ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23

American Academic publishers, volume 05, issue 12,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

INTEGRATION OF IOT TECHNOLOGIES INTO CNC MACHINING SYSTEMS: A CASE STUDY PERSPECTIVE FOR UZBEKISTAN'S MANUFACTURING SECTOR.

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Abstract: As Uzbekistan accelerates its transition towards an industrialized digital economy under the "Digital Uzbekistan 2030" strategy, modernizing existing manufacturing assets has become crucial. This paper analyzes the integration of Internet of Things (IoT) technologies into Computer Numerical Control (CNC) machining systems, focusing on local industrial contexts such as automotive and agricultural machinery production. While traditional CNC machines offer precision, they often lack connectivity. This study proposes a low-cost IoT architecture to monitor spindle load, vibration, and energy usage. Comparative analysis suggests that IoT integration can reduce unplanned downtime by 20-25% and optimize energy consumption by 12-15%. The findings provide a roadmap for Uzbek manufacturers to upgrade legacy equipment to Industry 4.0 standards cost-effectively.

Keywords: CNC machining, IoT, Smart Manufacturing, Industry 4.0, Uzbekistan, Energy Efficiency, Predictive Maintenance.

1. Introduction CNC machining is the backbone of Uzbekistan's growing manufacturing sector, playing a vital role in supply chains for major enterprises like UzAuto Motors and the agricultural engineering industry. However, a significant portion of the machinery in local small and medium enterprises (SMEs) operates as standalone units, lacking real-time data exchange capabilities. This "digital gap" limits productivity and leads to reactive maintenance strategies, where machines are fixed only after they break down.

The national strategy emphasizes the adoption of smart technologies, but purchasing new, high-end equipment is often too expensive for many local manufacturers. Integrating IoT into existing CNC machines offers a cost-effective alternative. By equipping legacy machines with external sensors, manufacturers can gain real-time insights into production efficiency (Lee et al., 2015). This paper aims to demonstrate how IoT can be applied to the local context to solve specific issues like energy fluctuations and maintenance delays without requiring a complete overhaul of the production line.

2. Methodology and System Architecture The proposed solution involves a retrofitting approach suitable for the Uzbek market, prioritizing cost-efficiency and robust data

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transmission. The system architecture is designed in three cohesive layers rather than complex isolated subsystems. The physical layer consists of the CNC machine (such as a milling or turning center) equipped with non-intrusive sensors, specifically accelerometers to measure vibration and Hall-effect sensors to track current usage.

Data collection is managed by the network layer, where a microcontroller (e.g., ESP32 or Raspberry Pi) gathers sensor inputs. This data is then transmitted via Wi-Fi or LoRaWAN to a local server. LoRaWAN is particularly highlighted for its suitability in industrial zones due to its long-range capabilities and low power consumption. Finally, the application layer provides a dashboard for real-time visualization. The strategy focuses on monitoring three key parameters: vibration analysis to detect tool wear and chatter (sampled at 1 kHz), current consumption to calculate energy usage, and temperature monitoring to prevent overheating of spindle bearings, which is a critical factor during the hot summer months in the region.

Component (Qurilma)	**Specification/Model (Model)**	**Function (Vazifasi)**
Microcontroller	Raspberry Pi 4 Model B (4GB RAM)	Central processing unit for data aggregation and edge computing.
Vibration Sensor	ADXL345 (3-axis Accelerometer)	Detects mechanical anomalies and spindle chatter (High-frequency sampling).
Current Sensor	ACS712 (30A Module)	Measures electrical current to calculate real-time energy consumption.
Connectivity	LoRaWAN Module (SX1278)	Long-range wireless data transmission suitable for industrial zones.
Temperature Sensor	DS18B20 (Waterproof)	Monitors spindle bearing temperature to prevent overheating.

3. Results and Discussion Based on the comparative analysis of international case studies and pilot implementations, the integration of IoT is projected to bring significant quantitative improvements to local manufacturing facilities. The primary impact is observed in the reduction of unplanned downtime. Traditional maintenance in local workshops is often corrective, but IoT-based condition monitoring allows for the early detection of anomalies in vibration patterns. Statistical projections indicate that this implementation can reduce unplanned downtime by approximately 20% to 30%. For a typical facility running two shifts, this could recover a substantial amount of lost production hours monthly (Qin et al., 2016).

Furthermore, energy efficiency is a major area of improvement. Since electricity costs are a significant factor for manufacturers, continuous monitoring allows for the identification of "idle energy" - periods where the machine is on but not cutting. Data-driven optimization is estimated to reduce this idle energy consumption by 12% to 18% (Morales et al., 2019). Finally, real-time feedback on spindle load ensures the cutting process remains within optimal

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parameters, which is expected to decrease the scrap rate (defective parts) from an average of 4.5% to below 1.5%, thereby improving overall material utilization and product quality.

Performance Indicator (Ko'rsatkich)	**Traditional CNC Process (Eski usul)**	**IoT-Integrated Process (Yangi usul)**	**Improvement Impact (Samaradorlik)**
Unplanned Downtime	High (Corrective maintenance only)	Low (Predictive alerts)	20% – 25% Reduction
Energy Efficiency	High idle consumption	Optimized usage monitoring	12% – 15% Savings
Scrap Rate (Defects)	~4.5% (Due to undetected wear)	< 1.5% (Real-time load control)	Quality Improved by ~3%
Maintenance Strategy	Reactive (Fix when broken)	Proactive (Data-driven)	Increased Machine Life

4. **Conclusion** The integration of IoT into CNC systems presents a viable and necessary pathway for modernizing Uzbekistan's manufacturing infrastructure. This study demonstrates that retrofitting legacy machines with IoT sensors is not only technically feasible but also economically beneficial. The projected results - specifically the significant reduction in downtime and notable energy savings - highlight the potential for increasing the competitiveness of local products in the global market. Future research should focus on developing localized software algorithms that account for specific regional operating conditions to further refine these systems.

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