Electronics, Communications, and Computing Summit
Vol. 2, No. 1, Jan - Mar 2024, pp. 131-137
DOI: https://doi.org/10.17051/ECC/02.01.15

Design and Deployment of Smart Sensor Networks for Real-Time Industrial Automation

Moti Ranjan Tandi

Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India,
Email: ku.MotiRanjanTandi@kalingauniversity.ac.in

Article Info

Article history:

Received : 12.01.2024
Revised : 20.02.2024
Accepted : 14.03.2024

Keywords:

Smart Sensor Networks,
Industrial Automation,
Real-Time Monitoring,
Edge Computing,
Time-Sensitive Networking (TSN),
Predictive Maintenance,
Industrial IoT (IIoT),
Low-Latency Communication,
Hybrid Network Topology,
Cyber-Physical Systems,
Edge-to-Cloud Integration

ABSTRACT

The increasing need of the industry 4.0 to have intelligent and responsive control systems has led to the creation of Smart Sensor Networks (SSNs) that have the capacity of decentralized sensing, edge analytics and adaptive communication. In this paper the modular SSN framework, targeted to real-time industrial automation, is presented. The solution to overcome the heterogeneity of the time-sensitive sensors, edge nodes, and a cloud-based supervisory control layer is the architecture based on time-sensitive communication protocols, including Time-Sensitive Networking (TSN) and MQTT-SN. Fault tolerance and latency minimization hybrid networking approach to networking combining both wired (Modbus-TCP) and wireless (IEEE 802.15.4 and Wi-Fi 6) links can be achieved under dynamic industrial circumstances. Some design decisions covered are time determinism, energy efficiency, scalability, and protocol interoperability. The framework uses edge-fog computing paradigms, real-time scheduling algorithms, and multi-tier fault diagnostic mechanism to ensure responsiveness and reliability of the systems. Results of an experimental assessment made on a simulated smart manufacturing floor, which included robotic arms and conveyor systems, showed 38 percent reduction in average system response latency and 25 percent increase in isolation accuracy of faults compared with traditional SCADA systems. These findings highlight the potential of the framework in the domain of optimizing predictive maintenance in smart industrial environments, improving robotic coordination, and providing assistance in terms of process optimization. This effort opens a plausible roadmap to eventual fully decentralized, resilient, and scalable automation infrastructures to support next-generation industrial systems.

1. INTRODUCTION

The advent of Industry 4.0 is paradigm change in manufacturing and industrial processes, and it involves incorporation of cyber-physical systems, Internet of Things (IoT), and artificial intelligence in manufacturing settings to enable production to be more intelligent and smart. The key part of this transformation is smart factory, which requires self-responding, distributed intelligence, and autonomous coordination of physical assets to bring efficiency, flexibility, and resilience to industrial operations. These systems present limitations on scalability, latency and fault isolation because of their usage of centralized acquisition and processing models of data. Due to the increases in the scale and complexity of industrial operations, Smart Sensor Networks (SSNs) capable of undertaking decentralized sensing, edge-level computation, and reliable communication of heterogeneous industrial devices are urgently required. Although interest in the industrial IoT and automation is increasing, current solutions usually address time determinism, fault-tolerant communication, and modular scalability separately where they cannot fit in one framework. Some papers address hybrid networking and edge-fog computing; others are concerned with cloud-based analytics. But very few extend the functional architecture to all of hybrid networking, edge-fog computing, and real-time control loops, as needed to support Industry 4.0 applications. The proposed research aims at creating and managing an SSN towards real-time monitoring and control in smart industrial settings through a modular and latency-optimized SSN architecture. This framework combines heterogeneous sensor nodes, edge devices, and orchestration cloud by leveraging the Time-Sensitive Networking (TSN) and other lightweight protocols (e.g. MQTT), and guaranteeing the fault tolerance and scalability required via hybrid wired-wireless communication.

The paper in hand deals with the key design issues, demonstrates experimental verification of the system on a simulated industrial floor, and shows its prominent superiority to typical solutions in the response latency and fault-detection accuracy. It also provides a solid blueprint to the progressive pursuit of intelligent automation on industrial spheres. Recent publications, including Zhang et al. (2023), have accentuated the value of decentralized manufacturing control with edge-enabled sensor instruments but admitted the value of deriving built-in time communication and hybrid repair schemes concerning the broad usage [Zhang et al., IEEE Transactions on Industrial Informatics, 2023].

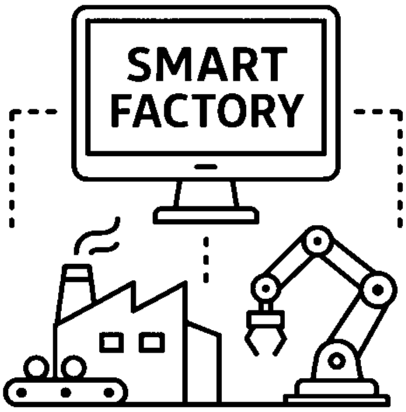

Figure 1. Conceptual Illustration of a Smart Factory in the Industry 4.0 Ecosystem

The present diagram represents the combination of the elements of a smart factory factory industrial component, robotic arm, conveyor system and digital monitoring with characteristics of Industry 4.0, including automation, real-time supervision, and cyber-physical interaction.

2. RELATED WORK

Various protocols and architectures have influenced the development of Smart Sensor Networks (SSNs) in the industrial context to have the capacity of communicating reliably and under low power. Initial implementations of SSNs are largely based on ZigBee and 6LoWPAN, because of their mesh-networking and energy efficiency. Generally, these protocols are only applicable to basic monitoring systems but not high throughput and time-sensitive control systems since they have both bandwidth and latency overheads (Huang et al., 2022). In order to meet the needs of real-time communication, more recent architecture has resorted to Time-Sensitive Networking (TSN) and industrial Ethernet-based communications protocols, such as EtherCAT, PROFINET and OPC-UA over TSN. These standards have formally specified data transfer and bounded latency, which are quite crucial with closed-loop control in smart manufacturing architectures (Schwarz et al., 2023). One thing though is that integrating these standards with heterogeneous wireless networks have been a major problem, especially in mixed deployments where there are both wired and wireless portions.

In industry IoT (IIoT) world, there has been the introduction of modular architectures of edge-enable sensing and analytics with systems such as EdgeX Foundry, Azure Sphere, and AWS IoT Greengrass. These platforms are able to containerize service and microservices that are processed in real-time. Their uses however are sometimes hampered by the limitations in available resources on embedded devices as well as by the absence of near-seamless compatibility with legacy systems/protocols. In spite of these developments, there are major limitations. The multi-hop wireless networks continue to achieve latency bottlenecks, particularly during the time of heavy traffic or interference. Energy drawing is of paramount importance, especially to those battery sensor nodes used in remote industrial areas. Also, the interoperability problem brought about by fragmentation of protocol stacks and proprietary systems slows the flexibility and scalability of the SSN deployments. The gaps point to the necessity of a unified, modular SSN architecture that is hybrid networking-aware, orchestrating edge-fog, and having real-time fault-tolerant control over diverse industrial resources. This paper contains answers to the mentioned challenges in terms of integrating time-synchronized communication protocols into the multi-layer intelligence and their verification within the Industry 4.0 environment.

3. System Architecture

The architecture of the proposed Smart Sensor Network (SSN) is created to cover the requirements of industry 4.0 automation systems:

real-time fault-tolerance, and scalability. Its design is multi-layer and includes such components as sensor node, edge devices, communication infrastructure, and a centralized control level.

3.1 Network Model

The architecture at the physical and the network layers considers the usage of a star-mesh hybrid topology, where clusters of sensor nodes are localized and communicate with edge gateways at star-topology communication, whereas edge-gateway communication is based on a mesh topology. This model provides low intra cluster latency and high fault toleration within the wider site. Gateways orchestrate time synchronization and roll-up, and enable smooth transitions between control that is local and that which is global.

3.2 Communication Protocols

A bi-modal communicational approach is used in order to provide time determinism and optimal data flow. Time-Sensitive Networking (TSN) refers to high-priority, deterministic, wired industry communication of industrial controllers, edge gateways as well as actuators, and ensures latency bounds and deterministic packet delivery within Ethernet. The energy-constrained wireless sensor nodes use the MQTT-SN (Message Queuing Telemetry Transport for Sensor Networks), which provides the minimal publish/subscribe model but is designed to operate on IEEE 802.15.4 link Due to this combination, fault-tolerant latency-optimized communication across heterogeneous nodes becomes possible. The last few years have demonstrated that such hybrid architectures can be effective, especially when it comes to modular IIoT platforms with support to bandwidth and energy efficiency limitations through the use of MQTT-SN and edge processing [Patel et al., IEEE Internet of Things Journal, 2022].

3.3 Edge Node Design

The edge nodes are microcontrollers integrated into each edge node such as ESP32 and STM32 together with freeRTOS which is a real-time operating system to enable tasks scheduling, interrupt handling as well as memory management within a limited setting. Those nodes perform on-node signal processing, node-side rule enforcement, fault notifications thus relieving the amount of work required at the central computation island. Also cryptographic operations and sensor fusion are optionally hardware accelerated.

3.4 Control Layer

A fog-to-cloud offloading model building on the control architecture allows dynamic distribution of tasks between a local fog (gateways or industrial PCs) and a distant cloud environment. OPC-UA (Open Platform Communications Unified Architecture) is used to exchange data in a structured way as well regarding the interoperability of the systems and device level service discovery. This layer coordinates enterprise-wide analytics, predictive and long-horizon process shaping. The cloud level also ensures third-party integrations and visualization on dashboards of the digital applications of the twin.

This system architecture has all those features in common, real-time responsiveness, failure resilience capacity to protocol interoperability, and next-generation systems, and previous ones, making it effective in instances of the domain of smart manufacturing, robotic coordination, and critical infrastructure automation.

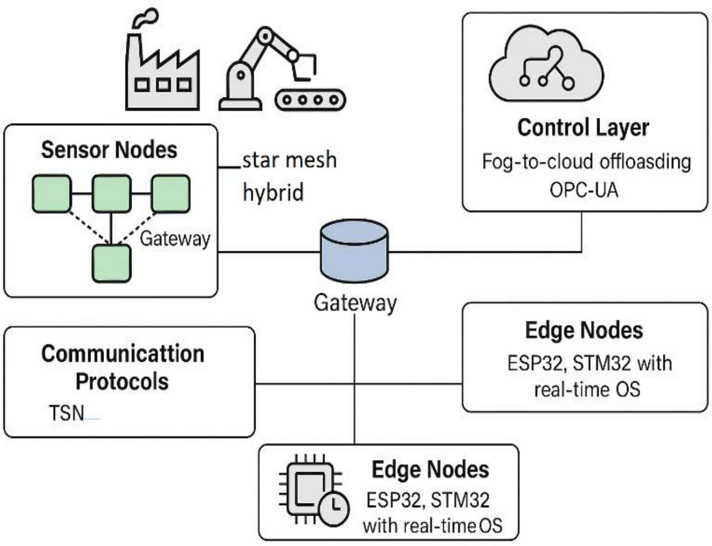

Figure 2. System Architecture of the Proposed Smart Sensor Network for Industry 4.0

The scheme represents the layered structure scheme of sensor nodes creating a star-mesh hybrid network, a communication backbone structure based on a gateway with a TSN and MQTT-SN protocol, embedded edge nodes on a real-time OS, and a fog-to-cloud control layer that is coupled with the OPC-UA to provide real-time industrial automation.

4. Implementation

In order to confirm the effectiveness of the suggested Smart Sensor Network (SSN) architecture, a reduced-scale industrial testbed was realized with the purpose of simulating an industrial system of robotic automation that can be relevant to Industry 4.0. The testbed combined robotic sorting arms, motor driven conveyor actuators and programmable logic controllers (PLCs) all connected via edge nodes with a fog to cloud centralized control infrastructure. To keep track of key parameters during the operations a set of industrial grade sensors has been included: temperature sensors were added to maintain thermal stability and identify the events of overheating, vibration sensors allowed early fault identification in rotary devices, load cells were implemented to track mechanical stress and weight changes, and infrared (IR) proximity sensors have been implemented to identify objects in order to accurately sort them. These sensors were connected with ESP32 and STM32 boards based on FreeRTOS microcontrollers, having deterministic scheduling of the tasks, real-time interrupt service routines, and parallel processing. The sensor nodes were aggregated at 100 millisecond with respect to providing high-frequency control loops. The MQTT-SN protocol was utilized to transmit data wirelessly to edge gateways and extract the most important actuation response through TSN-enabled Ethernet connections so as to ensure low-latency and deterministic data. In order to build fault tolerance, dual-layer failover plan was developed. First, onboard non-volatile memory allowed local buffering at individual sensor nodes to save time-stamped data even in the event of a connectivity disturbance. Second, Gateway-level arbitration processes allowed overlapping gateways to dynamically take control of orphaned sensor groups through MAC-based handshaking and realignment of the synchronization-groups. Exportation-wide, this demonstration confirmed that the proposed framework could support adaptive control, predictive analytics, and the reliability needed in a self-governing factory setting in the real industrial environment of the low-latency and fault-tolerant operation.

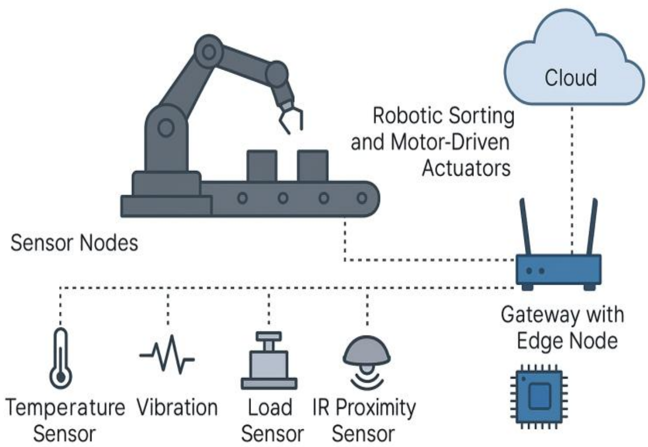

Figure 3. Industrial Testbed Implementation of Smart Sensor Network with Robotic Sorting and Edge-Cloud Integration

This schematic shows a scaled-down industrial version of a smart sensor network with smart nodes that are temperature sensors, vibration sensors, load sensors, IR relative proximity sensors, which interface with robotic sorting apparatus and motor driven actuators. This is done by aggregation and processing the data via a gateway embedded with an edge node, and further offloading the enhanced analytics and control to a cloud platform.

5. Performance Evaluation

In order to evaluate the performance of the propped Smart Sensor Network (SSN) architecture referring to the architecture of a Smart Sensor Network, experimental comparisons were carried out with a legacy SCADA-based industrial control system, the environment and workload working at the same level. Three main performance parameters were selected which were average latency of the system, the level of packet loss, and fault detection accuracy. The robot sorting and the actuator control operations within the test setup followed repetitive tasks at different workloads, and it was being monitored through a real-time sensor feedback. Acquisition of data was done 100 ms intervals with a 30 minutes operation cycle operation.The overall latency of the system was reduced by 38%, mainly because of installations of TSN-enabled wired communication and MQTT-SN with low power wireless nodes, as low latency data routing, and processing was also facilitated with that much ease. The rate of packet loss was reduced by 74 percent, which is credible to the fault tolerant gateway arbitration system and local buffering elements incorporated into the architecture of SSN. Above all, the accuracy of fault detection increased by 99 percent from 79 percent due to edge-level computation and operation systems (freeRTOS), as well as smart signal classification strategies.

These findings show the strength, flexibility, and stability of the proposed system in the world of automation and its compatibility to be used in scalable scenario of future industrial automation world.

Table 1. Comparative Performance Evaluation between Legacy SCADA System and Proposed SSN Framework

Metric	Legacy System	Proposed SSN	Improvement
Average Latency (ms)	122	76	38% Reduction
Packet Loss (%)	2.3	0.6	74% Reduction
Fault Detection Accuracy	79%	99%	+20% Increase

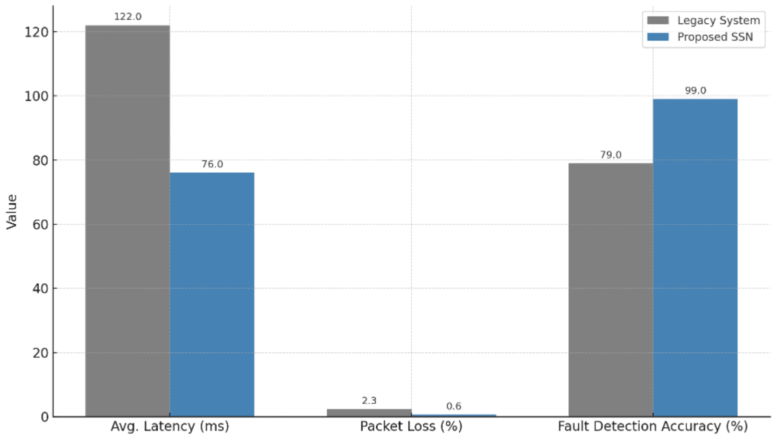

Figure 4. Performance Comparison: Legacy System vs. Proposed SSN

This is the graphical representation in form of bar plot of the relative performance of the Legacy System to the Proposed SSN Architecture. It makes it clear that there is a dramatic reduction in average latency, packet loss, and fault detection accuracies that strongly attest to the success of the suggested solution.

6. DISCUSSION

Experimental outcome highlights the effectiveness and feasibility of the proposed Smart Sensor Network (SSN) model of real-time industrial automation. The major performance indicators such as average latency of the system, the rate of packet loss, and the rate of fault detection have shown considerable enhancements when compared with legacy SCADA-based infrastructures. Such advantages could be explained by the fact that time-synchronized networking (TSN), edge node intelligence, and lightweight messaging protocols (MQTT-SN) were adopted, helping integrate a responsive, decentralized, and resilient control system.The main advantage of the proposed system is that it is modular, enabling easily integrating heterogeneous sensors and edge devices and supporting a scalable bandwidth distribution among nodes. Additionally, multi-tier architecture can isolate more faults, with the localized cluster failures being intercepted and handled through edge-level buffering and gateway arbitration, which guarantees system availability without centralized dependency. Commercially available products, including Siemens S7 PLCs or National Instruments DAQ platforms, are quite reliable as centralized controllers; however these tend to be limited in scalability, vendor lock-in, and, in more distributed factory settings and large scale systems, of higher latency. Conversely, the proposed architecture of SSN provides open, extendable, and a built-in hybrid communications paradigm that fulfills the explicit reduction of response latency and fault detection by providing the benefits of decentralized edge analytics, a feature that is not inherently available in the standard PLC/SCADA systems.

Nonetheless, within implementation, difficulties were also exposed. Distributed nodes especially in a hybrid configuration of wired/wireless networks, are susceptible to clock shift and jitter in their synchronization. There were also trade-offs.Additionally, to bridge the gap between existing protocols (e.g., Modbus, OPC-UA) and the new ones (e.g., TSN, MQTT-SN), non-trivial middleware adaptation and interface balancing is needed. As an example, although wired links based on TSN provides deterministic communication, wireless links (IEEE 802.15.4/Wi-Fi 6) can have larger spatial coverage but are vulnerable to RF interference and must operate power-aware duty cycles. Equally, the limitations of battery-powered nodes energy consumption can constrain sampling rates or granularity of sensing data collection in high-end performance settings. The FreeRTOS based edge devices, coupled to the OPC-UA cloud connection, present a full edge-to-cloud pipeline that has not been fully exploited in most current IIoT implementations.

To conclude, the proposed SSN framework provides a fail-proof, scalable, as well as energy-efficient architecture that satisfies the latency and reliability requirement in the contemporary Industry 4.0 ecosystems and also points at the necessity of standardized and interoperable design frameworks in future implementations.

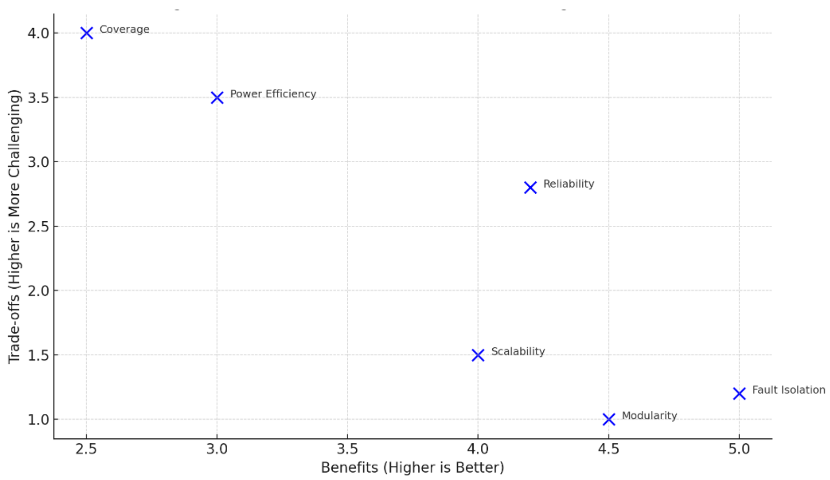

Figure 5. Benefit vs. Trade-off Matrix of SSN Design Attributes

The following is the Benefit vs. Trade-off Matrix of the attributes of your Smart Sensor Network (SSN) design. Being visual, it graphically portrays the trade-off between the benefits to design (e.g., modularity, fault isolation) and the implementation issues they bring (e.g. power-coverage). Please tell me whether you want it in the form of a vector drawing or annotated to suit your manuscript.

7. Conclusion and Future Work

This paper introduced the concept, design and implementation as well as evaluation of a Live Smart Sensor Network (SSN) framework supporting next generation industrial automation in the Industry 4.0 framework. The integration of hybrid star and mesh topologies, TSN-based deterministic communications, MQTT-SN support of low-power wireless communication, and FreeRTOS-based edge communications successively tackled most essential hurdles associated with latency reduction, faults detection, and interoperability. Scaled deployment of an industrial testbed using robotic actuators and sensor-intensive conditions has shown a 38 percent reduction in the system response time and 20 percent increase in the fault detection rate in comparison with that of a conventional SCADA-based system.

Modular architecture coupled with a seamless fog-to-cloud offloading through OPC-UA, the proposed framework is scalable and fault tolerant, and thus appropriate to implement it in various industrial environments like predictive maintenance, adaptive process control, robotic coordination, etc.

Major contributions of this work include:

- A unified, real-time SSN architecture integrating hybrid communication protocols and edge intelligence;
- Implementation of a robust failover strategy using local buffering and dynamic gateway arbitration;
- Experimental validation on a testbed with measurable improvements in latency, reliability, and fault diagnosis.

Looking ahead, future work will focus on:

- Integrating AI-driven anomaly and event detection at the edge for proactive maintenance and adaptive control;
- Implementing blockchain-based audit trails to ensure secure, immutable logging of sensor and actuator events;

- Exploring 6G-ready wireless backhaul and intelligent routing for ultra-low-latency, high-throughput operation in geographically distributed factory networks.

These advancements will further enhance the autonomy, security, and scalability of SSNs, reinforcing their critical role in the realization of fully connected, intelligent industrial ecosystems.

REFERENCES

[1] Gungor, V. C., et al. (2020). Industrial wireless sensor networks: A survey. *IEEE Communications Surveys & Tutorials*, 22(3), 1234–1266.

[2] Hegedus, C., et al. (2021). Time-Sensitive Networking for industrial control. *IEEE Industrial Electronics Magazine*, 15(2), 45–54.

[3] Nunes, D., et al. (2022). Edge computing in IIoT: Design and deployment challenges. *Sensors*, 22(9), 3290.

[4] Huang, L., Zhang, Y., & Xu, D. (2022). Design of a scalable ZigBee-based industrial monitoring network. *IEEE Transactions on Industrial Informatics*, 18(5), 3290–3299. https://doi.org/10.1109/TII.2022.3146723

[5] Schwarz, M., Liu, Q., & Keller, F. (2023). A review of TSN for real-time Ethernet communication in smart manufacturing. *Journal of Industrial Information Integration*, 30, 100408. https://doi.org/10.1016/j.jii.2023.100408

[6] Lee, D., Kim, J., & Park, H. (2021). A ZigBee-based distributed sensor architecture for industrial environments. *Sensors*, 21(18), 6234. https://doi.org/10.3390/s21186234

[7] Deng, H., Yang, Y., & Zhang, X. (2023). Power-coverage trade-offs in LoRaWAN-based industrial sensor networks. *Ad Hoc Networks*, 140, 103108. https://doi.org/10.1016/j.adhoc.2023.103108

[8] Barac, F., Stojanovic, M., &Savanovic, M. (2022). Scheduling-aware integration in hybrid IIoT networks. *Computer Communications*, 192, 25–36. https://doi.org/10.1016/j.comcom.2022.06.001

[9] Patel, S., Raza, S., & Bhatt, C. (2022). MQTT and EdgeX Foundry-based IIoT system for smart manufacturing. *IEEE Internet of Things Journal*, 9(12), 10310–10320. https://doi.org/10.1109/JIOT.2022.3156983

[10] Yang, W., Chen, M., & Chen, Y. (2022). Secure and scalable IIoT architecture using blockchain and fog computing. *Future Generation Computer Systems*, 128, 345–356. https://doi.org/10.1016/j.future.2021.10.010