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IoT Based Real Time Monitoring System for CNC Machine

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Abstract

In the era of Industry 4.0, integrating and implementing Internet of Things (IoT) technologies into manufacturing processes is critical for increasing efficiency and reducing machine failures. This study addresses the lack of real-time monitoring systems in CNC machines by focusing on critical parameters such as temperature, humidity, and vibration, all of which are essential for maintaining CNC operations' precision and efficiency. In this study, the Arduino Mega and NodeMCU ESP8266 microcontrollers are used as primary data acquisition and transmission units. Data is collected using advanced sensors such as the DHT22 for temperature and humidity, and the ADXL-345 for vibration. The collected data is presented in real time via the MATLAB and Blynk. The results of this study show that the percentage of error for temperature and humidity is 0.8789% and 2.1165% respectively. Comparing the maximum and minimum values across five data sets throughout the facing process revealed slight temperature variations, with a maximum of 34.3°C and a minimum of 33.5°C. The humidity levels varied more significantly, ranging from 67.7% to 72.8%. The vibration data showed significant variations: the x-axis ranged from -2.28 m/s^2 to 0.35 m/s^2, the y-axis from -0.43 m/s^2 to 2.28 m/s^2, and the z-axis from 7.76 m/s^2 to 12.20 m/s^2. This study highlights the importance of real-time monitoring in CNC machine and provides a cost-effective IoT-based real-time monitoring solution for CNC machines.

1. Introduction

The integration of the Internet of Things (IoT) into Industry 4.0 has significantly transformed manufacturing processes, with the goal of increasing efficiency and speed. IoT's primary goal is to create self-reporting devices that allow for real-time communication, which includes key components such as IoT platforms, sensors, unique identifiers, and internet connectivity. This network of physical devices within manufacturing systems allows for more efficient control and monitoring. The key benefits of IoT include cost-effectiveness, minimal space requirements, low power consumption, and system portability during implementation [1]. The advent of IoT presents exceptional opportunities for the manufacturing sector, facilitating real-time resource monitoring and elevating safety and performance [2].

Over the past five decades, machine tools have evolved from basic equipment to complicated computer numerical control (CNC) technology, proving economically viable in various production cases [3]. CNC machining, which is controlled by pre-programmed software, has made significant advances with technologies such as G-code, M-code, CAD, and CAM software. The use of CAD/CAM software not only increases production rates but also ensures accuracy and saves time when compared to manual programming, resulting in high repeatability and efficient production of complex components [4].

In precision manufacturing, high vibrations in CNC machines present significant operational challenges. These vibrations, with unknown amplitude and frequency, complicate efforts to maintain optimal machine performance, risking both the longevity and quality of CNC operations. Unwanted vibrations during machine operation can cause system disruptions, leading to faults such as imbalance, wear, and misalignment [5]. Effective solutions require integrating technological innovation with an understanding of CNC machine dynamics, with vibration monitoring emerging as a key strategy [6]. Additionally, temperature and humidity fluctuations can affect CNC machine performance by compromising precision, inducing tool wear, and impacting sensitive electronic components. Machine tool precision and accuracy are influenced by a variety of issues, including geometric faults in the fuselage structure, clearances, servo control errors, and, most significantly, temperature and humidity deformations [7]. Therefore, monitoring of temperature, humidity, and vibration is very important.

Condition Monitoring (CM) addresses challenges such as inefficiencies, product quality compromises, and higher operating expenses, with a rising emphasis on continual structural health monitoring to mitigate unplanned failures [8]. The benefit of real-time monitoring is enabling industries to prevent unscheduled downtime, implement preventive maintenance, and gather diagnostic data [9]. By leveraging IoT technology, various manufacturing resources and their statuses are effectively captured [10]. Real-time monitoring of live sensory data is critical for continuously assessing the health of machines, significantly lowering the risk of unexpected failure [11]. Consequently, there is a need for a device capable of monitoring CNC machine condition and providing real-time data to operators.

To sum up, this study aims to explore a cost-effective IoT-based real-time monitoring solution for CNC machines. The primary objective is to seamlessly integrate IoT capabilities into CNC machines, with a particular emphasis on monitoring in real-time.

2. Methodology

2.1 Framework of the Study

This study consists of 5 layers, each contributing to the seamless functionality of an IoT-based real-time monitoring system for CNC machines. The sensor layer's foundation consists of DHT22 and ADXL-345 sensors that capture vital data on temperature, humidity, and vibration. The data acquisition and processing layer uses Arduino Mega and NodeMCU ESP8266 microcontrollers to collect and process data efficiently. The communication layer uses Wi-Fi connectivity to facilitate seamless communication. The core security and optimisation layer protect data integrity and system efficiency through encryption, authentication, and power optimisation. At the top tier, the application and user interface layer prioritise MATLAB and Blynk App Interface optimisation to provide a user-friendly experience. These layers work together to create a real-time monitoring system that is efficient, secure, and easy to use.

Table 1 *Framework of the Study*

Application and User Interface Layer	MATLAB, Blynk App Interface
Security and Optimization Layer	Data Encryption, Authentication, and Power Optimization
Communication Layer	Wi-Fi Connectivity
Data Acquisition and Processing Layer	Arduino Mega and NodeMCU ESP8266
Sensor Layer	DHT22 and ADXL-345 Sensors

2.2 Block Diagram of the Study

The CNC machine serves as the central hub for real-time monitoring, with the DHT22 sensor for temperature and humidity and the ADXL-345 sensor for vibration. The Arduino Mega and NodeMCU ESP8266 microcontrollers process this data, acting as intelligent hubs for accurate data acquisition and analysis. A dependable power supply ensures uninterrupted operation, which is critical for maintaining system efficiency. The MATLAB and Blynk app simplify data transmission by providing user-friendly, real-time monitoring on laptops or smartphones, allowing for complete oversight of the CNC machine's conditions.

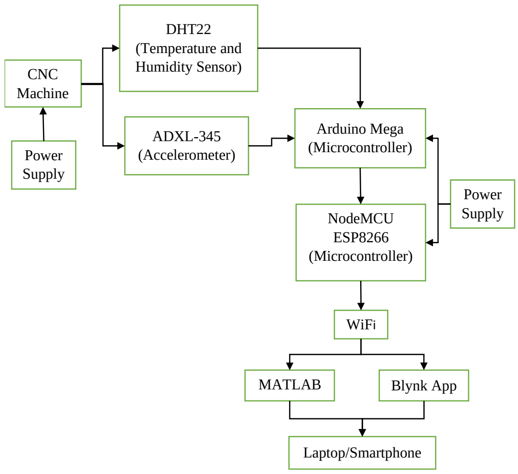

Fig. 1 *Block Diagram of the Study*

2.3 Flowchart of the Study

The flowchart of the study is structured into three main stages: initial, intermediate, and finishing. Initially, the study set precise goals, guided by Dr. Yusri, and conducted an extensive literature review to select suitable sensors (DHT22 and ADXL-345) and microcontrollers (Arduino Mega and NodeMCU ESP8266). In the intermediate stage, the system architecture was developed, integrating sensors with microcontrollers using the Arduino IDE and C++ for real-time data collection and transmission via the Blynk app. Finally, the fully operational system collected real-time data on temperature, humidity, and vibration, transmitting it through the NodeMCU ESP8266 to the Blynk app and MATLAB for continuous monitoring and analysis. It provides user-friendly, real-time graphical representations and insights into CNC machine conditions.

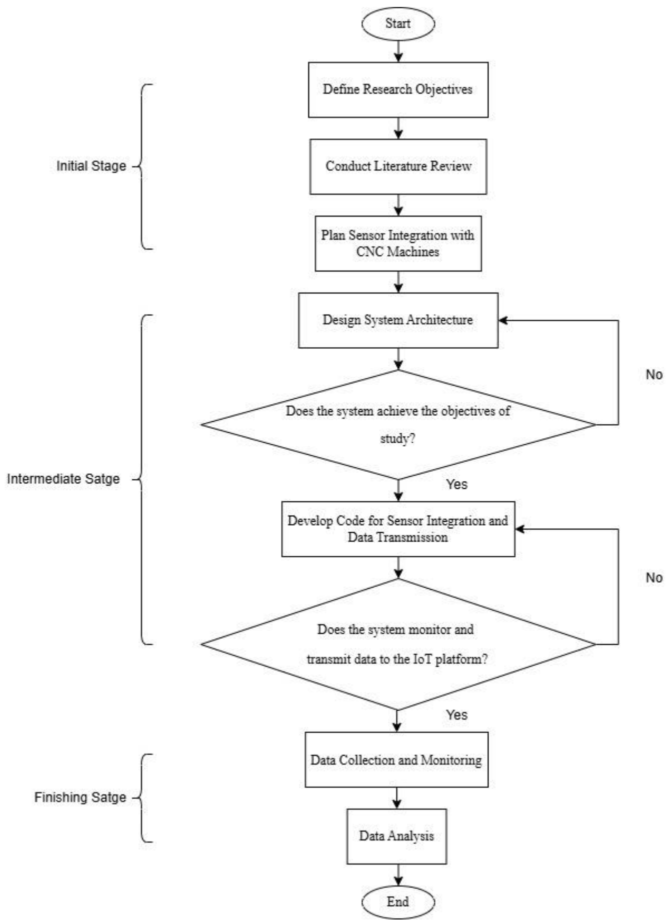

Fig. 2 *Flowchart of the Study*

2.4 Flowchart of the Real Time Monitoring System

The real-time monitoring system for CNC machines starts by connecting the Arduino Mega and NodeMCU ESP8266 to the laptop (power supply). The Arduino Mega is then programmed using the Arduino IDE to ensure that all wires are properly connected. Then, the ADXL-345 sensor is calibrated. After entering the SSID and password into the code, the Wi-Fi connection is set up. The NodeMCU ESP8266 code is then uploaded via the Arduino IDE, and the serial monitor is checked to ensure connectivity with both Blynk and Wi-Fi. The NodeMCU ESP8266 is connected to the Arduino Mega for data transmission. Following these steps, sensors are mounted on the CNC machine's spindle, and the machine is ready for the facing process. Temperature, humidity, and vibration data are collected using DHT22 and ADXL-345 sensors. The data is plotted in real-time using MATLAB and saved in text files. The NodeMCU ESP8266 transfers raw data to the Blynk app via Wi-Fi, displaying temperature, humidity, and vibration data in real-time.

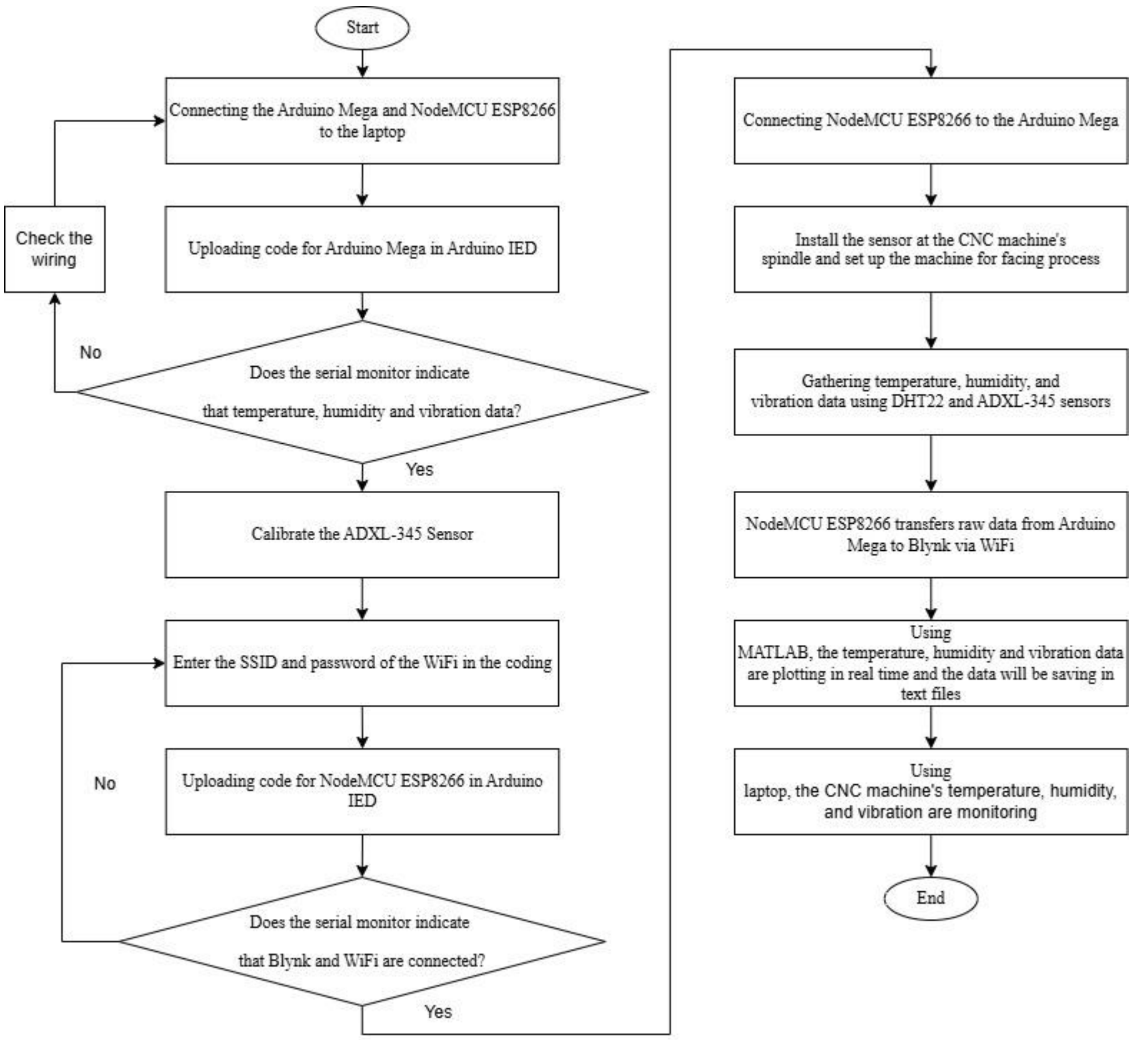

Fig. 3 *Flowchart of the Real Time Monitoring System*

3. Results and Discussions

3.1 Real Time Monitoring System Setup

Figure 4 and Table 2 show the circuit schematic diagram and wire connection of the real-time monitoring system. These illustrate how the Arduino Mega, NodeMCU ESP8266, DHT22 sensor, and ADXL-345 accelerometer are interconnected.

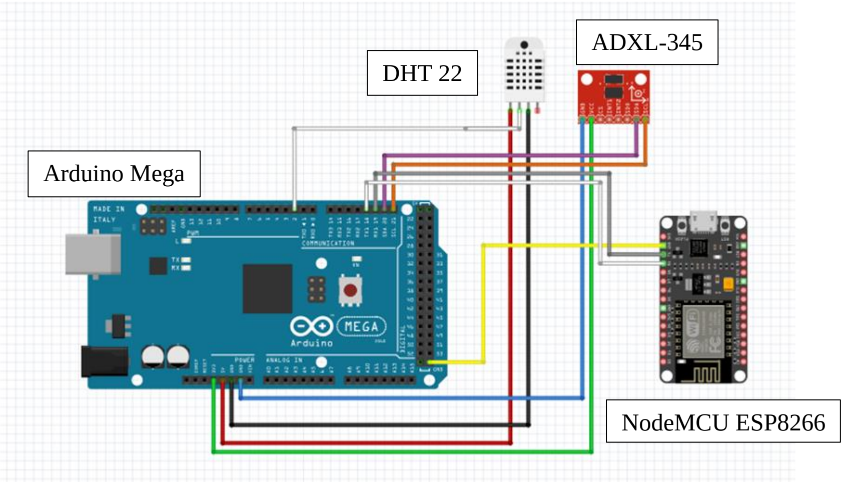

Fig. 4 *Circuit Schematic Diagram*

Table 2 *Wire Connection*

Component	Arduino Mega Pin	NodeMCU ESP8266 Pin	Description
DHT22 (Temperature & Humidity Sensor)	5V, GND & Digital IO 2	N/A	Power Supply: Connect VCC of DHT22 to 5V and GND of DHT22 to GND of Arduino Mega. Data Pin: Connect the data pin of DHT22 to Digital IO 2 of Arduino Mega.
ADXL-345 (Accelerometer)	3.3V, GND, SDA & SCL	N/A	Power supply: Connect VCC of ADXL-345 to 5V of Arduino Mega and GND of ADXL-345 to GND of Arduino Mega I2C connection: SDA of ADXL-345 to SDA of Arduino Mega, SCL of ADXL-345 to SCL of Arduino Mega
NodeMCU ESP8266 (WiFi Module)	TX1 & RX1	RX & TX	Serial communication: Connect TX of NodeMCU to RX1 of Arduino Mega, RX of NodeMCU to TX1 of Arduino Mega
Power Supply	Type-B USB Port	Micro USB Port	USB Connections: Connect the Type-B USB port of Arduino Mega and the Micro USB port of NodeMCU ESP8266 to the laptop.

3.2 Installation of the IoT Based Real Time Monitoring System on CNC Machine

Figure 5 shows the installation of IoT-based real-time monitoring system on the VERTICAL CENTER NEXUS 410A-II in Precision Machining Research Centre UTHM, the installation process involves several critical steps to ensure accurate data collection and reliable monitoring of the machine's operational conditions.

Fig. 5 *Installation of the IoT Based Real Time Monitoring System on CNC Machine*

The machining process used in this study is the facing process, where material is removed from the surface of a workpiece to create a flat surface perpendicular to the rotational axis. The process parameters are set with depth of 2 mm, depth of cut of 0.5 mm, spindle speed of 900 min^-1, cutting speed of 150 mm/min, and feed rate of 0.2 mm/rev. A face mill tool with a 60 mm diameter ensures the operation is completed on the Aluminum 6061 block blocks with 100 mm in width, 100 mm in length and 50mm in height. Proper sensor placement is critical for accurate measurement of temperature, humidity, and vibration. The DHT22 sensor, responsible for monitoring temperature and humidity, is attached to the spindle of the VERTICAL CENTER NEXUS 410A-II. This strategic placement ensures it captures the most relevant environmental data, reflecting the current conditions affecting the machining process. The ADXL-345 accelerometer, which monitors vibrations, is also placed near the spindle, the primary source of vibration [12]. This positioning ensures precise vibration data collection, essential for identifying potential issues with the machine's operation. The accelerometer is mounted on a breadboard to ensure precise orientation, accurately capturing vibrations along the intended axes. Cable ties and tape organize and secure the wiring, ensuring stable, reliable connections.

3.3 Results of the IoT Based Real Time Monitoring System

MATLAB and Blynk are used to perform advanced visualization and analysis on data collected from the sensors. These visualizations provide immediate insight into the machine's operating conditions, assisting in the identification of trends, anomalies, and potential problems. The robust data handling capabilities of MATLAB and Blynk enable detailed analysis, efficient storage, and thorough documentation of the collected data, ensuring comprehensive monitoring of the CNC machine.

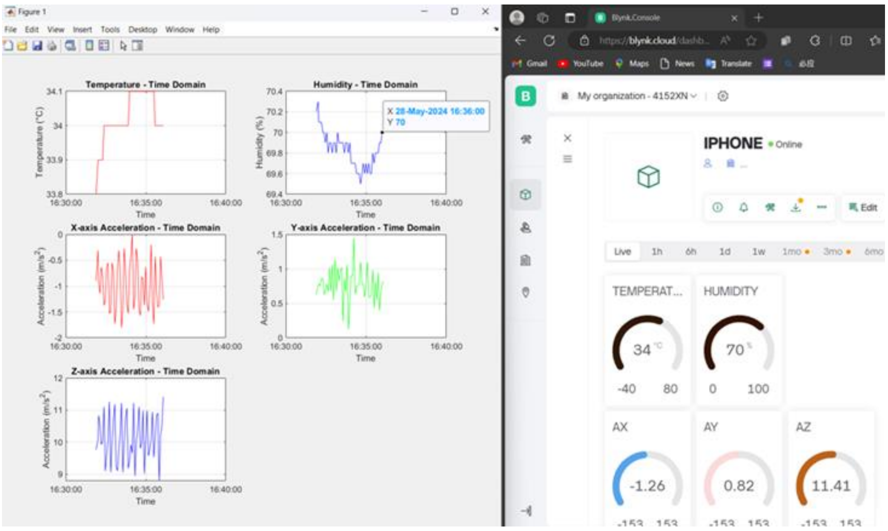

Fig. 6 *Real Time Monitoring Results in MATLAB and Blynk*

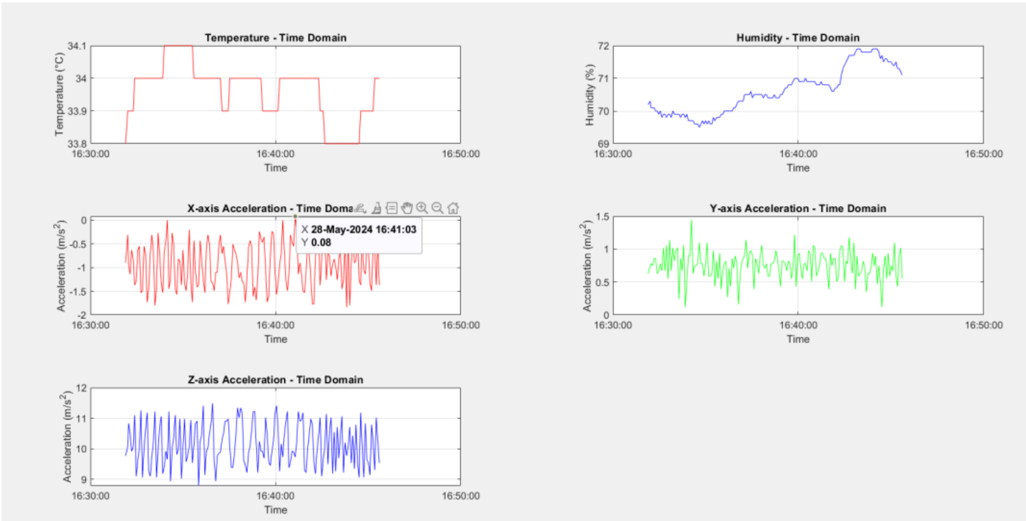

Fig. 7 *Comprehensive Results of Temperature, Humidity, and Vibration for the Facing Process*

3.4 Verification of the Results

3.4.1 Comparison of the Temperature and Humidity Results

A Kimo AMI 310 instrument was used to compare the results of temperature and humidity data from the DHT22 sensor. Since the Kimo AMI 310 is accurate and reliable, it served as a reference point to determine the accuracy of the DHT22 readings. Under the same environmental conditions, the DHT22 sensor and the Kimo AMI 310 recorded data at the same time. The percentage of errors between the temperature and humidity readings from the DHT22 sensor and the Kimo AMI 310 instrument is calculated. By calculating the percentage error for each set of readings, we can quantify the accuracy of the DHT22 sensor compared to the Kimo AMI 310. The results are then averaged to provide an overall assessment of the performance of the DHT22 sensor.

The following formula is used to calculate the percentage of error:

$$Percentage\ of\ error, \% = \frac{|Kimo\ Reading - DHT22\ Reading|}{Kimo\ Reading} \times 100\% \quad (1)$$

The percentage of error for temperature and humidity is calculated from three sets of data and tabulated in Table 3.

Table 3 *Percentage of Error for Temperature and Humidity*

No	DHT22 Reading (Temperature)	DHT22 Reading (Humidity)	Kimo Reading (Temperature)	Kimo Reading (Humidity)	Percentage of Error (Temperature)	Percentage of Error (Humidity)
1	33.8	69.6	34.0	68.0	0.5882%	2.3529%
2	33.9	68.2	34.3	68.7	1.1662%	0.7278%
3	33.7	69.5	34.0	67.3	0.8824%	3.2689%
Average					0.8789%	2.1165%

According to Table 3, the average percentage of error for temperature and humidity is 0.8789% and 2.1165% respectively. This indicates that DHT 22 sensor is accurate for monitoring the temperature and humidity.

3.4.2 Calibration of the ADXL-345 Accelerometer

The calibration process used to validate and improve the performance of the ADXL-345 for real-time CNC monitoring is described in AUTODESK Instructables [13]. The function calibrateADXL345() assists in doing this by calibrating each axis individually, ensuring that the positive axis points upwards against gravity. To prevent movement, place the accelerometer on a stable calibration block. Calibration for each axis is performed by adjusting the respective code sections inside the calibrateADXL345() function, after which computed offsets are used for the adjustment of future measurements to bring up accuracy and reliability. For this case, the calibration process was only applied to the Y-axis and Z-axis, since the X-axis reading was already accurate and did not need calibration.

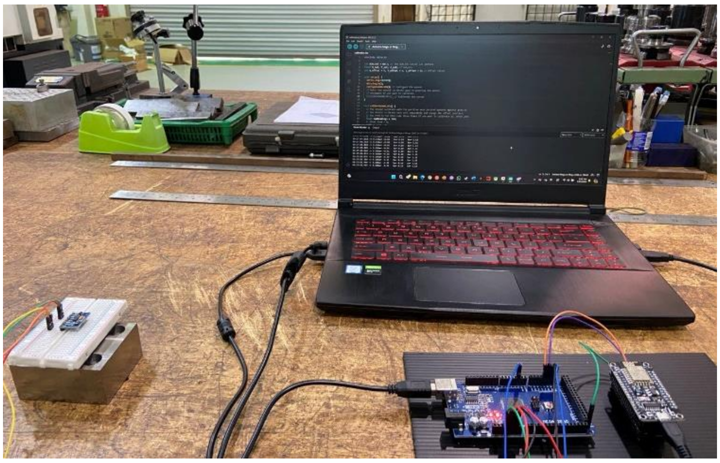

Fig. 8 *Calibration of the ADXL-345 Accelerometer*

3.5 Data Analysis

The CNC machine was monitored five times during the facing process, and the maximum and minimum values recorded are shown in Table 4. and Table 5 below. By comparing the maximum and minimum values in the five sets of data, we found that the temperature was slightly different, with the highest maximum recorded at 34.3°C and the lowest minimum at 33.5°C. The humidity levels varied widely, ranging from a high of 72.8% to a low of 67.7%. The vibration data on the x, y, and z axes showed significant differences. The x-axis showed a maximum of 0.35 m/s^2 and a minimum of -2.28 m/s^2, while the y-axis showed a maximum of 2.28 m/s^2 and a minimum of -0.43 m/s^2. The z-axis vibration varied from a maximum of 12.20 m/s^2 to a minimum of 7.76. Therefore, this data can be used as a valuable guide for future operations.

Table 4 *Maximum Values Recorded During Facing Process*

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5
Temperature, ℃	34.0	34.1	34.3	34.1	33.9
Humidity, %	70.6	71.9	72.2	72.8	70.9
Vibration in X-axis, m/s^2	0.04	0.08	-0.27	0.08	0.35
Vibration in Y-axis, m/s^2	1.65	1.45	1.37	1.80	2.28
Vibration in Z-axis, m/s^2	11.49	11.49	11.38	11.41	12.20

Table 5 *Minimum Values Recorded During Facing Process*

Parameter	Set 1	Set 2	Set 3	Set 4	Set 5
Temperature, ℃	33.7	33.8	33.9	33.8	33.5
Humidity, %	69.5	69.5	69.7	67.7	69.5
Vibration in X-axis, m/s^2	-2.00	-1.84	-1.77	-1.84	-2.28
Vibration in Y-axis, m/s^2	0.12	0.12	0.27	-0.24	-0.43
Vibration in Z-axis, m/s^2	8.83	8.79	8.83	8.87	7.76

4. Conclusion and Recommendations

In conclusion, this study has successfully developed and implemented an IoT-based real-time monitoring system for CNC machines. This system uses various of advance sensors, including the DHT22 for temperature and humidity measurements and the ADXL-345 for vibration analysis. The Arduino Mega and NodeMCU ESP8266 were the primary data acquisition and transmission units respectively. Data visualisation and analysis were facilitated by MATLAB and the Blynk app, which provided a comprehensive and user-friendly interface for monitoring machine conditions. The results demonstrated the system's ability to consistently and accurately monitor critical parameters, ensuring the reliable operation of CNC machines. We validated sensor accuracy by comparing sensor data to a reference measurement (Kimo AMI 310). Furthermore, the calibration of the ADXL-345 accelerometer resulted in precise vibration data, which was critical for diagnosing potential issues with the machine's operation. Despite its successes, the monitoring system has some weaknesses. The system currently lacks a dependable long-term cloud storage solution, as Blynk's free version only keeps data for a limited time. The temperature and humidity readings can be affected by environmental factors such as weather and the conditions within the Precision Machining Research Centre UTHM. Furthermore, the system's software could be improved to allow for more detailed analysis, such as frequency domain analysis of vibration data using Fast Fourier Transform (FFT).

Based on the outcomes of this project, several recommendations can be made for future improvements and applications. Firstly, for accurate data collection, utilize 3D printing or other manufacturing processes to produce suitable mounts for sensors, particularly the ADXL-345 accelerometer, ensuring proper sensor placement. Secondly, ensure solid wire connections by using high-quality, shielded wires of appropriate length to prevent sensor disconnection, thereby enhancing data integrity and preventing signal loss. Thirdly, integrate a reliable cloud storage solution for long-term data archiving, facilitating easier analysis of historical data and trend identification. Fourthly, enhance the coding of Arduino IDE and MATLAB to display vibration data in the frequency domain via Fast Fourier Transform (FFT). Lastly, establish a notification system for alerting users during abnormal conditions and develop an automated control system to respond to anomalies detected by the monitoring system, such as automatically shutting down the CNC machine in the event of excessive vibrations to prevent damage and ensure safety.

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