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VIBRATION-BASED TOOL CONDITION MONITORING AND AUTOMATIC FEED RATE CONTROL IN CNC MILLING MACHINES

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ABSTRACT

This study presents the design and implementation of a mechatronic system aimed at improving the efficiency of machining operations in Computer Numerical Control (CNC) machines. This developed system automatically adjusts the feed rate of the CNC milling machine based on the wear condition of the cutting tools by monitoring their status via sensors during the milling operation. This system, integrating mechanical, computer, and electronic engineering disciplines, adopts an interdisciplinary approach to minimize errors and production losses arising from operators' lack of experience. Data acquired through a vibration sensor is utilized to optimize machining parameters (cutting speed and feed rate), with the goals of extending tool life, improving the surface quality of the workpiece, and reducing overall production costs. While existing systems in the literature primarily focus on tool condition monitoring, this study proposes a universal solution that can be adapted to various brands and models of CNC machines, capable of adjusting the feed rate automatically without altering the original structure of the machine.

1. INTRODUCTION

In today's modern manufacturing industry, CNC machines are used as primary production tools. The efficient utilization of these high-cost machines is a critical concern for enterprises. However, the difficulty of finding experienced operators and the complexity of correctly adjusting machining parameters are among the major factors that negatively affect productivity. In conventional methods, the evaluation of tool wear and machining conditions largely relies on the operator's knowledge and experience. Operator-induced errors lead to decreased machine efficiency, reduced product quality, and increased production costs. Tool Condition Monitoring (TCM) systems have long been a subject of research aimed at addressing these challenges.

Tool failures account for approximately 20% of downtime in modern machine tools, leading to reduced productivity and economic losses. A reliable monitoring system can mitigate these issues and enable the optimal utilization of tool life [1].

An effective and reliable TCM system has the potential to enhance cutting speed by 10–50%, minimize downtime due to tool-related interruptions, and contribute to an overall manufacturing cost reduction of approximately 10–40% [2].

In addition to traditional approaches such as the Taylor equation [3], recent technological advancements have brought sensor-based monitoring methods to the forefront.

Leal et al. analyzed the accuracy of an online method for measuring machining parameters from cutting force signals in milling processes. They conducted their experiments on a numerical control machine tool, where a dynamometric platform was mounted to measure cutting force. The setup included a DMG 1035 three-axis machining center, a Kistler 9257A dynamometer with a Kistler 5070 amplifier, and a Keyence FU-67V optical sensor for spindle speed measurement. Cutting force signals were collected using an NI PCI 6251 module with an NI BNC 2110 connector block, while data acquisition and processing were carried out with LabVIEW 8.2 software [4].

Gouarir et al. presented an in-process tool wear prediction system that utilized a force sensor to monitor the progression of tool flank wear and employed machine learning (ML), specifically a Convolutional Neural Network (CNN), to predict tool wear. The proposed methodology achieved an estimated accuracy of 90% [5].

Copper et al. demonstrated that a Generative Adversarial Network (GAN)-based anomaly detection system is capable of achieving 90.56% accuracy in tool wear detection for a milling TCM application using acoustic signals measured during the milling process [6].

Maia et al. demonstrated the effectiveness of Acoustic Emission (AE) signals combined with Short-Time Fourier Transform (STFT) analysis in identifying and distinguishing wear mechanisms during the turning of AISI 4340 steel with cemented carbide tools. The findings of their study underscore the practical advantages of acoustic emission (AE) signal analysis in tool condition monitoring, providing a reliable approach to improve machining efficiency, extend tool life, and lower operational costs [7].

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Gao et al. proposed a self-adjusting tool wear monitoring system that integrates multi-sensor data with advanced neural network models, achieving accurate and reliable wear prediction across varying machining conditions while reducing cost and complexity [8].

Yuqing et al. proposed a vibration-based data fusion method using time-frequency features, probabilistic Principal Component Analysis (PCA), and statistical inference to improve damage identification in Numerical Control machine tools. Experimental results reveal clear distinctions among tool damage states, demonstrating the method's strong potential for accurate tool condition monitoring [9].

Zhou et al. proposed a cutting-condition independent TCM approach for milling, based on vibration singularity analysis, where Holder Exponents were employed to estimate signal singularities and vibrations were recorded using a triaxial piezoelectric accelerometer (PCB-356A15) mounted on the spindle [10].

Li et al. developed a multi-sensor dataset for milling to enhance efficiency and quality, particularly for complex workpieces. The dataset includes force, vibration, noise, and current signals collected under various milling parameters - depth, width, feed rate, and spindle speed and workpiece materials (Aluminum 7030 and CK45 steel) [11].

Chen and Pan aimed to apply the Industrial Internet of Things (IIoT) to automated processing systems for real-time monitoring of production line conditions, analyzing the causal relationship between vibration, surface roughness, and tool wear, with successive milling of medium carbon steel workpieces [12].

Kodrič et al. developed a low-cost TCM system on a Raspberry Pi platform, in which tool wear was detected through vibration monitoring, selected for its simple sensor installation and effectiveness in estimating tool life [13].

Sun et al. proposed an online tool wear monitoring method for robotic milling, where vibration signals are mapped into visual patterns, enabling robust wear detection without manual feature selection [14].

In this paper, a guidance system based on vibrations generated during machining is developed to assist CNC operators in determining optimal cutting parameters. This system enhances the competence of inexperienced operators while enabling experienced operators to optimize their machining processes.

2. MATERIAL AND METHOD

Material

The experiments were conducted using a 3-axis Argo A85 CNC vertical machining center (Fig. 1) located in the Machine Laboratory of Tekirdağ Namık Kemal University, Vocational School of Technical Sciences. In the trials, a DIN 2379 cold work tool steel workpiece with dimensions of 100×100×40 mm and a hardness of 20 HRC (Rockwell Hardness C) was used. Fig. 2 shows three different TaeguTec cutting tools and two different Weldon-type tool holders employed in the experiments.

The insert tools used in the experimental studies were selected from previously used inserts capable of achieving surface roughness values of ≤1 µm Ra (Fig. 3).

The technical specifications of the cutting tools used in the experiments are given in Table 1.

Fig. 1. Argo A85 CNC vertical machining center

Fig. 2. Cutting tools and tool holders

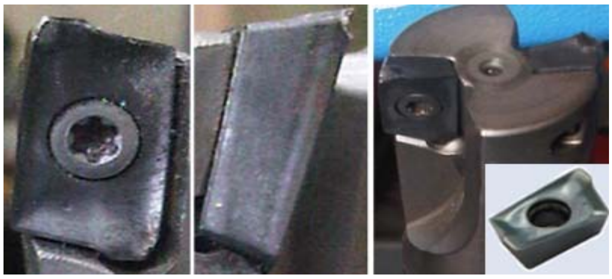


Fig. 3. Inserts used in the experiments

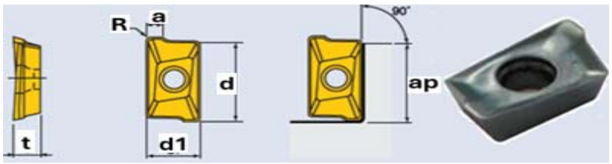
Table 1 *Technical specifications of the cutting tools [15]*

Tool Type	***Insert Type***	***Number of Inserts***	***Dimensions (mm)***	
			Cutting Diameter	***Head Length***
TeaguTec Chase Mill TE90AP 432-W25-12-C		*4*	*32*	*40*
TeaguTec Chase Mill TE90AP 225-W25-12-LC	*APKT 1204 PER-EM*	*2*	*25*	*85*
TeaguTec Chase Mill TE90AP 220-W20-12-C		*2*	*20*	*30*

The technical specifications of the TaeguTec carbide cutting tools used in the experiments are presented in Table 2. Due to their material costs, carbide tools are more expensive than high-speed steel (HSS) tools. The lifespan of these tools directly depends on the condition of the machines and the experience of the human operators. The developed system makes a significant contribution to reducing cutting tool costs by continuously monitoring vibrations, which are one of the primary causes of tool wear and poor surface quality in machining processes.

Table 2 *Technical specifications of the carbide cutting inserts used in the experiments [15]*

Insert Type	*Dimensions (mm)*					
	d	*d1*	*a*	*t*	*R*	*ap*
APKT 1204 PER-EM	*13.1*	*8.3*	*1.6*	*4.76*	*0.8*	*12*



For tool condition monitoring, a vibration sensor, a load cell, and a photoelectric proximity switch were employed. A PIC18F4523 microcontroller (MCU)-based board, designed using Proteus software by Labcenter Electronics, was used for data acquisition and stepper motor control. Proteus is a printed circuit board (PCB) design and circuit simulation software. The MCU is equipped with a serial communication module (USART) and a digital-to-analog converter (DAC) module. Signals from the sensors were processed using software developed in the MicroBasic Pro for PIC environment, and the machine's feed rate potentiometer was controlled with the assistance of the stepper motor. The developed user interface was implemented in Visual Basic .NET, and Ethernet-based communication was established between the computer and the control board.

A CMCP420VT-type vibration sensor, shown in Fig. 4, was used to detect vibrations occurring on the machine during machining. It provides a 4-20 mA current output that is proportional to the overall vibration in terms of velocity and is capable of transmitting signals over a long distance without signal loss. It features a sensitivity of 100mV/g (±5%) at 25°C with a range of 50 g peak, and a frequency response spanning 2 - 2,000 Hz.

In the system, the second physical signal measured is force, which was captured by installing a 2-ton ESIT TCS 2 load cell with a 4–20 mA output between the workpiece and the vise to record force variations on the workpiece induced by vibrations. It is shown in Fig. 5.

In the system, a reflective proximity switch was used to detect the movement of the tool arm and determine which tool was engaged in machining. Three different tools were employed in the system, and for each tool, upper and lower limit values of vibration and force signals were defined for use in feed rate control. The operator interface software utilizes the limit values of the corresponding tool's vibration and force signals based on the digital signal received from the proximity switch each time the tool arm moves. Fig. 6 shows an image of the Sick WT160-F182 38 proximity switch used in the study.

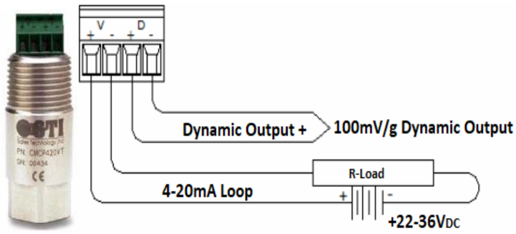


Fig. 4. CMCP420VT vibration velocity sensor

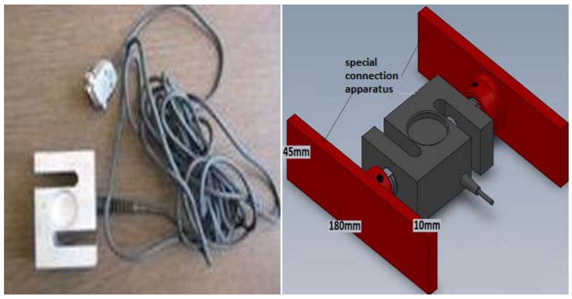


Fig. 5. ESIT TCS2 2-ton load cell

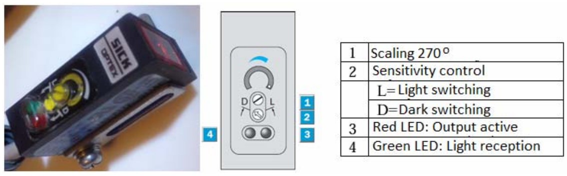


Fig. 6. Sick WT160-F182 photoelectric proximity sensor

Method

In this study, a computer-aided data acquisition and control system was designed to maintain optimal feed conditions by continuously monitoring machining operations performed on CNC machines. Using mechatronic design methods, a stepper motor was controlled based on data collected from sensors through a custom-developed computer program and microcontroller software. This stepper motor is mechanically connected to the CNC machine's feed rate knob, allowing it to be regulated. In selecting the components used in the designed system, commonly accepted sensors from previous studies were utilized. However, the vibration (RMS – Root Mean Square) and cutting force data obtained from the sensors were not used to predict tool life; instead, they were employed to control the feed rate of the CNC machine via the developed computer program. The flow chart of the control system designed for this project is shown in Fig. 7. The flow diagram includes one analog vibration input, one analog force input, and one digital input.

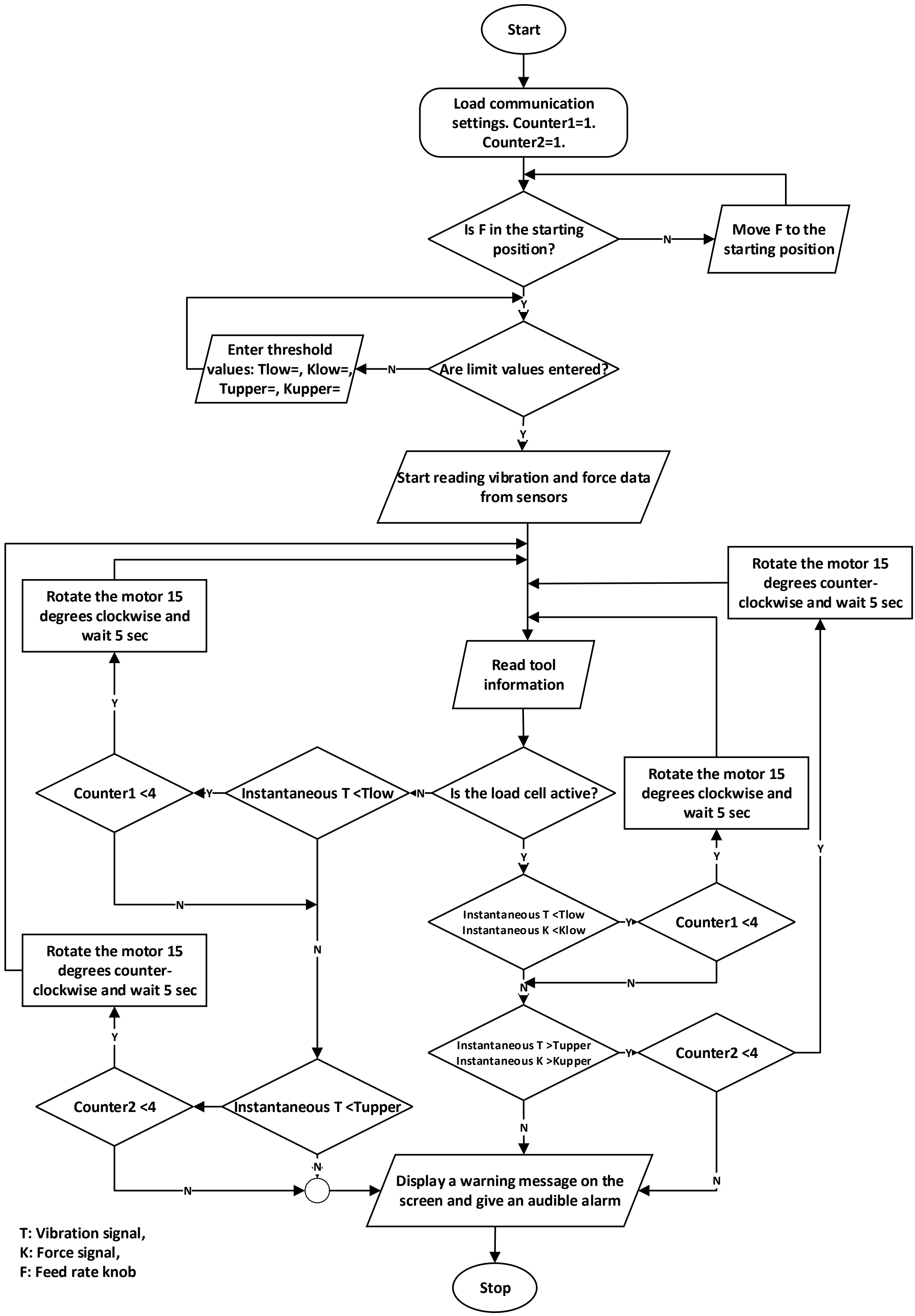


Fig. 7. Flow chart of the system

The research and experimental studies were carried out in three stages, as follows:

- Electronic design of the system
- Design of the system software
- Practical testing of the system under real conditions

The block diagram of the implemented system is presented in Fig. 8, and the system components are given in Fig. 9. Fig. 10 shows the location of the sensors used in the system.

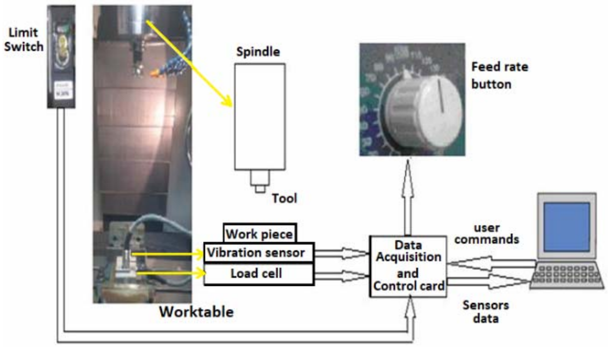


Fig. 8. Block diagram of the system

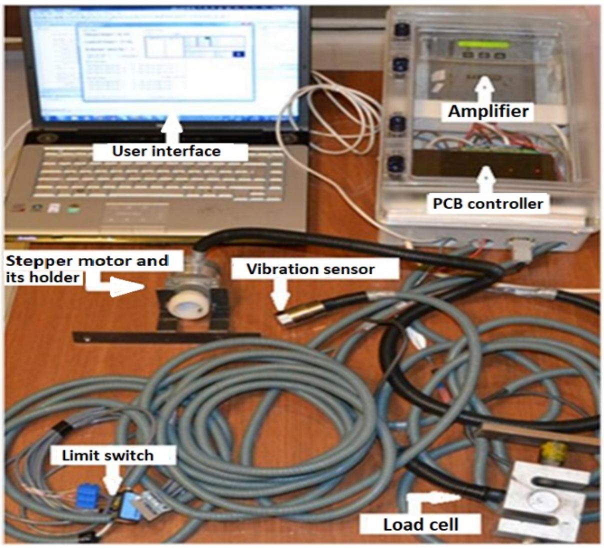


Fig. 9. Components of the developed system

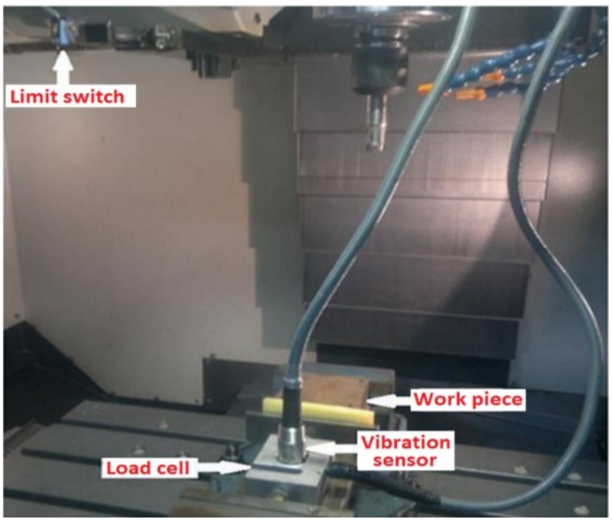


Fig. 10. Sensors mounted on the CNC machine

The design and simulations of the control board were carried out using the Proteus ISIS electronic circuit design software, and the printed circuit of the developed board was prepared in the Ares PCB design. Fig. 11 shows the data acquisition and control board with the PIC18F4523 microcontroller, along with its electronic circuit diagram in ISIS. The electronic board was designed to be expandable, allowing for system enhancements in future studies. Two additional analog sensors and three digital sensors can be integrated into the system.

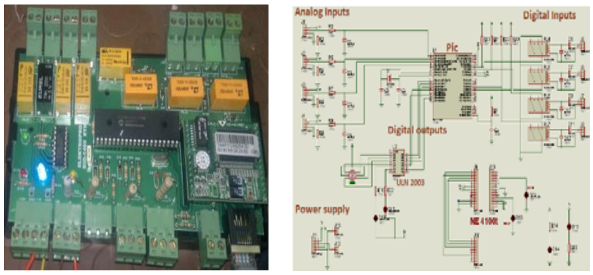


Fig. 11. Control board and its circuit diagram

The stepper motor and the machine's feed rate knob are connected via a specially designed coupling component. The motion of the stepper motor is directly transferred to the feed rate commutator knob through the coupling component, shown in Fig. 12. A microcontroller-based system was chosen to drive the stepper motor due to its low cost, ease of programming, and high performance. The stepper motor, which rotates the feed rate commutator, is driven using a two-phase full-step method to achieve high torque. The NE 4100T Ethernet module is used to enable high-speed communication between the laptop and the microcontroller.

Fig. 13 shows the user interface, developed using the Visual Basic .NET programming language, which enables human operators to communicate with the hardware system.

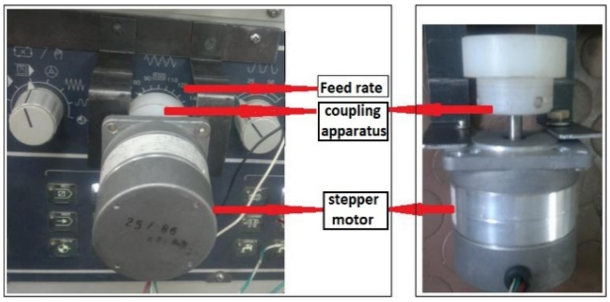


Fig. 12. Stepper motor and coupling component

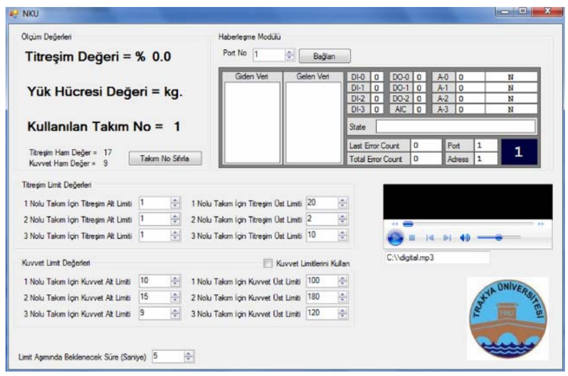


Fig. 13. User interface screen of the developed system

Experimental Studies

During the experiments, three different tools with two distinct wear levels were used. Vibration and force data obtained from machining with new and worn inserts were compared. It was observed that as the tool wore, both the vibration amplitudes and force signals increased significantly. When the measured values exceeded the predetermined threshold limits, the system automatically reduced the feed rate without operator intervention. Similarly, when the values remained below the threshold limits, the system adjusted the feed rate to increase it. The experimental conditions are presented in Table 3, and the measurement values are given in Table 4.

Table 3 *Cutting conditions used in the experiments*

Tool No	*Tool Diameter (mm) - Number of Cutting Edges*	*Spindle Speed (rpm)*	*Feed Rate (mm/min)*	*Depth of Cut × Length (mm)*
1	*32 - 4*	*1000*	*200*	*1x100*
2	*25 - 2*	*1000*	*150*	*1x100*
3	*20 - 2*	*1200*	*180*	*1x100*

Table 4 *Lower and upper threshold vibration values of overall RMS Acceleration (m/s^2) and obtained Ra values*

Tool No	*Vibration Lower Limit (RMS)*	*Vibration Upper Limit (RMS)*	*Ra_min (μm)*	*Ra_max (μm)*
1	*1*	*12*	*~0.1*	*≤1*
2	*1*	*24*	*~0.1*	*≤1*
3	*1*	*4*	*~0.1*	*≤1*

3. CONCLUSION

In this study, a computer-controlled system was developed by integrating the fields of computer science, electronics, and mechanical engineering - the core disciplines of mechatronics - that can be universally applied to different CNC machine tools. The system monitors cutting tool wear and adjusts the tool feed rate accordingly. The designed system stands out for its low cost, high performance, and portability. Experiments conducted on an Argo A85 CNC milling machine demonstrated that the system could successfully regulate the tool feed rate based on vibration and force limit values, maintaining control over the machining process.

During the experiments, three main difficulties were encountered, and solutions were found for these problems:

• **Signal Noise:** Noise in the signal from the vibration sensor was eliminated by using a shielded cable.

• **Temperature Effect:** The issue of the sensor overheating was resolved by placing it in a location unaffected by temperature.

• **Sensor Performance:** Experiments have shown that the vibration sensor is a more effective method than the load cell for detecting tool condition.

The performance of the developed system was verified through operations conducted using experimentally determined lower and upper vibration limit values. The system successfully regulated tool feed rates within these limits, effectively controlling the machining process. Thus, it demonstrated the potential to increase production efficiency by providing real-time guidance to CNC machine operators. Furthermore, the proposed system reduced tool costs and machining times while maintaining surface quality. These findings demonstrate the system's applicability in industrial manufacturing processes and provide a significant contribution to the literature on tool condition monitoring systems.

Discussion

The most significant industrial contribution of this study is that it offers a universal and low-cost solution that can be externally adapted to different brands and models of CNC machines available on the market. Many existing systems are designed for specific machine models and are often costly. The portability of the proposed system makes it an economic alternative, particularly for small and medium-sized enterprises (SMEs).

Since the system operates based on threshold values determined by experienced operators, it eliminates differences in operator experience and ensures standardization in production. This feature makes it an ideal tool for serial production, enabling each operator to achieve similar quality and efficiency standards.

Future Work

In future studies, the system’s potential can be further enhanced and its industrial applicability broadened through:

• **Adaptation to Different Machines:** Modifying the system to be compatible with various CNC machine models.

• **Alternative Sensor Usage:** Employing a contact microphone as a secondary control signal instead of the less efficient load cell, providing a more economical solution.

• **Advanced Motor Control:** Integrating an encoder into the system to develop a more sophisticated motor control algorithm for feed rate adjustment.

REFERENCES

[1] Kurada S., Bradley C., A review of machine vision sensors for tool condition monitoring, Computers in Industry 34(1) (1997) 55-72

[2] Rehorn A.G., Jiang J., Orban P.E., State-of-the-art methods and results in tool condition monitoring: a review, International Journal of Advanced Manufacturing Technology 2005, 26 (7-8) (2005) 693-710

[3] Lee S.Y., In-process tool condition monitoring systems in CNC turning operations, Ph.D. Thesis, Iowa State University (2006)

[4] Leal-Muñoz E., Diez E., Perez H., Vizan A., Accuracy of a new online method for measuring machining parameters in milling, Measurement, 128 (2018) 170-179

[5] Gouarir A., Martinez-Arellano G., Terrazas G., Benardos P., Ratchev S., In process tool wear prediction system based on machine learning techniques and force analysis, Procedia CIRP 77 (2018) 501–504

[6] Cooper C., Wang P., Zhang J., Gao R.X., Roney T., Ragai I., Shaffer D., Convolutional neural network-based tool condition monitoring in vertical milling operations using acoustic signals, Procedia Manuf. 49 (2020) 105–111

[7] Maia L.H.A., Abrão A.M., Vasconcelos W.L., Júnior J.L., Fernandes G.H.N., Machado Á.R., Enhancing Machining Efficiency: Real-Time Monitoring of Tool Wear with Acoustic Emission and STFT Techniques, Lubricants, 12(11) (2024) 380

[8] Gao H., Chen C., Su Y., Xu M., The investigation of a self-adjusting tool wear monitoring system, In Proceedings of the IEEE International Conference on Mechatronics and Automation (2006) 1690–1694

[9] Yuqing Z., Xinfang L., Fengping L., Bingtao S., Wei X., An online damage identification approach for numerical control machine tools based on data fusion using vibration signals, Journal of Vibration and Control 21 (2015) 2925–2936

[10] Zhou C.A., Yang B., Guo K., Liu J., Sun J., Song G., Jiang Z., Vibration singularity analysis for milling tool condition monitoring, International Journal of Mechanical Sciences 166 (2020) 105254

[11] Li G., Zheng H., Xu S., Zhu K., Liu Y., Jiang R., Sun L., Ning Y., Multi-Sensor monitoring dataset for milling process with varied parameters and materials, Data Brief. 55 (2024) 110703

[12] Chen C.S., Pan P.Y., Applied Internet of Things to Analyze Vibration, Workpiece Roughness, and Tool Wear: Case Study of Successive Milling, Processes 13(4) (2025) 978

[13] Kodrič M., Korbar J., Pogačar M., Čepon G, Development of a resource-efficient real-time vibration-based tool condition monitoring system using PVDF accelerometers, Measurement 251 (2025) 117183

[14] Sun M., Zhang P., Guo K., Sun J., Li D., Huang T., Tool wear status monitoring in robotic milling of GFRP under variable robot postures and cutting parameters, Journal of Manufacturing Processes 152 (2025) 789-804

[15] TaeguTec Product Catalogs. https://www.taegutec.com/pages/en.