Development of Methane Monitoring System for Dairy Cow Eructation

Chung-Yen Chuang[1], Chang-Lung Tsai[1], Chin-Cheng Wu[1, *]

[1] Department of Biomechatronic Engineering, National Ilan University, Taiwan

* Corresponding Author: chincheng@niu.edu.tw

ABSTRACT

Methane emissions from dairy cow eructation constituted a significant greenhouse gas source in livestock production and were closely linked to rumination activity. Accurate, continuous, and non-invasive monitoring of eructation events was proven essential for assessing animal health, optimizing feed strategies, and reducing environmental impact. Conventional approaches—including manual observation, jaw-movement sensors, and respiration chambers—remained costly, labor-intensive, and unsuitable for real-time, long-duration deployment.

In this study, an IoT-based acoustic–gas integrated system was developed, combining an omnidirectional microphone with a MEMS methane sensor and a micro-pump to enable localized air sampling. The ESP32 microcontroller facilitated on-board signal processing, Wi-Fi transmission via MQTT protocol, and redundant local storage. This system supported synchronous collection of acoustic features and methane concentrations without imposing behavioral disturbances on the animals.

Keywords: methane, eructation, jaw movement, IoT

INTRODUCTION

Methane (CH_4) was recognized as a potent greenhouse gas with major contributions from the livestock sector, particularly from ruminants that released CH_4 via eructation during feeding and rumination. Accurate, continuous, and individual-level quantification of methane emissions was considered essential for emission inventories, dietary evaluation, and the advancement of Precision Livestock Farming (PLF). However, many approaches encountered critical limitations. Fixed-point gas analyzers were confounded by livestock house airflow and geometric misalignment [1], respiration chambers and tracer gas methods [2], while accurate, were unsuitable for routine production environments, and wearable behavioral devices such as jaw recorders [3] only provided indirect information without capturing methane concentration dynamics. Moreover, farm conditions characterized by dust, humidity, and ventilation posed challenges for sensor stability, power management, and system packaging. To address these constraints, this study proposed a wearable monitoring architecture that comprised an acoustic sensing module to detect eructation events, a gas-sensing module with localized sampling for improved response, low-power processing and wireless communication. The proposed system enabled non-invasive, low-power, acoustically triggered methane monitoring with synchronous acquisition of sound and gas data, and its feasibility was validated under in situ livestock house conditions, offering a practical pathway for scalable emission quantification in sustainable ruminant farming.

MATERIALS AND METHODS

The methane monitoring system was designed as a compact, modular platform consisting of four main subsystems: (i) an acoustic sensing module, (ii) a methane detection module, (iii) a communication module, and (iv) a power management module. Figure 1 illustrates the proposed system architecture of the methane monitoring system. All modules were configured under the design principles of compactness, scalability, low power consumption, and operational stability to enable long-term deployment under livestock house   conditions.
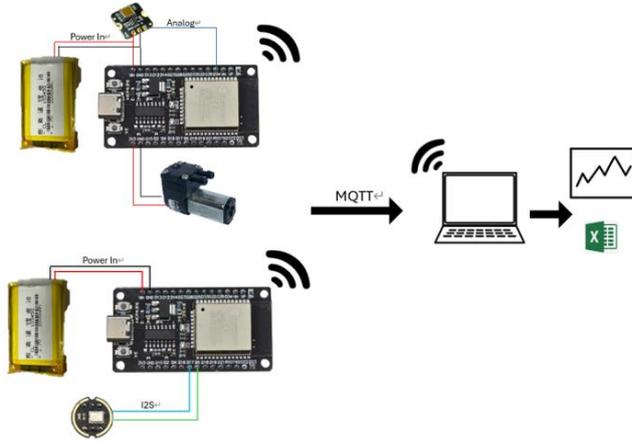

Figure 1. System architecture of the methane monitoring system

The acoustic sensing module was implemented using an INMP441 omnidirectional digital microphone, which featured a low-noise preamplifier and an integrated ADC. The sampling rate was set at 16 kHz, and the data were acquired through the I²S interface of an ESP32 microcontroller. On the microcontroller side, raw acoustic data were first bit-shifted to prevent overflow, then rectified to obtain absolute values, and subsequently processed to compute the Mean Absolute Value (MAV) for feature extraction.

$$MAV = \frac{1}{N}\sum_{i=1}^{N}|X[i] \gg 14| \tag{1}$$

Where $x[i]$ is the raw signal and N is the number of readout data. The module used the MQTT communication protocol to transmit data to the Node-RED server platform via Wi-Fi. The data packet format adopted JSON structure.

The methane sensing module consisted of a MEMS-based methane gas sensor (Fermion, 1–10000 ppm, DFRobot) coupled with a miniature diaphragm pump. The pump was activated in response to acoustic triggers, enabling localized air sampling during eructation events. This design enhanced signal contrast by concentrating on short-duration emission windows and reduced sensor response time compared to passive diffusion. Sensor outputs were acquired digitally via the I²C interface of the microcontroller and recorded synchronously with acoustic features to establish temporal correspondence between sound events and methane concentration changes.

The system core was built around a low-power ESP32 microcontroller, which supported both on-board signal processing and wireless data communication. Data were transmitted to a central server via Wi-Fi, while redundant storage was maintained locally on a microSD card to safeguard against transmission interruptions. Event timestamps, acoustic MAV features, and sensor readings were stored in synchronized data packets, ensuring accurate temporal alignment for subsequent analysis. The system was powered by a rechargeable lithium-ion battery managed through a protection circuit and a DC/DC converter to maintain regulated supply voltages for the sensing and control units. The design emphasized energy efficiency,

employing a duty-cycling strategy in which the wireless transmission remained inactive outside identified eructation events. This configuration enabled extended system operation under field deployment while maintaining stable sensing performance.

RESULTS & DISCUSSION

In the experiments, both INMP441 modules continuously captured long-duration acoustic signals from the livestock house environment. Representative raw traces are shown in Figure 2, indicating that the modules maintained stable data acquisition over extended periods and effectively differentiated background noise from transient acoustic events. These findings validated the feasibility of the system for long-term environmental monitoring, beyond mere short-term event detection.

Real-time data transmission was accomplished with a reporting interval of 200 m/s, and the Node-RED dashboard consistently displayed acoustic intensity trends with a latency of less than 1 second, confirming that the Wi-Fi/MQTT communication framework was stable during prolonged operation and that data integrity was preserved throughout continuous monitoring sessions.

These results highlight the system's strong potential for actual deployment in livestock housing, where continuous monitoring and reliable wireless communication are essential. Future work was planned to include direct field trials on-site to further validate the robustness of the acoustic–gas integrated platform under authentic farm conditions.
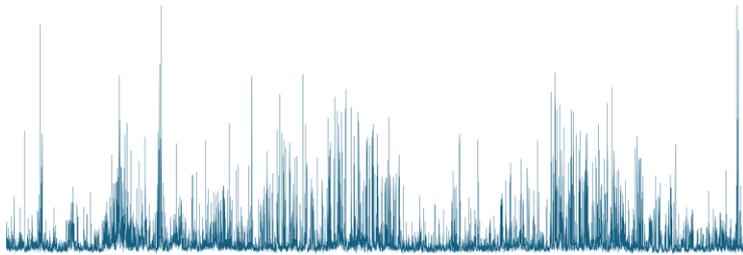

Figure 2. Long-term raw acoustic signals recorded by acoustic sensing modules during livestock house monitoring.

CONCLUSIONS

This study demonstrated that an edge computing acoustic–gas integrated module was capable of reliable operation under livestock farming conditions. The findings suggested several future directions for extending system capabilities: (i) multi-node networked deployment to generate spatial emission distribution maps at the farm scale; (ii) integration of machine learning methods to improve event classification accuracy; (iii) incorporation into broader carbon emission monitoring frameworks as a basis for carbon accounting and potential carbon-trading schemes; and (iv) miniaturization into a wearable monitoring device, integrated into halters or head collars, to enable long-term, individual-level measurements of both methane emissions and associated behavioral patterns. Overall, the system exhibited strong cross-disciplinary application potential, showing particular promise as a non-invasive monitoring approach for daily farm operations and as a foundation for the development of intelligent, wearable technologies in future livestock management.

ACKNOWLEDGEMENTS

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