JURNAL ILMIAH TEKNIK INDUSTRI
ISSN: 1412-6869 (Print), ISSN: 2460-4038 (Online)
Journal homepage: http://journals.ums.ac.id/index.php/jiti/index
doi: 10.23917/jiti.v24i2.12002

IIoT-Based Monitoring and Predictive Maintenance of Industrial Machine Tools Using CtrlX Automation Platform

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Abstract. *The emergence of the Industrial Internet of Things (IIoT) is transforming traditional industrial maintenance into a predictive, data-driven process. This paper presents a comprehensive architecture for an IIoT-enabled monitoring and maintenance system focused on industrial machine tools. Leveraging proximity sensors to capture rotation speed, axial movement, and tool position, the system integrates sensor data with microprocessors such as Arduino STM32 and PID controllers to ensure real-time control and analysis. The architecture utilizes both local processing through Arduino IDE and centralized visualization via Node-RED, enabling efficient data transmission to cloud services through an Internet gateway. Key technologies such as 5G communication, big data analytics, and digital twins are incorporated to enhance predictive maintenance capabilities, reduce downtime, and improve overall equipment effectiveness (OEE). Despite the promise of IIoT integration, challenges such as interoperability, cybersecurity, and legacy system adaptation remain significant. This study proposes a scalable and intelligent CPS framework to overcome these obstacles and highlights the potential of Machine Tool 4.0 in achieving smarter, more autonomous, and sustainable manufacturing ecosystems.*

Keywords: *IIoT, predictive maintenance, machine tools, arduino STM32, CPS, smart manufacturing, PID controller, Node RED, digital twins*

I. INTRODUCTION

In the era of rapid technological advancement, wellmaintained industrial machinery and efficient production lines are fundamental to maintaining continuous and high-quality manufacturing processes. Effective monitoring and maintenance strategies are critical to preventing unexpected failures, reducing downtime, and optimizing productivity. Traditionally, such tasks relied heavily on manual inspection and reactive maintenance, often initiated only after a breakdown occurred. However, this reactive approach can lead to prolonged downtimes, reduced production efficiency, and increased operational costs.

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Submited: 17-07-2025 Revised: 28-11-2025
Accepted: 16-12-2025

With the emergence of the Industrial Internet of Things (IIoT), industrial systems are evolving toward smarter and more connected environments. IoT enables real-time data acquisition, seamless communication, and advanced analytics, transforming traditional industrial systems into intelligent infrastructures. Sensors, embedded systems, and networked communication technologies can now collect and transmit vast amounts of operational data from machine tools, which is critical for predictive maintenance and performance optimization. [1]

However, implementing IoT-based monitoring and maintenance systems in industrial environments presents several challenges. One of the primary concerns is interoperability—integrating heterogeneous machines from different manufacturers that use varied communication protocols. Managing, storing, and analyzing the large volumes of data generated is another significant hurdle. Moreover, deriving actionable insights from raw data and presenting them in an interpretable form for decision-makers remains a complex task. Effective integration of IoT in industrial environments requires standardized protocols, scalable infrastructure, and intelligent data processing frameworks.

Machine tools—core components in manufacturing—are often referred to as "mother machines" because they enable the production of nearly all other machinery. The evolution of machine tools has paralleled the industrial revolutions: from manually operated mechanical systems (Machine Tools 1.0) to computer-controlled systems (Machine Tools 3.0), and now to the era of Machine Tool 4.0. This latest stage, enabled by Cyber-Physical Systems (CPS), IoT, and cloud computing, signifies a new generation of intelligent, interconnected, and adaptive machines capable of self-monitoring, diagnosing, and optimizing their own performance.

The adoption of IoT technologies in machine tool monitoring provides numerous benefits. These include real-time fault detection, reduced maintenance costs, prolonged equipment lifespan, enhanced energy efficiency, and improved overall equipment effectiveness (OEE). Through predictive analytics, operators can anticipate failures before they occur, schedule maintenance activities with minimal disruption, and optimize machine parameters for better productivity.

Furthermore, IoT facilitates the transition from traditional factory models to smart manufacturing ecosystems. By integrating sensors, edge computing devices, and cloud platforms, data collected from machine tools can be processed locally or remotely to support complex decision-making processes. This not only improves operational efficiency but also opens new possibilities for remote diagnostics, automated reporting, and AI-driven optimization.[2]

Despite the potential, the road toward full IoT adoption is not without its obstacles. Issues such as cybersecurity, data privacy, legacy system integration, and high initial implementation costs need to be addressed. Industrial environments often contain legacy equipment that lacks IoT compatibility, requiring retrofit solutions or middleware to bridge technological gaps. In addition, the sheer volume of data generated necessitates robust cybersecurity measures to ensure that sensitive operational data remains secure from external threats.

Emerging technologies such as 5G, blockchain, and digital twins further enhance the capabilities of IoT-based monitoring systems. 5G offers low-latency, high-bandwidth communication essential for real-time monitoring, while blockchain ensures secure and tamper-proof data exchanges. Digital twins—virtual replicas of physical machines—allow for advanced simulation, monitoring, and predictive maintenance in a virtual environment, reducing the risks and costs associated with physical testing.

In this paper, we explore the integration of IoT technologies into industrial systems for the purpose of monitoring and maintaining machine tools. The objective is to present a comprehensive framework and review of methodologies that enable predictive maintenance and enhance the performance of machine tools through the application of IoT. The paper is structured as follows: Section 2 reviews current approaches and objectives in machining process optimization. Section 3 focuses on the architecture of cyber-physical systems and their implementation in industrial monitoring, including data modeling and system integration. These insights are essential for the development of high-performance, IoT-enabled industrial environments.[3]

Ultimately, the fusion of IoT and machine tools is paving the way for a new industrial paradigm—where machines are not only operated but also intelligently managed. This transformation has the potential to reshape manufacturing as we know it, enabling higher efficiency, reduced waste, and greater responsiveness to market demands. As industries continue to embrace digital transformation, IoT will serve as a cornerstone in achieving smart, autonomous, and sustainable manufacturing systems.

II. Related Works

The development of Cyber Physical (CPS) systems in the context of conventional machine monitoring has been a significant research focus in recent years. The system integrates physical components with digital elements to preventive the efficiency and operational accuracy of the machine.

Traditional Maintenance Practices. Historically, equipment and production lines were inspected and maintained manually after failures occurred. This reactive approach often resulted in significant downtime, negatively impacting production quality and capacity while increasing operational costs. This traditional method, though widely used, is no longer sufficient in the face of modern industrial demands.

The Role of Advanced Communication Technologies. With the advent of wireless sensor networks and advanced communication technologies, real-time data from equipment and production lines can now be collected, analyzed, and shared instantly. This enables predictive maintenance, significantly reducing the chances of sudden failures. These technologies facilitate seamless communication between devices, creating a more robust maintenance ecosystem.

Big Data for Predictive Maintenance. The integration of big data allows for the storage and analysis of vast amounts of operational data from equipment and production lines. Patterns and anomalies can be identified early, enabling proactive decision-making. Impact: Big data analytics reduces downtime and ensures optimal production performance.

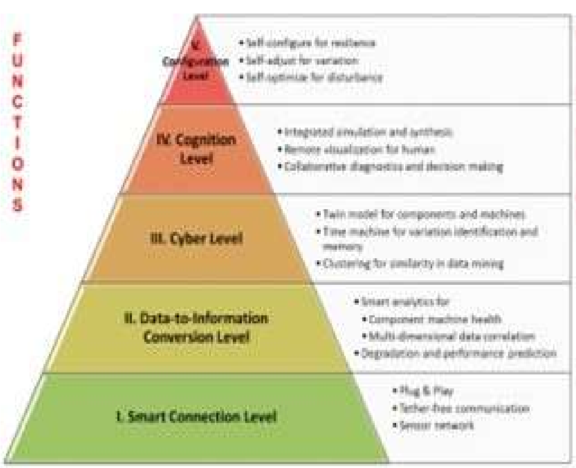

Figure 1. 5C of CPS Architecture

Digital Twins and Industrial Internet Integration. Digital twins, as virtual replicas of physical assets, enable real-time monitoring and simulation of equipment performance. When integrated with the Industrial Internet, they allow for remote diagnostics and maintenance. Impact: This fosters a shift towards smart factories, improving reliability and scalability.

III. ARCHITECTURE OF CPS FOR MANUFACTURING

The 5-level CPS architecture (fig. 1), named 5C, consists of methodologies and guidelines to step-by-step design and deploy CPS for manufacturing from data acquisition stage to

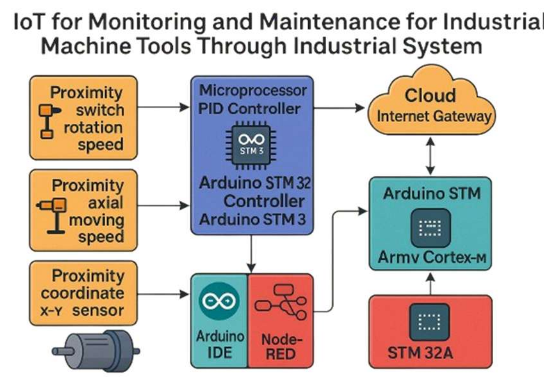

Figure 2. Architecture IIoT System of Monitoring and Maintenance for Industrial Machine Tools.

analysis and final value creation.

Smart Connection. Acquiring accurate and reliable data from machines and their components is the first step in developing a CyberPhysical System application. The data might be directly measured by sensors or obtained from controller or enterprise manufacturing systems such as ERP, MES, SCM and CMM. Two important factors at this level have to be considered.

First, considering various types of data, a seamless and tether-free method to manage data acquisition procedure and transferring data to the central server is required where specific protocols such as MTConnect (Vijayaraghavan et al. 2008) and etc. are effectively useful. On the other hand, selecting proper sensors (type and specification) is the second important consideration for the first level.

Data to Information Conversion. Meaningful information has to be inferred from the data. Currently, there are several tools and methodologies available for the data to information conversion level. In recent years, extensive focus has been applied to develop these algorithms specifically for prognostics and health management applications. By calculating health value, estimated remaining useful life and etc., the second level of CPS architecture brings selfawareness to machines.

IV. IoT Architecture Planning

IoT Device Planning

a. **CtrlX CORE (Bosch Rexroth)**. Acts as the main edge controller that connects to various industrial sensors and actuators. It collects real-time data such as vibration, temperature, and motor load from machine tools and processes them locally before forwarding selected metrics to cloud or SCADA systems. Its modular and Linux-based architecture enables the deployment of custom applications and services, including predictive

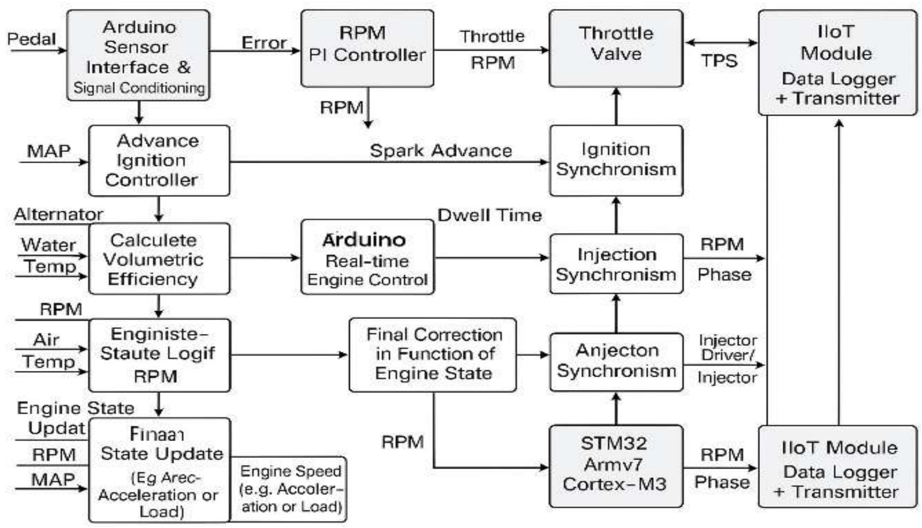

Figure 3. IIoT System of Monitoring and Maintenance for Industrial Machine Tools Block Diagram

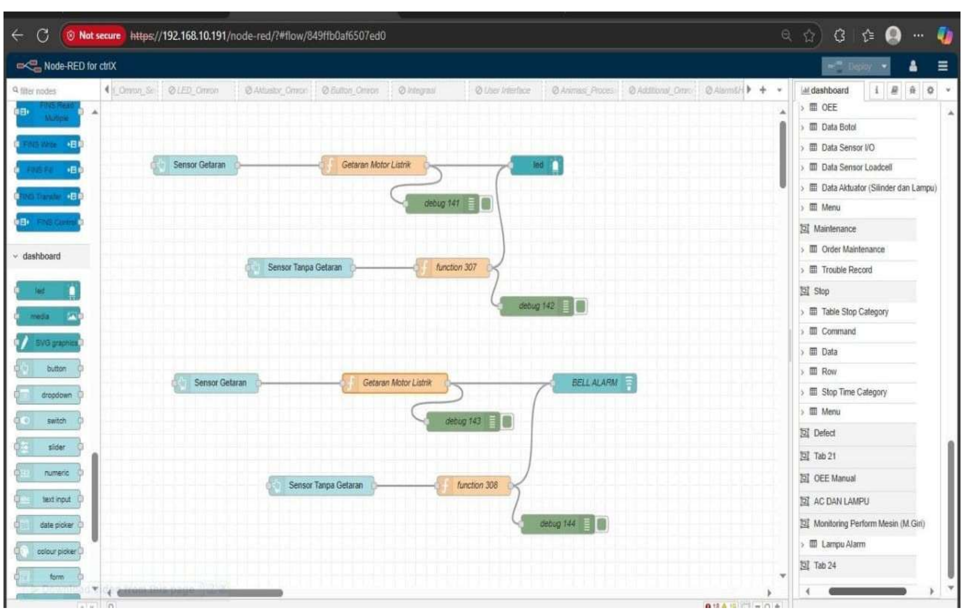

Figure 4. Node-Red Program

algorithms and IIoT protocols (e.g., MQTT, OPC UA).

b. **Sensor**. Proximity switch rotation speed sensor: Functions to capture signals regarding the number of rotations and the speed value of the electric motor. Proximity axial moving speed: Functions to receive axial movement signals on the machine table. be it speed or stroke length. Proximity coordinate: Functions to receive signals about the position point of a tools

c. **Actuators**. Motor Driver DC: Moving tools, machine tables, rotating spindles

d. **Connectivity**. Internet Gateway: Receive data from Arduino STM32 Armv7 Cortex-M3 and send to node red.

e. **Local Controls**. PID Controller: To regulate a process variable by continuously adjusting a control output based on the error between the desired setpoint and the actual process value. It achieves this by using a feedback loop that incorporates three control

f. **Software on Each IoT Device**

- *Node Red*: Displays data simulation from machine input related to its performance, namely: stroke length, rotation, machine

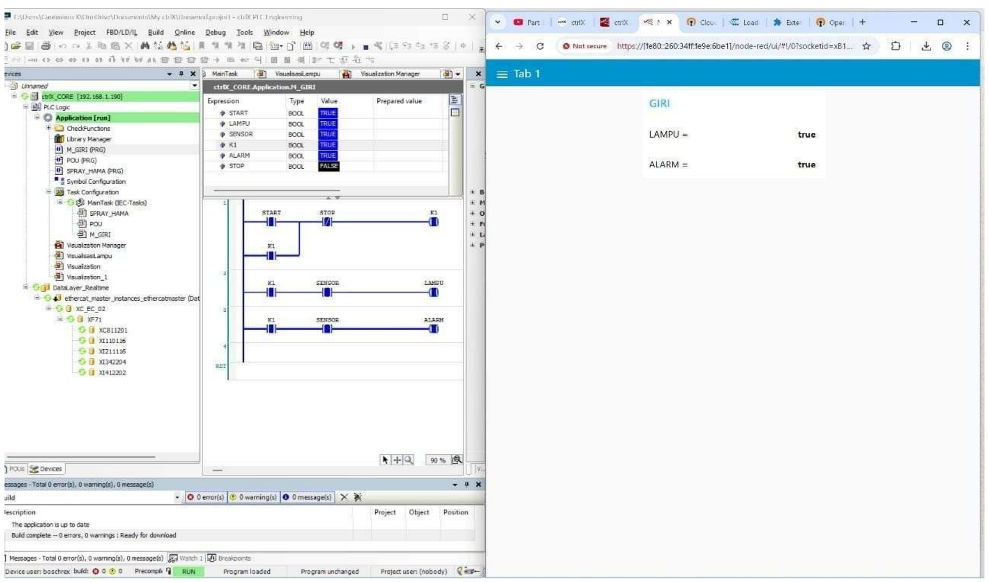

Figure 5. PLC Display System On

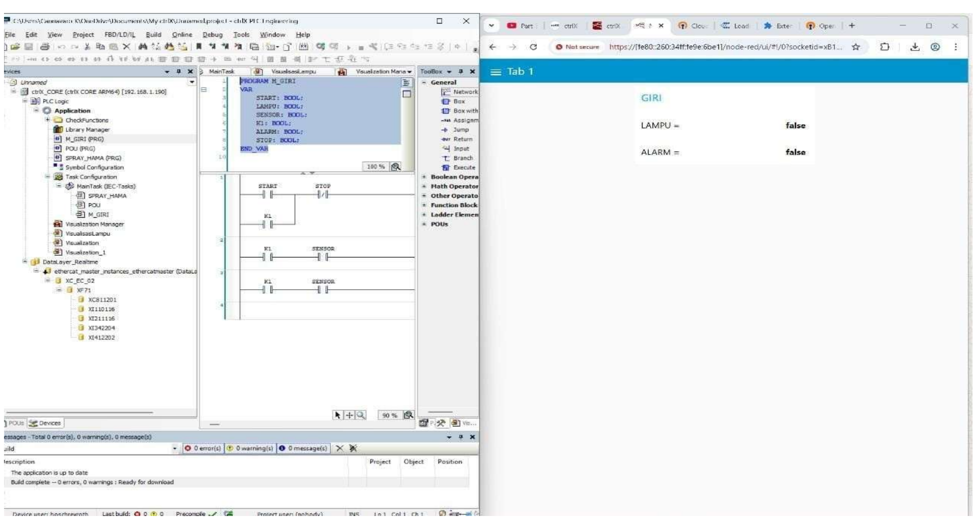

Figure 6. PLC Display System Off.

position. Ultimately formulated to determine machine vibration.

- *Arduino IDE*: Contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them.
- *PLC Runtime*: Integrated within CtrlX CORE the PLC functionality handles local control tasks, signal processing, and logic execution based on sensor input conditions (e.g., vibration threshold, temperature limits). This eliminates the need for an external hardware PLC, reduces system complexity, and allows logic changes via software updates.

IoT Processor

a. **IoT Device Processor Needs**. Arduino STM 32: to convert the signal information from the Proximity switch rotation speed sensor to the node red
b. **IoT Gateway Processor Needs**. Arduino STM 32 Armv7 Cortex-M3: to collect data from various devices and process it before sending it to the server or cloud and translate various communication protocols.

IoT Project Benefits and Challenges

a. **Background.** Well-maintained equipment and production lines are the basis for regular production in the factory. It is important to monitor and maintain equipment and production lines during the operation process effectively to avoid failure. Traditionally, equipment and production lines were manually inspected and maintained after failures appeared. However, this strategy cannot avoid the negative impact of equipment downtime on quality and capacity, which is costly. With the development of wireless sensor networks, advanced communication technologies, big data, artificial intelligence, and digital twins
b. **Data Needs.** Meaningful information has to be inferred from the data. Currently, there are several tools and methodologies available for the data to information conversion level. In recent years, extensive focus has been applied to develop these algorithms specifically for prognostics and health management applications. By calculating health value, estimated remaining useful life and etc., the second level of CPS architecture brings selfawareness to machines
c. **IoT Benefits.** In general, Machine Too l4.0 defines a new generation of machine tools that are smarter, better connected, widely accessible, more adaptive and more autonomous. The information on these models can be highly valuable to establish a high-performance manufacturing system.
d. **Challenges.** Historically, equipment and production lines were inspected and maintained manually after failures occurred. This reactive approach often resulted in significant downtime, negatively impacting production quality and capacity while increasing operational costs. This traditional method, though widely used, is no longer sufficient in the face of modern industrial demands.
e. **Countermeasures and Remediations**. The integration of big data allows for the storage and analysis of vast amounts of operational data from equipment and production lines. Patterns and anomalies can be identified early, enabling proactive decision-making. Impact: Big data analytics reduces downtime and ensures optimal production performance.

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