Real-Time, Low-Cost, Multiple Criteria Gas Sensing for Fire Applications

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Abstract

A multi-criteria gas sensing suite and supporting architecture was developed to support high density, low-cost, measurements of exhaust gas constituents through numerous large-scale fire testing. The resulting framework, designed to be flexible in sensor application, system scale, and form-factor, was implemented to create a resilient data collection network of sensor suites. The developed measurement devices provide accessibility to scalable gas analysis measurements. In addition to large scale fire testing, variants to the original sensor suites have been successfully implemented to capture spatially resolved gas dispersion measurements for natural gas leakage studies and applied to characterize the chemical heat release rate from battery energy storage testing.

Keywords: Fire Detection, Multi-criteria, Gas Sensors, Gas Sampling

Introduction

Multi-criteria gas sensing has long been shown to be advantageous in the detection of a fire, minimizing false alarms, and for use in determining heat release rate. Oftentimes however the sensors used are expensive and cannot readily be deployed for mass use, thus spatially resolved time-dependent gas data in fire environments is often difficult to come by. With the development of a novel sensor architecture platform and associated algorithms, the authors have developed a means for the monitoring of multiple gasses and other relevant parameters in a spatially dense manner. The architecture lends itself to a wide variety of sensor types (electrochemical, catalytic, SSD, NDIR, and PID) that are presently on the market and may be obtained for relative minimal cost in comparison to typical laboratory gas analyzers. A board and up to 10 sensors can be assembled for under $1000 USD.

The sensor suite developed has been successfully deployed in numerous large-scale burns tests, has been used as the framework architecture for detailed combustible gas dispersion measurements, and has been used to measure and calculate heat release rate (HRR) and off-gas concentrations from lithium-ion battery energy storage systems. Each application of the suite implemented the sensor suite architecture in a slightly different manner, however the underlying framework remained constant.

Motivation

A large-scale fire test series required nearly 300 different gas sensors be located throughout a test structure, maintaining a consistent quality of the data collection with a limited budget. Based on the requirements to measure concentrations for O_2, CO_2, CO, NO, NO_2, HCl, HCN, NH_3, volatile organic compounds (VOCs), and unburned hydrocarbons (UHCs) in nominally 25 different locations, it became apparent that standard gas analysis equipment would not be feasible from a cost or implementation perspective. As such, it was necessary to develop a system and supporting architecture to support the primary testing initiative. An ideal set of design parameters, summarized below, was developed to identify critical architecture requirements and bound the design initiative. Based on this conceptual system design, the basic hardware and system level architecture was developed.

- **Low Cost:** It was anticipated that individual sensors or entire sensor suites may be damaged during a given series of testing. Thus, the system would need to be inexpensive such that components can be readily replaced in the field prior to additional testing.
- **Flexibility:** Due to the spatial variations of the intended measurand throughout the test structure, the sensor suite should have the ability to accept a wide variety of sensor types, ranges, and output signals to allow the addition, removal, or substitution of sensors.
- **Resiliency:** As the sensor packages are intended to be placed into a fire or other adverse environment, the sensor suite should continue to operate in the event of multiple sensor failures. Failure of sensor components should not adversely affect the continued data collection from operational sensors.
- **Data Integrity:** Data collected should be transmitted in real-time to the data capture system. Additional on-board storage should also be present as an automatic backup if the ability to transmit data is compromised.
- **Scalable:** The overall architecture should be readily scaled from a single sensor suite to multiple suites with minimal effort thus allowing for high spatial density.
- **Flexible structure:** The suite should readily lend itself to a variety of different housings such that it can be integrated into numerous different environments based on the use case.

- **Streamlined Connections:** A single data and single power connection should be provided for each suite to streamline the implementation of sensor suites into applications. While the power and data requirements vary based on sensor selection, a uniform connection to the sensors shall be used to further streamline hardware connectivity.
- **Data Acquisition:** The sensor suite should not rely on any given software data acquisition system. Instead, the system should be flexible in the manner by which data is transmitted and recorded, thus enabling the use of low-cost or open-source architectures to collect an ethernet based data transmission.
- **Simplicity of Calibration:** The sensor suite should be simple to calibrate. Using calibration coefficients, the processed data should be available at the point of data storage along with the raw data collected.

Sensor Suite Development

The sensor suite architecture is built within the PlatformIO IDE, a platform-independent integrated development environment which relies on a decentralized architecture. The environment selected allows for extreme flexibility across various operating systems and has embedded support for more than 35 development platforms (e.g., Raspberry Pi RP2040, Espressif 32), 800 boards (e.g., Arduino, Adafruit, Sparkfun), and 20 frameworks (e.g., Arduino IDE, CMSIS). Core programming for this application was executed in C\#, Python, and Visual Studio.

Hardware Interface

The construction of the sensor suite is comprised of two primary hardware components: a main logic board, responsible for data collection and communication, and a set of individual sensor boards, configured for the specific sensors installed. The Arduino development platform was used within PlatformIO to develop the firmware required for data collection, processing, and communication. An ESP32 module, operable over a wide range of temperatures with ultra-low power consumption and featuring Wi-Fi and Bluetooth capability, was identified for this application based on cost, functionality, and flexibility. For purposes of data collection, the main boards feature 12 analog input channels (16 bit) that utilizes a programmable gain amplifier, auto ranged from 0-256 mV to 0-5 V based on the sensor requirements. Sensor breakout boards, designed for sensor mounting and communication, were developed to provide defined gain and bias voltages to the various types of sensors installed.

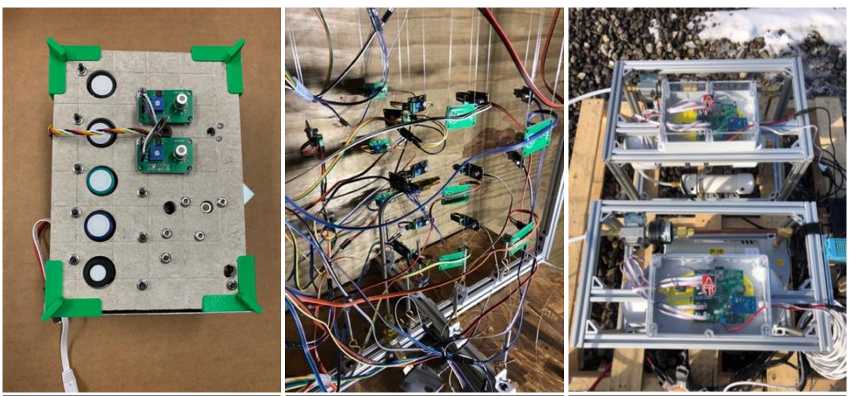
Software Platform

A Labview graphic user interface (GUI) was developed to control, document, and visualize the data collected from the main logic boards.

The custom-built script was designed to initiate data streaming from all connected boards simultaneously based on a selected configuration firmware set, pertaining to the installed sensors, and a user defined sampling rate. Measurements from all channels are simultaneously logged locally on each main board via a MicroSD card and streamed via ethernet where the signals are time stamped and recorded. Voltage values measured at each sensor are reconstructed from the digital signal based on the ADC configuration at the time of the measurement, scaled based on user defined calibrations and sensor configurations, displayed locally, and written to a data file. Collected data is sent to a producer/consumer programming architecture, applied within the Labview script, where the converted data is available for live calculations and data visualization processing. This process allows for a large volume of data packets to be continuously streamed from the main boards without inhibiting real-time calculations and visualization.

Applications

The sensor platform has been successfully implemented into several experimental programs and in the process has been improved to provide additional real-time measurement and analytical capabilities. In each of the highlighted use cases, the platform employed a different sensor configuration and was uniquely integrated into the test setup. A brief synopsis of each use case is provided below.



(a) Large-Scale Multi Gas Testing Box | (b) Spatially Resolved CH_4 Configuration | (c) Heat Release Rate Configuration

Fig. 1. Various implementations and use-cases of the sensor suite.

Large-Scale Multi Gas Testing

A series of large-scale experiments evaluating fire growth under ventilation limited conditions was conducted in which 25 sensor suites were placed throughout the two-story structure to monitor 10 distinct gasses (O_2, CO_2, CO, NO, NO_2, HCl, HCN, NH_3, VOCs, and UHCs) at each location throughout the duration of the test. While a single sensor suite is relatively inexpensive, it was desirable to extend the lifespan of each suite for as long as possible through implementation of a hardened enclosure. For this specific use-case a cement board box was built to house the main board and to provide protection to the individual sensor boards, with holes provided for the sensors to be in contact with the environment for measurement purposes, Fig. 1(a). Calibrations were conducted on each suite of sensors used in the testing; an example set of calibrations is shown in Fig. 2 for the array of sensors applied. During testing, data from each box was continuously streamed to the DAQ and user selected information was displayed on screen in real-time.

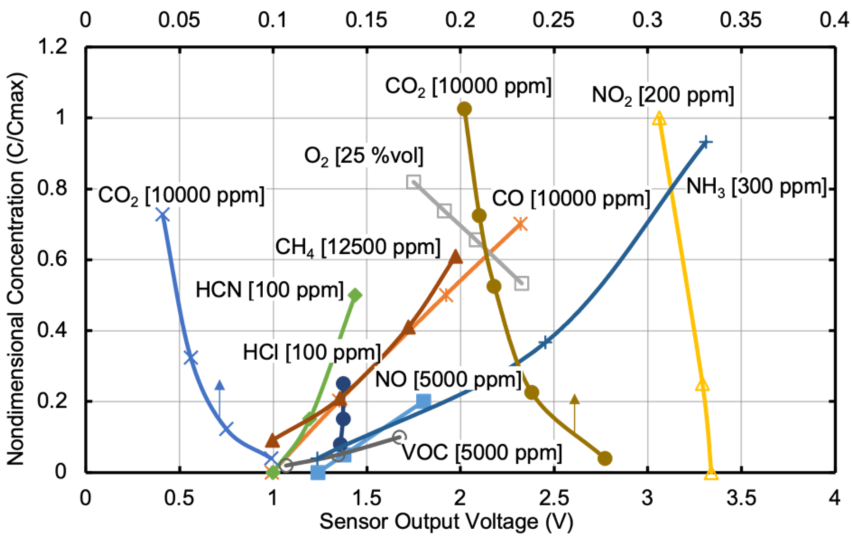


Fig. 2. Sample calibration set for sensor suite applied to testing.

Spatially Resolved Gas Concentration Measurements

Small gas leaks from appliances and appurtenances are highly influenced by the ambient conditions in the environment including temperature, humidity, and ventilation conditions. To gain a thorough understanding of the gas concentration of various release scenarios in the near field, a spatially dense sensor network was set up using exclusively CH_4 sensors. In total 52 CH_4 sensors were placed in a nominal 1 m^3 volume to measure gas concentration in radial and vertical profiles. The sensor boards were strung on 0.5 mm fishing line and could be readily adjusted along the Z-axis while the main support system allowed for an entire sensor string to be adjusted in the XY plane, Fig. 1(b). Evaluating the relative magnitudes of the gas concentration measurements, Fig. 3, the effects of leakage characteristics and ambient conditions on gas accumulation became evident.

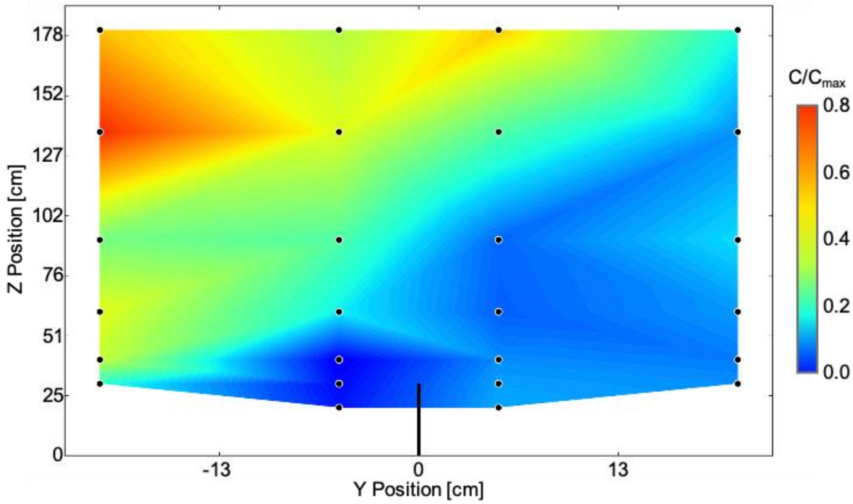


Fig. 3. Contour representation of relative methane concentrations.

<u>Heat Release Rate Measurements</u>

NFPA 855 and the International Fire Code require large-scale testing of battery energy storage systems above a certain size to demonstrate fire performance. Various test protocols applied require calculations of chemical heat release rate from the fire event through oxygen consumption calorimetry approaches, thus requiring real-time O_2, CO, and CO_2 measurements within the exhaust flow. For this application, the sensor platform was built into an active gas sampling system using a sample probe, cold water and moisture absorption system, pump, and sampling chamber, Fig. 1(c). In addition to the calorimetry gases, UHC and H_2 gas concentration measurements were captured with the sensor suite. Multiple sampling systems were deployed for redundancy and real-time gas concentration and HRR measurements were provided. HRR determined through oxygen consumption calorimetry was compared with the HRR calculated through mass loss, Fig. 4, and showed good agreement amongst various calibration heptane pool and propane sand burner fires. In a cross-analyzer study, the real time concentration measurements from a traditional gas analyzer configuration were compared to those collected simultaneously from the sensor suite developed. The measured gas concentrations showed good agreement between the two analyzer systems for the constituents analyzed and the resulting HRR rates were demonstrated to agree over the test duration with the mass loss measurements collected for the additional calibration burns conducted, Fig. 5.

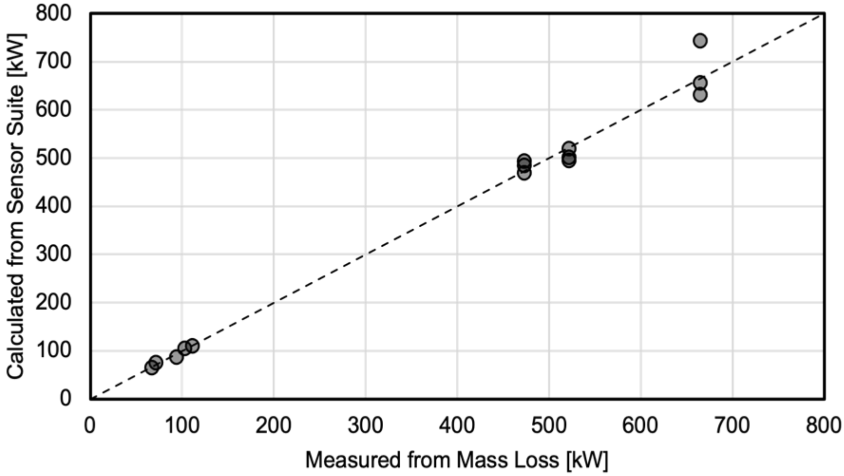


Fig. 4. Calibration of sensor suite heat release rate calculation.

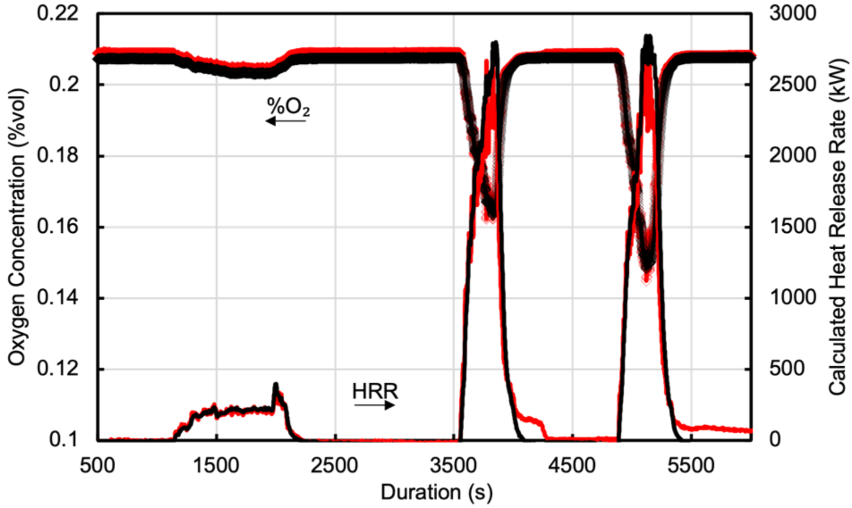


Fig. 5. Measured oxygen concentration and calculated heat release rate from traditional analyzers (red) and developed sensor suite (black).

Conclusions

The multi-criteria gas sensing suite and supporting architecture developed has demonstrated the accessibility of low-cost gas analysis measurements for use in fire testing. Initially designed to support high density measurements of exhaust gas constituents through a large-scale fire testing evolution, the developed framework has been successfully applied to numerous fire and life safety testing applications of varying scales. The flexibility to effortlessly scale the date collection system and interchange sensors enables the user of this, or a similar, framework to rapidly evolve with new sensor technologies and increase data densities within testing environments for minimal additional cost.

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