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A wireless sensor–actuator system for hazardous gases detection and control

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ABSTRACT

Wireless Sensors Networks (WSN) have recently been applied in a number of hazardous gas detection applications. The state-of-the-art works make an emphasis on sensing and delivering of alert message over the WSN to an operator. Instead, in this paper, we propose a wireless sensor–actuator system which aims at quick gas detection and immediate isolation of gas leak source. The low power wireless sensor node includes catalytic gas sensors, micro processing unit and wireless transceiver which communicates with wireless actuator using ZigBee/IEEE802.15.4 standard and BACnet protocol. Wireless actuator consists of power management circuit, micro processing unit and gas valve. The experimental results demonstrate the sensor node long lifetime while fulfilling performance requirements, quick detection of a hazardous gas and fast actuation time.

1. Introduction

In the last two decades, the Wireless Sensor Network (WSN) paradigm has taken hold of the minds – WSNs has been adapted to a great number of applications [1–3]. Indeed, tiny wireless sensor nodes can be deployed in difficult-to-access areas, ensuring autonomous monitoring of physical conditions and delivering the data to a user over the network. However, energy resource onboard, e.g. a battery, is a limiting factor preventing the application of WSNs in hazardous and combustible gases monitoring domain where gas sensors are typically power hungry devices.

Monitoring of combustible gas leaks is the problem of vital importance at gas production enterprises and landfills: if not properly detected, a gas leak can result in human victims and pecuniary loss. The sensor nodes can support an operator in detecting of a damaged (not leakproof) boiler or a gas leak in a gas infrastructure. Wired gas monitoring systems have disadvantages related to difficulties with wiring, vulnerability and inflexibility of wired communications. Moreover, in case of monitoring gases with different densities, it is necessary to distribute sensors at various height levels. It leads to extra troubles with wiring. In contrast to wired solutions, WSNs are more suitable and flexible for the task of continuous environmental monitoring in large areas.

A number of approaches have been proposed recently for gases monitoring using WSNs. The first approach involves the application of low power sensors implemented using *chemical sensing films* [4,5]. The sensor nodes employing the gas sensors of this kind are characterized by long term operation, but fail to meet the standard safety requirements [6] on early gas leak detection. The second approach involves the application of power hungry *spectroscopy based sensors* [7] onboard of autonomous WSN devices. These sensors can consume up to 500 mA, but are featured by high selectivity and fast response time that ensures safe and early hazardous gases detection.

The employment of *catalytic or semiconductor sensors* [8] is a viable trade-off between film and optical based approaches for gases detection using WSNs: they are more energy efficient than optical based solutions and, at the same time, have better response time, selectivity and sensitivity than film based solutions. In this work we use catalytic sensors.

Focusing on gas sensing [9,10] and communication of alert messages over the WSN to an operator [2], the problem of immediate actuation, that is obviously an important action to prevent an accidental situation, is not well investigated in the literature. Closing a gas valve blocks the damaged boiler or a gas pipeline to prevent the leak of significant gas concentration while expecting the actuation command from an operator.

The goal of this paper is to demonstrate a wireless sensor–actuator system, which contains a wireless sensor node and wireless actuator that efficiently detect and react on gas leak in time. The practical contribution of this work is twofold:

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- *Sensing circuit:* We implement and demonstrate an energy-aware gas sensor node which ensures early gas detection. Upon detection the node wirelessly communicates with the actuator to close the source of gas emission.
- *Wireless actuator:* We develop an integrated wireless actuator. The sensor node can wirelessly actuate a gas valve. This enables us to integrate sensing and actuator capabilities in a single network rather than having them separately.

The rest of the paper is organized as follows. Section 2 introduces the reader with the related works in the field. Section 3 presents the design of sensor–actuator system. Experimental results in terms of response time of the sensors, power consumption of sensor nodes, and average actuation time are discussed in Section 4. Finally, we provide concluding remarks in Section 5.

2. Related work

When designing an energy-constrained embedded system like a WSN node [25] with a power-hungry sensor, designers typically focus their attention on energy efficient sensing technologies (sensors), relevant sensing platforms, and intelligent approaches, which can help further reduce the node power consumption. Since overviews of sensor technologies are widely presented in the literature [12,13], in this section we discuss power consumption (and its analysis in WSN) of gas sensing platforms relevant to our work and overview the actuation approaches proposed recently.

The results of this work in terms of power consumption of the sensing circuit improve the state-of-the-art on hazardous gas detection using WSN paradigm. The Wobscholl [14], Flyport [15], and Wasp mote [16] platforms are based on catalytic and/or semiconductor sensors and consume 1000, 800, and 750 mW, respectively. The Wobscholl node is an "R&D" prototype ensuring automatic calibration. In contrast, Flyport and Wasp mote are commercial platforms. They require frequent calibration and may result in inaccurate gas measurement due to only one sensor embedded in the sensing circuit that ignores environmental effects. The wireless sensor node proposed in Ref. [17] is based on two sensors in Wheatstone circuit. This work significantly reduces the power consumption of gas sensor nodes (up to 264 mW). The result is achieved due to careful power-aware platform design and pulse heating profile for the sensors. The pulse heating profile is realized by frequent turning on/off of heating pulses. The application of this approach may result in *inaccurate measurements* since the moisture does not fully evaporate from the sensor surface and lead to *sensor damage* because of frequent heating pulses variation. In this work, we apply constant heating profile to ensure full moisture evaporation and avoid the sensor damage. To the best of our knowledge, the lowest power consumption solution for sensor nodes based on catalytic sensors is proposed in Ref. [18] and is 124.3 mW. To achieve this result, the authors "substituted" a reference sensor in Wheatstone circuit by complex four stage heating profile. The sensor response is measured between heating pulses of different amplitude in contrast to measuring sensor response from active and reference sensors as it is done in Wheatstone circuit. This approach helps to significantly reduce the power consumption, but has a number of drawbacks: (i) extra hardware is required to filter and amplify measured signal, (ii) four stage heating profile must be carefully adjusted.

Our design ensures reliable operation of sensor node in line with safety requirements [6] and low power consumption (w.r.t. the wireless sensor nodes based on Wheatstone sensing circuits) as of 227 mW by applying improved hardware.

The power consumption can be further reduced by applying the state-of-the-art techniques such as context-adaptive sensing [12] which requires an extra PIR sensor, the Internet of Things with cognitive technologies [19], careful power consumption analysis using WSN simulator [20], and application of on-board intelligence [21,22]. Alternatively, the application of energy harvesting technologies [23] can improve the sensor node lifetime.

Works [17] and [18] discuss the problem of actuation, but do not demonstrate actual design of actuators and do not estimate the actuation time. Flyport [15] and Wasp mote [16] platforms have 'plug and play' wireless actuators for visual and/or sound alarming. These actuators, clearly, can notify the service personnel, but cannot block the source of gas leak. Designs proposed in Ref. [10,14] focus on sensing of hazardous gases and do not address the actuation problem. A home automation ZigBee-based system proposed in Ref. [27] is integrated with WiFi network to allow a user to control the house via the Internet. A radiator valve used in this work is controlled using a sensor node. This actuator has a battery power supply. Since the application studied in this work is not an emergency one, the actuation time and power consumption are not evaluated.

The advantage of our design includes integration of sensing and actuation capabilities in one wireless system which can promptly react on dangerous situations.

3. System design

In this section, we first make the system's overview and then describe its design in more details.

Fig. 1 shows typical composition of a WSN for hazardous gases detection. Wireless sensor nodes monitor environmental conditions and in the case of dangerous gas detection notify a WSN operator sending an alert message over the WSN/network. In parallel, a sensor node can perform actuation action, e.g. close a gas valve, to block possible gas emission. Actuation of gas valve can be executed faster than sending an alert message to the operator and waiting for his decision. As specified in Section 1, most of the state-of-the-art works investigate *sensor node-operator* chain [2,12]. In this work, we focus on *sensor node-actuator* chain and present the design of energy-aware wireless sensor node and wireless actuator in this section.

3.1. Wireless sensor node design

Catalytic gas sensor is the main power sink onboard of sensor nodes for hazardous gases detection [17]. The system configuration was designed with the low-power consumption requirement in mind to ensure the long-term operation while retaining high performance of the design. The sensor node is composed of a control unit, a sensing circuit, a radio transceiver, and a power supply.

Control unit: The designed wireless gas sensor node is controlled by the embedded Micro Controller Unit (MCU) ADuC836, *DD4*. It is specified for 3 V operation and has 8051 MCU core, two independent 16-bit Σ–Δ analog-to-digital converters (ADC), digital-to-analog converter (DAC), on-chip Flash/EE memory, power supply monitor, power-down mode with wake-up timer. These features make it suitable for the portable battery powered embedded systems.

Radio: The node is connected to the WSN via the ETRX3 module, *DD3*. It is the 2.4 GHz ISM band ZigBee/802.15.4 transceiver which has +3 dBm output power, −98 dBm sensitivity and small current consumption in sleep mode. The ZigBee transceiver is operated by AT commands which are transmitted through UART interface of the ADuC836 at baud rate 19,200 bps.