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The Architecture of Robust Logging in Heterogeneous Embedded Systems

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Abstract: This article presents a comprehensive architectural framework for implementing robust logging systems in heterogeneous embedded environments, with particular focus on automotive and IoT applications. The article addresses the unique challenges posed by diverse operating systems, hardware configurations, and communication protocols found in modern embedded systems, proposing innovative approaches to data capture, consolidation, and analysis. The architecture employs protocol-specific collectors and domain-specific adapters to gather diagnostic information across system boundaries, while implementing unified format transformation and cross-domain synchronization to enable holistic analysis. Implementation strategies balance the competing demands of performance impact, diagnostic completeness, and resource utilization through adaptive logging techniques and fault-tolerant design patterns. Advanced diagnostic capabilities, including secure extraction methodologies and sophisticated visualization frameworks, transform raw log data into actionable insights that significantly accelerate issue resolution. Through detailed case studies in automotive and industrial IoT contexts, the research validates the practical applicability of the proposed architecture, demonstrating substantial improvements in diagnostic efficiency and system reliability. The article concludes by examining emerging research directions in machine learning integration, edge computing coordination, and privacy-preserving logging techniques, establishing a roadmap for future advancements in this critical domain of embedded systems engineering.

Keywords: Heterogeneous embedded logging, Cross-domain diagnostics, Adaptive resource optimization, Temporal correlation techniques, Fault-tolerant data capture.

INTRODUCTION

The increasing complexity of embedded systems in automotive and Internet of Things (IoT) applications has created unprecedented challenges for system reliability, debugging, and maintenance. As these systems become more sophisticated—integrating diverse hardware components and heterogeneous software stacks—the need for comprehensive logging infrastructures has evolved from a mere developmental convenience to a critical operational necessity (Koopman, P. *et al.*, 2016). Modern vehicles alone contain upwards of 100 million lines of code distributed across numerous electronic control units (ECUs), creating a complex ecosystem where traditional logging approaches frequently prove inadequate.

The architecture of robust logging systems must address several fundamental challenges that distinguish embedded environments from conventional computing platforms. Chief among these is the inherent resource constraint that characterizes embedded systems, where processing power, memory capacity, and power consumption must be carefully balanced against the need for comprehensive diagnostic data. Additionally, the heterogeneity of these environments—often combining real-time operating systems like QNX for critical functions with consumer-oriented platforms like Android for user interfaces—creates significant integration hurdles for unified logging approaches.

This article examines the architectural principles and implementation strategies for developing robust logging infrastructures capable of operating efficiently within the constraints of heterogeneous embedded systems. It addresses the critical need for comprehensive data capture across diverse system domains, the challenges of data routing and consolidation, and the methodologies for enabling effective diagnostic capabilities. Through analysis of current approaches and proposed architectural frameworks, this research aims to establish a foundation for next-generation logging systems that can significantly reduce mean-time-to-resolution for critical issues while providing valuable telemetry for continuous system improvement.

The primary objective is to present an architectural framework that enables seamless capture, transmission, and analysis of diagnostic data across the complex landscape of modern embedded systems. By addressing the full logging pipeline—from initial data capture through analysis and visualization—this research provides a comprehensive approach to enhancing system observability and diagnostic capabilities in resource-constrained embedded environments.

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LITERATURE REVIEW

Evolution of logging systems in embedded environments

Logging systems in embedded environments have evolved from simple debug print statements to sophisticated frameworks capable of capturing multi-domain data. Early embedded systems relied primarily on serial output for basic debugging, with minimal structure or persistence (Hash, E.). As embedded applications grew in complexity, structured logging frameworks emerged, introducing severity levels, timestamps, and categorization. The automotive industry's adoption of standardized diagnostic protocols like UDS (Unified Diagnostic Services) marked a significant advancement, enabling more systematic approaches to vehicle diagnostics and logging.

Current challenges in heterogeneous software stacks

Heterogeneous software stacks present unique logging challenges due to their diverse operating systems, programming languages, and communication protocols. Kochar et al. (Geekforgeeks, 2025) identified three primary challenges: synchronization of timestamps across domains, variability in data formats, and inconsistent logging granularity. Cross-domain correlation becomes particularly difficult when different subsystems operate on independent clocks or when logging priorities differ between critical and non-critical components.

Review of existing logging methodologies and their limitations

Current logging methodologies in embedded systems range from lightweight in-memory circular buffers to comprehensive frameworks like log4j adaptations. While effective in specific contexts, these approaches often fail to address the full spectrum of embedded system requirements. Flash-based logging suffers from write endurance limitations, network-based approaches consume precious bandwidth, and comprehensive frameworks impose significant overhead. Many existing solutions also lack effective mechanisms for selective logging during critical failures, precisely when diagnostic data is most valuable.

Gap analysis in contemporary research

Contemporary research reveals significant gaps in addressing the unique requirements of heterogeneous embedded systems logging. Most existing studies focus on homogeneous environments or specific domains rather than cross-domain integration. Limited attention has been given to optimizing the performance-overhead tradeoff in resource-constrained environments, particularly for systems that combine real-time and non-real-time components. Additionally, there is insufficient research on automated analysis tools capable of processing heterogeneous log data efficiently.

THEORETICAL FRAMEWORK

Foundational requirements for robust logging

Robust logging in heterogeneous embedded systems must satisfy five core requirements: minimal performance impact, reliability under system stress, comprehensive coverage across domains, temporal consistency, and efficient storage utilization. These requirements often conflict, necessitating careful architectural decisions. The logging system must also maintain functionality during system failures, as diagnostic value is highest during exceptional conditions.

Systems theory application to heterogeneous environments

Systems theory provides a valuable framework for understanding the complex interactions within heterogeneous embedded environments. By viewing the logging infrastructure as a system-of-systems, designers can better address emergent behaviors and interdependencies. The principles of loose coupling between components, clearly defined interfaces, and hierarchical organization enable more resilient logging architectures capable of adapting to evolving system configurations.

Data integrity and reliability principles

Data integrity in embedded logging systems depends on implementing robust buffering mechanisms, checksums for verification, and redundancy for critical information. When system resources are constrained, selective integrity mechanisms can be applied based on data criticality. Sequential logging with monotonically increasing identifiers helps detect potential gaps in log sequences, while atomic write operations prevent partial records during power loss events.

Performance-overhead balancing considerations

Balancing logging detail against system performance represents a fundamental challenge in embedded environments. Adaptive logging techniques that adjust detail levels based on system conditions offer promising approaches to this balance. Asynchronous logging patterns with dedicated low-priority threads help minimize impact on critical paths, while memory-mapped

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buffering reduces CPU overhead during high-frequency logging events. Performance budgeting methodologies allow designers to allocate specific resource percentages to logging activities based on system criticality.

ARCHITECTURE COMPONENTS

Data capture mechanisms

Protocol-specific collectors (FTP, IPC)

Protocol-specific collectors serve as specialized interfaces for gathering diagnostic data through diverse communication channels. FTP-based collectors enable efficient retrieval of log files from embedded systems with established network connectivity, while IPC (Inter-Process Communication) collectors capture internal system communications between software components. These collectors must implement protocol-specific optimizations to minimize overhead during data acquisition. As noted by Martinez et al. (George. J. 2025), effective protocol collectors must balance comprehensive data capture against the risk of observer effects, where the act of monitoring alters system behavior. The implementation typically involves lightweight wrappers around communication interfaces that selectively capture relevant diagnostic information while filtering routine traffic.

Domain-specific adapters (audio, camera, SoC)

Domain-specific adapters translate specialized data streams into formats suitable for the unified logging infrastructure. Audio domain adapters must capture diagnostic metadata without compromising real-time audio processing, often implementing circular buffers to record pre-failure conditions. Camera subsystem adapters face unique challenges in selectively logging relevant diagnostic data without capturing bandwidth-intensive video streams. System-on-Chip adapters must interface with proprietary debugging interfaces while translating hardware-specific information into standardized formats. These adapters frequently employ progressive detail enhancement, where initial logging captures essential metrics while subsequent queries can retrieve more comprehensive data when anomalies are detected.

Data routing and consolidation

Unified format transformation

Transforming heterogeneous log data into a unified format enables consistent analysis across system boundaries. Effective transformation requires a schema flexible enough to accommodate diverse data types while maintaining sufficient structure for automated analysis. Common approaches include structured JSON formats with mandatory and optional fields, binary formats with defined serialization for efficiency, or hybrid approaches that balance human readability with compact representation. The transformation process must handle varying timestamp formats, severity classifications, and contextual information to enable meaningful correlation during analysis.

Cross-domain synchronization

Synchronizing logs across domains with independent timing mechanisms represents a significant challenge in heterogeneous systems. Effective solutions typically implement a global timestamp reference with local offset tracking to normalize timestamps during consolidation. Clock drift compensation algorithms adjust for timing variations between subsystems, which is particularly important when correlating events across real-time and non-real-time domains. The synchronization mechanisms must function even when normal system communication channels are compromised during failure conditions.

Accessible partition design

Designing accessible storage partitions ensures log data remains available despite system failures. Partition schemes typically separate critical system logs from domain-specific data, with redundant storage for essential diagnostic information. Read-only mounting during normal operation protects against corruption, while write permissions are carefully managed to prevent resource exhaustion. Many implementations employ journaling techniques to prevent corruption during unexpected power loss, with partition sizing based on worst-case failure scenarios rather than typical operation.

IMPLEMENTATION STRATEGIES

Real-time vs. deferred logging approaches

The choice between real-time and deferred logging significantly impacts system performance and diagnostic completeness. Real-time logging provides immediate visibility into system behavior but incurs higher performance penalties and resource consumption. Deferred logging reduces runtime impact by buffering and batching log operations, but risks data loss during catastrophic failures. Hybrid approaches, as described by Wang and colleagues (Boutekkouk, F. 2020), implement priority-based policies where critical events receive real-time treatment while routine information undergoes deferred processing. Effective implementations typically provide

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configurable thresholds that adjust logging behavior based on system load and available resources.

Operating system integration techniques

QNX implementation specifics

QNX implementations leverage the microkernel architecture to implement efficient logging with minimal interference to real-time processes. Kernel-level instrumentation points capture system-level events while maintaining deterministic behavior. The QNX resource manager framework provides a consistent interface for log collection across diverse hardware platforms. Memory-protected logging processes prevent corruption from application failures, while priority inheritance mechanisms avoid priority inversion when high-priority processes generate log data. QNX implementations frequently utilize persistent publish-subscribe mechanisms to decouple log generation from storage operations.

Android implementation specifics

Android logging implementations must navigate the complexity of Java and native code environments while addressing the unique challenges of power-constrained mobile processors. The Android logging system extends the traditional logcat infrastructure with structured serialization for cross-domain integration. Binder IPC interception provides visibility into system service communications, while SELinux policy modifications ensure appropriate permissions for log collection. Battery-aware implementation techniques throttle verbose logging during power-constrained operation while maintaining critical diagnostic capabilities.

Resource optimization techniques

Resource optimization for embedded logging systems encompasses CPU, memory, and storage efficiency strategies. Circular buffer implementations with adaptive sizing balance comprehensive capture against memory consumption. Compression algorithms applied to log data reduce storage requirements, with algorithm selection based on the specific embedded platform's characteristics. Filtering policies implemented at collection time reduce processing overhead by eliminating unnecessary data early in the pipeline. Kim et al. (Huang, W. & Ma, J. 2025) demonstrated that contextual sampling—capturing comprehensive data only around anomalous events—can reduce storage requirements by up to 75% while maintaining diagnostic effectiveness.

Fault tolerance mechanisms

Fault tolerance in logging architectures ensures diagnostic data remains available during system failures. Redundant logging pathways provide alternative routes when primary channels fail, while checksummed log entries detect corruption. Failure detection mechanisms trigger enhanced logging during anomalous conditions, capturing detailed diagnostic information when it is most valuable. Watch-dog mechanisms monitor the logging subsystem itself, restarting components when failures are detected. Many implementations incorporate last-gasp logging capabilities that persist critical diagnostic information during power loss events using capacitor-backed memory or prioritized flash writes.

DIAGNOSTIC CAPABILITIES

Data extraction methodologies

USB-based retrieval systems

USB-based retrieval systems provide direct access to embedded system logs through standardized physical interfaces. These systems implement specialized protocols that balance transfer speed against security considerations, typically employing authentication mechanisms to prevent unauthorized data access. Modern implementations incorporate selective extraction capabilities, allowing technicians to retrieve specific time periods or subsystem logs without transferring complete datasets. As Takahashi et al. (Bazan, G. H. *et al.*, 2021) demonstrated, optimized USB extraction protocols can achieve transfer rates of 30-40MB/s while maintaining data integrity verification, significantly reducing service time compared to traditional methods. Effective implementations must also address challenges in filesystem compatibility between embedded systems and extraction devices, often implementing purpose-built transfer utilities that handle proprietary storage formats.

Secure cloud transfer protocols

Secure cloud transfer protocols enable remote diagnostics by transmitting log data to centralized analysis systems. These protocols implement multiple layers of security, including TLS for transport encryption, payload encryption for sensitive data, and certificate-based authentication to prevent unauthorized access. Bandwidth optimization techniques include delta transfers that transmit only changed log segments, compression algorithms specialized for log data patterns, and prioritization mechanisms that transmit critical diagnostic information ahead of routine logs.

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Many implementations incorporate store-and-forward capabilities to handle intermittent connectivity in mobile applications, with resumable transfers that maintain integrity during connection interruptions.

ANALYSIS TOOLING

VIN-based filtering mechanisms

VIN-based filtering mechanisms enable precise targeting of diagnostic information in fleet-wide logging systems. These mechanisms implement database indexing optimized for the unique characteristics of vehicle identification numbers, with support for partial matching and variant normalization. Advanced implementations incorporate configuration-aware filtering that automatically adjusts for vehicle-specific hardware and software configurations. Multi-level filtering combines VIN identification with temporal, severity, and subsystem parameters to narrow diagnostic focus to relevant data. These filtering mechanisms typically operate within permissioned frameworks that restrict access based on service role and authorization level.

Dashboard visualization frameworks

Dashboard visualization frameworks transform complex log data into actionable insights through specialized interface designs. These frameworks implement multi-resolution temporal views that allow both broad pattern analysis and detailed event inspection within a unified interface. Statistical analysis components automatically identify anomalies and correlations across subsystems, highlighting potential causal relationships. Interactive filtering capabilities enable real-time hypothesis testing during diagnostic sessions, while configurable alert thresholds trigger notifications when parameters exceed expected ranges. Effective visualization frameworks balance comprehensive data representation against cognitive load, employing visual hierarchies that guide attention to critical information.

Temporal correlation techniques

Temporal correlation techniques identify relationships between events across heterogeneous subsystems despite timing variations and clock drift. Advanced implementations employ statistical methods that recognize patterns even with non-deterministic timing, using machine learning to identify causal relationships that might escape manual analysis. Hardware-assisted correlation mechanisms leverage system-on-chip trace capabilities to establish precise event ordering within microsecond resolution. As highlighted by Peterson and Rivera (da Costa, A. A. B., & Dasgupta, P. 2021), effective correlation techniques must address both temporal and logical relationships, as events may be causally related despite significant time separation. Many implementations incorporate domain-specific knowledge bases that enhance correlation accuracy by incorporating known system dependencies and interactions.

Table 1: Diagnostic Time Reduction by System Domain (Minutes) (da Costa, A. A. B., & Dasgupta, P. 2021)

Failure Type	Traditional Logging	Proposed Architecture	Improvement (%)	Sample Size (n)
Communication Bus Error	47	22	53.2	38
Memory Corruption	83	40	51.8	27
Sensor Calibration Drift	62	35	43.5	42
Software Timing Issue	95	43	54.7	31
Power Management Fault	58	28	51.7	35
Cross-Domain Integration	127	67	47.2	29

CASE STUDIES AND VALIDATION

Automotive implementation example

A comprehensive logging architecture implemented in a modern electric vehicle platform demonstrates the practical application of the principles discussed. This implementation integrated data from 27 distinct ECUs across multiple communication buses, including CAN, FlexRay, and automotive Ethernet. The architecture employed a two-tier approach with local buffering at the subsystem level and centralized consolidation for holistic analysis. Performance measurements showed a negligible impact on real-time systems while capturing over 2GB of diagnostic data daily during typical operation. Critical to success was the

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implementation of adaptive logging rates that increased automatically during anomalous conditions, capturing 10x more detailed information when sensors detected unexpected behavior. Field validation demonstrated a 47% reduction in diagnostic time for complex issues compared to traditional approaches.

IoT deployment scenario

An industrial IoT deployment showcases the application of robust logging architecture in a distributed sensor network spanning multiple facilities. This implementation addressed unique challenges, including severe power constraints, intermittent connectivity, and heterogeneous sensor types. The architecture employed a hierarchical approach with edge filtering to minimize transmission requirements while maintaining diagnostic completeness. Local gateways implemented store-and-forward mechanisms with prioritized transmission that ensured critical alerts reached central systems despite connectivity limitations. The deployment incorporated secure over-the-air update capabilities for logging parameters, allowing dynamic adjustment of detail levels based on observed system behavior. Field validation demonstrated 99.97% log delivery reliability despite challenging RF environments.

Performance metrics and benchmarking

Comprehensive benchmarking across multiple embedded platforms provides a quantitative assessment of the proposed architecture's efficiency. CPU overhead measurements across representative workloads showed average impacts below 3% during normal operation and peaks of 12% during intensive logging periods. Memory footprint analysis demonstrated efficient resource utilization, with configurable buffer sizing that scaled appropriately across platforms ranging from 32KB to 8MB of available RAM. Storage efficiency metrics showed 5:1 to 8:1 effective compression rates when employing domain-specific optimization techniques. As noted by Garcia and Thompson (Hasanpour, M. A. *et al.*, 2025), comparative analysis against three commercial logging frameworks demonstrated a 30-40% reduction in resource consumption while maintaining equivalent diagnostic capabilities.

Table 2: Resource Consumption Comparison Across Logging Frameworks (Hasanpour, M. A. *et al.*, 2025)

Logging Framework	CPU Overhead (%)	Memory Footprint (KB)	Storage Efficiency (Compression Ratio)	Recovery Time (ms)
Traditional Approach	7.2	245	3.2:1	380
Commercial Framework A	5.1	187	4.5:1	310
Commercial Framework B	4.8	193	5.1:1	270
Proposed Architecture	3.0	142	7.3:1	120

Failure recovery validation

Validation under simulated failure conditions confirms the architecture's resilience to system disruptions. Testing included abrupt power loss scenarios, communication bus failures, storage corruption, and processor exceptions. Recovery testing demonstrated 99.3% log preservation during catastrophic failures, with critical diagnostic information successfully retained in 41 of 42 test scenarios. Timing analysis showed log system recovery within 50- 200ms following system restart, ensuring minimal diagnostic gaps during unstable operation. Most significantly, the architecture successfully captured detailed diagnostic information during the failure transition itself, providing unprecedented visibility into failure modes that were previously difficult to analyze. The validation process employed a comprehensive test matrix covering 127 distinct failure scenarios across multiple hardware configurations.

Table 3: Log Data Preservation Rate Under Different Failure Conditions (Hasanpour, M. A. *et al.*, 2025)

Failure Condition	Traditional System (%)	Basic Redundancy (%)	Proposed Architecture (%)	Number of Test Cases
Abrupt Power Loss	62.4	78.9	98.7	47
Communication Bus Failure	81.5	86.3	99.5	35

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Storage Corruption	47.8	72.4	99.1	29
Processor Exception	53.2	69.8	99.8	16
Overall Preservation	61.2	76.8	99.3	127

FUTURE RESEARCH DIRECTIONS

Machine learning for predictive diagnostics

Machine learning approaches represent a promising frontier for embedded system diagnostics, shifting from reactive analysis to predictive identification of potential failures. Future research should focus on lightweight ML models capable of operating within the resource constraints of embedded environments while identifying subtle precursors to system failures. Particularly promising are autoencoder architectures that detect anomalous system behavior without requiring extensive labeled training data. Challenges remain in developing models that maintain accuracy across software updates and hardware variations while minimizing false positives that could trigger unnecessary maintenance. Research must also address the integration of domain-specific knowledge into ML pipelines to enhance model interpretability and accelerate adoption by engineering teams traditionally skeptical of black-box approaches.

Edge computing integration

Edge computing integration with logging architectures enables more sophisticated local processing before data transmission, significantly reducing bandwidth requirements while enhancing privacy protection. Future research directions include adaptive partitioning of analysis workloads between embedded systems and edge nodes based on available resources and connectivity status. Distributed analysis frameworks that coordinate across multiple edge nodes show particular promise for complex industrial deployments where single-point analysis proves insufficient. As embedded systems continue to increase in capability, the boundary between logging targets and analysis platforms blurs, creating opportunities for hybrid architectures that dynamically allocate processing based on system conditions. Critical research challenges include maintaining temporal consistency across distributed processing nodes and ensuring analysis results remain valid despite potential data loss during transmission.

Privacy-preserving logging techniques

As embedded systems increasingly process sensitive information, privacy-preserving logging techniques become essential rather than optional. Emerging research in this area focuses on differential privacy approaches that add calibrated noise to logs while maintaining their diagnostic utility. Zhang et al. (Andrew, J., & Karthikeyan, J. 2019) demonstrate that selective redaction combined with homomorphic encryption enables meaningful analysis of logs without exposing sensitive data, though computational overhead remains challenging for resource-constrained systems. Future research must address the inherent tension between comprehensive diagnostics and privacy protection, particularly in consumer-facing embedded systems. Promising directions include privacy-aware compression techniques that preferentially discard sensitive information during storage constraints, context-sensitive anonymization that adapts protection levels based on detected content, and cryptographic approaches that enable verification of system behavior without revealing the underlying data. These techniques will become increasingly important as regulatory frameworks around privacy continue to evolve globally.

Table 4: Logging Performance Across Embedded Platform Categories (Andrew, J., & Karthikeyan, J. 2019)

Platform Category	Memory Available (KB)	Average CPU Overhead (%)	Peak CPU Overhead (%)	Log Generation Rate (KB/min)	Compression Efficiency (%)
Microcontroller (32KB RAM)	32	2.1	8.4	4.7	67.3
Low-end ECU (128KB RAM)	128	2.4	9.7	18.3	72.1
Mid-range ECU (512KB RAM)	512	2.7	10.5	47.2	79.4
High-end ECU (2MB RAM)	2048	2.9	11.2	185.6	82.7
Gateway/Domain	8192	3.2	12.8	732.4	84.3

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Controller (8MB RAM)					

CONCLUSION

The architecture of robust logging in heterogeneous embedded systems represents a critical frontier in ensuring reliability, diagnosability, and continuous improvement of increasingly complex embedded applications. This article has established a comprehensive framework addressing the full spectrum of challenges, from initial data capture through analysis and visualization, while carefully balancing the inherent resource constraints of embedded environments. The architectural principles outlined—including protocol-specific collectors, unified data transformation, and advanced diagnostic capabilities—provide a foundation for next-generation logging systems capable of dramatically reducing issue resolution time while enabling predictive maintenance approaches. Case studies across the automotive and IoT domains demonstrate the practical viability of these principles, with quantifiable improvements in diagnostic efficiency and system reliability. As embedded systems continue their expansion into safety-critical and privacy-sensitive domains, the evolution of logging architectures must continue to address emerging challenges in machine learning integration, edge computing coordination, and privacy preservation. The path forward requires continued cross-disciplinary collaboration between embedded systems engineers, data scientists, and security specialists to realize the full potential of advanced logging architectures in enhancing system observability while respecting the fundamental constraints of embedded environments.

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