CHEMICAL ENGINEERING TRANSACTIONS

VOL. 91, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Valerio Cozzani, Bruno Fabiano, Genserik Reniers

ISBN 978-88-95608-89-1; **ISSN** 2283-9216

DOI: 10.3303/CET2291021

A Hazardous Area Personal Monitoring System for Operators in Gas Depots and Storage Tanks

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This work describes a smart monitoring system for the detection of flammable gas residues, toxic gases, and reduced oxygen concentrations. The proposed system aims at reducing the risk of fires and explosions, thus increasing the safety of workers engaged in maintenance or inspection of gas storages. The monitoring system is based on compact battery-powered wearable sensor nodes containing sensors for LPG flammable compounds, toxic gases, and oxygen. The designed system can also increase plants safety by incorporating an intrusion detection system, which prevents unauthorized access to safety-critical areas to prevent accidents. The sensor nodes transmit data through a LoRa low power radio channel to a remote server whereas they allow for the identification of the operators for the access to restricted areas exploiting a Bluetooth Low Energy (BLE) proximity technique.

1. Introduction

The worker safety in industrial hazardous environments is nowadays a critical issue especially in Oil&Gas, gas storage and distributions or chemical plants, where an explosive atmosphere may be present (Riad et al., 2020), and in which the consequence of a possible accident can be catastrophic (Kelava et al., 2008) (Powell et al., 2008) (Seveso, 2015). The focus of this paper is the development of a wearable monitoring system able to increase the operator safety in gas distribution and storage companies (Fan et al., 2019) (Haitao et al., 2014) (Fraiwan et al., 2011). The flammable and potentially explosive compounds considered are propane or mixture of propane and a smaller fraction of butane, due to their widespread use in heating systems not connected to natural gas pipeline. Companies that supply these mixtures, which at environmental temperature can be stored in liquid form and are generally called liquid petroleum gas (LPG), carry out refilling operations of the gas cylinders either inside plants or directly in customer deposits. During preliminary studies in collaborations with a company in the sector namely, *Petrolgas* in Florence, and Italian national institute for insurance against accidents at work (INAIL), the most common criticalities in the context of industrial hazardous environments have been analyzed with the goal of designing a monitoring system based on wearable smart sensing nodes aiming at reducing the risk of fires and explosions (ISPRA, 2013). The sensing part of the node hosts electrochemical sensors for oxygen and toxic gas detection and a catalytic sensor for LPG detection. While electrochemical sensors have a reduced power consumption, catalytic sensors require a relative high amount of power to operate. This issue has been solved by implementing an adequate powering strategy and exploiting a tradeoff between measurement accuracy, sampling time and energy requirements. The sensor node can generate alarms in case of low oxygen concentration and of potentially explosive concentrations of LPG. When the worker is inside the plant, the sensor node can transmit measurements data with a LoRa transmitter, which transmits periodic data to a gateway responsible for the reception of LoRa packets and for the final transmission of data to the network server (Abrardo et al., 2019). The gateway has a backhaul Internet connection needed to forward the data to a remote application server using a message forwarding protocol. This choice allows for low power consumption and a transmission range able to cover a standard plant area. The received data can be visualized, for example from the plant control room, or exploiting further processing, used to generate safety commands in presence of a potential hazard for the operator. The operator can be warned via alarm information

Paper Received: 16 January 2022; Revised: 27 March 2022; Accepted: 18 May 2022
Please cite this article as: Landi E., Parri L., Fort A., Mugnaini M., Vignoli V., Tamang D., Tani M., 2022, A Hazardous Area Personal Monitoring System for Operators in Gas Depots and Storage Tanks, Chemical Engineering Transactions, 91, 121-126 DOI:10.3303/CET2291021

sent from multiple sensor nodes. Moreover, the information received from the sensor node network is stored in the cloud server which can be accessed using the appropriate application programming interface (Tani et al., 2021).

2. State of the art

The interest in the development of innovative portable instruments for the detection of dangerous gas concentrations in hazardous working areas is increasing in the last years. This fact is also evident from the large availability of commercial products specifically designed to increase the safety of workers in refineries, chemical or Oil&Gas plants. There exists simple wearable battery powered gas detectors such as the *BWC series* devices from *Honeywell*, that can generate acoustic and vibration local alarms or more sophisticated devices like the *ALTAIR 4XR* series from *MSA* consisting in a detector of toxic and explosive gases with a Bluetooth connectivity or the *Honeywell QRAE* series that is also able to implement a mesh-like network in between devices connected to a proprietary centralized monitoring software. These devices can cover different application environments where different constraints such as battery lifetime, sensors lifetime, device physical dimensions or the need to be connected to a central monitoring station are required. Starting from the characteristics of a typical commercial device, this work aims to find a tradeoff between safety requirements, like measurement sampling frequency, and operation requirements, like battery lifetime, exploiting different technologies to design a flexible and scalable device that can be easily integrated in a monitoring platform through an open protocol. The designed device can generate alarms in case of dangerous concentrations of gases and periodically transmits data exploiting the LoRa wireless modulation and LoRaWAN network protocol to a remote server allowing the collection of data in a cloud platform. This data will be used in future developments to implement more accurate monitoring strategies to automatically detect possible criticalities, like gas leakages, with the possibility of integrating data from other sensors and systems already present in the plant.

3. Sensor node structure

The sensor node structure is shown in Figure 1, it is physically composed of two parts, the *Main Board* and a *Sensor Hat*. The *Main Board* contains a logic unit, a communication module and a power management subsystem and is connected to the *Sensor Hat* shield. The *Sensor Hat* has been designed to interface the gas sensors through specific front-end electronic circuits. The gas sensors used in this project are amperometric electrochemical sensors for the detection of carbon monoxide and oxygen and a catalytic sensor (frequently also called *Pellistor*) for the detection of propane, butane, and methane.

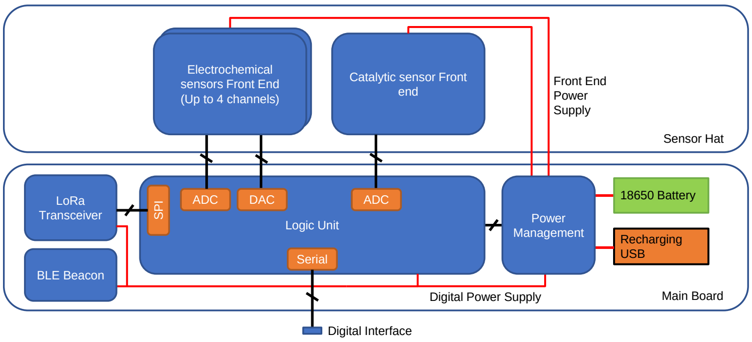

Figure 1 – Sensor node structure.

The *Sensor Hat* allows to host up to four electrochemical sensors and an infrared sensor for the detection of carbon dioxide. The infrared sensor and two electrochemical sensor slots are not used in this project, and they have been reserved for future device expansions.

The system is powered by a lithium battery (18650 type), the *Main Board* allows to recharge it by connecting a 5V USB charger (a standard smartphone battery charger). Figure 2, shows the 3D renderings and a photo of the sensor node with a plastic enclosure.

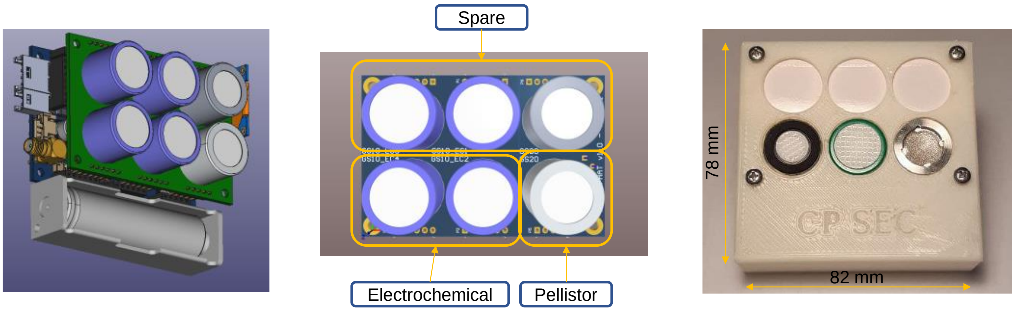

Figure 2 - 3D renderings and a photo of the internal structure and an enclosure of the sensor node.

The node package was designed to be attached, depending on the specific application, on the belt or on the helmet of the operator.

3.1 Main board

The *Main Board* is one of the two electronic printed circuit boards (PCBs) that compose the sensor node. From an architectural point of view, the *Main Board* can be considered composed by a *Logic Unit,* a *Power Management subsystem* and a radio interface consisting of a *Lora Transceiver* and *BLE Beacon*. The *Logic Unit* is based on a low Power ARM microcontroller (STM32L4QT5) by *STMicroelectronics*. The microcontroller embeds a 12-bit analog to digital (ADC) converter used to acquire the analog signals from the *Sensor Hat* board, this voltage signals are then converted to a gas concentration by the embedded firmware, exploiting calibration parameters that can be loaded on the node by a PC and a serial interface. The microcontroller also embeds a digital to analog (DAC) peripheral to generate specific voltage signals required in the *Sensor Hat* board to correctly bias the sensors as described in the next section. By specific digital outputs, the microcontroller can drive two power switches in the *Power Management subsystem* to power as needed the conditioning electronic circuits in the *Sensor Hat* board. The communication with the radio transceiver is implemented by an SPI bus. Finally, the *Main Board* embeds a buzzer for local alarms in case of dangerous gas concentrations detection and a Bluetooth Low Energy (BLE) beacon, detectable by BLE gateway. The detection of the node associated to an authorized operator can, for example, deactivate access alarms or unlock gates or doors in restricted access areas.

3.2 Sensors Hat

The *Sensor Hat* board implements the conditioning electronics based on low-power components, necessary to transform the sensors electrical signals to be acquired with the microcontroller ADC. The electrochemical sensors are essentially composed of three electrodes and an electrolyte material. On the surface of the electrode defined as *Working Electrode* (WE), that is exposed to the gas through a membrane, a redox reaction occurs. The complementary redox reaction occurs at the interface of the opposite electrode, defined *Counter Electrode* (CE) that is in contact with the WE through an ionic conductor (the electrolyte) and an electric conductor that is represented by the external conditioning electronic circuits as shown in Figure 3. Without entering the details, by measuring the electrical current that flows in between WE and CE, it is possible to derive the concentration of the target gas in the environment. The current generated by the sensor is amplified and converted into a voltage to be acquired with the ADC converter. The third electrode, named *Reference Electrode* (RE) is placed close the surface of the WE and it is used to maintain a specific potential (usually 0 V but it depends on sensor type) with respect to the WE, to guarantee the correct functionality of the sensor. This voltage is set by the DAC (V_{bias} in Figure 3) of the microcontroller, specific electronics is implemented to adjust the CE potential and keep it stable. The other sensing technology used is the catalytic sensor, which is composed by a pellet of catalyst loaded ceramic whose electrical resistance changes in the presence of combustible gases. The sensing element of this sensor needs to be heated, to trigger the chemical reaction. Obviously, the pellet resistance may significantly vary with the temperature, for this reason the sensor also contains an identical pellet that is not exposed to the gas, used as a reference element. By measuring the output of a voltage divider composed by the two elements (the sensing and the reference one), as shown in Figure 3, it is possible to compensate this parasitic effect. The measurement of the resistance is obtained through the voltage across the sensing elements, which is amplified and then acquired by the ADC.

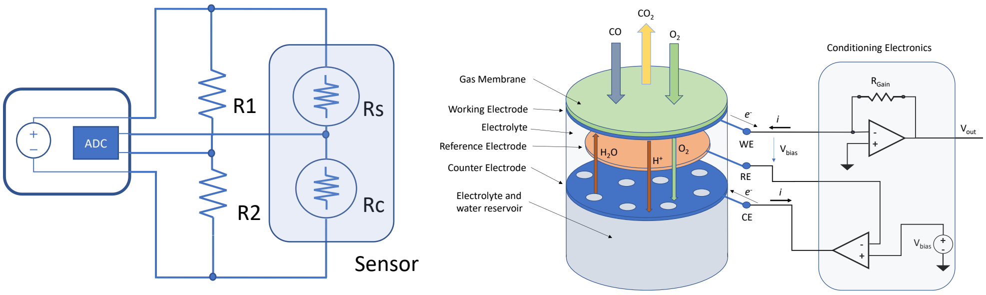

Figure 3 – (left): Conditioning electronics for catalytic sensors. (right): Conditioning electronics for electrochemical sensors.

3.3 Power consumption optimization strategy

The sensor node was designed using low-power components (Addabbo et al, 2019) (analogue and digital), based on a trade-off between power consumption and measurement performances. It is powered by a standard 18650 type lithium battery whose energy capacity is around 2000 mAh. For the target application, this amount of energy must be sufficient to cover at least one working week (5-6 days) recharging the device only at the end of the week. The two conditioning electronics for the sensors are very different in terms of energy consumption, the average energy consumption of electrochemical conditioning electronic is much less than the energy consumption of the catalyst sensor that is around 200 mW. The simplest idea to increase the battery lifetime, is to power off sensor conditioning electronics when the measurement is not performed but in practice this is not always possible. Gas sensors, usually require a considerable warm-up time before providing an accurate measurement. Electrochemical sensors may require some minutes before being operative, depending also on the front-end structure. In this application, it is not possible to turn them off, but this does not represent a big issue since the power consumption of the conditioning electronics is very small. On the other hand, the catalytic sensor requires a relatively high amount of energy to operate, but usually a stable measurement can be achieved warming up the sensor for approximately one minute. Table 1 is shows the battery lifetime considering a continuous operative mode (for higher risk environments where it is mandatory to continuously sample the presence of explosive and toxic gases to generate immediate local alarms). The power consumption was estimated by considering measuring and transmitting data every 2 minutes, powering up the catalytic sensor with a duty cycle of 50%, In this case it is possible to obtain a battery lifetime sufficient to cover 6 working days.

Table 1 – Power consumption analysis at full duty cycle

Sensors and Conditioning electronics power consumption for continuous operation				
Phase	**Device**	**Consumption (mW)**	**Total (mW)**	
Measurement/TX	Main Board	15	216.0	
	Catalytic Sensor	200		
	Electrochemical Sensors	0.66		
	Radio Module (1 TX every 120 s)	0.3		
Average cycle power consumption			216.0	mW
Battery capacity			7.4	Wh
Battery Lifetime			**34.3**	**h**

4. Sensors test

In this section the results obtained testing the system components in laboratory conditions and under known and controlled gas concentrations are reported. In detail, the system was tested exploiting gas mixtures at different concentrations, realized starting from reference gas tanks and a system based on a set of mass flow meters able to dose gas flows realizing the desired mixture composition under a constant total flow (100ml/min).

4.1 CO e O_2 sensors test

The results obtained by testing the CO and O_2 sensors and the designed front-end electronics are shown in this subsection. The used sensors are *Alphasense CO-A4* for CO and *Alphasense O2-A1* for O_2. In Figure 4, the test results obtained by applying calibration coefficients previously determined are shown. The tests show that with the designed electronics based on low complexity circuits and low-power components with limited performance, it is possible to obtain an accuracy of ± 2 ppm for CO in a 0 to 50 ppm range and ±0.5% for oxygen, sufficient for the application.

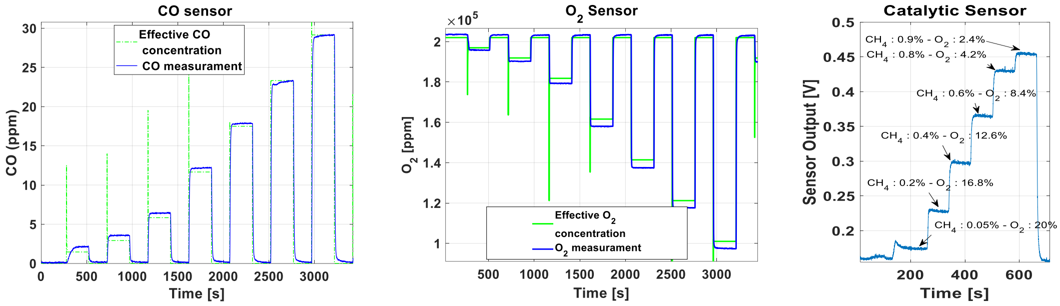

Figure 4 – CO and O_2 electrochemical sensor tests and catalytic sensor test with methane.

4.2 Catalytic sensor test

The results obtained by testing the catalytic sensor (*CH-A3* from *Alphasense*) and the designed front-end electronics are shown in this subsection. From Figure 4 it is evident that the sensor with the designed conditioning electronics can detect concentration lower than 1% of methane with a good resolution. The sensor detects, with different sensitivity, butane propane and methane, the sensitivity of the sensor toward methane is the lowest one (butane and propane sensitivity is 150% of methane sensitivity), this is the reason why this sensor was tested with this gas. The minimum explosive level (LEL) for methane is 5% while for butane is 1.8% and for propane is 2.1% in volume. For example, the sensor that was calibrated, and whose test is shown in Figure 4, exhibits a response of 2%/V (assuming as the output of the sensor a voltage as shown in Figure 3). This means that (from the producer specifications) the response toward propane and butane is 3%/V (150% the sensitivity to methane). Considering the LEL values we have that the LEL of methane corresponds to 2.5 V (5%), the one of butane (1.8%) to 0.6 V whereas the LEL of propane (2.1%) gives 0.7 V. From these considerations it is possible to set the alarm threshold for this sensor to 0.5 V having a good safety margin for all these gases.

5. Network architecture

The data collected from the developed sensor nodes must be transmitted to a central server through a reliable wireless communication technology. In this regard, LoRaWAN emerges as potential solution due to its advantages in terms of communication requirements and installation costs. This technology provides a far longer range than WiFi or Bluetooth connections (Mekki et al., 2019), and it is applicable for indoor as well as outdoor scenarios, especially in the areas where the cellular networks have poor connectivity. It is an open-source wireless communication technology, which uses unlicensed band and is composed of LoRa physical layer and a Medium Access Control (MAC) layer. The network architecture is deployed in a star-of-stars topology. The Network server is responsible for managing data rate setting for each end-device by means of an Adaptive Data Rate (ADR) scheme with the aim of maximizing both the battery life and network capacity. It also performs the tasks of de-duplicating the packets received from multiple gateways and forwards a single packet to the application server. With the aim of developing a complete end-to-end ad-hoc network infrastructure, we integrated our sensor node with Hope RFM 92/95 transceiver module (Hope RF. RFM95/96/97/98(W)) which transmits data at the physical layer using a LoRa modulation. The sensor nodes are configured by the serial interface with the node ID and LoRaWAN keys using a standard activation by personalization method (ABP). The nearby gateway installed inside the plant receives the packets and forward the messages to the central network server using it's backhauled IP connectivity. This choice allows for low power consumption and a transmission range able to cover a standard plant area. In this way, it is possible to view and analyse the received data, which can be further exploited, with further processing, to generate safety commands in case of hazardous alarm information from the sensor node. Moreover, the information received from the sensor node is stored in the cloud server which can be accessed by a web page or a specific application programming interface (Tani et al., 2021). As for the choice of gateway, an open source *LPS8 LoRaWAN Gateway* by *Dragino* is used, which provides long ranges at low data-rates with 10 parallel demodulation paths. We rely on an open source *Chirpstack LoRaWAN Network Server* stack which provides each component to realize an overall network infrastructure that can be installed locally or in a cloud platform.

6. Conclusions

This work shows the design of a new wearable device for the detection of some toxic and explosive gases. From the tests it was shown that even using a cheap and low power electronic system and standard commercial sensors it is possible to obtain sufficient measurement accuracy to implement safety monitoring for hazardous areas. Compared with the most diffused commercial devices, the developed sensor node can operate for one working week without recharging its battery. The system can host different sensor types allowing to read almost all available commercial sensors for portable devices. Moreover, it implements a long-range communication protocol that, at the same time, allows to transmit data in a range able to cover the area of typical Oil&gas or chemical plants (1-2 km depending on area morphology) and save battery energy. The wireless network is scalable, with additional gateways it is possible to increase the operating area without changing the system architecture. Future developments will be performed in the server side, implementing specific data post processing, also based on Machine Learning algorithms, integrating data coming also from other sensors that can be already present on the plant to automatically detect the insurgence of critical situations.

Nomenclature

dBm – Decibel milliwatt, Power expressed as $10\ log_{10}\left(\frac{Power[mW]}{1mW}\right)$

Acknowledgments

The work was funded with the project CP-SEC, the authors wish to thank Dr. Paolo Bragatto (INAIL) for the useful suggestions that have been very useful for the final design of the system.

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