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REVIEW ARTICLE

Survey on Edge Computing and Internet of Things for Low-latency Industrial Automation

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ABSTRACT

Edge computing and internet of things (IoT) have significantly changed the face of industrial automation, which is now able to support low-latency communication, real-time decision-making, and generally enhanced operational efficiency in smart manufacturing environments. This review delivers an in-depth survey of the research trends, the architectures, and the applications which combine the two technologies – edge and IoT – in industrial settings. Based on the examination of numerous researches, the article demonstrates how the local data processing at the edge not only lessens the congestion of the network but also increases the reliability and thus makes possible predictive maintenance, smart manufacturing, and energy optimization main contributors of industrial IoTs (IIoT) such as message queuing telemetry transport, constrained application protocol, and fog computing frameworks, and points their significance in achieving deterministic and secure industrial operations, unveils issues that have been left unsolved, such as scalability, interoperability, energy efficiency, and real-time analytics under high data loads, amid substantial progress made so far. In the end, they have a roadmap with emphasis on artificial intelligence-driven edge optimization, 6G-enabled connectivity, and environmentally friendly IIoT ecosystems as the key to unlocking not only the full potential of industry 4.0 but also the beyond.

Key words: Edge computing, industrial automation, industrial internet of things, internet of things, low-latency communication

INTRODUCTION

Industrial automation has changed various industries, which means that it has gone beyond the traditional manufacturing ones. Basically, it is the use of control systems and information technologies to reduce human intervention in the production of goods and services. Whereas mechanization gave us machines that helped the workers with their physical tasks, automation takes this idea further by drastically lessening the requirement of human beings for sensory and cognitive functions.[1,2] At present, industrial automation is moving away the control of single devices to the continuous, integrated automation solutions throughout the whole production environments.

Internet of things (IoT) means interconnection of physical devices, which are embedded with sensors and software. IoT t represents a general concept for the ability of network devices to sense and collect data from around the world. The numbers of Internet connected devices are increasing at the rapid rate.[3,4] These devices include personal computers, laptops, tablets, smart phones, personal digital assistant, and other hand-held embedded devices. The interconnected devices are also known as smart devices over the internet. IOT allows control the physical devices remotely through existing internet connection.[5,6] IOT devices can be connected to the internet and controlled from anywhere in the world, as long as there is an internet connection[7,8] such as quality of service (QoS) and environments.

Edge computing paradigms represent a significant shift in the way computation and analytics is performed by bringing them closer to the data sources. Edge environments are made up of resource-limited devices such as smartphones, wearables, single-board computers, routers, and switches, as well as moderately capable resources such as base stations and local networks. These systems cut down the reliance on centralized cloud

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servers by executing the initial data processing at the network edge.[9,10] Cloud computing is still used as a complementary method to offer large-scale storage and advanced machine learning (ML) or optimization capabilities. Edge paradigms such as mobile edge computing and fog computing (FC) have been lithium-ion pivotal enablers for IoT-based applications in the areas of smart homes, smart grids, precision agriculture, retail automation, and connected vehicles

Industrial automation, robotics, autonomous guided vehicles (AGVs), and motion-control systems require extremely reliable and deterministic communication to be able to operate correctly and in real-time.[11,12] Data transmission delays, even if they are slight, may result in loss of efficiency, production errors, or safety hazards. Hence, IoT networks in the manufacturing industry have to be equipped with strong communication protocols that ensure very low latency, high reliability, and stable performance.[13,14] Low-latency communication makes it possible for machines, sensors, controllers, and cloud services to interact without any interruption,[15] which, in turn, leads to higher operational efficiency, less downtime, and better decision-making due to real-time analytics

Structure of the Paper

This paper is structured as follows: Section II reviews edge computing and IoT architectures and their industrial applications. Section III discusses low-latency communication and trends in industrial automation, while Section IV examines the integration of edge-IoT systems, highlighting benefits and key applications. Section V surveys recent literature on edge-IoT frameworks, and Section VI concludes with future research directions.

EDGE COMPUTING AND IOT: A CONCEPTUAL FRAMEWORK

Edge computing permits information from IoTs to be analyzed at the edge of the system before being sent to the data center or cloud. While a single device creating information can transmit it over a system effectively, issues emerge when the quantity of gadgets transmits information simultaneously increases. Not only will quality suffer because of idleness, yet the expenses in data transfer capacity can be gigantic. Edge-computing equipment and administrations help take care of this issue by being a local source for processing and storing a significant number of these frameworks. An edge gateway, for instance, can process information from an edge device, and afterward just send the important information back through the cloud, lessening transmission capacity needs.[16]

Architectures of Edge Computing

Edge computing is typically structured into a three-layered architecture, allowing seamless data processing and management between end devices and cloud infrastructure. The end layer consists of devices that generate and collect data, such as IoT sensors (temperature, motion, and environmental sensors), smartphones, drones, smart cameras, autonomous vehicles, and industrial robots. These devices transmit data to higher layers for processing. Some high- performance devices, such as smartphones and industrial robots, can perform limited local processing before sending data forward, as shown in Figure 1.

The edge layer includes edge nodes responsible for processing data closer to the source. Common edge nodes include 5G base stations, which process mobile network data before sending it to cloud servers, gateways, and routers that filter and analyze data, and local edge servers that store and process data for real-time applications.[17] This layer reduces latency, minimizes cloud dependence, and enhances security by keeping sensitive data closer to its source. In this layer, data remain at the origin hence decreasing the probability of security risks. This also allows the architecture to increase the speed and response time. While edge computing minimizes cloud reliance, certain tasks, such as deep learning model training and big data analytics, still require high-performance computing provided by cloud infrastructure.

Edge Computing in Real-life Applications

The progress of IoT year by year and the merits of edge computing are attracting a great deal of attention and are already being used in many scenes.

Face recognition system

Face recognition system that automatically recognizes a person from the digital image of

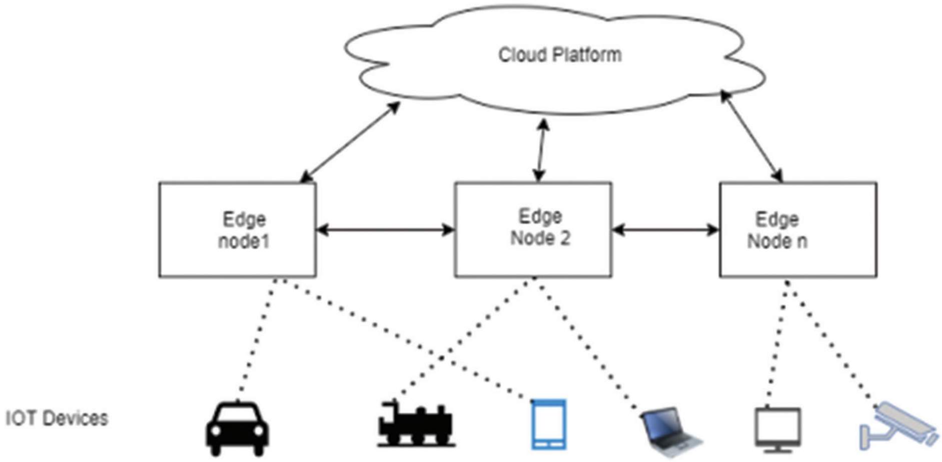

Figure 1: Edge computing architecture

the camera and has been introduced as a security enhancement such as immigration control, company entry/exit, and PC logon. Face recognition systems require high real-time performance, but the use of edge computing has made it possible to perform high-speed authentication.

Wearable device

A wearable device can be worn on the part of the body, such as the head, wrists, or ankles. Since it can be worn such as glasses or a wristwatch, it is used in fields such as health management, medical fields, and industry. Besides, smart watches can be used in conjunction with smartphones act as wearable devices and are becoming consumers as edge computing that utilizes mobile devices.

Human behavior analysis service

As the face recognition system, the wearable device is a mechanism that performs image processing of face recognition at the edge part and analyses it in cooperation with the data on the cloud. Wearable devices can predict and track the movement of a person extracted from camera images the analysis data of the tracking is processed in the temporary memory of the computer. For each camera, and besides a flow line of people, it is used for the analysis of purchasing behavior at retail stores.

Edge computing as the savior of the IoT era

In modern times, vast amounts of data are stored in cloud and processed on the cloud, such as the spread of IoT, digitization, diversification of data, and quality improvement.[18] However, the amount of data is increasing the processing on the cloud that cannot be completed in time, and scalability problems (delay in data processing) will occur. Meanwhile, edge computing, which distributes communication traffic, come to be used, Therefore, edge computers can be said to be the savior of the IoT era and will increase the value of big data.

Deploying Edge Computing in Industrial IOT (IIOT)

The Industrial Internet of Things (IIoT) system consists of a large number of heterogeneous node devices interconnected through diverse communication networks, including sensor networks, wireless Wi-Fi networks, mobile communication networks (3G/4G/LTE/5G), and dedicated industrial buses. A large number of distributed heterogeneous industrial devices form an edge network, collecting industrial data in real time, and transmitting it to the cloud server for computing and control.[19] With the development of IIoT, the scale of such networks is becoming larger, and traditional cloud data center networks struggle to satisfy the real-time, security, and reliability requirements of IIoT for massive data trans-mission and processing. For example, in a smart factory, a large number of production devices collect a large of sensory data, sometimes the data volume gets the level of GB per second.

LOW-LATENCY INDUSTRIAL AUTOMATION

Low-latency communication plays a key role in ensuring the success of IoT applications, particularly in industrial automation, robotics, and control systems.[20] In applications such as robotic assembly lines, AGVs, and industrial motion control, even minor delays in data transmission can lead to significant inefficiencies, operational failures, or safety hazards. Therefore, IoT networks require robust communication protocols that offer minimal delay, high reliability, and deterministic performance to meet the stringent requirements of industrial environments.

Recent Trends A. Emerging Trends in Industrial Automations

The industry has undergone three revolutions: Mechanization, electrification, and information. The fourth industrial revolution (also referred to as "Industry 4.0"), currently underway, is marked by the pervasive deployment of IoT devices and services. In this revolution, a wide range of devices are being deployed in a self-organizing manner, typically relying on control and communication systems to manage their operation and interaction. For example, in supervisory control and data acquisition systems, proprietary communication systems have been mostly replaced by sensorbus and fieldbus systems, they share similarities in terms of physical and logical organization complexity. In addition, they share common requirements for determinism, reliability, interoperability, and traffic convergence.

Timing and determinism

Industrial automation typically runs real-time applications with stringent requirements on their temporal behavior and accuracy when responding to internal and external events. Beyond network throughput, the commonly used performance metrics, packet transmission latency, and its time variations (jitter) are critical concerns for many industrial control systems. These factors accumulate non-deterministic delays in data transmission, which are unsuitable for real-time industrial applications. Therefore, to ensure correct operation, industrial automation systems require a certain degree of determinism.

Reliability and availability

Production losses in industrial automation due to unexpected stops caused by failures or deterioration of the communication environment are unacceptable. Therefore, the reliability and availability of the system are critically important to ensure accurate and continuous operation under all conditions. Reliability can be quantified using appropriate metrics, such as mean time between failures (MTBF) or the probability of no failure within a specified period.

Interoperability

Interoperability is crucial for industrial automation due to its many advantages. For example. By enabling seamless communication and coordination between various systems, businesses can experience enhanced accuracy and productivity. Real-time data exchange and coordinated control across the entire automation system also facilitate efficient decision-making, reducing errors, and delays. Interoperability also improves scalability and flexibility, allowing for easier system expansion and modification.

Traffic convergence

Industrial automation applications make use of different traffic types for different functionalities, for example, sensing, control, alarming, and the like.[21] The diverse traffic types have different characteristics and thus impose varied QoS requirements. The traffic can generally be classified into critical traffic and best-effort traffic. Critical traffic typically has stringent QoS requirements, and different types of critical traffic may have particular QoS demands depending on the specific application scenarios.

Common B. Communication Technologies Used in Industrial Automation Applications

Industrial automation applications heavily rely on wired fieldbus standards as the existing wireless technologies have still not been able to provide stringent guarantees on the QoS metrics. Fieldbus standards currently used in industrial automation include PROFINET, SERCOS, HART and CAN standards.[22] The use of wireless technologies in automation industries has mainly been limited to monitoring purposes. In recent years, automation industry has slowly started to investigate wireless technologies even for tight closed loop control applications. Several initiatives have been taken recently to pave the way for promoting wireless Besides these wireless technologies, many proprietary radio stack implementations are also actively being used. Lack of globally acceptable standards and application programming interfaces limit the interoperability and extensibility of currently used automation devices. Furthermore, wireless technologies currently used in industrial applications are unable to satisfy the stringent reliability and latency requirements. Coexistence features and regulatory constraints used by these technologies (e.g., listen-before-talk, radio duty cycle restrictions, and transmit power limitations) have the downside of non-deterministic medium access and low coverage technologies for industrial automation.

System C. System Architecture for Process industrial Automation

The automation industry has been centered on a five layer hierarchical architecture for years; a commonly used architecture model is the five level purdue reference model, which later formed the basis for the ISA-95 standard. The model is typically expressed as levels from highest to the lowest one: business systems, plant (enterprise resource planning [ERP], material requirements planning, and manufacturing execution systems [MES]), operation unit level, machine/process automation, controller level, and sensor/actuator level.[23] In many industrial visions, the traditional automation pyramid, structurally separating hierarchical levels, has come to its end. IIoT/Industry 4.0 in Process Industry environment can be considered to include the following main elements: The digital automation systems themselves, smart equipment, and the Internet-based cloud-borne technology. The platform connects the sensors, actuators, controllers, robots, etc., to computational capabilities. To enable handling of the dynamic engineering processes, it is necessary to connect the existing factory automation systems with ERP and MES over the IoT infrastructure.

INTEGRATION OF EDGE COMPUTING AND IOT FOR INDUSTRIAL AUTOMATION

With the advanced development of the IoT technology, there have been certain paradigm changes in various sectors of the world, particularly in sectors related to automation and predictive maintenance. During the past 10 years, the prospect of the IoT to simplify the industrial processes has become the object of broader attention since it is expected to enable the capacity to observe the processes, gather data, and make an informed decision in real-time. The IoT-enabled gadgets have established themselves as the agent of the realization of high productivity, operational cost reduction, and promoted efficiency of an entire system [Figure 2]. IoT is giving the industries some of the authority to be concerned and proactive about how they manage and maintain their systems; because they will be able to know when the failures and the bottlenecks will come ahead of time before they can be actualized.

Advantages of Industrial Automation

Reduced latency

Processing data locally at the edge eliminates the time lag associated with sending data to and from a distant cloud.[24] This is critical for time-sensitive applications such as robotics, real-time control, and safety systems.

Improved operational efficiency

Faster data processing allows for real-time decision-making and immediate automated responses, leading to less downtime and greater productivity.

Enhanced security and privacy

Processing sensitive data locally reduces the need to transmit it over networks to the cloud,

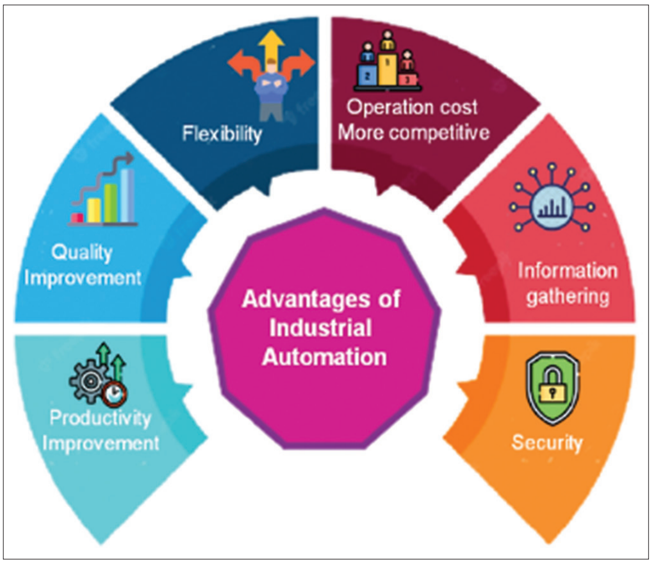

Figure 2: Architecture of the proposed ML-based risk-based authentication framework in a multi-server environment.

minimizing exposure to cyber risks. This is vital for protecting proprietary manufacturing data.

Optimized bandwidth utilization

By filtering and processing raw data at the edge, only critical information or aggregated insights are sent to the cloud. This reduces network congestion and saves on data transmission costs.

Increased reliability

Edge systems can operate autonomously even if the internet connection is interrupted, ensuring the continuity of critical production processes.

Information gathering

Using data gathering, data from many sources can be shared analyzed. The acquired data must be analyzed using smart functions to transmit alerts or triggers to other systems. IoT is used to provide fresh concepts for challenges and improve the effectiveness of the procedures.

Scalable and flexible growth

Companies can add localized processing nodes without requiring major changes to their central infrastructure. This allows for flexible growth and the easy integration of new devices.

Smart Industrial Automation Systems Using IoTs

The IIoT is a term used to describe a linked system of interrelated detectors, equipment, and other components to enhance automated industrialization. This enabled system surveillance and remote control. The primary function of IoT is to improve the industrial automation process. The IoT concept is utilized to assess, turn on, and manage various machines in the shipping, automotive, textile, agricultural, food, and beverage industries.[24] Using data gathering, data from many sources can be shared and analyzed. The acquired data must be analyzed using smart functions to transmit alerts or triggers to other systems. IoT is used to provide fresh concepts the effectiveness of the procedures. It focuses on maintaining efficient interfaces and interactions using controllers, robots, and monitors. Concepts from the IIoTs were used to improve the effectiveness digital industrialization and its role in product design. Software and IoT idea modules have been used in contemporary industrial processes. The adoption of IoT across several industrial sectors has increased exponentially over the past few decades. There may be 24 billion IoT gadgets. These gadgets create enormous amounts of data that require effective storage and processing. Increased machine-to-machine and direct-to-device connections are also a part of this process, which involves data sharing. A strong IoT standards stack that can manage all problems with data transportation and analysis at different stages is required to address this massive data expansion.

Applications of IoT in Industrial Automation

The deployment of IoT technologies in industrial automation has resulted in substantial advancements across various sectors, transforming how processes are managed and optimized. The IoT enables machines, devices, and sensors to communicate and interact in real time, creating a highly interconnected industrial ecosystem. This section examines the most significant applications of IoT in industrial automation, with a focus on predictive maintenance, smart manufacturing, supply chain management, quality control, and energy management, as shown in Figure 3.

Predictive maintenance

The most widely recognized applications of the IoT in industrial automation are predictive maintenance. Traditional maintenance strategies often involve either reactive approaches where machinery is repaired after a failure or preventive maintenance, which typically involves regular service intervals that may not align with the actual equipment needs.

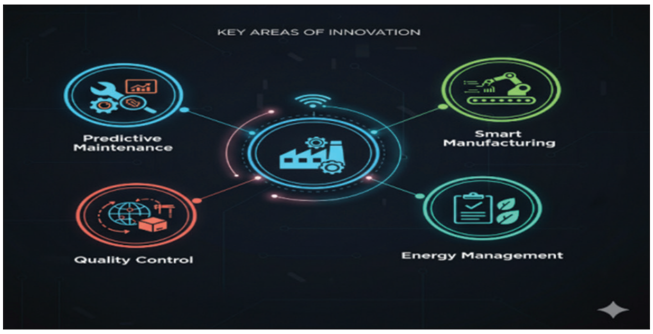

Figure 3: Applications of internet of things in industrial automation

Smart manufacturing

The IoT has also played a pivotal role in the development of smart manufacturing. In this approach, factories utilize IoT technologies to create highly automated and flexible production environments.[25] By connecting machines, sensors, and enterprise systems, the IoT enables real-time monitoring, optimization, and control of manufacturing processes.

Supply chain management

Another major application of IoT in industrial automation is supply chain management, where IoT enhances visibility and efficiency throughout the supply chain. From tracking inventory levels to optimizing logistics, IoT solutions provide real-time data that can be used to streamline processes and reduce operational costs.

Quality control

The use of IoT in quality control has emerged as a key application for ensuring that products meet stringent quality standards. In industrial settings, IoT sensors are used to perform real-time quality inspections during production, providing immediate feedback on product quality and allowing manufacturers to correct defects before products reach the final stage. This reduces the number of defective goods and minimizes waste.

Energy management

The primary concern in industrial settings is energy consumption IoT which has solutions for energy management. Connecting energy meters and sensors to a centralized IoT platform enables companies to track the actual energy usage of various machinery and processes within an industry in real-time.

LITERATURE REVIEW

This section related studies on the integration of edge computing and IoT in industrial automation and real-time systems, showcasing their roles in enhancing low-latency communication, operational efficiency, real-time decision-making, and system reliability.

Sreedevi *et al.* proposed an edge computing architecture for agricultural monitoring systems that address bandwidth constraints while maintaining real-time alerting capabilities. Traditional cloud-centric approaches to agricultural IoT often struggle with network, particularly in rural environments with unreliable connectivity. Node-RED is used as an edge processing platform to filter, aggregate, and selectively transmit sensor data from temperature, soil moisture, and humidity sensors, demonstrating the practical value of edge computing for making smart farming technologies more accessible and cost-effective, particularly in regions with limited connectivity options.[26]

Ebadinezhad *et al.*, the design and performance message queuing telemetry transport (MQTT) and constrained application protocol (CoAP) protocols of IoT that ensures low latency illustrate the performance, these protocols concerning key performance indicators that include latency, power consumption, and reliability makes theoretical analysis conducting hands-on experiments on the test-bed environment, including tools for the simulation of real-world scenario software. The results show that CoAP is more suitable for applications that require minimum latency, while MQTT provides better reliability in message delivery.[27]

Kotha *et al.* investigate the integration of dynamic customer relationship management (CRM) and Power Automate within the framework of the IIoT and data analytics. We investigate how IIoT-driven data collection and analytics can enhance CRM systems through automation, enabling businesses to achieve personalized customer interactions, predictive analytics, and operational efficiency. By leveraging power automate, organizations can streamline workflows, automate repetitive tasks, and integrate IIoT data into CRM systems for real-time decision-making.[28]

Mishra and Sealy present an integrated framework leveraging the latest advancements in industrial automation, particularly focusing on the synthesis of programmable logic controllers (PLCs), human–machine interfaces, the IoT, and the IIoT within a Docker container environment. It emphasizes the transformative impact of technologies such as the MQTT protocol, Docker containers, and digital twins, on enhancing efficiency, industrial automation, mechanical devices to sophisticated PLCs and the integration of cutting-edge IoT devices, a framework event-driven interactions, operational efficiency through the use of MQTT for efficient system communication, and Docker for application scalability and portability.[29]

Eleftherios *et al*., this paper examines the convergence of Mining 4.0 and mining digitization, with a specific emphasis on the pivotal role that remote sensing, edge computing, and decentralized communication systems play in data transmission and real-time monitoring in light of enhancing mining operations' safety and efficiency puts forward a European solution based on open standards and tools, revolving around an IIoT gateway that is a core component of the proposed communication system. This gateway will function as an intermediary between the edge and cloud-based platforms and will facilitate real-time monitoring through the establishment of resilient wireless communication.[30]

Raman and Halam embedded sensor network architecture, implementation, and prospective applications in smart industrial automation and control systems. It examines sensors, data processing, and communication protocols that enable industrial sensor integration network scalability, energy efficiency, data dependability, and current solutions and research directions. In addition, integrated sensor networks are changing industrial automation and control systems. It enables continuous checking, foresight support, and flexible control. These networks use cutting-edge ML and analytics algorithms to maximize system performance, resource usage, and intelligent decision-making. This page presents embedded sensor network case studies and examples from many industrial domains.[31]

Forsström and Lindqvist explore a solution using FC and IoT technologies to address the potential of combining scalable distributed systems technologies for enabling a distributed cluster using lightweight IoT devices. The study answers research questions related to the expected overhead, as well as how workload and chunk size affect computational time and system scalability. This is done to evaluate the performance and potential of the proposed technology for Industry 5.0 and future IIoT applications. The results demonstrate significant potential for the approach; however, the authors also identify necessary improvements required to achieve performance superiority over traditional cloud-based approaches and to enable widespread adoption.[32]

Table 1 provides a summary of edge computing and IoT-enabled frameworks for industrial automation and real-time applications, highlighting the study focus, proposed approaches, key findings,

Table 1: Comparative analysis of edge computing and IoT-enabled frameworks for industrial automation and real-time systems

Reference	Study on	Approach	Key findings	Challenges/ Limitations	Future directions
Sreedevi *et al*., (2025)	Edge computing architecture for agricultural monitoring	Node-RED-based edge processing to filter and transmit IoT sensor data	Reduces bandwidth use and enables real-time alerts even in low-connectivity areas	Limited scalability for large-scale IoT networks	Extend framework to multi-node edge networks with adaptive load balancing
Ebadinezhad *et al*., (2025)	Low-latency communication using MQTT and CoAP protocols	Experimental comparison on test-bed with latency and power metrics	CoAP offers lower latency; MQTT offers higher reliability	Protocol efficiency may vary with hardware and topology	Hybrid protocol frameworks integrating adaptive switching
Kotha *et al*., (2025)	IIoT-driven CRM integration with Power Automate	Real-time analytics and automation through IIoT data pipelines	Enhances decision-making and customer personalization	Dependent on cloud-edge coordination	Apply ML-based orchestration for predictive automation
Mishra and Sealy, (2024)	Integrated IIoT framework with Docker and MQTT	Container-based IIoT deployment for real-time automation	Improves scalability, portability, and real-time data exchange	Requires skilled setup and orchestration	Edge containerization with AI-based optimization
Eleftherios *et al*., (2024)	Edge computing in Mining 4.0	IIoT Gateway for decentralized communication	Ensures real-time monitoring and system resilience	High energy consumption in continuous edge operations	Incorporate renewable energy-aware edge systems
Raman and Halam, (2023)	Embedded sensor networks for industrial control	Integrated sensors and ML for predictive automation	Improves monitoring, resource use, and decision support	High computational demand for complex ML models	Edge-AI model compression and lightweight inference
Forsström and Lindqvist, (2023)	Fog computing framework for distributed IoT systems	Distributed clusters with lightweight IoT devices	Achieves scalability and reduced latency	Requires performance tuning for high-load systems	Optimize fog-edge collaboration with 6G integration

IoT: Internet of things, IIoT: Industrial internet of things, CRM: Customer relationship management, CoAP: Constrained application protocol, MQTT: Message queuing telemetry transport, AI: Artificial intelligence, ML: Machine learning identified challenges or limitations, and suggested future research directions.

CONCLUSION AND FUTURE WORK

Edge computing and the IoT are a major step toward achieving fast, smart, and self-sufficient industrial automation. When computational tasks are decentralized and data are processed closer to the source, edge-IoT systems have a great impact on the reduction of network congestion, enhancement of response time, and enabling of real-time decision-making which is absolutely necessary for any kind of industrial operations nowadays. This review has been focused on the current frameworks, architectures, and applications that exemplify how industrial systems powered by the edge can become not only more efficient and scalable but also secure in a wide range of sectors such as manufacturing, energy, and logistics. However, on top of these benefits, there are still issues to be solved such as interoperability problems, data privacy concerns, insufficient computing power at the edge, and the requirement for standardized frameworks which can facilitate the deployment of the edge at a large scale. Further studies may consider embedding AI and ML capabilities at the edge to enable predictive maintenance, adaptive control, and self-governing operations. Besides, the fusion of 6G connectivity and federated learning could speed up local analytics and collaborative intelligence among distributed nodes. Moreover, it would be vital to create energy-saving and eco-friendly edge architectures to cohere with the environment while ensuring performance. In addition, there should be a focus on facilitating secure data exchange using blockchain and privacy-enhancing technologies. Tackling these issues will be the stepping stones toward Industry 5.0, which will be characterized by smart, resilient, and human-centric industrial ecosystems.

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