VIBRATION BASED TOOL WEAR MONITORING IN END MILLING OF S50C VIA A LOW-COST DATA ACQUISITION SYSTEM

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ABSTRACT: *Milling operations are essential in modern manufacturing due to their ability to produce complex and high-precision components. However, excessive heat generation and vibration during cutting can accelerate tool wear, resulting in reduced tool life, compromised product quality, and unexpected machine downtime. This study presents the development of a real-time tool condition monitoring system using an Arduino-compatible microcontroller platform. The system integrates a microcontroller with an infrared temperature sensor, a tri-axis accelerometer, and cloud technology to capture and analyse vibration and temperature data during machining. Experimental trials were conducted on S50C carbon steel using carbide cobalt end milling tools at various spindle speeds. Predefined vibration and temperature thresholds were set as indicators for maintenance alerts, at which vibration levels above 6 m/s2 and temperatures exceeding 70°C triggered warning signals via LEDs and buzzers. The results show rising vibration and temperature readings corresponding to progressive tool wear, confirming their effectiveness as condition monitoring indicators. The system enables immediate on-site alerts through visual and audible signals, as well as remote monitoring via a cloud dashboard, providing a practical and low-cost solution for enhancing operational reliability in smart manufacturing environments.*

KEYWORDS*:* *Tool Wear, Vibration Signals, IoT, Data Acquisition*

1.0 INTRODUCTION

In the evolving landscape of smart manufacturing driven by Industry 4.0, real-time monitoring has emerged as a pivotal strategy for mantaining productivity, minimizing unexpected downtime, and extending equipment life by leveraging real-time data acquisition and intelligent analytics [1-2]. Milling operations, especially end milling, play a crucial role in producing high-precision components across various sectors, yet they remain vulnerable to challenges such as tool wear, excessive vibrations, and thermal instability, which significantly degrade machining performance and product quality [3-4]. Traditional maintenance strategies (corrective and preventive) are reactive in nature, often failing to detect early signs of tool degradation and leading to costly production halts and inefficient tool usage [5-6]. Real-time monitoring leverages Internet of Things (IoT) frameworks to enable continuous tracking of key machining parameters such as temperature, vibration and tool condition, facilitating timely interventions that help reduce unplanned downtime [7-8]. However, significant gaps remain in accurately correlating vibration patterns with tool wear progression under dynamically changing machining conditions, such as variations in spindle speed, feed rate, and depth of cut [9]. The complexity of interpreting vibration signals is further compounded by sensor placement errors, environmental disturbances, and inconsistent material responses, making tool wear prediction based solely on vibration unreliable [3,10].

These challenges highlight the need for a reliable, real- time monitoring approach that can effectively track changes in machining conditions and associate them with tool degradation trends. To address these limitations, this study presents a microcontroller-based real-time monitoring system that integrates ADXL345 accelerometers and MLX90614 temperature sensors using the ESP8266 microcontroller with IoT connectivity. The proposed system captures and analyzes vibration and temperature signals during the end milling of S50C carbon steel with carbide cobalt tools to establish a robust correlation between machining parameters and tool degradation. S50C steel is selected due to its industrial relevance and wear-resistant properties, making it an ideal candidate for tool wear studies [11]. The specific objectives of this study are: (1) to investigate the influence of spindle speeds on tool wear characteristics, (2) to examine the relationship between spindle speeds and vibration signal behavior, and (3) to evaluate the impact of spindle speed on temperature patterns during machining. The ultimate goal is to define critical thresholds for vibration and thermal signals that can serve as indicators of tool health, supporting predictive maintenance decisions. The integration of this low-cost, scalable monitoring system with cloud-based dashboards not only demonstrates the feasibility of real-time tool condition monitoring but also aligns with Sustainable Development Goal (SDG) 9 by promoting sustainable industrial innovation and infrastructure. This research contributes to the broader effort of developing intelligent, adaptive manufacturing systems that enhance machining efficiency, product quality, and operational reliability.

2.0 METHODOLOGY

The methodology explains the predictive maintenance approach, including equipment installation for machine condition monitoring, experimental evaluation, and data analysis.

2.1 Workpiece and cutting tool

To carry out tool moniotirng in an end milling oerpation, both the workpiece and the cutting tool must be engaged in the process. The material that was used for the workpiece in this study is a S50C carbon steel bar block. The machining experiment uses an endmill carbide cobalt of 6 mm.

2.2 Machine and machining parameters

The objective of this study is to assess the performance of a tool monitoring system designed for tool condition monitoring, implemented on the CNC Milling Machine Gate/ECM 1. The machining parameters used for the study as in Table 1. By referring to Table 1, the selected spindle speeds of 1500 rpm and 2000 rpm for this study is fall within the recommended range for carbide tools machinng medium carbon steels. The chosen of depth of cut (0.75 mm) was used to generate sufficient cutting forces and thermal loads for measurable sensor data while avoiding excessive tool loading that could cause premature failure, therefore ensuring stable tool/workpiece engagement. The feed rate of 225 mm/min offers a balanved chip load per tooth, preventing excessive rubbing at low feeds and overloading at high feeds and falls within the optimal range for carbide cobalt end mills machining S50C.

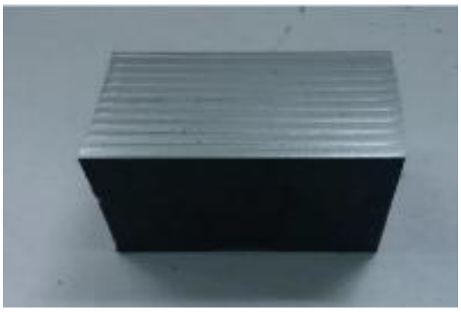


Figure 1. S50C carbon steel bar block

Figure 2. 6 mm endmill carbide cobalt

Table 1. Machining parameters used for the study

Set	Spindle speed (RPM)	Depth of Cut (mm)	Feed Rate (mm/min)
1	1500	0.75	225
2	2000	0.75	225

2.3 Tool condition monitoring system

Data is collected using a tool condition monitoring system as shown in Figure 3. This low-cost data acquisition system records real-time vibration and temperature during the experimental study, The reading are compared to set limits (vibration and temperature within safe levels, and tool wear under 0.3 mm based on ISO 8688). If the worn tool beyond these limits, the tool is checked for wear.

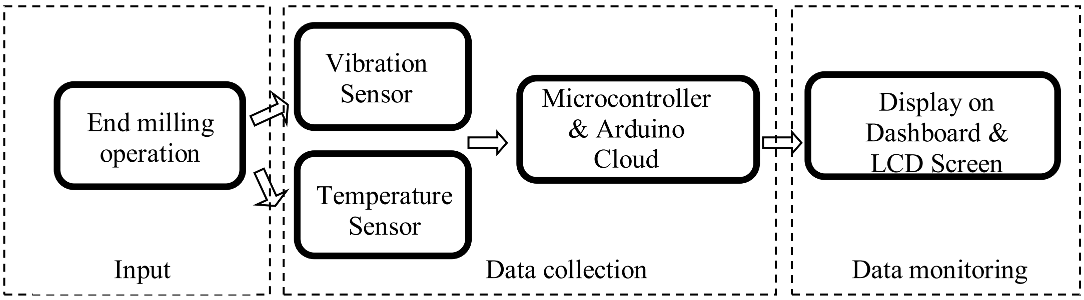
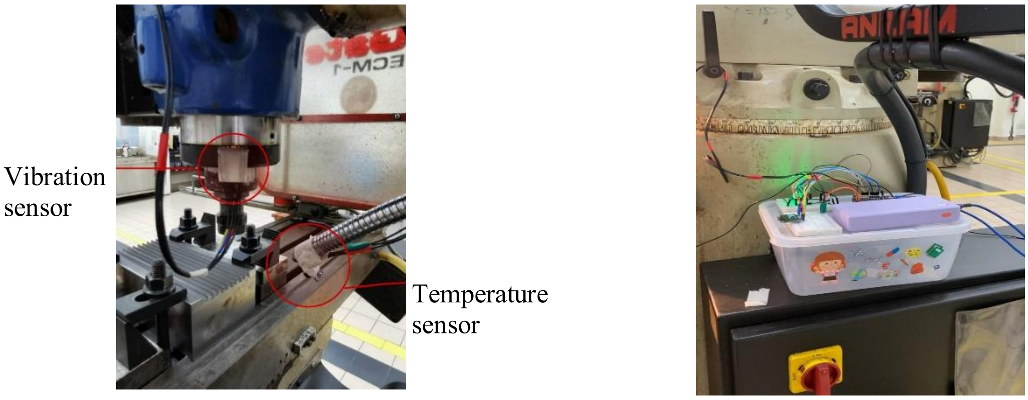


Figure 3. Tool condition monitoring system



(a) (b)

Figure 4. On-machine placement of tool condition monitoring system on CNC milling machine (a) Positioning of vibration and temperature sensors (b) Setup of Arduino based microcontroller system

The tool condition monitoring system developed in this study plays a crucial role in collecting, processing and transmitting data during the end milling process to enable predictive maintenance. It integrates key hardware components including sensors, a microcontroller, cloud storage and real-time monitoring interfaces. An ADXL345 tri-axis accelerometer was used to capture vibration data in the x,y and z axes, while an MLX90614 infrared sensor monitored temperature in the cutting zone from a safe distance, both selected for their precision and compatibility. These sensors were connected to an ESP8266 microcontroller, which processes the data and transmits it wirelessly to Arduino Cloud via its built-in Wi-Fi, functioning simultaneously as an IoT gateway. The Arduino Cloud platform stores and visualizes the data on a customizable dashboard that can be accessed remotely, enabling real-time condition monitoring and early fault detection.

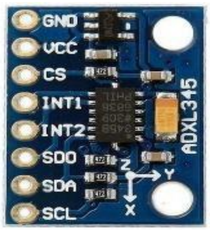


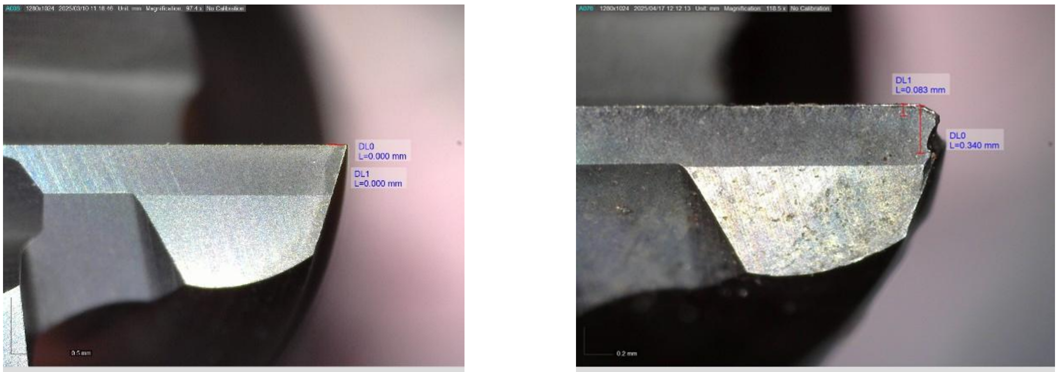
Figure 5. ADXL345 sensor

Figure 6. MLX90614 sensor

A LCD screen was incorporated into the system to display and signal the operational status of the cutting tool. The monitoring interface utilizes separate LED indicators for temperature and vibration. For temperature monitoring, a green LED is activated when the measured values is below 60°C, while a yellow LED signals a temperature range of 61 to 70°C. When the temperature exceeds 70°C, a red LED illuminates accompanied by an audible buzzer, indicating that the allowable limit has been surpassed. For vibration monitoring, a green LED corresponds to values below 4 m/s^2, a yellow LED represents readings between 4 m/s^2 and 6 m/s^2, and a red LED together with a buzzer, alerts when vibration levels exceed 6 m/s^2. Based on these predefined thresholds, the system reliably indicates the cutting tool's condition and effectively triggers visual and audible alarms throughout the monitoring process.

2.3 Tool wear inspection via optical microscopy

Tool wear was evaluated using a Dino-Lite digital microscope, which enables close-up visual inspection of the cutting tool edges at high magnification. The Dino-Lite microscope was set up with consistent lighting and calibrated magnification to ensure accurate and repeatable measurements. Images were captured for each cutting edge, particularly focusing on the flank face and cutting tip. Key wear parameters such as DL0 (flank wear depth) and DL1 (wear land length) were measured. The measurements were taken in millimeters. The results of this inspection were later correlated with vibration data and tool life (run count) to analyze tool degradation mechanisms under varying spindle speeds and depths of cut. Figure 7 presents of the cutting tool (captured using the Dinol-Lite digital microscope) before the machining process and after reaching a worn state. In Figure 7 (b), a measured flank wear of 0.34 mm is recorded, indicating significant tool degradation. This wear pattern was observed after the tool completed a total cutting distance of 84,000 mm.



(a) (b)

Figure 7. (a) Image of fresh cutting tool under parameter set 1 (1500 rpm, 0.75 mm, 225 mm/min) (b) Image of worn cutting tool under parameter set 1 (1500 rpm, 0.75 mm, 225 mm/min)

3.0 RESULT AND DISCUSSION

This section presents the findings and results of the experiment for the tool condition monitoring system which focuses on vibration and temperature. This study outlines spindle speeds of 1500 rpm and 2000 rpm, a constant feed rate of 22 mm/min and a constant depth of cut 0.75 mm. The tool wear progression is monitored by removing the tool after every 10 runs. This process was repeated until the tool read a flank wear of 0.3 mm in accordance to ISO 8688 standard for tool life evaluation.

3.1 Tool wear vs cutting distance

Figure 8 shows the impact of machining parameters on tool wear, specifically flank wear (DL0) and cutting distance. Experiments with S50C carbon steel using carbide cobalt tools under two distinct parameter sets revealed significant differences in tool longevity.

- Set 1 (1500 RPM, 0.75 mm depth of cut) exhibited the best performance, achieving a substantial 84,000 mm cutting distance with a wear depth of 0.340 mm. This suggests minimized thermal and mechanical stresses due to lower spindle speed.

- Set 2 (2000 RPM, 0.75 mm depth of cut) experienced the most accelerated tool wear, reaching 0.294 mm after only 26,000 mm. This rapid deterioration points to thermally dominant wear, where high spindle speed generated significant heat, accelerating tool degradation.

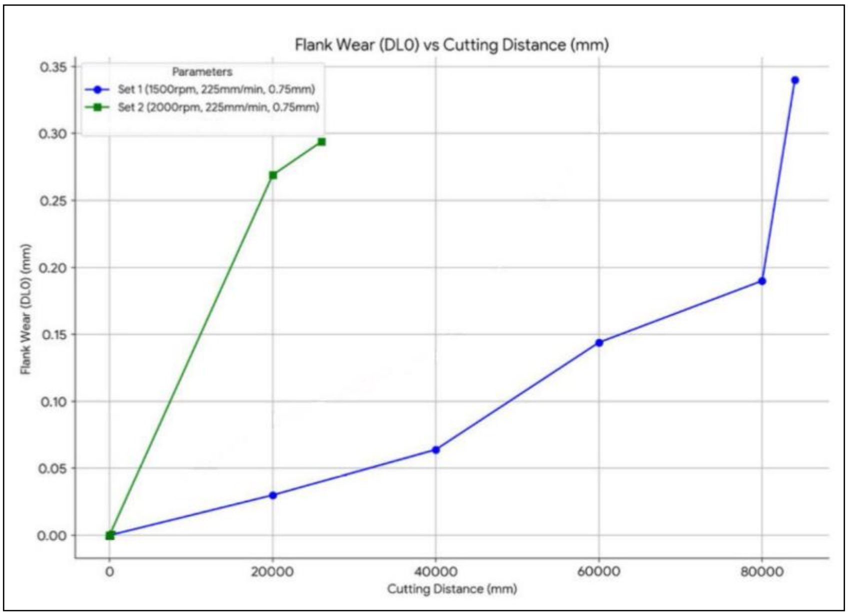


Figure 8. Progression of flank wear (DL0) versus cutting distance at two different parameters

3.2 Vibration vs cutting distance

Figure 9 represents the relationship between average vibration accelration and the total cutting distance completed before significant tool wear occurred.The findings are summarized as follows:

- Set 1 (1500 RPM, 225 mm/min feed rate, 0.75 mm depth of cut) achieved the highest performance, completing 42 runs (84,000 mm cutting distance) with the lowest average vibration of 2.96 m/s². This reflects a more stable cutting process and slower tool wear progression, likely due to reduced thermal and mechanical stress.
- Set 2 (2000 RPM, 225 mm/min feed rate, 0.75 mm depth of cut) recorded the lowest performance, reaching only 13 runs (26,000 mm cutting distance) and the highest average vibration of 4.5 m/s². The rapid tool degradation in this set is attributed to the elevated spindle speed, which likely induced excessive heat and vibration, accelerating wear.

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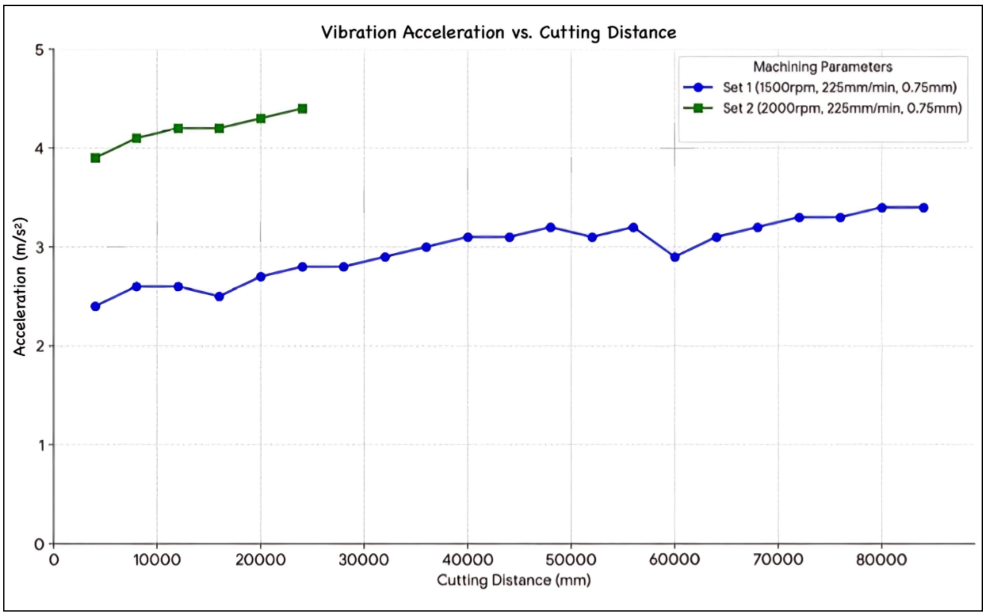

Figure 9. Graph shows the relationship of vibration acceleration acquired through Arduino Cloud versus cutting distance at two different parameters

3.3 Temperature vs cutting distance

Figure 10 presents the correlation between average temperature and the total cutting distance before notable tool wear occurred across two machining sets. The performance results are as follows:

- Set 1 (1500 RPM, 225 mm/min feed rate, 0.75 mm depth of cut) delivered the best tool performance, completing 42 runs (84,000 mm cutting distance) with the lowest average temperature of 55.0°C. The lower spindle speed and moderate cutting conditions effectively minimized heat generation, leading to slower wear progression and prolonged tool life.
- Set 2 (2000 RPM, 225 mm/min feed rate, 0.75 mm depth of cut) experienced the fastest tool wear, completing only 13 runs (26,000 mm cutting distance) with the highest average temperature of 75.0°C. The elevated spindle speed likely caused excessive thermal energy at the cutting zone, accelerating tool degradation. This aligns with previous studies [12] linking high spindle speeds with increased heat and wear rates.

In summary, the data confirm that higher temperatures correspond with faster tool wear and shorter operational life. Optimizing spindle speed is essential to manage heat generation, extend tool longevity, and maintain cutting efficiency in CNC milling of S50C steel.

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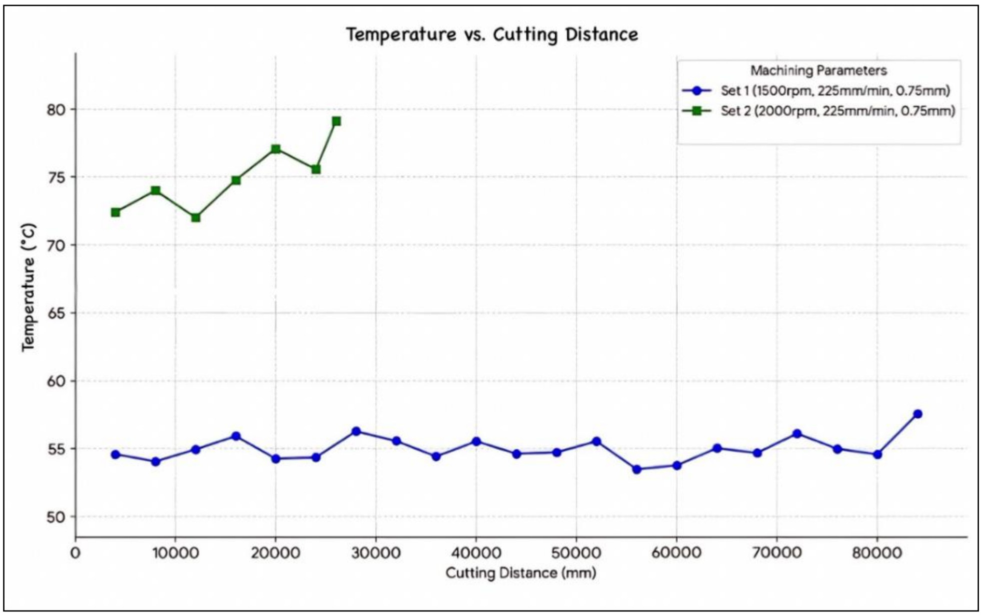

Figure 10. Graph shows the relationship of temperature data acquired through Arduino Cloud versus cutting distance at two different

4.0 CONCLUSION

This study successfully developed and implemented a microcontroller-based tool condition monitoring system for the end milling of S50C carbon steel, achieving all outlined objectives and demonstrating the potential of predictive maintenance through real-time data acquisition. By integrating ADXL345 accelerometers and MLX90614 temperature sensors with an ESP8266 microcontroller and Arduino Cloud, the system provided continuous, reliable monitoring of vibration and thermal signals via a user-friendly dashboard and local OLED screen. Experimental findings established a clear correlation between increased spindle with elevated vibration levels, directly indicating accelerated tool wear and highlighting the critical role of machining parameter optimization. Moreover, distinct changes in vibration accelerations were consistently observed as tool wear progressed, validating the system's ability to predict tool degradation and enabling timely maintenance interventions that reduce downtime, extend tool life, and improve machining efficiency. To further enhance this system, future research should include expanded machining parameter sets particularly variations in feed rate and depth of cut, and integrate additional sensors such as acoustic emission, cutting force, and current sensors to form a multi-sensor fusion framework.

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REFERENCES

[1] Y. M. Al-Naggar, N. Jamil, M. F. Hassan, and A.R Yusoff ,"Condition monitoring based on IoT for predictive maintenance of CNC machines", *Procedia CIRP*, vol. 102, pp. 314-318, 2021.

[2] T. Zonta, C. A da Costa, R. da Rosa Righi, M. J. de Lima, E. S. da Trindade, and G. P. Li, "Predictive maintenance in the Industry 4.0: A systematic literature review", *Computers and Industrial Engineering*, *150*, 2020.

[3] A. Rauf, M. Khan, M. S. Jaffery, and S. Butt, "Effects of Machining Parameters, Ultrasonic Vibrations and Cooling Conditions on Cutting Forces and Tool Wear in Meso Scale Ultrasonic Vibrations Assisted End-Milling (UVAEM) of Ti-6Al-4V under Dry, Flooded, MQL and Cryogenic Environments – A Statistical Analysis", *Journal of Materials Research and Technology*, vol. *30*, 2024.

[4] X. Li, X. Liu, C. Yue, S. Liu, B. Zhang, R. Li, S. Y. Liang, and L. Wang,"A data-driven approach for tool wear recognition and quantitative prediction based on radar map feature fusion", *Measurement*,vol. *185*, 110072, 2021.

[5] A. Desai, and A. Mital, "Design for maintenance: basic concepts and review of literature", *Internationa Journal Product Development,* vol. 3, no. 1, 2006.

[6] H. Ab-Samat, and S. Kamaruddin, "Opportunistic maintenance (OM) as a new advancement in maintenance approaches: A review", *Journal of Quality in Maintenance Engineering*, vol. *20,* no.2, pp. 98–121, 2014.

[7] Fisher, M. (n.d.). *Condition Monitoring for Predictive Maintenance Purposes A dissertation submitted.*

[8] M. P. Sharma, and M. Parveen Kantha, "Blynk" Cloud Server based Monitoring and Control using "NodeMCU." *International Research Journal of Engineering and Technology*, 2020.

[9] N. Jamil, M. F. Hassan, S. K. Lim, and A. R. Yusoff, "Predictive maintenance for rotating machinery by using vibration analysis", *Journal of Mechanical Engineering and Sciences*, vol. 15, no. 3, 2021.

[10] J. Z., Zhang, and J. C. Chen, "Tool condition monitoring in an end-milling operation based on the vibration signal collected through a microcontroller-based data acquisition system", *The International Journal of Advanced Manufacturing Technology*, vol. *39*, no. 1, pp. 118–128, 2008.