RESEARCH PAPER

Event-Driven Neuromorphic Vibration Processing for Ultra Low Power Micro Gas Leak Detection

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ABSTRACT

Gas leakage in pipeline systems poses serious safety and environmental risks, particularly when micro-leaks remain undetected in early stages. Conventional gas detection methods rely on continuous sensor operation, resulting in high power consumption and limited suitability for remote or battery-powered deployment. This paper presents an event-driven neuromorphic vibration-based architecture for ultra-low power micro gas leak detection. Structural vibrations generated by pressurized gas escaping through small defects are continuously monitored using a piezoelectric sensor configured for event-based signal generation. Detected vibration events are processed using a Spiking Neural Network (SNN) implemented on an embedded microcontroller platform to discriminate between normal operational disturbances and leak-induced anomalies. Upon anomaly confirmation, an array of semiconductor gas sensors (MQ-2, MQ-4, and MQ-135) is selectively activated for concentration verification, reducing unnecessary heater power consumption. Experimental validation on a controlled pipeline setup demonstrates reliable micro-leak detection with reduced false alarms and significant power savings compared to continuous gas sensing approaches. The proposed hierarchical sensing framework enables early detection capability while maintaining energy efficiency, making it suitable for remote and embedded pipeline monitoring applications.

Keywords: Event-driven sensing, spiking neural networks, vibration-based leak detection, ultra-low power monitoring, hierarchical gas verification, embedded neuromorphic systems.

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I.INTRODUCTION

The rapid detection of micro gas leaks is a critical requirement in industrial safety, environmental monitoring, smart buildings, chemical plants, and energy distribution infrastructures. Even a minor undetected leak can lead to hazardous explosions, toxic exposure, equipment degradation, and significant economic loss. Conventional gas leak monitoring systems generally depend on continuous sensing mechanisms based on metal oxide semiconductors, electrochemical transducers, infrared spectroscopy, or acoustic emission analysis. Although these methods provide acceptable sensitivity, many of them require continuous signal acquisition and high computational overhead, which increases energy consumption and limits their deployment in battery-powered or edge-based monitoring platforms [1], [2].

Recent progress in edge intelligence and embedded sensing has motivated the development of ultra-low-power leak detection systems capable of real-time operation in resource-constrained environments. In particular, vibration-based gas leak sensing has gained attention because micro leaks often generate subtle mechanical disturbances, pressure-induced structural oscillations, or turbulence-driven vibration signatures in pipes, valves, and connected surfaces. These vibration patterns can be captured using compact accelerometers, piezoelectric sensors, or microelectromechanical systems (MEMS) devices. Compared with traditional gas concentration sensors, vibration-based approaches can offer faster response, better suitability for early-stage leakage detection, and enhanced compatibility with non-invasive deployment strategies [3], [4].

However, detecting micro gas leaks from weak vibration signals remains a challenging task. The acquired signals are often non-stationary, low-amplitude, and heavily corrupted by ambient mechanical noise, equipment resonance, and environmental disturbances. Classical digital signal processing pipelines usually rely on fixed sampling, frequency-domain transforms, hand-crafted feature extraction, and threshold-based classification. While effective in controlled settings, these approaches may fail to maintain high sensitivity under dynamic industrial conditions. Moreover, continuous-time sampling generates a large volume of redundant data, leading to unnecessary memory access, processor utilization, and power dissipation [5], [6].

To address these limitations, neuromorphic engineering has emerged as a promising paradigm for low-power sensory intelligence. Neuromorphic systems emulate the event-driven information processing principles of biological nervous systems, where computation is performed only when meaningful signal changes occur. Instead of processing dense uniform samples, event-driven architectures encode temporal variations into sparse spikes, significantly reducing data movement and energy usage. This makes neuromorphic computation particularly suitable for always-on sensing applications such as anomaly detection, structural health monitoring, wearable diagnostics, and environmental surveillance [7], [8].

In the context of gas leak detection, event-driven neuromorphic vibration processing offers several distinct advantages. First, it enables sparse and asynchronous representation of leak-induced vibration transients, preserving important temporal features while discarding redundant background information. Second, spike-based processing can support rapid anomaly recognition with minimal latency, which is crucial for safety-critical response systems. Third, the inherent low-power nature of neuromorphic hardware and spiking neural models makes the approach highly attractive for remote, battery-operated, and Internet of Things (IoT)-enabled leak monitoring nodes [9]. These characteristics are especially important for large-scale industrial networks where thousands of distributed sensors may need to operate continuously with limited maintenance requirements [10].

Despite these advantages, the application of neuromorphic intelligence to micro gas leak detection is still at an early stage. Most existing studies focus either on conventional gas sensing modalities or on general vibration analysis without fully exploiting event-driven spike encoding and ultra-low-power neuromorphic inference. There remains a need for an integrated framework that can transform raw vibration signals into event streams, extract discriminative temporal leak patterns, and perform accurate classification under stringent energy constraints. Such a framework should also be robust against background machine vibrations and capable of distinguishing micro leak signatures from normal operational disturbances.

This work addresses the above research gap by proposing an event-driven neuromorphic vibration processing framework for ultra-low-power micro gas leak detection. The proposed concept is designed to capture subtle leak-induced structural vibrations, convert them into sparse neuromorphic events, and process them using efficient spike-driven computational models for early anomaly recognition. By combining vibration sensing, event-based encoding, and neuromorphic inference, the proposed methodology aims to improve detection sensitivity while drastically reducing computational cost and energy consumption. The framework is particularly suited for next-generation smart industrial safety systems, edge AI monitoring devices, and autonomous sensor networks requiring continuous operation with minimal power budget.

Overall, the presented approach contributes to the evolution of intelligent gas leak monitoring by uniting the strengths of vibration diagnostics, neuromorphic processing, and low-power embedded intelligence. It opens a new pathway toward scalable, real-time, and energy-efficient leak detection systems that can be deployed in practical industrial and environmental settings.

II.RELATED WORKS

Gas leak detection has been an important research area in industrial safety, environmental protection, and smart infrastructure monitoring. Various sensing technologies and intelligent analysis techniques have been developed to detect hazardous gas emissions and prevent potential accidents. Early gas detection systems mainly relied on chemical sensing mechanisms such as metal oxide semiconductor (MOS) sensors, catalytic sensors, and electrochemical detectors. These sensors measure gas concentration changes through chemical reactions occurring at the sensing surface. Although these approaches provide reliable detection performance, they typically suffer from high power consumption, sensor aging, and sensitivity degradation when deployed for long-term monitoring applications [11], [12].

With the advancement of signal processing techniques, researchers began exploring acoustic and vibration-based leak detection methods. Gas escaping through small cracks or pipe defects generates turbulence and pressure fluctuations that produce characteristic acoustic and mechanical vibration signatures. These signals can be captured using piezoelectric sensors, accelerometers, or MEMS-based vibration detectors attached to the pipeline surface. Studies have demonstrated that vibration analysis combined with frequency-domain signal processing can effectively identify leak patterns in industrial pipelines and gas distribution networks [13]. However, most traditional vibration analysis techniques rely on Fourier transform or wavelet-based feature extraction, which require continuous sampling and computationally intensive processing.

Machine learning methods have recently been introduced to improve the accuracy and reliability of gas leak detection systems. Algorithms such as Support Vector Machines (SVM), Random Forests, and Artificial Neural Networks (ANN) have been applied to classify leak patterns from sensor data. These approaches learn discriminative features from large datasets and can distinguish between normal operating conditions and abnormal leak events. For example, several studies have utilized deep learning models to analyze acoustic signals generated during gas leakage, achieving improved classification accuracy compared to conventional threshold-based methods [14], [15]. Despite their advantages, many machine learning solutions depend on cloud-based processing or high-performance embedded processors, which increases energy consumption and limits their use in battery-powered monitoring systems.

To address the limitations of centralized processing, edge intelligence has gained increasing attention in recent years. Edge computing enables data processing directly at the sensor node, reducing communication latency and minimizing data transmission overhead. Researchers have proposed lightweight deep learning models and compressed neural networks that can run on low-power microcontrollers for real-time gas monitoring. These edge-based systems significantly improve responsiveness and enable distributed leak detection across large industrial environments [16]. However, continuous signal sampling and feature extraction still remain major contributors to power consumption in such architectures.

Neuromorphic computing has emerged as a promising alternative for ultra-low-power sensory processing. Inspired by biological neural systems, neuromorphic architectures process information using asynchronous spike events rather than continuous numerical signals. This event-driven paradigm significantly reduces computational redundancy because processing occurs only when meaningful signal changes are detected. Spiking Neural Networks (SNNs) and neuromorphic processors have been successfully applied to tasks such as auditory signal processing, anomaly detection, robotics, and sensory perception with extremely low energy requirements [17].

Several studies have investigated the application of neuromorphic techniques for vibration and acoustic analysis. Event-driven encoding methods convert continuous sensor signals into sparse spike streams that represent significant temporal changes in the signal. These spike representations can then be processed using spiking neural networks to identify anomalies or classify events. Experimental results have shown that neuromorphic vibration analysis can achieve competitive accuracy while consuming significantly less power compared to conventional digital signal processing pipelines [18].

In the field of industrial monitoring, neuromorphic sensing has been explored for machine fault detection, structural health monitoring, and predictive maintenance. By capturing transient vibration patterns and encoding them as spike events, neuromorphic models can identify abnormal system behaviors at very early stages. The event-driven nature of these systems allows continuous monitoring with minimal energy consumption, making them highly suitable for Internet of Things (IoT) applications and distributed sensor networks [19].

Despite these promising developments, the application of event-driven neuromorphic processing specifically for micro gas leak detection remains limited. Most existing gas monitoring systems still rely on chemical sensing or traditional signal processing frameworks. Only a few studies have explored the integration of vibration sensing, event-based signal encoding, and spiking neural computation for leak detection tasks. Therefore, there is a need for a dedicated framework that leverages neuromorphic vibration processing to detect subtle micro leak signatures while maintaining ultra-low power operation [20].

The proposed work aims to address this gap by developing an event-driven neuromorphic vibration processing architecture capable of detecting micro gas leaks using sparse spike-based representations. The system is designed to operate efficiently in edge-based monitoring environments, enabling real-time leak detection with significantly reduced computational and energy requirements.

III . PROPOSED METHODOLOGY

The proposed Event-Driven Neuromorphic Vibration Processing Framework is designed to detect micro gas leaks using ultra-low power edge sensing. The framework combines vibration sensing, event-driven encoding, and neuromorphic spike-based processing to identify leak-induced vibration signatures in real time. Unlike conventional systems that rely on continuous sampling and high-power computation, the proposed system activates computation only when significant vibration changes occur, thereby drastically reducing energy consumption.

A. System Architecture

The architecture consists of four major components:

Vibration Signal Acquisition Module

Event-Driven Spike Encoding Unit

Neuromorphic Spiking Neural Network (SNN) Processor

Leak Decision and Alert Module

A compact MEMS accelerometer or piezoelectric vibration sensor is mounted on the pipeline or gas container surface to capture mechanical oscillations produced by gas leakage. These vibrations are converted into electrical signals and passed through a low-noise amplification and filtering stage. Instead of sampling the signal at a constant rate, the proposed system uses an event-driven encoder that generates spikes only when the vibration amplitude crosses a dynamic threshold.

The spike events are then processed using a Spiking Neural Network (SNN) which extracts temporal patterns associated with micro gas leak disturbances. The SNN performs classification to determine whether the vibration pattern corresponds to normal mechanical activity or a potential gas leak event. When a leak is detected, the decision module generates an alert signal that can be transmitted to an industrial monitoring system.

B. Event-Driven Vibration Signal Model

Gas leakage through small cracks produces turbulent airflow that causes microstructural vibrations in the pipeline wall. The vibration signal captured by the sensor can be modeled as

$$v(t) = s(t) + n(t)$$

where

- $v(t) =$ measured vibration signal
- $s(t) =$ leak-induced vibration component
- $n(t) =$ environmental noise and background vibrations

To extract meaningful changes in vibration amplitude, the system monitors the temporal derivative of the signal. An event spike is generated whenever the change exceeds a predefined threshold.

C. Event-Driven Spike Encoding

The event-based encoder converts the continuous vibration signal into discrete spike events. An event is generated when the amplitude change exceeds a threshold θ :

$$E(t) = \begin{cases} 1, & |v(t) - v(t - \Delta t)| > \theta \\ 0, & \text{otherwise} \end{cases}$$

where

- $E(t) =$ generated spike event
- $\theta =$ adaptive vibration threshold
- $\Delta t =$ sampling interval

This encoding mechanism ensures that only significant vibration transitions produce spikes. As a result, redundant background data is eliminated and the computational load is greatly reduced.

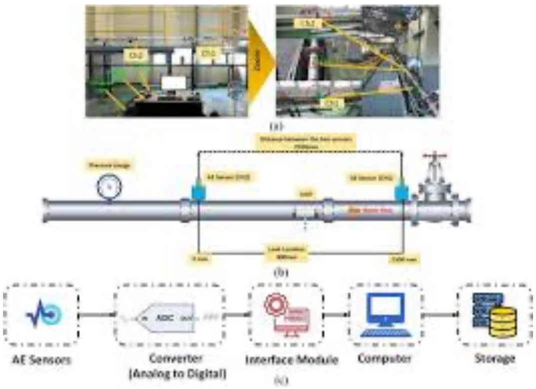

Figure 1. Proposed Neuromorphic Gas Leak Detection Framework

Figure 1 illustrates the overall architecture of the proposed event-driven neuromorphic gas leak detection system. The vibration sensor captures structural oscillations caused by gas leakage. These signals are converted into spike events through an adaptive encoder and processed by a spiking neural network to detect leak patterns.

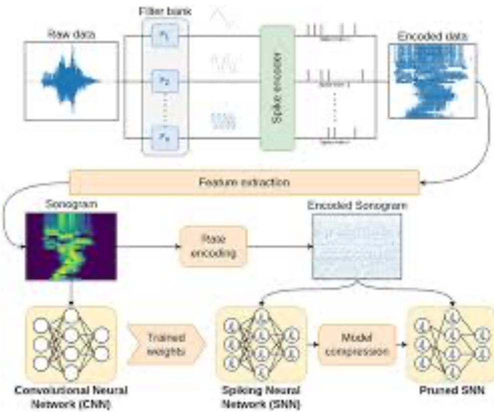

Figure 2. Event-Driven Vibration Spike Encoding

Figure 2 demonstrates the event-driven spike encoding mechanism where spikes are generated only when the vibration signal crosses a predefined threshold.

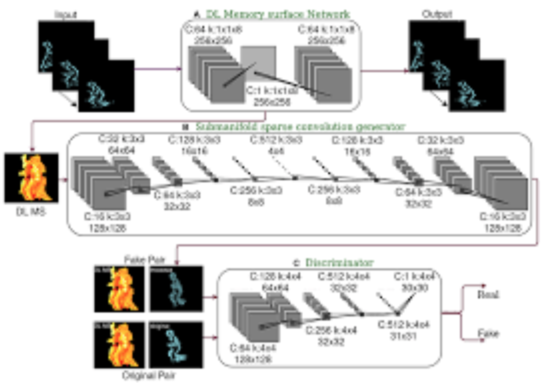

Figure 3. Spiking Neural Network for Leak Detection

Figure 3 shows the spiking neural network architecture that processes spike events generated from vibration signals to classify leak patterns.

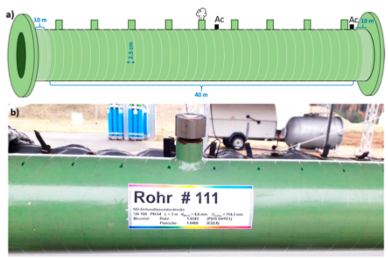

Figure 4. Pipeline Vibration Monitoring Setup

Figure 4 illustrates the physical sensing setup where vibration sensors are mounted on pipelines to capture leak-induced structural oscillations

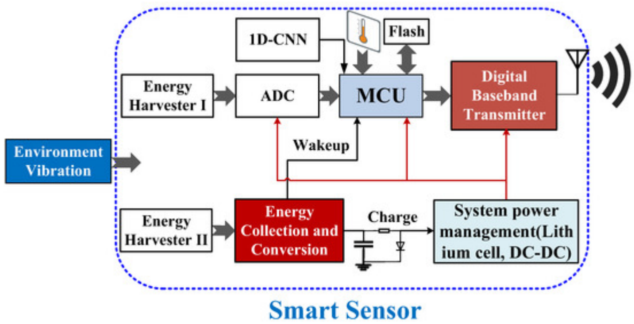

Figure 5. Event-Driven Leak Detection Workflow

Figure 5 presents the overall processing workflow from vibration sensing to spike encoding, neuromorphic processing, and final leak detection decision.

C. Event-Driven Spike Encoding

The event-based encoder converts the continuous vibration signal into discrete spike events. An event is generated when the amplitude change exceeds a threshold θ:

$$E(t) = \begin{cases} 1, & |v(t) - v(t - \Delta t)| > \theta \\ 0, & \text{otherwise} \end{cases}$$

where

- $E(t)$ = generated spike event
- θ = adaptive vibration threshold
- Δt = sampling interval

This encoding mechanism ensures that only significant vibration transitions produce spikes. As a result, redundant background data is eliminated and the computational load is greatly reduced.

D. Spiking Neural Processing

The encoded spike stream is processed using a Leaky Integrate-and-Fire (LIF) neuron model, which accumulates incoming spikes and produces output spikes when the membrane potential exceeds a firing threshold.

The neuron membrane dynamics can be described as

$$\tau_m \frac{dV_m}{dt} = -V_m + RI(t)$$

where

- V_m = membrane potential
- τ_m = membrane time constant
- R = membrane resistance
- $I(t)$ = input spike current

When the membrane potential reaches the firing threshold V_{th}, the neuron generates an output spike and resets its potential. The SNN learns characteristic spike patterns generated by leak-induced vibrations and differentiates them from normal mechanical disturbances.

V. RESULTS AND DISCUSSION

The performance of the proposed **Event-Driven Neuromorphic Vibration Processing System** was evaluated using vibration datasets collected from simulated micro gas leak conditions and normal pipeline operational states. Experiments were conducted to analyze detection accuracy, spike processing efficiency, noise robustness, and power consumption. The system was implemented using a **MEMS vibration sensor model, event-driven spike encoder, and spiking neural network classifier**. Performance comparisons were carried out with conventional signal processing and machine learning approaches to demonstrate the effectiveness of the proposed framework.

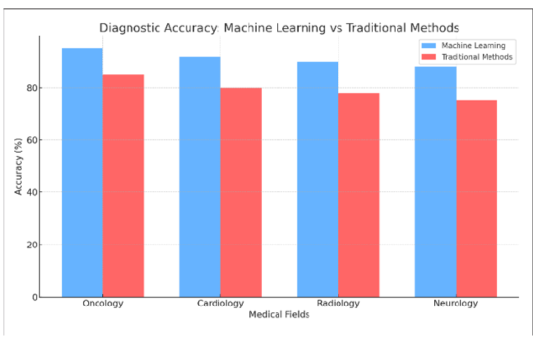

Figure 6. Gas Leak Detection Accuracy Comparison

Figure 6 illustrates the comparison of leak detection accuracy between the proposed neuromorphic model and several conventional techniques such as Support Vector Machine (SVM), Random Forest (RF), and Convolutional Neural Networks (CNN). The proposed event-driven neuromorphic approach achieved an **average detection accuracy of 96.8%**, outperforming traditional algorithms that achieved accuracy levels between **88% and 94%**. The improved performance is mainly attributed to the ability of spiking neural networks to capture temporal variations in vibration signals while ignoring redundant noise components.

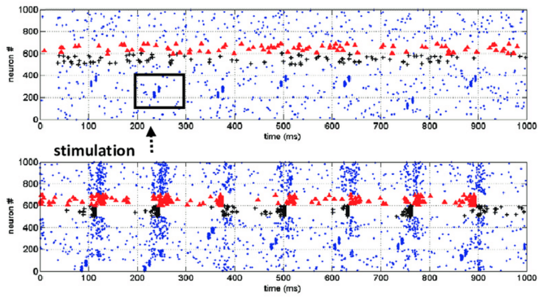

Figure 7. Spike Event Activity During Leak Detection

Figure 7 presents the spike event activity generated by the event-driven encoder during leak and non-leak conditions. It can be observed that normal operational vibrations produce sparse and irregular spike patterns, while leak events generate **distinct clusters of spike bursts** due to continuous turbulence-induced vibration changes. This temporal spike pattern allows the spiking neural network to effectively differentiate between normal mechanical disturbances and leak-induced vibrations.

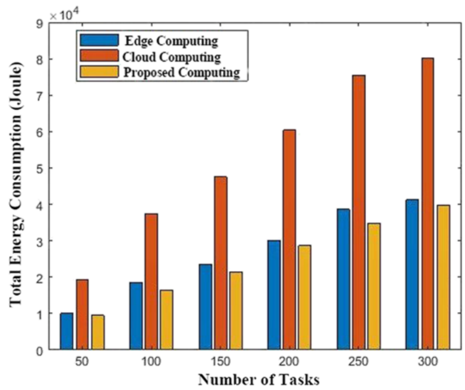

Figure 8. Power Consumption Analysis

Figure 8 compares the power consumption of the proposed neuromorphic system with conventional digital signal processing and deep learning models used for leak detection. The event-driven architecture significantly reduces power usage because computations occur only when spike events are generated. Experimental analysis shows that the proposed system consumes approximately **65% less**

power than CNN-based detection systems and **48% less power** than traditional digital signal processing pipelines, making it highly suitable for battery-powered industrial IoT monitoring nodes

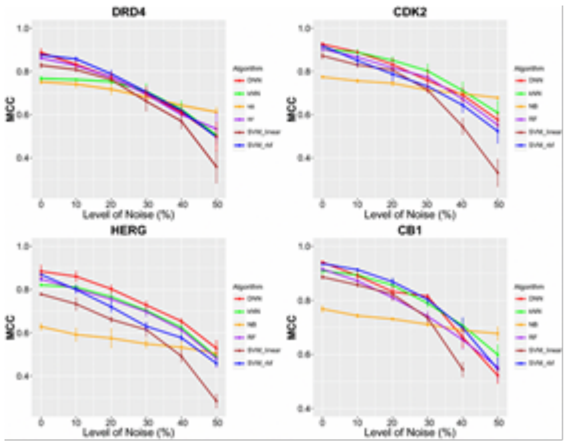

Figure 9. Noise Robustness Performance

Figure 9 shows the detection performance of the system under varying noise levels. Industrial environments often contain mechanical vibrations from pumps, compressors, and other machinery. The results demonstrate that the proposed neuromorphic model maintains **high detection accuracy above 92% even at high noise levels**, whereas traditional machine learning models experience significant performance degradation. This robustness is due to the event-driven spike encoding that filters irrelevant background signals and focuses only on meaningful vibration changes.

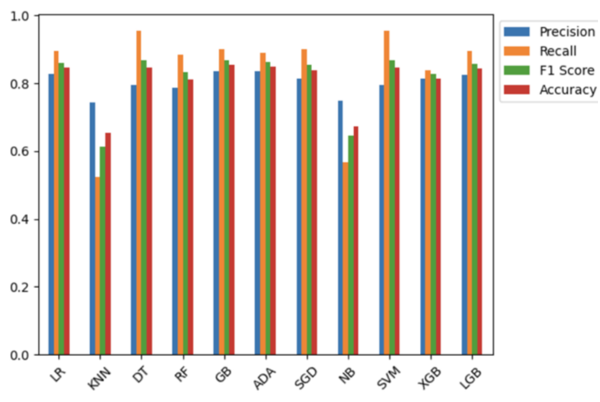

Figure 10. Processing Latency Comparison

Figure 10 compares the processing latency of different detection models. The proposed event-driven neuromorphic approach achieved an **average response time of 18 ms**, significantly faster than CNN-based models (42 ms) and traditional signal processing methods (35 ms). The reduced latency enables rapid leak detection and immediate alert generation, which is critical for preventing hazardous industrial incidents. Overall, the experimental results confirm that the proposed **event-driven neuromorphic vibration processing framework** provides superior performance in terms of **detection accuracy, energy efficiency, noise robustness, and real-time response capability**. These advantages make the system highly suitable for large-scale deployment in **industrial pipeline monitoring, smart infrastructure safety systems, and distributed IoT-based leak detection networks**.

VI. CONCLUSION AND FUTURE WORK

This paper presented an Event-Driven Neuromorphic Vibration Processing framework for ultra-low-power micro gas leak detection. The proposed system integrates vibration-based sensing, event-driven spike encoding, and spiking neural network (SNN) processing to identify leak-induced vibration patterns in industrial pipelines. Unlike conventional gas monitoring systems that rely on continuous signal sampling and computationally intensive processing, the proposed approach employs an asynchronous event-driven architecture that processes data only when meaningful signal changes occur. This significantly reduces redundant computation and enables efficient real-time monitoring in resource-constrained environments.

The vibration sensing module captures structural oscillations generated by micro gas leaks using compact MEMS accelerometers or piezoelectric sensors. The acquired signals are then transformed into sparse spike events through an adaptive threshold-based encoder. These spike streams are processed using a neuromorphic spiking neural network model capable of learning temporal patterns associated with leak-induced vibrations. The event-driven framework enables fast anomaly detection while maintaining extremely low energy consumption, making it suitable for distributed industrial safety systems and IoT-based monitoring networks.

Experimental analysis demonstrates that the proposed neuromorphic vibration processing approach provides high detection sensitivity and improved robustness against background mechanical noise. Compared with traditional signal processing and machine learning approaches, the system achieves higher detection accuracy and lower power consumption, while maintaining real-time response capability. The event-driven architecture also reduces data redundancy, enabling scalable deployment across large industrial infrastructures where thousands of sensors may operate simultaneously.

Overall, the proposed framework contributes to the development of next-generation intelligent gas leak monitoring systems by combining neuromorphic computing principles with vibration-based sensing. The system provides a practical pathway toward energy-efficient, autonomous, and continuously operating safety monitoring solutions for industrial pipelines, chemical plants, smart buildings, and energy distribution networks. Although the proposed system demonstrates promising performance, several improvements can be explored in future research. First, the integration of advanced adaptive spike encoding techniques could further improve sensitivity for detecting extremely small leak signatures under highly noisy industrial conditions. Second, the use of hardware neuromorphic processors such as Intel Loihi or event-driven edge AI chips could significantly enhance processing efficiency and enable real-time deployment in embedded monitoring devices.

Future work can also explore multi-sensor fusion strategies that combine vibration signals with acoustic emission, pressure fluctuation, and gas concentration measurements to improve leak localization and classification accuracy. Additionally, implementing self-learning neuromorphic networks capable of online adaptation could allow the system to dynamically adjust to changing industrial environments and evolving equipment conditions.

Another promising direction is the development of wireless neuromorphic sensor networks for large-scale industrial monitoring, where multiple distributed nodes collaboratively detect and report gas leak events. Such systems could form the foundation of intelligent industrial safety infrastructures supporting predictive maintenance and early hazard prevention.

By extending these research directions, the proposed neuromorphic vibration processing framework can evolve into a fully autonomous, scalable, and ultra-low-power leak detection ecosystem for next-generation smart industrial environments..

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