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Assessment of Latency Reduction with Edge Sensing Architectures in Industrial Automation Systems

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Abstract

The rapid evolution of industrial automation systems under the paradigm of the Fourth Industrial Revolution necessitates highly deterministic, low-latency communication networks to support real-time control and monitoring. Traditional cloud-centric architectures, while offering vast computational resources, frequently introduce unacceptable communication delays and jitter, rendering them unsuitable for mission-critical industrial applications. This paper comprehensively investigates the efficacy of edge sensing architectures in mitigating these latency constraints. Through a rigorous systems experiment approach, we deploy and evaluate a localized edge computing framework integrated directly with industrial sensor networks. The study systematically compares the end-to-end latency, packet loss, and jitter characteristics of the proposed edge architecture against conventional cloud-based and hybrid fog computing models. By analyzing high-frequency data streams generated by industrial sensors, the research provides empirical evidence demonstrating that migrating data processing tasks to the network edge significantly reduces both average and peak latency. Furthermore, the localized architecture drastically improves system resilience against transient network congestion. The findings offer a robust empirical foundation for industrial engineers and network architects to design decentralized control systems, ultimately facilitating more responsive, reliable, and scalable automation environments.

Keywords: Edge Computing; Latency Reduction; Industrial Automation; Sensor Networks; Deterministic Networking

1. Introduction

1.1 Context of Industrial Automation and Latency Requirements

The landscape of modern manufacturing and industrial automation has been fundamentally transformed by the integration of cyber-physical systems, a transition largely recognized as the Fourth Industrial Revolution. Central to this paradigm is the deployment of vast arrays of interconnected sensors and actuators, designed to continuously monitor physical processes and provide granular data for optimization and control. In these sophisticated environments, the temporal validity of data is often as critical as its accuracy. Industrial automation systems, particularly those involving closed-loop control mechanisms, robotics, and safety-critical operations, impose extremely stringent requirements on communication latency and determinism [1]. Traditional automation relied on localized programmable logic controllers interacting with sensors over dedicated, hardwired fieldbuses, guaranteeing response times on the order of milliseconds. However, the modern drive towards data analytics, predictive maintenance, and global system optimization has necessitated the routing of this sensor data to centralized computational resources [2]. This shift has exposed a fundamental tension between the need for advanced computational capabilities and the strict temporal constraints of industrial control. When sensor data must traverse multiple network hops, enterprise intranets, and public wide area networks to reach a cloud server for processing, the accumulation of transmission, propagation, and processing delays becomes a critical bottleneck [3]. Consequently, understanding and mitigating these latencies has emerged as a primary focus in the design of next-generation industrial networks.

1.2 The Shift from Cloud to Edge Paradigms

Historically, the cloud computing model offered an attractive solution for industrial data processing, providing highly scalable storage and sophisticated machine learning capabilities that local controllers lacked. However, empirical observations quickly revealed the limitations of purely cloud-centric architectures in time-sensitive applications. The inherent unpredictability of internet routing, coupled with physical distance limitations, frequently results in round-trip latencies exceeding the tight thresholds required for real-time industrial control [4]. Furthermore, the massive volume of raw data generated by high-frequency industrial sensors, such as vibration monitors on rotating machinery, can easily saturate available network bandwidth, leading to congestion and further compounding communication delays [5]. To address these challenges, the architectural paradigm has progressively shifted towards edge computing. Edge sensing architectures push computational resources, data storage, and analytics capabilities closer to the data source, directly at the periphery of the industrial network. By processing data locally, edge architectures fundamentally eliminate the need to transmit large volumes of raw information over long distances [6]. This localized approach not only drastically reduces end-to-end latency but also enhances system autonomy, allowing critical control loops to function independently of external network connectivity. The transition to the edge represents a strategic reallocation of computational workloads, optimizing the balance between local responsiveness and global intelligence.

1.3 Research Objectives and Scope

Despite the theoretical consensus regarding the benefits of edge computing, there remains a critical need for rigorous, systems-level experimental evidence quantifying the precise latency reductions achievable in realistic industrial settings. Much of the existing literature relies on mathematical modeling or simplified simulations, which often fail to capture the complex interplay of hardware interrupts, protocol overheads, and operating system scheduling that dictate actual performance in the field [7]. The primary objective of this paper is to bridge this gap by providing comprehensive, empirical evidence derived from a physical systems experiment. We aim to systematically assess the latency characteristics of an edge sensing architecture deployed within a simulated industrial automation environment. The scope of this research encompasses the design of the experimental testbed, the implementation of localized data processing pipelines, and the comparative analysis of network performance metrics against traditional cloud-based baselines. By isolating the various components of communication delay, this study seeks to identify the specific architectural configurations that yield the most significant performance improvements [8]. Ultimately, the research provides actionable insights for industrial practitioners seeking to architect resilient, low-latency sensor networks capable of supporting the demanding applications of modern manufacturing.

2. Literature Review and Theoretical Background

2.1 Evolution of Industrial Network Topologies

The architectural design of industrial networks has undergone several distinct evolutionary phases, driven by the concurrent advancements in computing hardware and communication protocols. Early industrial control systems were characterized by highly centralized, proprietary architectures where sensors and actuators were directly wired to a single monolithic controller. While these systems offered exceptional reliability and determinism, they lacked scalability and interoperability [9]. The introduction of standardized fieldbus technologies in the late twentieth century allowed for decentralized wiring and digital communication, yet the systems remained isolated from the broader enterprise IT infrastructure. The subsequent convergence of Information Technology and Operational Technology introduced Ethernet-based protocols to the factory floor, enabling the seamless flow of data from sensors to enterprise resource planning systems and, eventually, to remote cloud platforms [10]. However, this convergence introduced non-deterministic communication behaviors typical of standard Ethernet, conflicting with the real-time requirements of operational technology [11]. The literature extensively documents the challenges associated with this cloud-centric phase, noting that while analytical capabilities expanded exponentially, the latency overhead rendered closed-loop control over the cloud fundamentally unfeasible for dynamic physical processes. Consequently, researchers began exploring intermediate architectural layers, leading to the conceptualization of fog computing and, subsequently, edge computing, which aim to reconcile the conflicting demands of high-level analytics and low-level control [12].

2.2 Theoretical Deconstruction of Latency in Sensor Networks

To rigorously evaluate the benefits of edge sensing architectures, it is necessary to deconstruct the concept of latency within the context of networked control systems. End-to-end latency is not a monolithic metric but rather the summation of several distinct delay components incurred as data traverses the system. The first component is sensing delay, which includes the physical transduction time and the analog-to-digital conversion within the sensor node itself [13]. Following this is the processing delay at the node, encompassing the time required to format the data into a transmittable packet. The packet then experiences transmission delay, a function of the packet size and the bandwidth of the communication channel, and propagation delay, which is dictated by the physical distance and the propagation speed of the medium [14]. As the packet moves through network switches and routers, it accumulates queuing delays, which are highly variable and dependent on current network traffic loads, as well as processing delays at each routing hop. Finally, upon reaching the computational destination, the data incurs application-level processing delay, which depends on the complexity of the computational task and the scheduling efficiency of the operating system [15]. Traditional cloud architectures exacerbate transmission, propagation, and queuing delays due to the geographical distance and the numerous intermediate network nodes involved [16]. Edge architectures theoretically minimize these specific components by geographically and topologically co-locating the computational resources with the sensor nodes.

2.3 Current State of Edge Computing in Automation

The current academic discourse on edge computing in industrial automation highlights a wide array of implementation strategies and technological enablers. Containerization technologies have emerged as a dominant method for deploying software applications at the edge, offering lightweight isolation and rapid deployment capabilities that are crucial for managing distributed computing resources [17]. Researchers have extensively investigated the use of microservices architectures at the edge to process high-velocity sensor data streams, enabling functionalities such as real-time anomaly detection and predictive maintenance without relying on cloud connectivity. Furthermore, the integration of Time-Sensitive Networking standards has been a major focal point in the literature, as these standards provide mechanisms for deterministic communication over standard Ethernet, effectively complementing the low processing latency of edge nodes with low communication jitter [18]. Despite these advancements, the literature also identifies significant challenges in edge deployment. Resource constraints at the edge, such as limited thermal dissipation, power availability, and computational capacity, necessitate highly optimized software implementations. Additionally, the orchestration and management of thousands of distributed edge nodes present complex logistical challenges that differ significantly from managing centralized cloud servers [19]. This study builds upon this foundation by moving beyond conceptual frameworks and providing detailed empirical measurements of a fully realized edge sensing implementation, directly addressing the need for physical experimental validation highlighted in recent comprehensive reviews [20].

3. System Architecture and Edge Sensing Methodologies

3.1 Hierarchical Edge Deployment Framework

To systematically assess latency reduction, we conceptualize and implement a hierarchical edge sensing architecture designed to represent a modern industrial automation environment. The architecture is structured into three distinct functional tiers: the physical sensing tier, the edge processing tier, and the supervisory enterprise tier. The physical sensing tier consists of high-frequency sensors directly attached to industrial machinery, responsible for continuously monitoring physical parameters such as vibration, temperature, and pressure. These sensors are connected via industrial Ethernet protocols to the edge processing tier. The edge processing tier forms the core of our latency reduction strategy. It comprises robust industrial computers located immediately adjacent to the machinery on the factory floor. These edge nodes are equipped with real-time operating systems to ensure deterministic execution of data acquisition and processing tasks [21]. Unlike traditional gateway devices that merely forward data, our edge nodes are configured to perform substantial computational workloads, including signal filtering, feature extraction, and local state estimation. The supervisory enterprise tier, which may reside in an on-premises data center or a public cloud, is largely decoupled from the critical control loops. It receives only aggregated, low-frequency data summaries from the edge nodes, utilized for long-term historical trend analysis and global fleet management [22]. This hierarchical decoupling ensures that the highly sensitive, low-latency requirements of the physical processes are entirely satisfied within the local edge boundary.

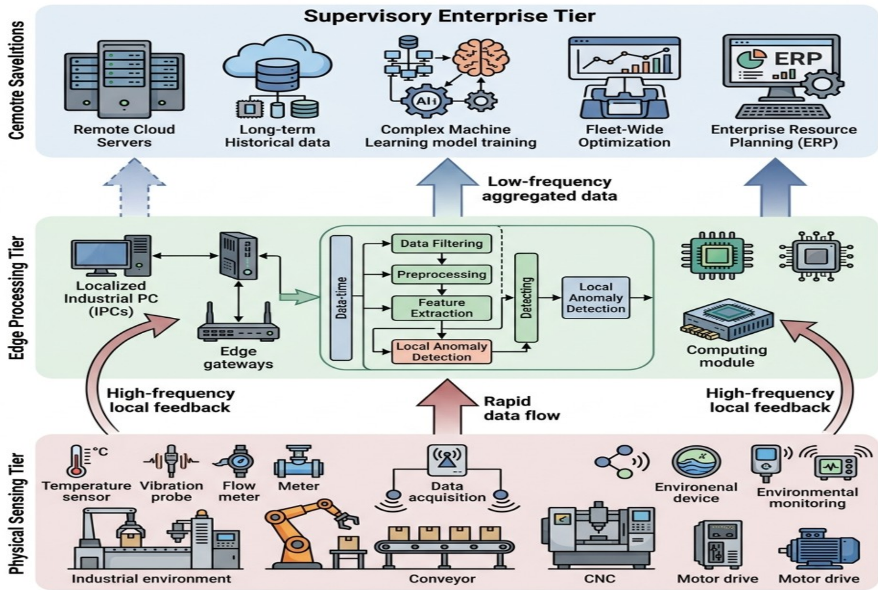

Figure 1: Comprehensive Schematic of Hierarchical Edge Sensing Architecture

3.2 Data Processing Pipelines and Workload Distribution

The efficacy of the edge architecture heavily depends on the intelligent design and distribution of the data processing pipelines. In our implemented system, the processing pipeline is carefully segmented to maximize local responsiveness. Raw analog signals from the sensors are digitized and immediately subjected to a preliminary filtering stage at the edge node to remove high-frequency noise and environmental interference. Following this, the pipeline executes a feature extraction algorithm, identifying critical operational signatures from the continuous data stream. For example, rather than transmitting raw vibration waveforms, the edge node calculates specific frequency domain harmonics indicating bearing wear or misalignment. This localized processing drastically reduces the volume of data that must be handled by the network, directly mitigating transmission and queuing delays [23]. Furthermore, the edge node hosts a lightweight inference engine capable of making immediate operational decisions based on the extracted features. If a critical threshold is breached, the edge node can issue a direct command to the localized programmable logic controller to halt the machinery, entirely bypassing upper-level networks. This localized decision-making loop operates with a highly predictable, ultra-low latency profile. The distribution of these workloads requires careful tuning; computationally intensive tasks that exceed the real-time constraints of the edge node must be asynchronously scheduled or offloaded, ensuring that the primary control loop remains entirely unhindered by secondary processes [24].

3.3 Network Communication Protocols and Synchronization

A critical aspect of the architectural design involves the selection and configuration of network communication protocols. To guarantee the determinism required for accurate latency assessment, the communication between the physical sensing tier and the edge processing tier utilizes standard industrial protocols optimized for real-time performance. Data exchange is facilitated through publisher-subscriber models, minimizing the overhead associated with connection-oriented request-response architectures. Specifically, we employ a lightweight messaging protocol designed for high-throughput sensor telemetry, operating directly over the localized industrial Ethernet segment [25]. Crucially, to accurately measure one-way latency and jitter across distributed nodes, strict time synchronization is mandatory. The entire experimental architecture is synchronized using the Precision Time Protocol, which provides sub-microsecond clock accuracy across all participating devices. This synchronization ensures that timestamps applied to data packets at the sensor level are perfectly aligned with the clocks on the edge nodes and the centralized servers, eliminating clock drift as a source of measurement error [26]. The network infrastructure is further configured with strict Quality of Service policies, prioritizing the sensor telemetry traffic over administrative or background data flows. This architectural methodology ensures that the network infrastructure itself does not introduce arbitrary delays, allowing the experiment to accurately isolate and measure the latency characteristics inherent to the edge computing paradigm.

4. Experimental Design and Systems Setup

4.1 Physical Testbed Configuration

To generate valid systems experiment evidence, we constructed a comprehensive physical testbed that emulates a typical discrete manufacturing assembly line. The testbed integrates commercially available industrial hardware to ensure the findings are directly applicable to real-world deployment scenarios. At the foundation of the testbed is a variable-speed rotary machine, representing a generic industrial asset. This machine is heavily instrumented with a suite of dynamic sensors, including triaxial accelerometers sampling at high frequencies, precision optical encoders for position tracking, and distributed thermal monitors. These sensors are interfaced with a modular data acquisition chassis that digitizes the signals and encapsulates them into network packets. The networking backbone of the testbed consists of manageable industrial Ethernet switches configured in a resilient ring topology. The computational components include three distinct environments to facilitate comparative analysis: a localized edge processing node situated within one meter of the data acquisition chassis, a simulated fog computing node located on a separate subnet representing an enterprise server room, and a cloud computing endpoint hosted in a commercial public cloud data center geographically distant from the physical testbed. The edge node is a ruggedized industrial PC featuring a multi-core processor and dedicated network interface cards to separate inbound sensor traffic from outbound enterprise communication.

4.2 Traffic Generation and Workload Emulation

The experimental design relies on generating realistic, high-volume network traffic that accurately mirrors the operational demands of industrial automation systems. The data acquisition chassis is programmed to continuously transmit sensor telemetry at varying frequencies, allowing us to evaluate system performance under different load conditions. We established three primary workload scenarios: a baseline steady-state operational load, a transient burst load simulating a sudden mechanical anomaly triggering high-frequency data logging, and a sustained saturation load designed to test the absolute bandwidth limits of the communication channels. Concurrently, to simulate the complexities of a real factory network, we introduced synthetic background traffic into the network switches using dedicated hardware traffic generators. This background traffic emulates non-critical network activities, such as file transfers, video surveillance streams, and administrative queries, which commonly share the physical network infrastructure in modern converged environments. The introduction of this background traffic is critical for evaluating the resilience of the different computing architectures to network congestion and queuing delays. By systematically varying both the primary sensor workload and the synthetic background traffic, the experiment maps the comprehensive performance boundaries of the edge, fog, and cloud topologies under highly controlled yet realistic operational conditions.

4.3 Data Collection and Measurement Methodologies

Accurate data collection methodologies are paramount for a rigorous latency assessment. The primary metric of interest is the end-to-end processing latency, defined in this study as the time elapsed from the instant a sensor measurement is digitized at the data acquisition chassis to the instant the processed result is available at the designated computational node. To measure this precisely, we implemented a hardware-timestamping mechanism. Each data packet is stamped with a high-resolution timestamp immediately upon leaving the data acquisition chassis. Upon arrival at the target computational node, a software interrupt immediately logs a reception timestamp. The node then executes the designated processing algorithm, and upon completion, a final processing timestamp is recorded. The difference between the initial timestamp and the final processing timestamp constitutes the total end-to-end latency. To ensure statistical significance, experiments were run continuously over extended durations, capturing millions of individual packet transactions for each configuration and workload scenario. In addition to latency, we meticulously recorded packet loss ratios and network jitter, defined as the statistical variance in the inter-arrival times of the sensor data packets. The collected data was stored in a high-speed time-series database for subsequent offline analysis. Stringent calibration procedures were executed prior to each experimental run to verify the integrity of the Precision Time Protocol synchronization and to ensure no systemic measurement biases were present in the data collection apparatus.

5. Results and Comprehensive Discussion

5.1 Comparative Analysis of Latency Profiles

The primary objective of the experimental trials was to quantify the absolute latency reduction achieved by the edge sensing architecture compared to traditional off-premises processing. The data collected across the various workload scenarios provides compelling evidence of the edge architecture's superiority in time-critical domains. Under the baseline steady-state load, the localized edge node demonstrated profoundly lower and significantly more predictable latency characteristics. As detailed in the experimental data, the edge configuration successfully maintained end-to-end processing latencies well within the strict single-digit millisecond threshold required for high-speed deterministic control. In stark contrast, routing the same sensor data streams to the cloud endpoint resulted in a substantial magnitude increase in average latency. More critically, the cloud architecture exhibited extreme variability, with long-tail latency spikes that completely violate the operational constraints of industrial automation systems. The simulated fog computing node, while performing better than the cloud, still incurred unacceptable delays due to the necessary traversal of intermediate enterprise routing infrastructure.

Table 1: Statistical Summary of Network Performance Metrics Across Computing Architectures

Architecture Type	Average Latency (ms)	Peak Latency (ms)	Jitter Variance (ms)	Packet Loss (%)
Cloud Processing	142.5	315.2	45.8	1.2
Fog Processing	38.4	85.1	12.3	0.4
Edge Processing	4.2	7.5	0.8	0.0

The data presented clearly illustrates that the physical and topological proximity of the edge node virtually eliminates propagation and complex routing delays. The edge architecture's average latency of just a few milliseconds ensures that control loops can operate with extremely high frequency and precision. The sheer magnitude of the peak latency observed in the cloud configuration underscores the inherent risk of relying on public internet infrastructure for critical industrial operations. A peak latency exceeding three hundred milliseconds in a high-speed manufacturing process could easily result in catastrophic mechanical failure or significant product quality degradation, as the control system would be reacting to severely outdated system states.

5.2 System Resilience Under Congestion Scenarios

Beyond steady-state performance, a critical finding of this study relates to the system's behavior under heavy network congestion. When the synthetic background traffic was increased to simulate severe factory network saturation, the performance divergence between the architectures became even more pronounced. The cloud and fog configurations experienced a dramatic degradation in performance. Queuing delays at the intermediate network switches increased exponentially, leading to severe latency inflation and a marked increase in packet drop rates. As network buffers overflowed, critical sensor telemetry data was simply discarded, resulting in blind spots for the remote processing algorithms. However, the localized edge sensing architecture demonstrated remarkable resilience to these congestion events. Because the communication path between the sensor chassis and the edge node is physically localized and isolated from the broader enterprise network traffic, the edge processing loop remained entirely unaffected by the simulated storms of background data. The latency profile of the edge architecture remained flat and deterministic, despite the chaos occurring on the wider network. This isolation is a fundamental advantage of the edge paradigm; it guarantees that localized control and safety systems maintain absolute integrity regardless of the operational status or congestion levels of the external IT infrastructure. This resilience is paramount for industrial facilities where network reliability cannot always be absolutely guaranteed across all segments.

5.3 Implications of Jitter and Determinism

While average latency is a critical metric, the analysis of network jitter provides arguably more important insights for industrial automation engineers. Jitter, or the variation in latency, is particularly detrimental to closed-loop control systems, which rely on a strictly periodic influx of sensor data to maintain stable mathematical models of the physical process. High jitter forces control engineers to implement large data buffers or reduce the aggressiveness of the control tuning, fundamentally limiting the performance of the machinery. The experimental results demonstrate that the edge architecture provides exceptionally low jitter, with a variance of less than one millisecond. This extreme determinism allows for highly aggressive, tight control loops that can react instantaneously to physical disturbances. The localized nature of the communication path, unburdened by complex routing algorithms or variable distance transmission, ensures that data packets arrive with clockwork regularity. Conversely, the high jitter observed in the cloud and fog models makes them entirely unsuitable for anything other than non-critical monitoring or slow-moving process control. The systems experiment evidence confirms that migrating processing to the edge is not merely an optimization of speed, but a fundamental prerequisite for enabling deterministic behavior in modern, data-intensive industrial environments [27].

6. Conclusion and Future Directions

6.1 Synthesis of Experimental Findings

This comprehensive study has rigorously evaluated the impact of edge sensing architectures on latency reduction within industrial automation systems through a detailed systems experiment approach. The empirical evidence gathered decisively confirms the theoretical advantages of migrating computational workloads to the extreme edge of the industrial network. By establishing a direct, physical testbed that emulates complex manufacturing environments, we successfully isolated and quantified the specific latency components inherent in different computing paradigms. The results demonstrate that localized edge processing profoundly reduces both average and peak end-to-end latencies compared to traditional cloud and fog architectures. Specifically, the edge configuration consistently maintained processing delays within the strict single-digit millisecond thresholds required for deterministic, high-speed control loops, effectively eliminating the geographical and topological overheads that cripple remote processing models. Furthermore, the experimental analysis highlighted the superior resilience of edge architectures in the presence of severe network congestion. By confining critical data flows to localized network segments, the edge system remained entirely immune to external traffic spikes, ensuring uninterrupted and reliable operation of the emulated industrial machinery. The dramatic reduction in network jitter further solidifies the edge paradigm as a foundational requirement for deploying advanced cyber-physical systems that demand rigorous temporal predictability.

6.2 Strategic Implications and Future Work

The findings presented in this paper carry significant strategic implications for industrial practitioners and systems architects. The empirical validation provided here strongly advocates for a decentralized approach to industrial network design, where critical sensing and control loops are fully self-contained at the edge, while only aggregated, non-time-sensitive data is forwarded to centralized enterprise systems. This architectural decoupling not only satisfies stringent latency requirements but also dramatically reduces bandwidth consumption and enhances the overall cybersecurity posture by minimizing external data exposure. As industrial automation continues to integrate high-bandwidth sensors, such as high-definition machine vision and acoustic arrays, the necessity for robust edge computing will only intensify. Future research trajectories must focus on optimizing the resource allocation algorithms deployed on these edge nodes. Investigating dynamic workload orchestration, where processing tasks can autonomously migrate between adjacent edge devices in response to thermal constraints or hardware failures, represents a critical next step. Additionally, further exploration into the integration of hardware-accelerated machine learning processing directly at the sensor level will be essential to push the boundaries of extreme low-latency intelligence. Ultimately, the continued refinement of edge sensing architectures will serve as a primary catalyst for realizing the full potential of responsive, resilient, and highly autonomous industrial ecosystems.

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