automatic control of cutting tools via a computer [1], [2]. CNC machines have become a standard in various industries, particularly in mass-production sectors that demand high precision and efficiency [3], [4], [5]. Although CNC machines offer numerous advantages, several major challenges remain, including high costs, operational difficulties, and maintenance processes that require specialized expertise.

The CNC Training Unit (TU-2A) machine is frequently used in educational institutions for training in mechanical engineering skills. However, this machine faces issues with its existing electronic and control systems, necessitating repairs and improvements to enhance its efficiency [6]. The conventional programming and maintenance processes for the CNC TU-2A still rely on manual methods, which are time-consuming and may increase the likelihood of operational errors.

Several previous studies have highlighted the importance of improvements in the electronic and control systems of CNC machines, such as the upgrade of the TU-3A control system for precision and CAD/CAM support [7], the development of simulation/virtual platforms for smart

manufacturing learning [8], the implementation of intelligent diagnostic systems for CNC maintenance [9], the development of a predictive maintenance framework based on machine learning in the automotive industry [10], and the retrofit of CNC lathes for vocational education with Mach3 controllers [11]. However, most of these studies focus on machines with high production capacity or on specific aspects, such as programming or machine efficiency. No research has specifically designed and developed new electronic and control systems for the CNC Training Unit TU-2A machine that address three main needs: (1) simplifying the programming process, (2) streamlining maintenance procedures for vocational education users, and (3) utilizing more affordable and accessible modern components without sacrificing machine performance and precision.

This research aims to fill this gap by designing and developing an electronic control system that enhances the performance of the CNC TU-2A machine while providing a more user-friendly programming interface. Additionally, this study seeks to identify potential improvements in machine maintenance by replacing existing electronic components with more advanced and accessible components, offering more efficient and affordable solutions for vocational education.

2. LITERATURE REVIEW

2.1 EMCO TU-2A CNC Machine

The TU-2A (Training Unit 2 Axis) is a CNC (Computer Numerical Control) machine specifically designed for training and educational purposes in manufacturing and machine programming [7], [12]. Manufactured by EMCO, a company renowned for developing and producing high-quality CNC machines, the TU-2A offers ease of use and flexibility, making it ideal as a learning tool for understanding the fundamentals of CNC technology, particularly in operating a two-axis machine [13]. Figure 1 shows the EMCO TU-2A CNC machine.



Figure 1. EMCO TU-2A CNC machine

The origin of the TU-2A stemmed from EMCO's initiative to provide a training platform that allows students or novice operators to familiarize themselves with and understand the basic concepts of CNC machine operation without dealing with the complexities of large industrial CNC machines. The primary function of the TU-2A is to teach programming and operation of a CNC machine with two axes, which include linear motion along the X and Z axes, as illustrated in Figure 2. This machine enables users to develop skills in G-code programming, the fundamental programming technique for CNC machines, as well as an understanding of machine motion programming, tool selection, and machine parameter settings [14]. Using this machine, students can learn to operate it with precision, control speed and feed rates, and complete simple manufacturing tasks.

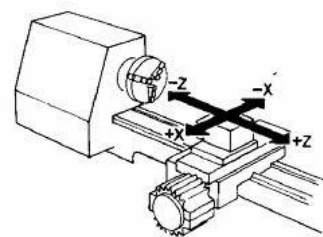


Figure 2. The axis system on a 2-axis CNC turning machine

The main components of the TU-2A include a computer-based control system, drive motors for the X and Z axes, a spindle or machine head that can be equipped with various cutting tools, and a cooling system to cool the cutting tools during machining [15], [16]. Additionally, the TU-2A is equipped with software that allows users to write and test their CNC programs and visualize the machining process in simulation mode. All these components work

together to provide a comprehensive machine operation experience within the scope of training.

2.2 MACH-3 Breakout Board

The MACH-3 CNC Breakout Board is a crucial component in the control system of a CNC (Computer Numerical Control) machine. This board serves as an interface between the computer running MACH-3 software and various machine components, such as stepper motors, relays, and other I/O devices [17]. In this system, MACH-3 controls the machine's operations by converting numerical commands into mechanical movements via electrical signals received by the breakout board. The board acts as an intermediary between the computer and the machine, managing the distribution of electrical signals necessary to drive the motors and control other devices [18].

The MACH-3 CNC Breakout Board originates from the development of more complex CNC systems, which initially required separate hardware and software to control the various machine components [19]. As a solution, this breakout board was designed to simplify connectivity and enhance ease of use and installation. It was first introduced as an alternative for connecting a PC to CNC hardware via parallel or USB ports. Figure 3 shows the configuration of the MACH-3 CNC breakout board.

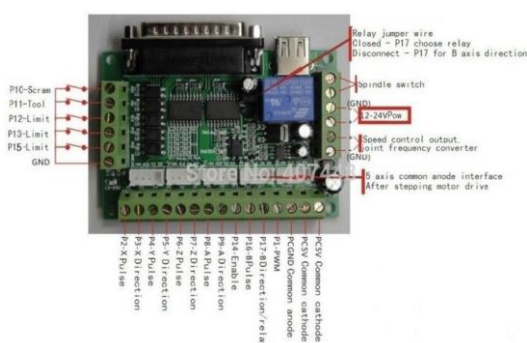


Figure 3. MACH-3 breakout board configuration

The configuration of this board typically includes several input and output ports for connecting components such as stepper motors, spindles, limit switches, and other supporting devices [20]. Typically, this breakout board is also equipped with motor drivers to control stepper motors through signals sent from the computer. Additionally, this board often features protective components, such as

fuses and optocouplers, to safeguard the equipment from damage caused by power surges or connection errors. In many applications, the MACH-3 CNC Breakout Board is used in DIY (Do It Yourself) systems and simpler CNC machine setups, offering a relatively affordable price and an easy-to-configure setup [21].

2.3 MACH-3 Turn

MACH-3 Turn is a software designed to control CNC (Computer Numerical Control) machines, specifically for programming and operating turning machines. As part of the CNC control system, MACH-3 Turn allows users to design, edit, and optimize cutting programs on turning machines with high precision. The primary function of this software is to control the machine's operation via G-code commands, ensuring it moves according to the operator's design. The MACH-3 Turn software interface is shown in Figure 4.

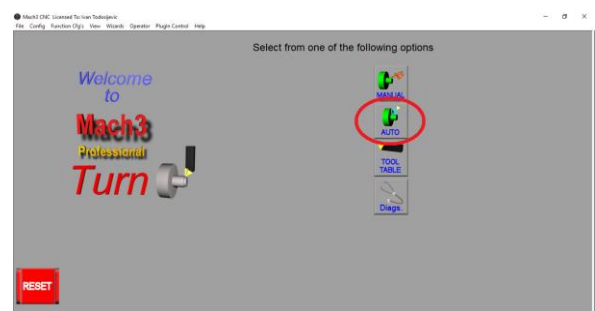


Figure 4. The interface of the MACH-3 Turn

MACH-3 Turn also features process simulation, automatic programming, and speed and position control, providing users with greater convenience when programming and operating turning machines. To use this software, the operator needs to install it on a PC connected to the CNC machine and input the appropriate commands based on the production process requirements, either manually or automatically. This software is widely used in the manufacturing industry to improve the efficiency and accuracy of machine production while minimizing the possibility of manual errors.

3. RESEARCH METHOD

3.1 Machine Design

This study employs a retrofit technique that requires a design specifically developed to upgrade the CNC TU-2A EMCO machine. The design process comprises both mechanical and electronic control system design. The mechanical design and the component details of CNC TU-2A EMCO are shown in Figures 5, 6, 7, and Table 1, respectively.

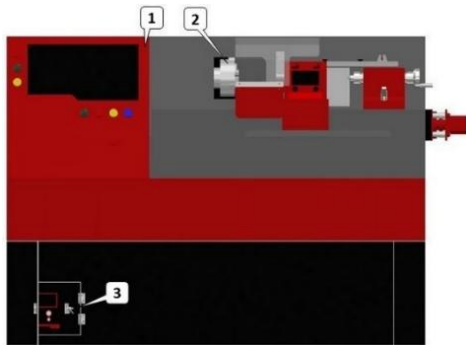


Figure 5. Front view of the TU-2A CNC machine body design

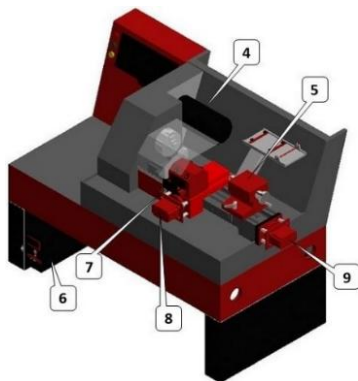


Figure 6. Isometric view of TU-2A CNC machine body design

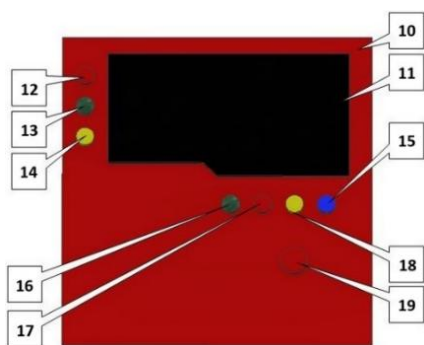


Figure 7. Control panel box

Table 1. Component details for the designs

Num	Component	Num	Component
1	Control panel box	11	LCD
2	Chuck	12	Stepper motor on/off switch
3	CPU door	13	Stepper motor indicator lamp
4	Spindle motor	14	Controller indicator lamp
5	Tailstock	15	Spindle motor on/off switch
6	CPU holder	16	Tool turret indicator lamp
7	Tool turret motor	17	Tool turret on/off switch
8	X-axis motor	18	Tool turret direction change switch
9	Z-axis motor	19	Emergency stop switch
10	Control panel box		

After designing the machine body, the next step is to design the electronic and control system. The design of the electronic and control system for this machine is shown in Figure 8.

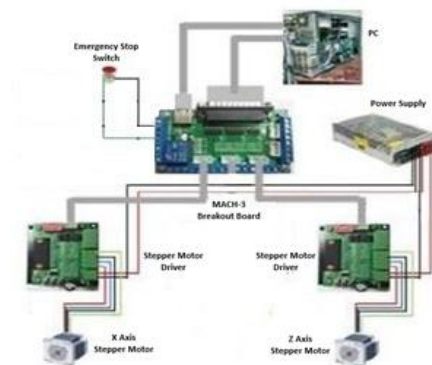


Figure 8. Electronic schematic

3.2 Calibration

Calibration is performed to ensure the machine's movement accurately follows the commands issued by the computer. For example, a movement command of 100 mm in the interface should result in an actual displacement of 100 mm along the X-axis of the CNC machine. To facilitate calibration, a

Dial Test Indicator (DTI) is used as an auxiliary tool, as shown in Figure 9. The Dial Test Indicator is used to track and record the movement of mechanical components in the machine, specifically those driven by stepper motors along the X and Z axes.



Figure 9. Dial Test Indicator (DTI)

The calibration is performed by adjusting the stepper motor rotation (step/mm) until the desired displacement of 1 mm is achieved. The stepper motor rotation value can be configured through the MACH-3 Turn application. The DTI (Dial Test Indicator) is calibrated to 0 and will be mounted on the surface, aligned with the stepper motor axis to be calibrated. Once the DTI is set up, the stepper motor is instructed to rotate and perform a 1 mm translational movement via the application. After the motor rotates and the translational movement is executed, the DTI will measure displacement with a 0.01 scale for each line, totaling 100 lines per 1 mm. From the DTI readings, the difference between the motor movement as commanded by the application and the actual displacement can be calculated, and the percentage error can be determined using equations 1 and 2.

$$\text{error} = |\text{scale} \times (\text{DTI value} - \text{DTI max value})| \quad (1)$$

$$\% \text{error} = \frac{\text{error}}{\text{desired displacement}} \times 100\% \quad (2)$$

3.3 Machine Testing

After all testing and calibration are complete, a machine trial will be conducted. The machine trial is carried out by feeding the workpiece. Once the machine is confirmed to be normal and properly calibrated, a trial run can be performed with the workpiece feeding. The purpose of this trial is to

ensure that the machine can perform the tasks automatically or via the program entered into the software. The design tasks to be executed during the machine trial will consist of three levels, from the easiest to the most complex, using workpieces made of Teflon (PTFE) and aluminum. The designs to be processed by the machine during this trial are as follows.

The first workpiece design is a basic one, which can be considered low difficulty as it only uses a straight-cutting program. This workpiece design is shown in Figure 10.

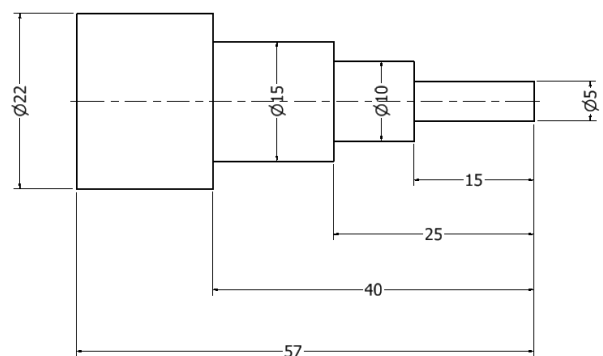


Figure 10. First workpiece design

In the second design, the complexity of the cutting process increases further, as it involves cutting the workpiece along straight, angled, and circular paths. This workpiece design is shown in Figure 11.

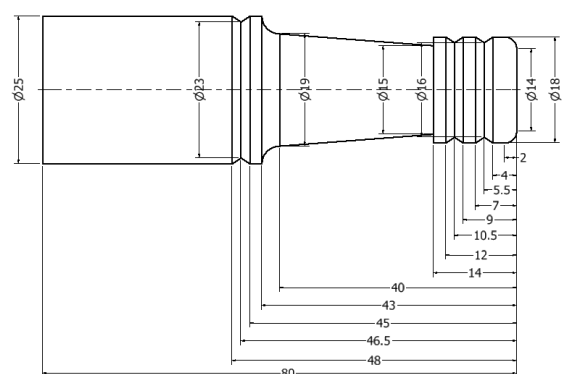


Figure 11. Second workpiece design

4. RESULTS AND DISCUSSION

4.1 Results of TU-2A CNC Machine

After the development, improvement, and maintenance activities on the EMCO TU-2A CNC Machine were completed, the outcomes of these enhancements and the dimensions are shown in Figures 12 and 13, respectively, and in Table 2.



Figure 12. Front view of TU-2A CNC machine



Figure 13. Control panel box of TU-2A CNC machine

Table 2. Dimensions of the TU-2A CNC machine and control panel box

Dimension	TU-2A CNC Machine	Control Panel Box
Length	1240 mm	490 mm
Width	750 mm	140 mm
Height	1260 mm	470 mm

4.2 Results of Calibration

After performing the calibration steps, calibration data was obtained, including error values and the percentage error in the motor's movement relative to the machine's actual movement. The first calibration was performed on the X-axis stepper motor. The calibration results for the stepper motor on the X-axis are shown in Figures 14, 15, 16, 17, 18, and 19, respectively.

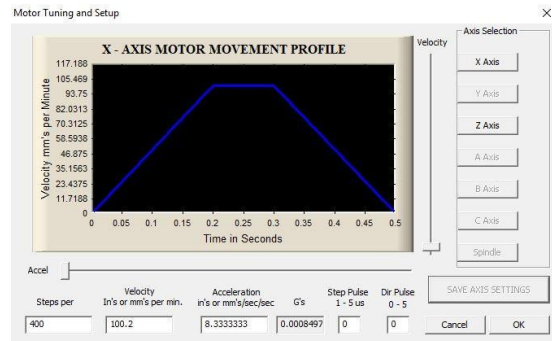


Figure 14. The first calibration result for the X-axis stepper motor – motor tuning



Figure 15. The first calibration result for the X-axis stepper motor – DTI

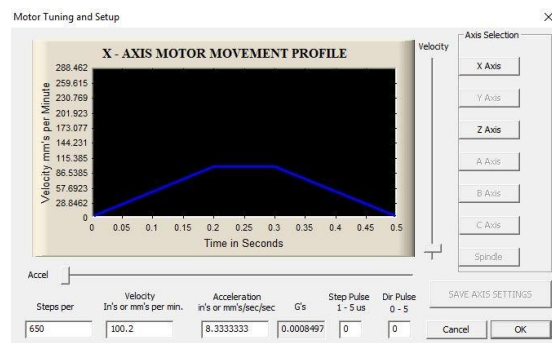


Figure 16. The second calibration result for the X-axis stepper motor – motor tuning



Figure 17. The second calibration result for the X-axis stepper motor – DTI

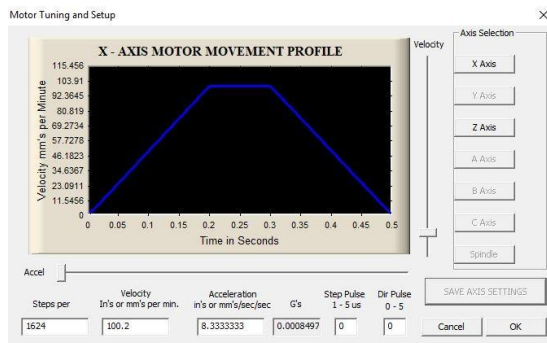


Figure 18. The third calibration result for the X-axis stepper motor – motor tuning



Figure 19. The third calibration result for the X-axis stepper motor – DTI

After the X-axis stepper motor is calibrated, the Z-axis stepper motor is calibrated. The calibration results for the stepper motor on the Z-axis are shown in Figures 20, 21, 22, 23, 24, and 25, respectively.

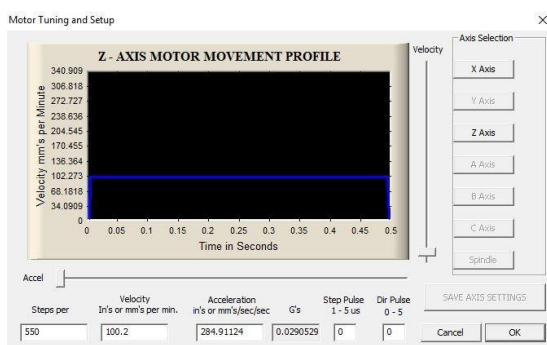


Figure 20. The first calibration result for the Z-axis stepper motor – motor tuning



Figure 21. The first calibration result for the Z-axis stepper motor – DTI

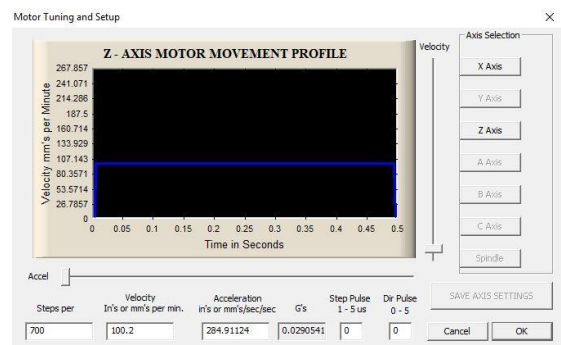


Figure 22. The second calibration result for the Z-axis stepper motor – motor tuning



Figure 23. The second calibration result for the Z-axis stepper motor – DTI

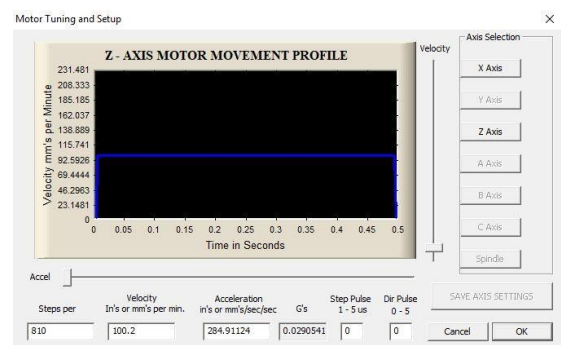


Figure 24. The third calibration result for the Z-axis stepper motor – motor tuning



Figure 25. The third calibration result for the Z-axis stepper motor – DTI

After obtaining the calibration results from the stepper motors on the X and Z axes, we can calculate the error and %error using Equations 1 and 2. The data from these calculations are subsequently input into a table and graph, as shown in Table 3 and Figure 26, respectively.

Table 3. Calibration results of the stepper motor on the X and Z axes

Calibration	Value			
	Motor Tuning (steps/mm)	Dial Test Indicator (line)	Error (%)	Real Movement (mm)
X-Axis Stepper Motor				
1	400	42,5	57,5	0,425
2	650	77	23	0,77
3	1624	100	0	1
Z-Axis Stepper Motor				
1	550	49	51	0,49
2	700	76	24	0,76
3	810	100	0	1

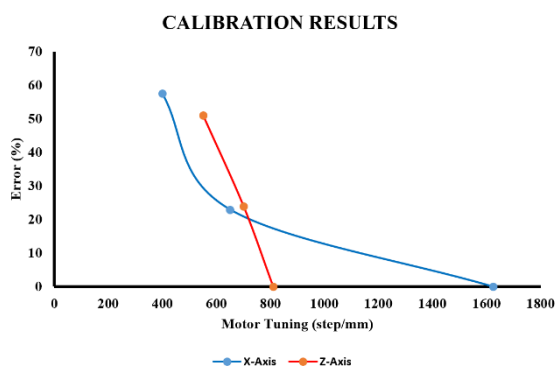


Figure 26. Calibration results as a graphic (Motor Tuning – Error)

Based on the data in Table 3 and the graph in Figure 17, the error decreases as the motor tuning value increases, which corresponds to the number of steps

the stepper motor takes per millimeter. The primary issue for the stepper motor system in the CNC TU-2A machine, for the X and Z axes, is reduced movement accuracy due to motor load [22], [23]. This load originates from various components, such as the tool turret housing and other mechanical elements, which affect the stepper motor's performance. When the stepper motor moves the X or Z axis, this additional load creates resistance to motion, potentially causing step loss and reducing positioning accuracy. The greater the load on the motor, the higher the torque required to maintain precise movement [24], [25], [26]. Under high-load conditions, the stepper motor may fail to complete steps accurately, resulting in movement errors.

One solution to address this issue is to adjust the motor tuning by increasing the steps per millimeter. The aim is to improve the resolution of stepper motor movement, enabling it to handle the additional load better and reduce errors [27]. However, this motor tuning adjustment must be done carefully, as it could affect the motor's speed and overall efficiency. With proper adjustment, the stepper motor can provide sufficient torque to counteract the added load while enhancing the CNC machine's movement accuracy without compromising the motor's overall performance [28].

4.3 Results of Machining Testing

After the calibration process was completed and the stepper motor movement matched the actual movement, the machine was tested by feeding the workpiece with two materials: Teflon (PTFE) and aluminum. These materials were processed according to the workpiece design shown in Figures 10 and 11. The results of the workpiece processing are shown in Figures 27, 28, 29, and 30, respectively.

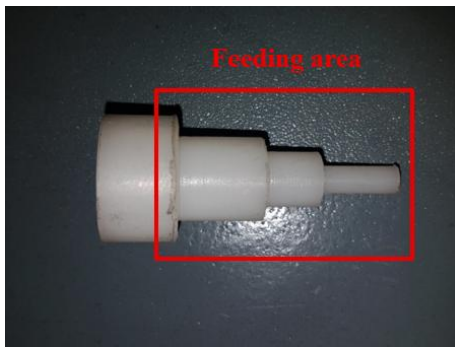


Figure 27. The results of the workpiece feeding for the first workpiece design – Teflon

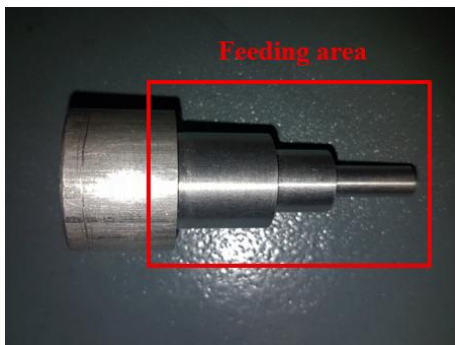


Figure 28. The results of the workpiece feeding for the first workpiece design – aluminum



Figure 29. The results of the workpiece feeding for the second workpiece design – Teflon



Figure 30. The results of the workpiece feeding for the second workpiece design – aluminum

Based on Figures 27, 28, 29, and 30, the images show the results of machining Teflon and aluminum workpieces according to the design. These designs were developed from the initial workpiece design, which represents the simplest difficulty level, and the second workpiece design, which is the most complex due to the need for more intricate programming.

From all the figures, the machining results for both Teflon and aluminum workpieces show neat, smooth, and precise outcomes. The machining errors remain within tolerance limits, approximately 0.01 to 0.02 mm. This indicates that the earlier calibration process was accurate and error-free. Therefore, it can be concluded that the CNC TU-2A machine is now ready to be used again for educational purposes, particularly for basic CNC machine operations. Additionally, the machine can now be maintained and repaired independently by the institution, as the control system and components have been replaced with readily available, cost-effective replacements.

4.4 Discussion

This study aims to develop the electronic and control systems on the CNC TU-2A machine to address the limitations identified in previous research. The results show that, after retrofitting, the CNC TU-2A machine demonstrates significant improvements in precision, ease of use, and component accessibility, making it more suitable for vocational education. This is highly relevant compared with earlier studies, such as those by Salam [7] on the control system of the TU-3A and Zheng [8] on virtual simulation platforms, which primarily focus on machines with higher production capacities or advanced features, such as CAD/CAM support.

One of the main contributions of this study is the simplification of the programming process for CNC machines, which was a major issue identified in previous research, including Shin [9], who examined intelligent diagnostic systems for CNC maintenance. The results of this study demonstrate a more efficient calibration process, with reduced

errors during machine movement as motor tuning was enhanced. This highlights the importance of addressing load issues, which Theissler [10] identified as a common challenge in research on predictive maintenance in the automotive industry.

Furthermore, this research addresses a significant gap identified by Widodo [11] in vocational education, where most studies have focused on retrofitting CNC systems for large-scale machines, often overlooking the needs of educational institutions seeking affordable, simplified solutions. The machine tested in this study, with its improved maintenance procedures and more affordable components, directly addresses this issue by providing a more accessible solution for teaching basic CNC technology. These results also emphasize the importance of a user-friendly interface for training, aligning with previous research, especially that of Salam [7] and Zheng [8], who highlighted the need for more user-friendly systems in educational settings.

5. CONCLUSIONS

The development of the electronic and control systems for the CNC TU-2A machine has significantly enhanced its performance by simplifying programming and improving maintenance efficiency. By retrofitting the machine with more modern, user-friendly components, the system now offers an interface ideal for vocational education. The calibration results show that the machine's precision and accuracy have improved, with machining errors now remaining within acceptable tolerance limits. This makes the machine not only more suitable for educational purposes but also easier for institutions to maintain and repair independently. The results of this study make a significant contribution to advancing CNC technology in educational settings, address challenges identified in previous research, and offer a more cost-effective solution without compromising performance.

REFERENCES

- [1] Muh. N. H. Amaluddin, R. Jamaludin, and A. Mahdali, "Analysis of the Influence of CNC Milling Macro Programs and Sub-
- programs Mazak on the Effectiveness of Manufacturing Cover of Pressure Cylinder Using CAM," *INTEK: Jurnal Penelitian*, p., 2024, doi: 10.31963/intek.v11i1.4657.
- [2] H. Attar, A. Abu-Jassar, A. Amer, V. Lyashenko, V. Yevsieiev, and M. H. Khosravi, "Control System Development and Implementation of a CNC Laser Engraver for Environmental Use with Remote Imaging," *Comput. Intell. Neurosci.*, vol. 2022, p., 2022, doi: 10.1155/2022/9140156.
- [3] N. V. Nalande, S. M. Patil, R. K. Shivdas, and V. V. Nalande, "Deep Learning for Vibration Signature Analysis in CNC Turning: A Review of Modern Techniques and Future Directions," *International Journal of Basic and Applied Sciences*, p., 2025, doi: 10.14419/cm93x48.
- [4] M. Soori, F. K. G. Jough, R. Dastres, and B. Arezoo, "Robotical Automation in CNC Machine Tools: A Review," *Acta Mechanica et Automatica*, vol. 18, pp. 434–450, 2024, doi: 10.2478/ama-2024-0048.
- [5] K.-C. Yao, D.-C. Chen, C.-H. Pan, and C. Lin, "The Development Trends of Computer Numerical Control (CNC) Machine Tool Technology," *Mathematics*, p., 2024, doi: 10.3390/math12131923.
- [6] N. Elgeme, R. Khershif, A. Elmrabet, and B. Omar, "Digital PID-Based Control for a Low-Cost CNC Plotter Machine," *University of Zawia Journal of Engineering Sciences and Technology*, p., 2025, doi: 10.26629/uzjest. 2025.02.
- [7] A. Salam, S. Rasyid, A. Alim, A. Uswat Hasnan, and K. Khalid, "Pengembangan Sistem Kontrol Mesin CNC Training Unit 3 Axis," *Jurnal Teknik Mesin Sinergi*, vol. 23, no. 1, pp. 129–136, Sep. 2025, doi: 10.31963/sinergi.v23i1.4990.
- [8] P. Zheng, J. Yang, J. Lou, and B. Wang, "Design and application of virtual simulation teaching platform for intelligent manufacturing," *Sci. Rep.*, vol. 14, no. 1, Dec. 2024, doi: 10.1038/s41598-024-62072-5.
- [9] H. Shin, L. Rothrock, and V. Prabhu, "Evaluating Technicians' Workload and Performance in Diagnosis for Corrective Maintenance," *Sensors*, vol. 24, no. 6, Mar. 2024, doi: 10.3390/s24061943.
- [10] A. Theissler, J. Pérez-Velázquez, M. Kettelgerdes, and G. Elger, "Predictive maintenance enabled by machine learning:

- Use cases and challenges in the automotive industry,” *Reliab. Eng. Syst. Saf.*, vol. 215, Nov. 2021, doi: 10.1016/j.res.2021.107864.
- [11] Widodo, Suhardjono, and M. K. Effendi, “The impact of CDIO implementation on retrofitting CNC-based universal turn drill in vocational education,” *MethodsX*, vol. 15, Dec. 2025, doi: 10.1016/j.mex.2025.103547.
- [12] R. A. Salim, S. Syahril, and N. Erizon, “Enhancing vocational education through augmented reality: Android-based learning media for CNC TU-2A instruction in technical and vocational high schools,” *Journal of Engineering Researcher and Lecturer*, p., 2025, doi: 10.58712/jerel.v4i2.188.
- [13] F. Prasetya *et al.*, “Revolutionizing CNC Lathe Education: Designing Instructional Media Integrated Using Augmented Reality Technology,” *TEM Journal*, p., 2024, doi: 10.18421/tem132-82.
- [14] Z. A. Rahman, S. B. Mohamed, M. Minhat, and Z. A. Rahman, “Design and Development of 3-Axis Benchtop CNC Milling Machine for Educational Purpose,” *International Journal of Integrated Engineering*, p., 2023, doi: 10.30880/ijie.2023.15.01.013.
- [15] J. M. I. Kwick, Ó. Hernández-Urbe, L. A. Cárdenas-Robledo, and R. A. Luque-Morales, “Extended Reality Applications for CNC Machine Training: A Systematic Review,” *Multimodal Technol. Interact.*, vol. 8, p. 80, 2024, doi: 10.3390/mti8090080.
- [16] X. Zhou and J. Pan, “Development and Application of Educational Mini CNC Milling Machines,” *E3S Web of Conferences*, p., 2022, doi: 10.1051/e3sconf/202235801045.
- [17] A. Dharmanto, N. Rofiq, A. Saepudin, A. Domodite, and Wilarso, “Design and Construction of Prototype of CNC Plasma Cutting Machine Simulator 3 Axis Based on Stepper Motor and Mach3 PC Software,” *JOURNAL OF MECHANICAL ENGINEERING MANUFACTURES MATERIALS AND ENERGY*, p., 2025, doi: 10.31289/jmemme.v9i1.14289.
- [18] J. Veeramony and M. N. O. Zahid, “A Customizable Controller for 3 Axis Modular CNC Machine,” *Journal of Modern Manufacturing Systems and Technology*, p., 2022, doi: 10.15282/jmmst.v6i2.8567.
- [19] R. Kumar, S. Sharma, R. Kumar, S. Verma, and M. Rafighi, “Review of Lubrication and Cooling in Computer Numerical Control (CNC) Machine Tools: A Content and Visualization Analysis, Research Hotspots and Gaps,” *Sustainability*, p., 2023, doi: 10.3390/su15064970.
- [20] A. B. Wicaksono and Hasbir, “Pengembangan Sistem Elektronik dan Kontrol Mesin CNC TU-2A,” Politeknik Negeri Ujung Pandang, Makassar, 2018. Accessed: 26 January 2026. [Online]. Available: <https://repository.poliupg.ac.id/id/eprint/2135/>
- [21] A. Intarapadung, “Development of Mini CNC Machine Design and Building for Making Ceramic Cup and Bowl Prototype,” *Pertanika J. Sci. Technol.*, p., 2021, doi: 10.47836/pjst.29.3.22.
- [22] M. Khairudin, R. Asnawi, and A. Shah, “The Characteristics of TB6600 motor driver in producing optimal movement for Nema23 stepper motor of CNC machines,” *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, p., 2020, doi: 10.12928/telkomnika.v18i1.12781.
- [23] C. Wang and D. Cao, “New Sensorless Speed Control of a Hybrid Stepper Motor Based on Fuzzy Sliding Mode Observer,” *Energies (Basel)*, p., 2020, doi: 10.3390/en13184939.
- [24] J. De Viaene, S. Derammelaere, and K. Stockman, “Load angle estimation for dynamic stepping motor motion applications,” *Mechatronics*, p., 2018, doi: 10.1016/j.mechatronics.2018.06.017.
- [25] F. Farimani, M. Mojarradi, E. Hekman, and S. Misra, “PneuAct-II: Hybrid Manufactured Electromagnetically Stealth Pneumatic Stepper Actuator,” *IEEE Robot. Autom. Lett.*, vol. 5, pp. 3588–3593, 2020, doi: 10.1109/lra.2020.2974652.
- [26] J. Pillans, “Reducing Position Errors by Vibration Optimization of Stepper Motor Drive Waveforms,” *IEEE Transactions on Industrial Electronics*, vol. 68, pp. 5176–5183, 2021, doi: 10.1109/tie.2020.2982123.
- [27] B. Bednarski, K. Jackiewicz, and A. Gałecski, “Influence of Microstepping Signal Shape on Shaft Movement Precision and Torque Variation of the Stepper Motor,”

- Energies* (Basel), p., 2021, doi: 10.3390/en14196107.
- [28] C.-K. Lai, B.-W. Lin, H.-Y. Lai, and G. Chen, "FPGA-Based Hybrid Stepper Motor Drive System Design by Variable Structure Control," *Actuators*, p., 2021, doi: 10.3390/act10060113.