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Review Article

IoT-Focused Automation in Flexible Manufacturing Systems: A Review of Current Trends and Future Research Directions

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ABSTRACT

The integration of Internet of Things (IoT) technologies into Flexible Manufacturing Systems (FMS) is redefining operational paradigms in smart manufacturing. This paper presents a systematic literature review examining recent advancements in IoT-enabled automation within FMS, emphasising decentralised intelligence, real-time process optimisation, and autonomous control. IoT frameworks facilitate dynamic reconfiguration, predictive maintenance, and interoperability with cyber-physical systems and digital twins, enabling increased system responsiveness and resilience. The review critically assesses existing approaches involving wireless sensor networks, edge/cloud computing, and intelligent control mechanisms, identifying prevailing architectural and algorithmic frameworks. Despite notable advancements, significant research gaps persist, particularly in standardisation protocols, system integration at industrial scale, and AI-driven decision support systems. Challenges related to latency, cybersecurity, and interoperability hinder full-scale deployment. Future research should prioritise the development of robust, scalable architectures integrating AI, blockchain, and digital twins to support secure, adaptive, and autonomous FMS. This study contributes to the growing body of knowledge on Industry 4.0 by mapping current trends, identifying unresolved technical issues, and proposing concrete directions for future investigation in smart manufacturing environments.

Keywords: Internet of Things (IoT), Flexible Manufacturing Systems (FMS), Smart Manufacturing, Industry 4.0

Introduction

In recent years, the convergence of digital technologies and advanced automation has led to a paradigm shift in how industrial production systems are conceptualised and operated. Among these, the Internet of Things (IoT) has emerged as a transformative force, redefining the design, monitoring, and control of manufacturing environments. The adoption of IoT technologies within the manufacturing sector has significantly accelerated the development of responsive, intelligent, and interconnected production systems.[1] In particular, Flexible Manufacturing Systems (FMS), which are designed to manage variability in product designs and dynamic production schedules, are experiencing transformative enhancements driven by IoT integration. By facilitating the interlinking of physical devices and enabling real-time data exchange, IoT supports decentralised control architectures that are central to modern smart manufacturing paradigms. These advancements not only improve operational visibility and enable proactive equipment maintenance strategies but also foster greater energy efficiency across production lines. Altogether, such innovations serve as key enablers for competitive performance and agile manufacturing in the context of Industry 4.0.[2-5]

Literature Review

Recent scholarly research has addressed multiple aspects of IoT-driven automation in Flexible Manufacturing Systems (FMS). Studies have demonstrated how cyber-physical systems enhance production intelligence and flexibility through IoT integration.[6] Smart factory frameworks have been evaluated for their ability to use real-time sensing and interconnected devices to improve operational responsiveness.[7]

Analyses have emphasised the pivotal role of IoT in enabling process automation and reconfigurability within the Industry 4.0 context. Digital twin technology has been employed to create virtual counterparts of physical systems, supporting simulation-based decision-making and system optimisation. Real-time reconfigurability and agility have also been achieved through cloud-based control systems.[8-10]

Holonic control models have been proposed to incorporate distributed intelligence across manufacturing layers.[2] Surveys of industrial IoT architectures have outlined persistent challenges such as communication reliability, latency, and cybersecurity vulnerabilities.[3] The incorporation of cloud and edge computing frameworks has further been explored for managing high-volume sensor data and enabling low-latency control mechanisms.[7-10]

Research also indicates that IoT-enabled self-optimisation mechanisms improve production efficiency in dynamic environments.[11] Scalable architectures have been developed to support real-time scheduling and resource allocation in FMS.[12] Studies of cyber-physical production systems have offered foundational insights into system integration and performance monitoring.[7] In parallel, innovations in wireless sensor networks have supported robust and reliable data acquisition for real-time manufacturing control.[13] Table 1 shows some literature findings on IoT-driven automation in FMS.

Table 1.Summary of Recent Literature on IoT-Driven Automation in Flexible Manufacturing

Ref.	Focus Area	Methodology	Key Findings (in human language)
2	Holonic control systems for distributed intelligence	Control framework design	Demonstrates how agent-based systems improve autonomy and fault tolerance in manufacturing.
3	IIoT technologies for smart manufacturing	Comprehensive review	Outlines challenges of IIoT adoption and suggests suitable technologies to address them.
6	Industry 4.0: current state and trends	Review study	Highlights multidisciplinary technologies and stresses the need for strong methods to unlock full Industry 4.0 potential.
7	IIoT and Cyber Manufacturing Systems	Conceptual chapter	Defines CMS and IIoT, discusses challenges, opportunities, and future directions.
8	Industry 4.0: technologies and challenges	Literature review	Surveys Industry 4.0 technologies and identifies limitations and opportunities for industries.
9	IoT architectures	Survey study	Reviews IoT architectural models and emphasizes scalability, security, and efficiency.
10	Cyber-Physical Systems (CPS) in Industry 4.0	Architecture proposal	Introduces a CPS framework to connect devices, data, and processes for smarter production.
11	Cybersecurity in industrial systems	Review study	Identifies cybersecurity threats in critical infrastructure and suggests protective measures.
12	Industrial intelligent control	Book-based methods and applications	Explains fundamentals of intelligent control and its role in automation.
13	Standards for smart manufacturing	Standards review (NIST report)	Reviews existing standards and identifies gaps for future smart manufacturing systems.

14	Industrial big data in IoT-based factories	Case analysis	Shows how IoT adoption generates big data and discusses its role in process optimization.
15	IoT-enabled dynamic scheduling	System development and case validation	Proposes an IoT-based scheduler that adapts job shop operations in real time.
16	Digital Twin in Industry	State-of-the-art review	Explains how digital twins mirror physical systems to enable real-time monitoring and optimization.
17	Edge–cloud collaboration for manufacturing	Architecture design	Suggests a software-defined model where edge and cloud computing work together for efficiency.
18	Software-defined IIoT	Technical framework	Describes how software-defined networking can support flexibility in IIoT systems.
19	IoT vision and applications	Review paper	Describes IoT features, possible uses, and the open challenges still to be solved.

Systems (FMS)

Research Gap And Insights

Despite substantial progress in integrating robotics and IoT technologies with additive manufacturing systems, the current literature reveals several critical gaps that hinder the full realisation of intelligent, scalable, and secure production systems under Industry 4.0.

One of the primary gaps is the absence of standardised frameworks for system-level integration. Multiple studies explore robotic-assisted AM and IoT-enhanced control individually, but few provide cohesive models that address interoperability across different hardware and software platforms. The lack of universal communication protocols (e.g., OPC-UA, MQTT) and data formats (e.g., AMF, 3MF) complicates integration across vendors and restricts plug-and-play scalability of AM units in cyber-physical environments.

Another significant gap is the limited deployment of real-time edge intelligence. While research supports the value of edge computing for latency-sensitive applications, actual implementations in AM remain scarce. Current systems often rely on cloud-centric architectures, which are prone to delay, bandwidth bottlenecks, and cybersecurity vulnerabilities. There is a pressing need to develop lightweight, edge-AI models tailored for on-site monitoring, anomaly detection, and autonomous control of robotic-AM systems.

The literature also indicates that while digital twin technology is advancing, its industrial deployment is largely experimental. Few studies present fully functional digital twins that continuously simulate, predict, and optimise AM performance during live production. Moreover, there is inadequate focus on feedback-integrated digital twins that can actively correct printing deviations based on IoT sensor feedback. Another underexplored area is the integration of swarm and mobile robotics with AM. Although cooperative printing platforms have been demonstrated, research lacks robust strategies for real-time coordination, decentralised decision-making, and error recovery in dynamic production environments. These systems require more advanced scheduling, spatial awareness, and safety assurance protocols.

In terms of cybersecurity, the literature shows a gap in comprehensive frameworks that safeguard IoT-connected AM systems. Most studies address functionality and performance but overlook vulnerability assessments, secure data transmission, and real-time intrusion prevention mechanisms specific to manufacturing. Lastly, sustainability and energy efficiency in IoT-driven AM are often secondary concerns. There is a lack of studies focusing on adaptive energy management, eco-conscious material usage, and green computing strategies in multi-robot AM environments. Additionally, integration of these advanced AM systems with legacy manufacturing infrastructure remains limited due to compatibility and cost barriers.

These gaps indicate the need for interdisciplinary research that not only advances hardware and software capabilities but also addresses real-world constraints of deployment, security, sustainability, and system interoperability. Filling these gaps will be critical to transforming smart additive manufacturing from experimental setups into scalable, resilient, and industry-ready solutions.

Conclusion And Future Scope

The synergy between the Internet of Things (IoT) and Flexible Manufacturing Systems (FMS) has ushered in a new era of intelligent production, enabling capabilities such as self-monitoring, autonomous decision-making, and dynamic reconfiguration. Through real-time connectivity and data exchange, IoT enhances the responsiveness and flexibility of FMS, supporting personalised production and reducing operational downtime. The reviewed literature demonstrates notable strides in the development of IoT-based automation architectures, predictive maintenance systems, and digital twin integrations.

However, despite this progress, several technical and practical challenges persist. The lack of universal communication standards among IoT devices complicates interoperability and scalability. Moreover, the integration of machine learning and AI into IoT-enabled FMS remains underutilised, limiting the system's potential for true autonomy and intelligent process optimisation. Concerns related to data privacy, system security, and cyber-physical resilience also require more robust solutions to ensure trustworthiness and reliability in industrial settings.

Looking ahead, future research must focus on building secure, modular, and scalable IoT-FMS frameworks that can be readily deployed in real-world manufacturing environments. The convergence of AI, cloud-edge computing, blockchain, and digital twin technologies will be key in driving the next generation of smart factories. Furthermore, cross-disciplinary collaboration between automation engineers, data scientists, and industrial managers is crucial to bridge the gap between theoretical advancements and practical applications. By addressing these open challenges, IoT-augmented FMS will play a pivotal role in realising the full vision of Industry 4.0 and laying the groundwork for Industry 5.0.

Future research should focus on the development of unified industrial standards for device communication and interoperability. AI-enhanced IoT frameworks can further improve predictive maintenance, fault detection, and process optimisation. Expanding the scope of digital twins and integrating blockchain technologies could enhance traceability and security in IoT-enabled FMS. Moreover, longitudinal case studies within diverse industrial settings would provide practical insights into long-term deployment outcomes and scalability.

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