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A Study on IoT-Based Data Collection and Monitoring Systems for CNC Machines in Smart Manufacturing

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Abstract.

The CNC machine tools are extensively applicable in the contemporary manufacturing industries where they are used in performing operations including turning, drilling, tapping and milling. Monitoring and data- collection in small and medium enterprises (SMEs) has to be strongly advantageous in enhancing productivity and reducing downtime. In this paper, the design and development of IoT-based data acquisition and monitoring of CNC machines is presented. Several sensors are incorporated in the proposed system and they include a vibration sensor, temperature sensor, pressure sensor and noise sensor to gather real time machine data. The data obtained is sent to the cloud-based systems to monitor and analyse. Fault detection and predictive maintenance can be performed by means of advanced methods like Artificial Intelligence (AI) and PLC programming. The system assists in tracking machining time, tool status and unforeseen failures. The solution proposed is consistent with Industry 4.0 and offers cost-effective and scalable solution to SMEs so that they can become efficient and productive.

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Keywords: Computer Numerical Control, Small Medium Enterprises, Internet of things, Artificial Intelligence, Programmable Logic Controller.

1. INTRODUCTION

Computer Numerical Control (CNC) machine tools are a component of the present manufacturing systems, which can perform more specific and automated tasks, including turning, milling, drilling, and tapping. Amidst rising demands on the production of high-quality and customized products, industries are shifting to high-level manufacturing technologies to enhance productivity and efficiency. Machine monitoring is not usually much in small and medium enterprises (SMEs), resulting in inefficiencies in the form of unexpected failures, more downtimes, and less productivity. The conventional type of monitoring systems does not have real-time data acquisition and smart analysis. Industry 4.0 has brought new technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing, which can make any manufacturing system smart. IoT provides an opportunity to monitor the parameters of the machines in real-time, whereas AI provides an opportunity to predict and make decisions. This study is centered on creating a data gathering and monitoring framework of CNC machine instruments that is based on irrational operations of IoT. The system gathers real-time information through sensors and offers information on how to enhance machine performance, decrease downtimes and have predictive maintenance.

2. LITERATURE REVIEW

Smart manufacturing is a data-driven paradigm that integrates interconnected machines, analytics, and autonomous decision-making to improve productivity and adaptability [1]. Industry 4.0 promotes vertical and horizontal integration of manufacturing systems, enabling real-time monitoring and intelligent production [2], [3]. Machine-tool interoperability can be supported through standards-based frameworks such as MTConnect [4], while controller-integrated monitoring enables extraction of parameters such as spindle speed and feed rate without external sensors [5]. Various sensing approaches, including force, vibration, acoustic emission, and temperature, have been applied for machining condition monitoring [6]. Energy consumption modelling has also become important for improving CNC efficiency and sustainable production [7].

Cyber-physical systems (CPS) provide the foundation for synchronized monitoring and real-time control [8]. Digital Twins extend CPS by creating virtual representations of physical assets, supporting predictive optimization and lifecycle management [9]. AI-based methods, including CNNs and deep learning, have been applied to tool-wear prediction, fault diagnosis, and machining-condition monitoring [10]. Recent CNN-LSTM and Transformer architectures further improve spatio-temporal and long-sequence modelling. Edge computing enables low-latency analytics while reducing dependence on cloud infrastructure. Despite these advances, comprehensive statistical validation of AI-driven predictive maintenance and efficient real-time synchronization between CNC machines and Digital Twins remain insufficiently addressed.

3. RESEARCH METHODOLOGY

The appropriate process parameters of the CNC machine tool are chosen. Upon the choice of the parameters, the proposed smart monitoring system is created based on the data acquisition and machine learning techniques of the IoT. The process of data collected by sensors input is analyzed and processed to provide predictions and guide decision-making in smart manufacturing of small and medium-sized enterprises (SMEs). Lastly, the proposed system performance is tested using a comparison between the experimental results of the proposed system to the traditional system parameters. A flow chart is used to represent the entire research methodology.

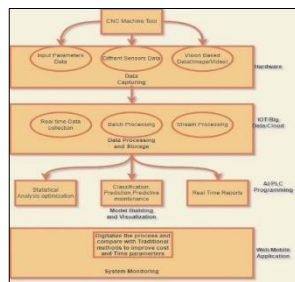


Figure 1. Research methodology

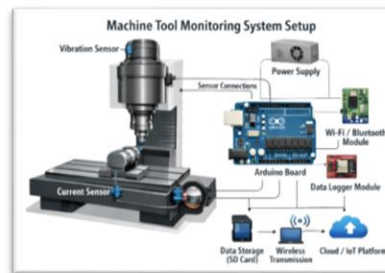


Figure 2. Sensor devices and Arduino microcontroller installed in the machine tool.

4. FINALIZED MODEL PARAMETERS AND TECHNIQUES

Several sensors were integrated into the CNC machine for real-time data acquisition, including a dynamometer for torque, force, speed, and power, an acoustic sensor for sound frequency, and a vibration sensor for machine vibration. A Raspberry Pi 3 Model B was used as the central acquisition unit due to its wireless connectivity, GPIO support, and

processing capability. Tool condition monitoring focused on wear, breakage, and misalignment using low-cost, non-invasive current, sound, and vibration sensors. Edge devices processed sensor data before cloud-based analysis using ANN and ANFIS models. Tri-axial IoT vibration sensors supported condition monitoring, while deep learning assisted abnormal vibration detection. Production performance was monitored using cycle time, production volume, and reject rate through a web-based OpenCV and Tesseract OCR system, with ANN used for performance analysis.

4.1. Finalized Parameters and Techniques

Table: 1 Finalized Parameters and Techniques

Parameter	Measure	Monitor	Technique
Tool Life and Tool Monitoring	Tool Breakage Tool Wear Monitoring tool Conditions	Advanced Artificial Neural Network (IoT),Big Data	Adaptive Neuro fuzzy integration (ANFI)
Vibration Monitoring	Vibration Levels Predictive Maintenance	Nested Neural network model, IoT, Big Data	Deep Learning Neural Network
Production Monitoring	Cycle Time Production Volume	Cyber Physical Monitoring, IoT ,Big Data	Artificial Neural Network (ANN)

5. EXPERIMENTAL SETUP

A Raspberry Pi-based IoT data acquisition system was developed to collect sensor data in real time and transmit it to a computer or cloud server through wired or wireless communication. Sensors were strategically positioned, with the vibration sensor attached to the spindle housing, sound sensor near the worktable, and force sensor at the workpiece setup. The collected parameters included torque, force, speed, power consumption, sound frequency, and vibration.

A structured database was developed to store timestamped sensor measurements. Experimental and Python-generated synthetic data were combined to create a balanced dataset for machine learning. Pandas and Matplotlib were used for statistical and correlation analysis, revealing positive relationships among torque, force, and vibration. Filtering, normalization, and feature extraction were applied to prepare data for ANN and predictive maintenance models.

6. DATA ANALYSIS AND INSIGHTS

Correlation analysis showed positive relationships among torque, force, and vibration, with increased torque generally associated with higher vibration. Sudden increases in sound frequency corresponded with tool-wear events. During normal operation, average torque remained stable between 34–38 Nm, while vibration spikes indicated possible tool misalignment or wear. Data preprocessing, including filtering and normalization, was established, and relevant features were engineered for ANN-based predictive maintenance models.

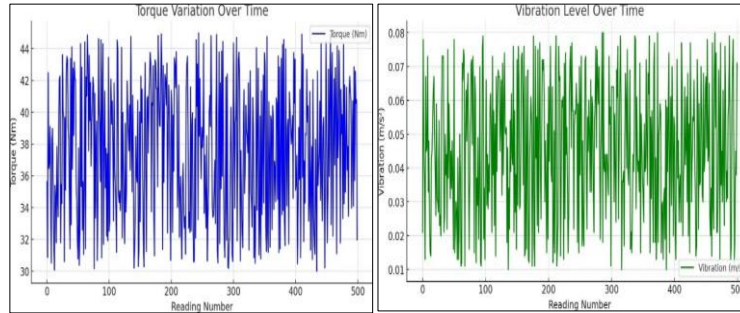


Figure 6.1.2.1: Torque Vs Time

Figure 6.1.2.2: Vibration Vs Time

This chart indicates the variation in torque (the rotational force which acts on the tool) in time.

- The torque variability is the changes in the cutting resistance during interaction of the tool. That has various material segments.
- Constant levels of torques typically point to good machining conditions.

This graph measures vibration intensity over time when CNC is being operated. Also, minor vibrations are normal and expected during cutting.

7. CONCLUSION

The article provides a description of the creation of an IoT-driven smart monitoring system of CNC machine tools to facilitate smart production and predictive maintenance in small and medium sized production companies (SMEs). The system combines the various sensors, which are force sensors, vibration sensors, and sound sensors to acquire real-time machining data. A data acquisition system was produced using Raspberry Pi and used to collect and send sensor data to a database to store and analyze.

The proposed system is low cost, scalable and flexible as opposed to the traditional monitoring systems. It is especially appropriate to SMEs in which cost of implementation and complexity of the system will be a significant issue. IoT, machine learning, and data analytics combined will help to monitor and find faults in real-time and enhance the quality of decisions in the manufacturing setting.

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