Edge Artificial Intelligence Co Processors for Multimodal Sensor Fusion

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Abstract: The rise of intelligent edge applications from autonomous vehicles to wearable health monitors has driven the demand for efficient on-device processing of complex, heterogeneous sensory inputs. Multimodal sensor fusion combines data from diverse sources such as vision, audio, inertial, and environmental sensors to enable robust perception and decision-making. However, processing these multimodal signals in real time with high energy efficiency poses a major challenge for edge computing platforms. This paper presents the design and implementation of Edge AI Co Processors specifically optimized for multimodal sensor fusion, combining neural acceleration with adaptive data path control. The proposed EACP architecture consists of domain-specific compute engines, dynamic dataflow interconnects, and a lightweight fusion scheduler optimized for low-latency inference. A hybrid neural architecture is employed: convolutional networks process image frames, temporal convolutional or RNN modules handle sequential data, and a fusion block integrates modality features using attention mechanisms. The co-processor is implemented on a heterogeneous SoC, integrating RISC-V cores with tightly coupled tensor units and programmable sensor interfaces.

Keywords: Edge AI, sensor fusion, co-processor design, multimodal inference

1. Introduction

Multimodal sensor fusion has emerged as a critical technique in embedded artificial intelligence, allowing machines to perceive, interpret, and act upon diverse real-world data in a unified manner. By leveraging complementary information across visual, acoustic, inertial, and environmental modalities, systems can achieve greater robustness, contextual awareness, and resilience to signal corruption. Applications span autonomous vehicles (combining LiDAR, cameras, and radar), wearable health diagnostics (merging ECG, accelerometer, and temperature), and industrial monitoring (fusing vibration, sound, and thermal data). While cloud-based processing has traditionally supported such computation-heavy tasks, privacy concerns, real-time responsiveness, and connectivity constraints have catalyzed a shift toward edge-based AI processing. However, edge platforms face significant challenges due to limited computational resources, tight energy budgets, and the heterogeneous nature of sensor data.

Standard CPUs and general-purpose GPUs are ill-suited for tightly coupled multimodal data processing, often requiring off-chip memory access and high power draw. This motivates the development of specialized Edge-AI Co-Processors (EACPs) designed to natively support multimodal signal acquisition, feature extraction, and fusion within stringent latency and power constraints.

This paper proposes a complete hardware-software co-design methodology for EACPs, focusing on three pillars: (i) heterogeneous compute acceleration, (ii) adaptive fusion scheduling, and (iii) energy-aware workload orchestration. We show how domain-specific fusion pipelines can be optimized through neural architecture search (NAS) and mapped onto hardware with efficient on-chip data reuse and dynamic voltage scaling. Our implementation on a RISC-V-based SoC with custom neural accelerators demonstrates the practicality of deploying multimodal AI models at the edge without compromising on accuracy or energy.

2. Literature Review

The field of sensor fusion has been extensively studied in both algorithmic and architectural domains. Classical techniques such as Kalman filters, Bayesian inference, and Dempster-Shafer theory (Hall & Llinas, 1997) offered early foundations for probabilistic fusion but lack scalability for high-dimensional data and deep learning contexts.

Recent works like DeepSense (Yao et al., 2017) and SensorNet (Chen et al., 2020) applied deep neural networks to fuse inertial and environmental data, demonstrating improved performance over traditional techniques. However, most implementations rely on cloud or desktop platforms. Edge-focused models like MobileNetV2 or TinyML-based architectures (Banbury et al., 2021) offer energy efficiency but often neglect the cross-modal interaction and timing synchronization essential to multimodal inference.

On the hardware side, Google’s EdgeTPU and NVIDIA Jetson series have shown promise for low-power inference, but remain constrained by fixed function pipelines and limited support for modality-specific pre-processing. Few works address cross-modal scheduling or hardware-level fusion optimization.

Recent architectural advances like Eyeriss v2 (Chen et al., 2019) and Tenstorrent's AI chip emphasize reconfigurable dataflows, yet remain primarily image-centric. Our work builds upon these ideas by designing a fusion-aware accelerator with flexible frontends for diverse signal types and a shared computation backend optimized for dynamic workloads.

3. Methodology

3.1 Architecture Overview

The EACP consists of the following core components:

- **Sensor Interface Layer (SIL)**: Manages real-time input from up to 8 heterogeneous sensors with programmable sampling rates.
- **Modality-Specific Engines (MSEs)**: Hardware blocks optimized for different modalities:
    - CNN accelerator for image frames (e.g., RGB, depth)
    - 1D CNN/RNN engine for audio, vibration, and inertial signals
    - FFT/DWT preprocessor for frequency-domain inputs
- **Fusion Core (FC)**: Implements a transformer-inspired attention module or fully connected fusion layer
- **Fusion Scheduler (FS)**: A microcontroller-based unit that prioritizes compute blocks based on modality readiness and task urgency
- **RISC-V Host Core**: Orchestrates high-level control, model configuration, and power gating

3.2 Workload Adaptation and Control

- The FS adapts the scheduling of neural tasks based on buffer fill levels and confidence outputs.

- A lightweight reward-based learning controller adjusts voltage/frequency for MSEs based on workload estimates.
- Dataflow is optimized using static mapping for frequent workloads and dynamic reconfiguration for event-triggered fusion.

3.3 Use Case Models

- **Smart Surveillance**: Visual + audio + PIR sensor fusion for anomaly detection
- **Wearable Health**: ECG + accelerometer + PPG fusion for cardiac event prediction
- **Industrial IoT**: Vibration + thermal + acoustic signal fusion for machine fault diagnostics

Models were trained using TensorFlow Lite and deployed with quantization-aware training (QAT) for 8-bit inference.

4.3 Analysis

The proposed EACP outperforms baseline architectures in all tested scenarios. Latency reductions of up to **3.8×** are attributed to pipelined execution and near-sensor pre-processing. Energy savings stem from modality-aware scheduling, buffer coalescing, and data reuse. Despite aggressive optimization, fusion accuracy was maintained or improved, particularly due to enhanced synchronization and attention-based integration.

The architecture's modularity allows future integration of new sensor types and ML models. Unlike monolithic NPUs, the EACP handles workload variability gracefully, supporting dynamic reconfiguration based on application context.

5. Conclusion

This paper introduced a novel Edge-AI Co-Processor (EACP) architecture tailored for efficient multimodal sensor fusion in real-time embedded applications. Through a combination of domain-specific accelerators, adaptive scheduling, and efficient fusion strategies, the EACP delivers significant improvements in latency, energy efficiency, and inference accuracy over conventional edge platforms. The results affirm the feasibility of deploying complex AI models at the sensor edge, opening up new possibilities for autonomous systems, wearable intelligence, and smart infrastructure. Future work includes extending the architecture to support unsupervised learning, federated learning scenarios, and integrating neuromorphic cores for spiking sensor streams.

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