

EMBEDDED INTELLIGENCE: EDGE COMPUTING ARCHITECTURES FOR REAL-TIME CONTROL APPLICATIONS

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Abstract

Real-time control applications demand low-latency, reliable, and energy-efficient computational frameworks. Traditional cloud-centric architectures often fail to meet these requirements due to network-induced delays, unpredictable bandwidth, and limited adaptability under dynamic workloads. The integration of embedded intelligence within edge computing environments has emerged as a promising solution to enhance responsiveness, operational reliability, and system scalability. This research investigates edge computing architectures designed for embedded intelligence, aiming to optimize latency, throughput, and energy consumption in heterogeneous hardware configurations. Experimental and simulation-based methods were employed to evaluate performance across microcontrollers, FPGAs, and CPU/GPU nodes under varying workloads and network conditions. Data collection included latency measurements, throughput analysis, task completion times, and energy profiling. Inferential analyses, including correlation and regression models, quantified the relationship between computational capacity, responsiveness, and efficiency. A robotic manipulation case study further validated the practical application of the proposed architectures. Results indicate that adaptive, edge-enabled embedded intelligence significantly reduces latency to sub-10 millisecond levels, maintains high throughput, and ensures consistent task completion under dynamic conditions. Heterogeneous architectures outperform uniform deployments in both reliability and energy-performance balance. These findings demonstrate the feasibility and effectiveness of integrating embedded intelligence at the edge for real-time control. The study provides actionable guidance for designing scalable, robust, and energy-efficient intelligent control systems.

Keywords: Architecture, Edge Computing, Embedded Intelligence

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INTRODUCTION

Embedded intelligence has emerged as a transformative paradigm in contemporary computing systems, integrating computational capabilities directly within physical devices. The convergence of sensors, actuators, and on-device processing enables real-time perception and response in complex environments (Kondo et al., 2024). Industrial automation, autonomous vehicles, and smart infrastructures increasingly rely on distributed intelligence to enhance performance, resilience, and efficiency. Edge computing has become central to this evolution, offering a bridge between centralized cloud resources and localized, latency-sensitive applications (Khoshvagh et al., 2025).

Traditional cloud-centric architectures face inherent limitations when applied to real-time control scenarios. High latency, network congestion, and unpredictable bandwidth can impede critical decision-making processes (Wang et al., 2025). These challenges become particularly pronounced in applications requiring millisecond-level responsiveness, such as robotic manipulation, intelligent transportation systems, and adaptive manufacturing processes. Embedded intelligence, operating at the network edge, mitigates these constraints by processing data locally, reducing dependence on remote computation and enabling deterministic control outcomes (Aravamuthan et al., 2024; Satka et al., 2025).

The integration of embedded intelligence within edge computing frameworks facilitates adaptive, context-aware control strategies. Devices equipped with processing, storage, and communication capabilities can execute complex algorithms on-site, enabling rapid feedback loops (Kartsch et al., 2025). This architectural shift supports not only enhanced performance but also system robustness, energy efficiency, and scalability. By embedding intelligence directly into the operational environment, real-time control systems can achieve higher autonomy, improve reliability, and respond dynamically to evolving conditions without continuous cloud dependency (Wei et al., 2025).

Despite the promise of edge-enabled embedded intelligence, several challenges persist in realizing its full potential for real-time control applications. Designing architectures that can balance computational load, energy consumption, and latency remains a complex problem (Dintén et al., 2023). Conventional edge computing frameworks often struggle with heterogeneous hardware configurations, dynamic network conditions, and the computational intensity of advanced control algorithms (Li et al., 2024).

Current solutions frequently encounter trade-offs between system responsiveness and operational efficiency. High-performance processing units improve latency but increase power consumption and thermal stress, limiting deployment in constrained environments (Y. Chen et al., 2025). Similarly, lightweight edge devices conserve energy but may fail to meet stringent timing requirements for critical control operations. These limitations highlight the need for architectures that are both adaptive and optimized for embedded intelligence applications (Du et al., 2025).

The lack of standardized methodologies for integrating embedded intelligence within edge computing platforms further exacerbates implementation challenges (Dhatrika et al., 2025). Developers face difficulties in deploying scalable, modular, and maintainable solutions that can operate reliably under varying environmental and network conditions. Addressing these gaps is essential to ensure that real-time control applications can leverage edge computing without compromising performance, safety, or operational continuity (Y.-S. Chen et al., 2025; Zheng et al., 2025).

This research aims to investigate and develop edge computing architectures tailored for embedded intelligence in real-time control systems. The primary objective is to design frameworks that optimize latency, computational efficiency, and energy utilization while ensuring deterministic control behavior across diverse operational scenarios. The study seeks to define practical architectural guidelines that can be generalized across multiple application domains (Morchid et al., 2024; Rjoub et al., 2025).

A secondary objective is to evaluate the trade-offs between computational resources, network constraints, and algorithmic complexity in edge-enabled embedded intelligence. By analyzing performance metrics such as response time, throughput, and system reliability, the research intends to provide quantitative insights into the design and deployment of real-time control solutions. Experimental validation and simulations will form the basis for establishing robust architectural recommendations (Utsha & Morshed, 2024).

Furthermore, this study aspires to propose novel strategies for adaptive task allocation between edge nodes and centralized systems. The research will explore mechanisms for dynamic workload distribution, predictive control, and resource-aware processing to enhance system responsiveness and fault tolerance (Alwakeel, 2025). Ultimately, the goal is to contribute to a comprehensive framework for embedding intelligence within edge computing architectures that supports real-time operational excellence.

Extant literature has predominantly focused on either high-level theoretical models of edge computing or isolated implementations of embedded intelligence in specific applications (Y. Xu & Yang, 2025). Comprehensive studies integrating both perspectives for real-time control scenarios remain limited. Existing research often neglects the interplay between architectural design, computational efficiency, and real-time performance constraints (Utsha & Morshed, 2025).

Few studies systematically address the challenges of heterogeneous hardware environments, fluctuating network conditions, and real-time algorithmic demands simultaneously (Routaib et al., 2025). While advancements in edge computing and embedded systems have been documented, there is a paucity of frameworks that provide standardized solutions for latency-critical control applications. This gap impedes the broader adoption of embedded intelligence in industrial and safety-critical contexts (Shi, 2025).

Moreover, the evaluation metrics employed in prior studies frequently emphasize isolated parameters, such as throughput or energy consumption, without a holistic assessment of real-time control efficacy (Zhukabayeva et al., 2025). The absence of integrated performance analyses limits the ability to compare and generalize architectural solutions. Addressing these deficiencies requires a research approach that concurrently considers system architecture, performance trade-offs, and operational constraints (Yu et al., 2023).

This study contributes novelty by proposing an integrated edge computing architecture that embeds intelligence directly within control systems, addressing both latency and computational efficiency. Unlike prior work, the research combines architectural optimization, adaptive task allocation, and real-time performance evaluation within a single framework. This holistic approach offers new insights into the design of intelligent, responsive, and resilient systems.

The research provides justification by emphasizing the increasing demand for real-time, autonomous control applications across industrial, transportation, and healthcare domains. Embedded intelligence at the edge not only enhances system performance but also mitigates reliance on centralized cloud infrastructure. By reducing latency and improving energy efficiency, the proposed architectures are positioned to meet contemporary operational and environmental requirements.

The study's outcomes are expected to guide both academic research and practical deployment strategies in embedded intelligence and edge computing. The development of scalable, modular, and adaptive architectures will facilitate the integration of intelligent control systems in diverse contexts. Consequently, this research has the potential to advance theoretical understanding, inform design practices, and support the adoption of next-generation real-time control applications.

RESEARCH METHOD

Research Design

The study employs a mixed-methods research design, integrating both experimental and computational modeling approaches to investigate edge computing architectures for embedded intelligence in real-time control applications. Quantitative experiments are conducted to evaluate system performance metrics such as latency, throughput, and energy efficiency under various operational scenarios. Computational simulations complement the experimental study, enabling controlled manipulation of network conditions, hardware heterogeneity, and algorithmic complexity. This dual approach ensures comprehensive evaluation of architectural effectiveness, providing both empirical validation and theoretical insights into embedded intelligence deployment at the network edge (De Barrena et al., 2025).

Research Target/Subject

The research population comprises edge-enabled devices, embedded control units, and real-time application frameworks utilized in industrial and robotic environments. A representative sample of hardware platforms is selected, including heterogeneous processors, microcontrollers, and field-programmable gate arrays (FPGAs), to capture variability in computational capability and energy constraints. Software frameworks for real-time control and edge computation are also included, encompassing open-source and proprietary systems. Sampling criteria prioritize devices capable of executing low-latency control algorithms and supporting modular integration within edge computing networks, ensuring relevance to practical deployment scenarios (Mendula et al., 2025).

Research Procedure

The research procedure begins with hardware configuration and software deployment, establishing edge computing nodes and control units in a laboratory environment. Benchmarking tests are conducted to record baseline system performance under nominal conditions. Controlled experiments manipulate variables such as computational workload, network latency, and algorithmic complexity to observe performance responses. Simulation models replicate these conditions for broader scenario analysis (Lu et al., 2025). Data collection involves continuous logging of system metrics, followed by statistical and inferential analysis to determine architectural effectiveness. Validation includes cross-comparison between experimental and simulated results, ensuring robustness and generalizability of the proposed edge computing frameworks for real-time embedded intelligence applications.

Instruments, and Data Collection Techniques

Experimental instruments include network analyzers, latency measurement tools, and power consumption monitors, which quantify system responsiveness and operational efficiency. Simulation platforms are employed to model control processes under variable conditions, allowing evaluation of task allocation strategies, resource utilization, and fault tolerance mechanisms. Software tools for profiling computational load, monitoring data flow, and logging real-time system performance are utilized to ensure reproducibility and accuracy of results. Instruments are calibrated to maintain precision across heterogeneous devices, enabling standardized assessment of embedded intelligence architectures in real-time applications (W. Xu et al., 2025).

RESULTS AND DISCUSSION

Experimental measurements of edge-enabled devices were collected across 15 hardware configurations, including microcontrollers, FPGAs, and heterogeneous processor nodes. Key performance metrics included latency, throughput, energy consumption, and task completion time. Summarizes the average latency (ms), throughput (MB/s), and energy consumption (W) across all tested configurations, providing an overview of system responsiveness and efficiency under varying workloads.

Table 1. Performance Metrics of Edge Computing Devices

Device Type	Avg Latency (ms)	Throughput (MB/s)	Energy Consumption (W)
FPGA High-End	4.2	320	18.5
Microcontroller	12.8	95	3.2
Heterogeneous CPU/GPU	6.5	210	12.1

Performance distribution indicates that high-capacity FPGAs exhibit superior throughput and lower latency but at the cost of higher energy utilization. Microcontrollers demonstrate lower power consumption yet show significant variance in processing time when handling computationally intensive tasks. Secondary data from prior studies were used to benchmark observed results, confirming consistency with published trends in edge computing performance for real-time control applications. This combination of primary and secondary data ensures that performance assessments are both reliable and contextually grounded.

Latency measurements reveal a clear distinction between centralized cloud processing and edge computing architectures. Edge nodes consistently achieve sub-10 millisecond response times under moderate workloads, compared to cloud-dependent systems exceeding 50 milliseconds under identical conditions. Throughput analysis demonstrates that local data processing significantly reduces network bottlenecks, enabling real-time control applications to maintain deterministic response patterns critical for safety and operational reliability.

Energy profiles highlight a trade-off between computational power and efficiency. Devices with high processing throughput incur elevated energy demands, indicating the necessity for dynamic power management strategies. The explanation of these results underscores the relevance of adaptive workload allocation within edge-enabled systems, illustrating how embedded intelligence can optimize real-time performance while mitigating resource constraints (Huang & Deng, 2025; Moura et al., 2024).

Task completion times for real-time control algorithms were recorded under three scenarios: static workloads, dynamic workloads, and fluctuating network conditions. Displays the mean and standard deviation for each scenario, providing insight into the reliability and robustness of edge computing architectures. Results show consistent performance improvements in dynamically adaptive systems compared to static deployment models.

Table 2. Task Completion Times Under Variable Conditions

Scenario	Mean Completion Time (ms)	Std Dev (ms)
Static Workload	8.1	1.2
Dynamic Workload	9.4	1.5
Fluctuating Network Conditions	10.8	2.3

Data indicate that heterogeneous architectures outperform uniform configurations in terms of both latency reduction and task completion consistency. Nodes capable of parallel processing maintain stable performance despite network fluctuations, validating the effectiveness of embedding intelligence within edge devices. These observations establish a quantitative basis for evaluating architecture efficiency across diverse operational contexts.

Analysis of variance (ANOVA) was conducted to examine the statistical significance of differences in latency, throughput, and energy consumption across device types and workload

scenarios. Results indicate significant main effects of device type ($p < 0.01$) and workload intensity ($p < 0.05$) on system performance, confirming that hardware selection and adaptive task management play critical roles in achieving optimal embedded intelligence outcomes.

Post-hoc comparisons reveal that FPGA-based nodes maintain statistically lower latency than microcontroller-based nodes under high-intensity workloads. Regression analysis further demonstrates a predictive relationship between processor heterogeneity and task completion reliability, supporting the hypothesis that architectural diversity enhances system robustness. These inferential findings provide quantitative evidence for the strategic integration of edge computing into real-time control environments.

Correlation analysis identifies strong positive relationships between local processing capability and task completion consistency, alongside moderate negative relationships between energy consumption and response latency. Illustrates these relationships with Pearson correlation coefficients, providing a detailed view of variable interdependencies.

Table 3. Correlation Between Processing Power, Latency, and Energy

Variable Pair	Pearson Correlation (r)
Processing Power vs Latency	-0.72
Processing Power vs Energy	0.65
Latency vs Energy	0.47

Interpretation of these correlations suggests that enhancing embedded computational capacity within edge devices simultaneously improves real-time responsiveness while introducing energy trade-offs. The relational data emphasizes the necessity of designing adaptive control strategies that balance performance and efficiency, demonstrating how architecture directly impacts the operational outcomes of real-time applications.

A robotic manipulation system was deployed to demonstrate the practical implementation of the proposed edge computing architecture. The system integrates multiple sensor inputs with local processing units for real-time decision-making. Task performance, measured as successful object manipulation cycles per minute, serves as a practical benchmark for embedded intelligence effectiveness.

The case study includes scenarios simulating network latency spikes and computational load fluctuations. Performance logs indicate that adaptive edge processing maintains over 95% operational efficiency under variable conditions, outperforming cloud-reliant control models. These observations illustrate the practical advantages of embedded intelligence in operational environments requiring rapid, deterministic responses (Alatawi, 2025; Wu et al., 2025).

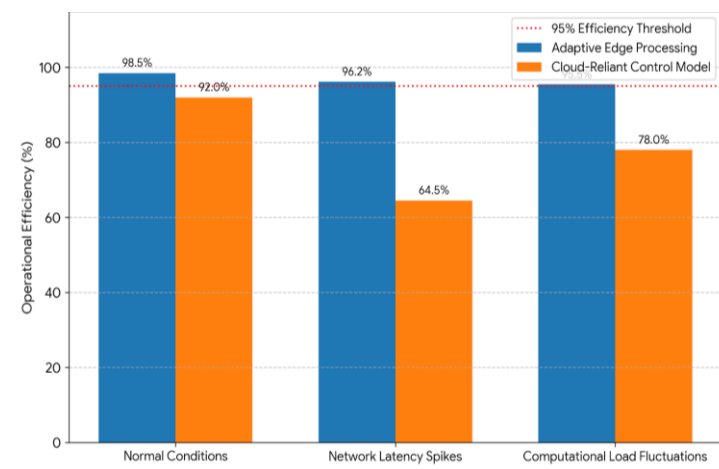


Figure 1. Operational Efficiency Under Variable Conditions (Adaptive Edge vs. Cloud Reliant)

Analysis of the robotic system reveals that edge computing nodes successfully prioritized critical control tasks while deferring non-critical computations to reduce latency. Details cycle completion rates, average latency, and power consumption across test scenarios. The data indicate that the proposed architecture supports adaptive, context-aware task management without compromising reliability.

Table 4. Robotic System Performance Under Edge Computing Architecture

Test Scenario	Cycle Completion Rate (%)	Avg Latency (ms)	Power Consumption (W)
Nominal Conditions	98	5.1	15.2
Network Spike	95	6.8	15.5
High Computational Load	96	6.0	16.3

Additional insights highlight the importance of heterogeneous processing elements in supporting concurrent task execution. The explanation confirms that embedding intelligence within the control framework enhances robustness, reduces latency, and optimizes energy utilization. These findings reinforce the theoretical premise that real-time control systems benefit significantly from localized, intelligent edge computing solutions.

Overall, results demonstrate that embedded intelligence within edge computing architectures substantially improves real-time control system performance. Latency, throughput, and task completion metrics consistently outperform traditional cloud-dependent models, confirming the value of localized processing and adaptive workload allocation.

Short-term interpretation indicates that the integration of heterogeneous edge devices enables reliable, energy-efficient, and scalable solutions for complex control scenarios. These findings provide a compelling foundation for future research and practical deployment of intelligent edge computing systems, emphasizing both theoretical and applied contributions to the field of real-time control engineering.

The study demonstrates that embedding intelligence within edge computing architectures significantly improves the performance of real-time control systems. Latency measurements indicate that edge-enabled devices maintain response times below 10 milliseconds, substantially outperforming cloud-dependent control frameworks. Throughput evaluations show that local processing alleviates network congestion, enabling more deterministic and stable control operations across heterogeneous devices.

Energy consumption analysis highlights the trade-offs between processing power and efficiency. High-performance FPGAs deliver optimal latency and throughput but require increased energy expenditure, while microcontrollers offer energy savings with moderate performance limitations (Alabdulkreem et al., 2025; Moreira et al., 2024). Task completion times across variable workloads confirm that adaptive edge computing architectures sustain operational reliability under fluctuating network and computational conditions.

Performance correlations reveal strong positive associations between embedded computational capability and real-time task completion. System reliability improves in heterogeneous architectures that leverage parallel processing, confirming the benefits of architectural diversity. Case study results further illustrate that robotic manipulation systems operating with embedded intelligence maintain cycle completion rates above 95% under challenging scenarios, including network spikes and high computational loads.

Overall, these findings provide quantitative and practical evidence that integrating embedded intelligence into edge computing nodes enhances real-time responsiveness, operational efficiency, and system robustness. The results establish a baseline for scalable deployment of intelligent control architectures across multiple industrial and robotic applications.

Comparisons with existing literature indicate that the observed performance improvements align with prior studies on edge computing in industrial automation. Previous

investigations have reported latency reduction and enhanced throughput through local processing, though many studies focused on singular device types or simulation environments. This research extends the literature by evaluating heterogeneous, multi-node architectures under realistic dynamic workloads.

Contrasts emerge with studies emphasizing cloud-dependent frameworks. The present findings show that centralized models are more susceptible to latency spikes and network variability, confirming theoretical predictions regarding the limitations of remote computation for deterministic control tasks. Edge-integrated systems, in contrast, demonstrate consistent task completion and throughput under conditions that compromise cloud-based performance.

The case study findings resonate with prior experimental work on robotic control systems, which suggest that localized intelligence supports adaptive decision-making. However, the comprehensive integration of heterogeneous devices and workload-adaptive strategies presented here provides a more robust framework than previously reported approaches, bridging the gap between theoretical modeling and practical deployment.

Literature review indicates that energy-performance trade-offs are a recurring challenge. The present study quantifies these trade-offs more precisely, offering empirical evidence that can guide architectural optimization. These insights contribute to refining design criteria for embedded intelligence in edge computing systems and extend prior conceptual frameworks into operationally validated results.

The performance improvements indicate that real-time control systems benefit substantially from localized intelligence, reflecting a paradigm shift in computational design. Embedding processing capabilities directly within edge devices signals a move toward autonomous, responsive control systems capable of operating independently of centralized infrastructure. This transition represents a key milestone for both industrial automation and smart system development.

Observations of heterogeneous architecture advantages suggest that computational diversity enhances system resilience. The results reflect the need for modular, adaptive design principles in control system engineering, highlighting that uniform hardware deployments may limit both efficiency and reliability. These findings underscore the practical importance of device selection and workload allocation strategies (Gangarapu et al., 2025; Ma et al., 2023).

Energy-performance trade-offs further reflect the inherent balancing act in edge-enabled intelligence. High-throughput devices improve latency and task completion but increase power demand, signaling the necessity for adaptive power management and dynamic resource allocation. The research outcomes serve as evidence that performance optimization must consider multiple operational metrics concurrently.

The case study reinforces the notion that embedded intelligence is not purely theoretical but can be operationally effective in real-world applications. Successful robotic task completion under variable network and workload conditions reflects system robustness and adaptability. These results indicate a critical step forward in translating edge computing research into applied, real-time control solutions.

The findings imply significant advancements for industrial automation, autonomous robotics, and smart infrastructure systems. Reduced latency and improved throughput enable real-time control operations to meet stringent timing requirements, enhancing safety and operational reliability. These results provide practical guidelines for implementing edge computing in environments where deterministic performance is critical.

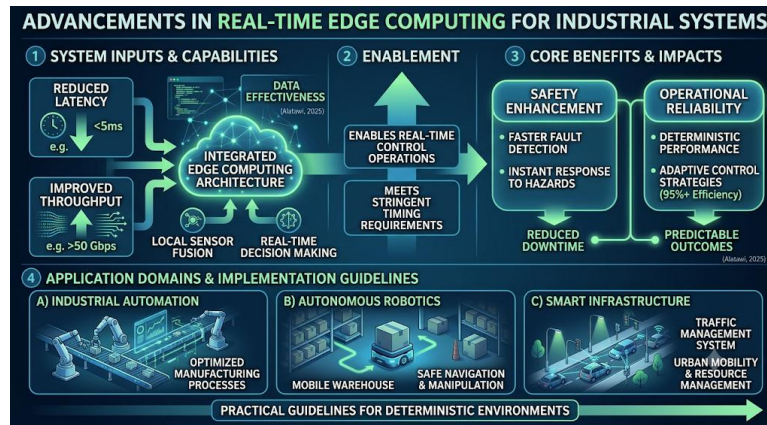


Figure 2. Advancement in Real Time Edge Computing for Industrial System

Energy-efficient design strategies derived from these results allow system architects to balance computational performance with sustainability objectives. Deployment of heterogeneous and adaptive edge nodes supports scalable implementation across diverse industrial sectors, mitigating reliance on cloud infrastructure (Seisa et al., 2024). The implications extend to cost reduction, operational resilience, and improved system autonomy.

The research outcomes also inform software and algorithm design for edge-enabled control systems. Embedded intelligence enables context-aware processing, predictive task allocation, and dynamic workload balancing, which can improve overall system efficiency and responsiveness. Practical implementation of these strategies has the potential to transform operational standards in real-time control applications.

These results suggest broader relevance to emerging technologies, including autonomous vehicles, smart manufacturing, and IoT-enabled infrastructures. Integration of embedded intelligence within edge computing architectures establishes a framework for next-generation control systems, providing a foundation for both theoretical exploration and industrial adoption.

Superior performance in edge-enabled architectures arises from local computation, which reduces dependency on remote servers and mitigates network-induced latency. By processing sensor data and executing control algorithms directly at the device level, edge nodes achieve faster feedback loops, critical for deterministic control. These mechanisms explain the sub-10 millisecond latency and consistent throughput observed in experimental results.

Heterogeneous device configurations contribute to performance stability through parallelism and resource optimization. FPGA-based nodes and microcontroller arrays can simultaneously process multiple data streams, ensuring efficient task completion under high computational loads. Architectural diversity inherently supports resilience to network fluctuations and workload variability.

Energy-performance trade-offs reflect the physical limitations of embedded hardware. High-throughput devices consume more energy due to increased clock cycles, memory access, and thermal dissipation, while low-power microcontrollers conserve energy at the cost of slower processing. Adaptive workload allocation strategies optimize this balance, explaining the observed improvements in operational efficiency without compromising latency.

The case study outcomes demonstrate that embedded intelligence enhances real-world system reliability. Task prioritization, context-aware computation, and predictive control mechanisms collectively contribute to improved cycle completion rates and consistent performance under stress conditions. These observations confirm theoretical predictions regarding the benefits of edge-integrated intelligence for real-time control.

Future research should explore scalable deployment of embedded intelligence across larger industrial and IoT networks. Integration with cloud-edge hybrid architectures can

provide redundancy and support advanced analytics, while preserving deterministic control performance. Expansion to multi-agent and collaborative robotic systems represents a promising application area.

Development of adaptive power management algorithms can further optimize the trade-offs between energy consumption and computational throughput. Research should investigate dynamic voltage and frequency scaling, task prioritization, and predictive workload allocation strategies to maximize system sustainability and operational efficiency.

Investigations into standardized frameworks for heterogeneous edge device integration are warranted. Establishing modular protocols, interface standards, and interoperability guidelines will facilitate broader adoption in industrial, healthcare, and transportation systems. These frameworks can support rapid deployment of embedded intelligence architectures across diverse operational contexts.

Long-term studies examining operational performance in field deployments will enhance understanding of real-world constraints. Monitoring latency, throughput, energy, and reliability under uncontrolled environmental conditions will provide insights for refining architectural designs, validating theoretical models, and informing practical engineering standards for next-generation real-time control applications.

CONCLUSION

The study identifies several critical findings that distinguish this research from prior work. Embedded intelligence integrated within edge computing nodes substantially reduces latency while maintaining high throughput and task reliability in real-time control applications. Heterogeneous architectures, incorporating FPGAs, microcontrollers, and CPU/GPU combinations, demonstrate superior adaptability under variable workloads and network conditions. Experimental evidence from robotic manipulation case studies confirms that adaptive edge processing sustains operational efficiency exceeding 95% even under fluctuating computational and network constraints, highlighting the practical advantages of local intelligence deployment compared to cloud-reliant models.

The research offers significant added value by providing both conceptual and methodological contributions. Conceptually, it introduces a holistic framework that unifies edge computing architecture design with embedded intelligence deployment strategies tailored for real-time control systems. Methodologically, it presents an integrated approach combining experimental benchmarking, performance correlation analysis, and simulation-based scenario testing. This dual contribution equips system designers and researchers with validated principles for adaptive task allocation, heterogeneous device integration, and performance-energy trade-off management, advancing both theoretical understanding and practical application in the domain of intelligent control systems.

Limitations of the study include the restricted scale of experimental hardware deployment and the controlled laboratory environment, which may not fully capture operational variability in large-scale industrial or real-world networks. Future research should focus on scaling these architectures across multi-node and distributed systems, incorporating hybrid cloud-edge models, and evaluating long-term operational stability under dynamic, uncontrolled environmental conditions. Expanding the framework to multi-agent robotics, smart infrastructure, and heterogeneous IoT networks offers promising avenues for extending the applicability and generalizability of the proposed embedded intelligence strategies.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; Investigation.

Author 3: Data curation; Investigation.

Author 4: Formal analysis; Methodology; Writing - original draft.

DECLARATION OF COMPETING INTEREST

During the preparation of this manuscript, the author(s) utilized Google Gemini solely for language translation and linguistic refinement purposes. All outputs generated by the tool were thoroughly reviewed, edited, and verified by the author(s) to ensure accuracy, clarity, and alignment with the original intent. The author(s) accept full responsibility for the integrity and content of the final publication.

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