



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



Andrey Somov^{a,*}, Alexander Baranov^b, Denis Spirjakin^b

^a CREATE-NET, Via alla Cascata 56/D, 38123 Trento, TN, Italy

^b "MATI" – Russian State Technological University, Orshanskaya 3, 121552 Moscow, Russia

ARTICLE INFO

Article history:

Received 3 January 2014

Received in revised form 17 February 2014

Accepted 18 February 2014

Available online 28 February 2014

Keywords:

Catalytic sensor

Power management

Sensor actuator system

Wireless sensor network

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.

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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:

* Corresponding author. Tel.: +39 0461 408400x1406; fax: +39 0461 421157.
E-mail address: andrey.somov@create-net.org (A. Somov).

- **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.

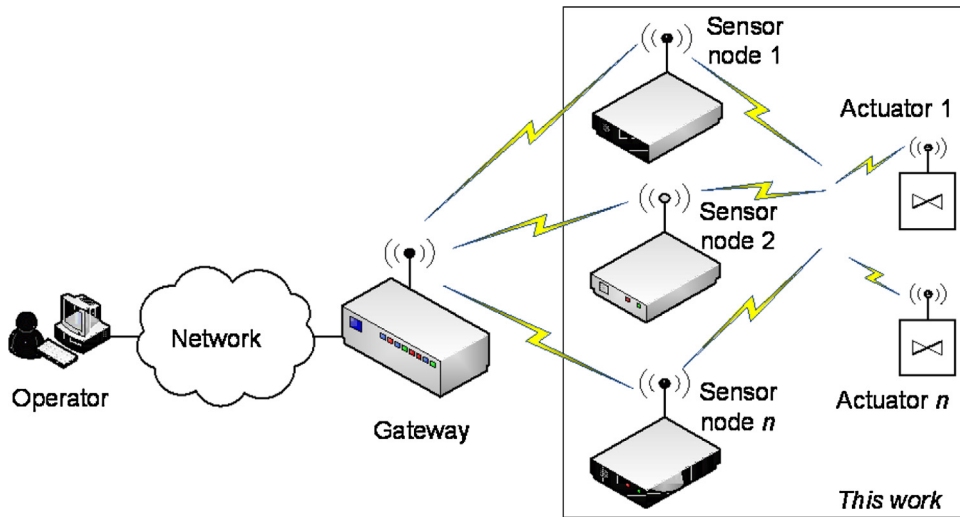


Fig. 1. Schematic diagram detailing gas WSN operation and showing the focus of this work.

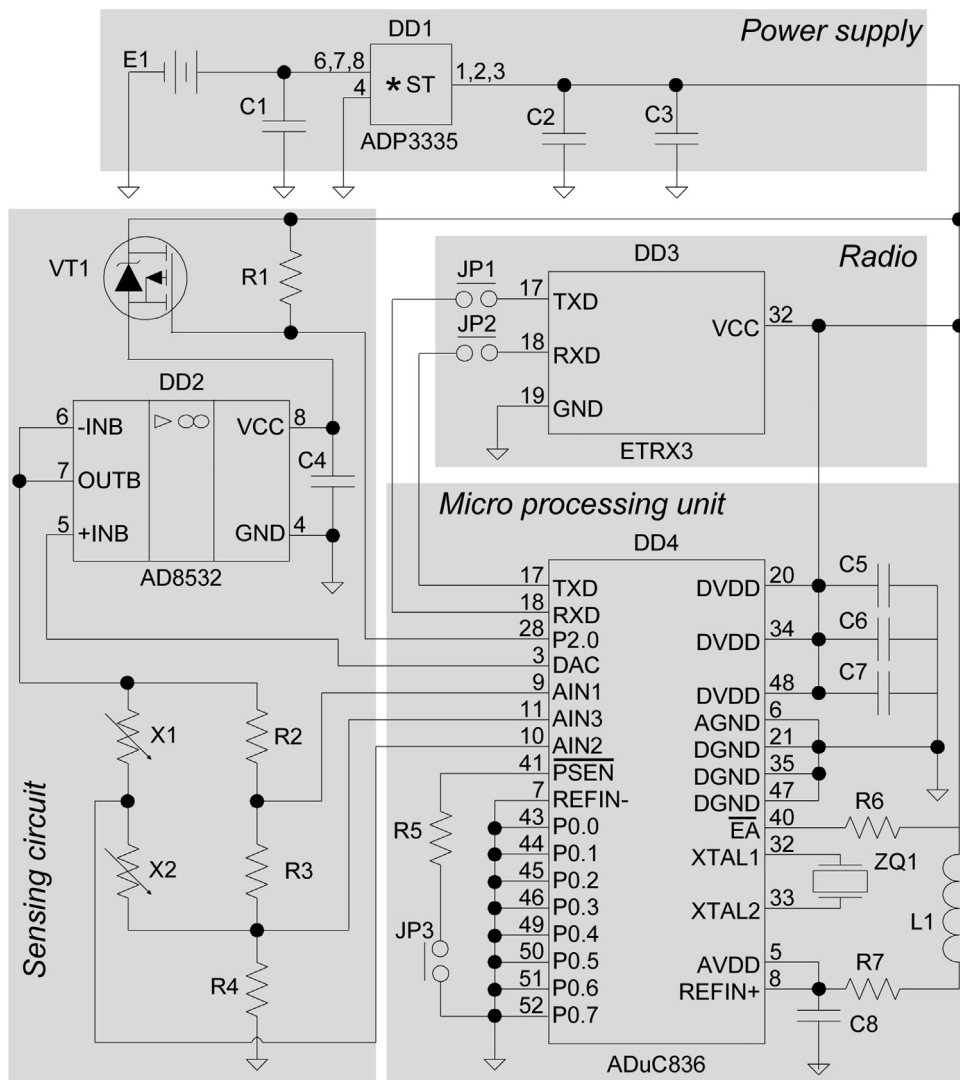


Fig. 2. Circuit schematic of wireless gas sensor node.

Power supply: The node is supplied by two Li-ion batteries of D type (3.6 V, 15,000 mAh) wired in series. E_1 in Fig. 2 shows the resultant power source. Battery power supply is stabilized to 3.3 V by low-dropout voltage regulator ADP3335, DD1, which accepts input voltage in 2.6–12 V range. The challenge in the selection of power supply circuit consists in the gas sensor which is a measuring device influenced by ambient conditions and noise. In this specific case, the sensor node is based on the catalytic sensor that must detect even negligible deviation of a complicated analogue signal. Linear regulators have low level of noise with respect to DC/DC, but at the same time are characterized by low efficiency due to the power dissipation on a regulating element. For example, the effective measuring circuit voltage response lies in the range of tens of μV up to a few mV (depending on a design of measuring circuit). That is why the main objective of the power supply circuit is to ensure the low level of noise in the circuit.

To increase the long-term operation of sensor node we plan to employ the energy scavenging technology, e.g. harvesting of indoor/outdoor light [26], for the batteries' replenishment.

3.1.1. Sensing circuit

Sensing circuit (see Fig. 2) is based on the Wheatstone bridge [24]. Operational amplifier AD8532, DD2, is used as a current buffer for the power supply of the sensing circuit. It is connected to the DAC output of the ADuC836, DD4, and switched by toggling the MOSFET IRLML6302, VT1.

The resistance of R_2 and R_3 is 1 k Ω each. The resistance of R_4 is 1 Ω and we wire it in series to the Wheatstone circuit to measure the heating current for the sensors. The heating current is measured by measuring R_4 voltage drop and applying Ohm's law. R_4 can be removed in the final prototype.

The Wheatstone bridge includes reference and active catalytic gas sensors of pellistor type [13], X_1 and X_2 , respectively, manufactured by NTC-IGD, Russia. Each sensor has platinum microcoils with thickness 10 μm covered by quartz isolation (2 μm). In the active sensor, X_2 , the microcoils covered by porous gamma alumina oxide impregnated by catalytically active metals (mixture of Pd and Pt). The reference sensor, X_1 , has only the microcoils covered by porous gamma alumina oxide material without catalytically active metals. Both reference and active sensors are placed in one package. It should be noted that a semiconductor sensor with similar technical parameters can be used instead of the catalytic one.

Alteration of the microhotplate resistance R_m depends on its temperature T_{sens} , which is related to catalytic gas combustion:

$$R_m(T_{\text{sens}}) = R_0(1 + \alpha(T_{\text{sens}} - T_0)) \quad (1)$$

where R_0 is the resistance of sensor at temperature T_0 (e.g. $X_2 = 11.7 \Omega$ at $T_0 = 20^\circ\text{C}$), α is the temperature coefficient of resistance (0.0027/ $^\circ\text{C}$ in our case).

Sensing circuit is enabled by switching on the current buffer then DAC output voltage setups on the Wheatstone bridge ($V_{W,\text{bridge supply}}$). The sensors rapidly reach the temperature at which gas combustion occurs ($T_{\text{sens}} \geq 450^\circ\text{C}$) due to high current which is passed through the sensors. Temperature of the active sensor T_{X_2} is derived using (1):

$$T_{X_2} = T_0 + \frac{(R_m/R_0) - 1}{\alpha} \quad (2)$$

Temperature of T_{X_2} can be estimated in details as (3):

$$T_{X_2} = T_0 + \left(\frac{0.5(V_{W,\text{bridge supply}} - V_{R_4}) - V_{W,\text{bridge output}}}{(V_{R_4}/R_4) - (V_{W,\text{bridge supply}} - V_{R_4})(R_4 + R_3)} - 1 \right) / \alpha \quad (3)$$

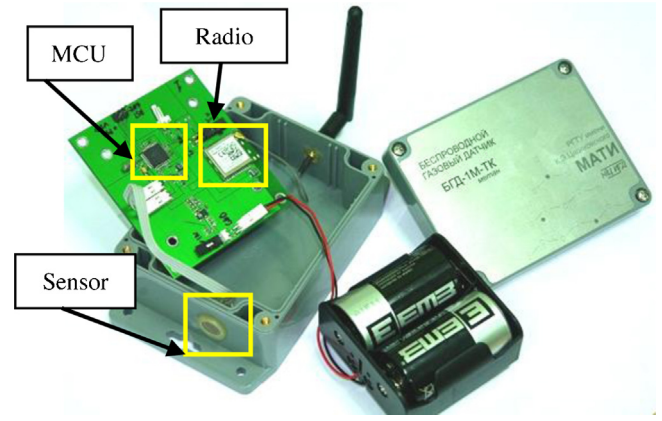


Fig. 3. Sensor node prototype with main parts highlighted.

where

$$V_{W,\text{bridge supply}} = \frac{DACL_{SFR_{\text{value}}} \cdot V_{\text{ext.ref}}}{256} \quad (4)$$

$$V_{R_4} = \frac{ADC1H/L_{SFR_{\text{value}}} \cdot V_{\text{int.ref}}}{65536} \quad (5)$$

$$V_{W,\text{bridge output}} = \frac{ADCOH/M_{SFR_{\text{value}}} \cdot 2V_{\text{int.ref}}}{65536} - V_{\text{int.ref}} \quad (6)$$

where $DACL$, $ADCOH/M$, $ADC1H/L$ – Special Function Registers (SFR) related to DAC and ADC of ADuC836 (more detailed information is provided in the MCU datasheet, $V_{\text{ext.ref}}$ – external reference voltage (3.3 V), $V_{\text{int.ref}}$ – internal reference voltage (1.25 V), $V_{W,\text{bridge out}}$ – the Wheatstone bridge output voltage, 256 and 65,536 are DAC and ADC resolutions, respectively.

The sensor node prototype is shown in Fig. 3.

3.1.2. Sensor calibration and remote programming

When fabricated the sensor is typically programmed by the manufacturing company. The sensor's technical specification provides the calibration values which should be programmed into the memory of micro processing unit of sensor node by a user. However, during its operation the sensor parameters degrade which necessitates periodical calibration approximately every year.

To calibrate the sensor, its output response voltage for a detected and known gas concentration has to be measured and recorded in the memory of the sensor node. The remote calibration of the sensors starts with the sensor node 'wake up' and its setting in calibration mode. While in this mode, the user can remotely set up the thresholds for gas detection and set other important parameters, e.g. measurement time, device ID.

3.1.3. Sensor node operation

The algorithm of the wireless sensor node operation is presented in Fig. 4. It is implemented in C language in Integrated Development Environment (IDE) "Keil μVision ".

The sensor node starts its operation with the initialization of MCU and wireless transceiver. Then sensor node periodically measures the gas concentration in the environment. To do so, the sensors have to be heated up to a predefined temperature (450 $^\circ\text{C}$ for methane). The heating signal is generated by MCU DD4 and operational amplifier DD2 (see Section 3.1.1). During the sensing mode the voltage on the sensor sensitive layer, also known as 'sensor response', is measured by a built-in ADC of MCU. The measured value is processed and compared with a preset threshold specified in the memory of the sensor node. If the measured methane concentration exceeds 1% vol. threshold, the node checks the status of the valve stored in its memory and if the valve is opened the

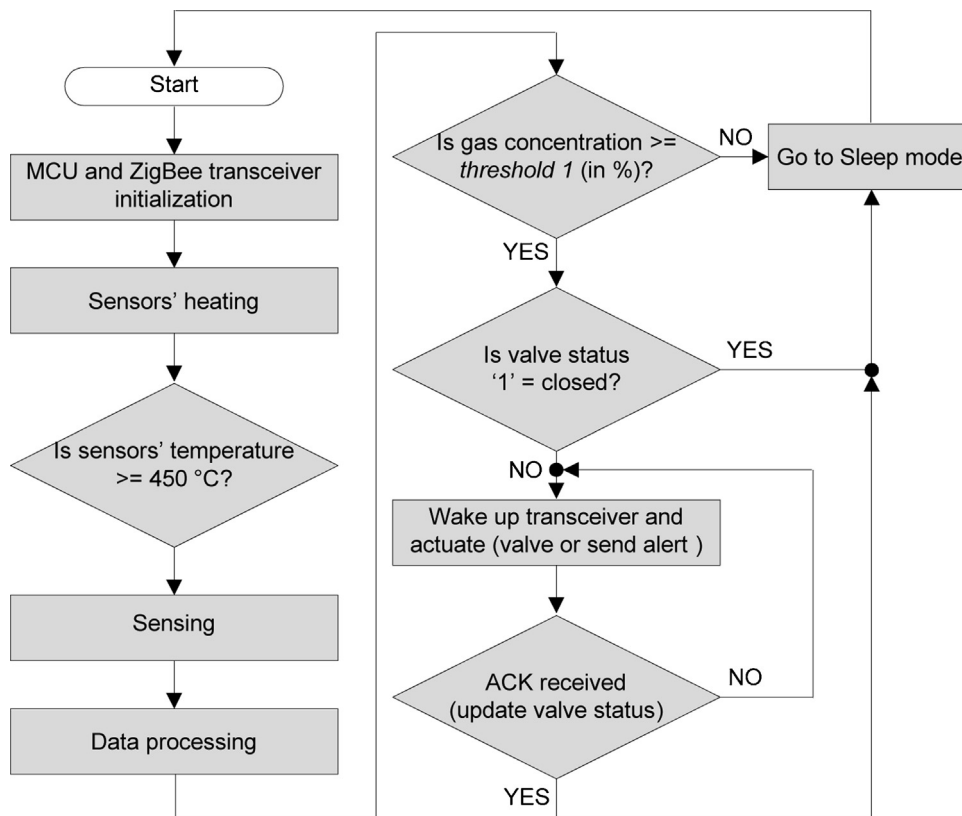


Fig. 4. Flowchart of the firmware for the embedded microcontroller of the wireless gas sensor node.

node activates ZigBee transceiver and sends a request to wireless actuator to close the gas valve. When the valve is closed and the acknowledgement is received by the sensor node it goes to Sleep mode. In the alternative situation, i.e. the concentration threshold is not exceeded and gas valve has been already closed, the sensor node goes in Sleep mode as well.

It is worth noting that the algorithm presented in Fig. 4 can be easily extended: upon detection of dangerous concentration of gas in the environment the sensor node can also notify a WSN operator by sending an alert message as it is shown in the algorithm. This situation, however, is out of scope of this work.

As specified in Section 4.1, we conduct the experiments on methane detection. For methane, the lower limit of its explosion is 5% vol. [6]. The dangerous situation occurs when methane concentration is up to 1% vol. and the system closes the gas valve. When the concentration is equal or below 0.15% vol. an extra measurement is typically conducted [17]. This is done in order to monitor the status of environment and capture in time a potentially dangerous situation.

3.2. Wireless actuator design

The wireless actuator consists of three blocks: power management, control unit with transceiver, and the set of relays turning on/off actuators. The block diagram of wireless actuator is shown in Fig. 5. The sensor node actuates the gas valve wirelessly relying on ZigBee/IEEE 802.15.4 standard. Data transmission is realized at 2.4 GHz frequency with bit rate up to 250 kB/s using BACnet protocol [11]. This communications protocol was designed for building automation and control networks. It enables the communication of building automation and control systems for applications such as Heating, Ventilating, and Air-conditioning Control (HVAC), access control, fire detection systems and their associated equipment. The

goal of BACnet is to provide the mechanisms for computerized building automation devices to exchange messages, regardless the service they perform.

The operation and control of wireless actuator shown in Fig. 6, is enabled by software algorithms implemented and programmed on onboard Micro Processing Unit (MCU) STM32F102C6. A user can upload software to MCU using JTAG interface. For precise control of input signals in the micro- and nanoseconds range, the wireless actuator has to be calibrated properly. The calibration notices are recorded in EEPROM M95640 which is connected to MCU using SPI. Apart from the information on calibration, the memory chip stores the information on the occurring events, e.g. emergency.

Wireless communication of actuator is enabled, as on the sensor node, by ETRX3 chip interfaced with MCU by UART. The transceiver is operated by AT commands from MCU.

For the wireless actuator stationary power supply is used. Power management block converts 220 V AC-based power signal into DC 24 V one (3 A maximum) and then divides this primary DC output

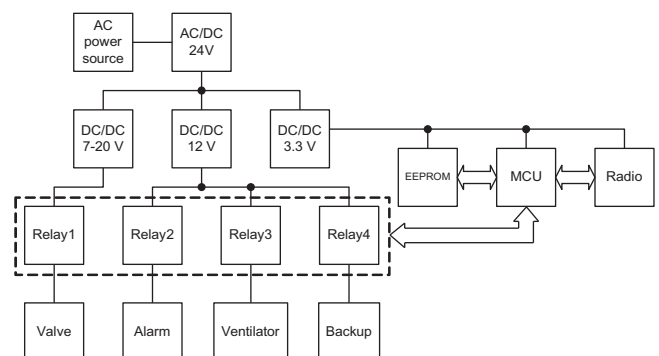


Fig. 5. Block diagram of wireless actuator.

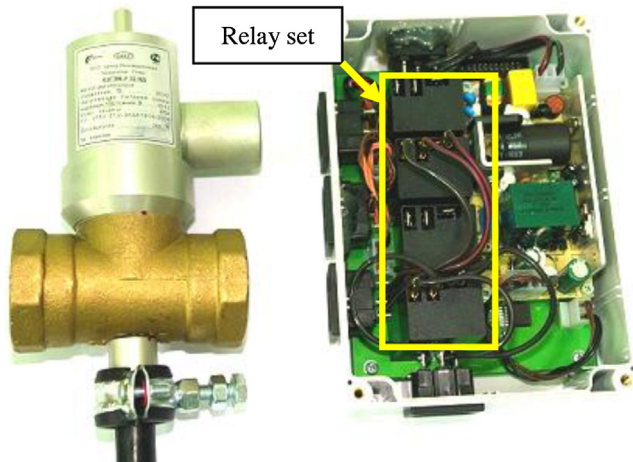


Fig. 6. Wireless actuator with unmounted gas valve.

into three DC sub voltages. The first sub DC source can be adjusted between 7 and 20 V and is used to control gas valve through a Relay 1. The output voltage can be adjusted by a voltage divider and digital potentiometer controlled by MCU. The valve is 5/4", the actuation voltage is 20 V (its standby voltage is 7 V) and pickup current is about 1 A.

The second sub DC/DC output is fixed at 12 V and serves to supply and control the relay set with other actuators, e.g. sound alarm and/or ventilation, that are not used in this work. The last sub DC/DC generates 3.3 V to supply control unit that includes MCU with memory and radio ZigBee transceiver.

4. Experimental results

In this section, we evaluate the performance of sensing circuit in terms of gas detection and consecutive response time. We also estimate its power consumption in active (sensing) mode and lifetime of sensor node. Finally, we conduct an experiment on defining the time required to detect methane, react on this event by closing the gas valve and sending an acknowledgement to the sensor node.

4.1. Response time

In this experiment we evaluate the response time of sensing circuit with respect to applied heating voltage. To do so, we generate on the output of MCU eight heating voltage levels in the range of 1.4–2.8 V. Different voltage levels result in different temperature the sensors are heated up that affects the response time.

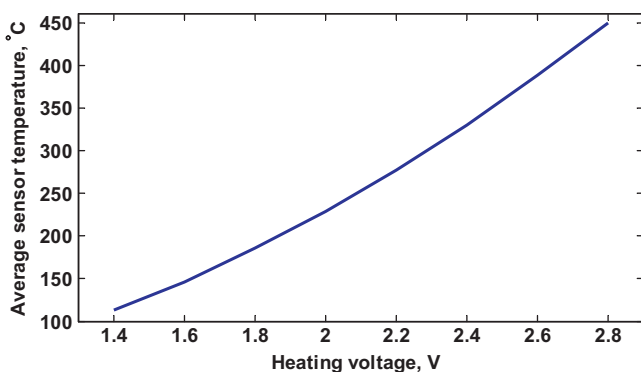


Fig. 7. Average sensor temperature in standby mode in normal conditions w.r.t. heating voltage.

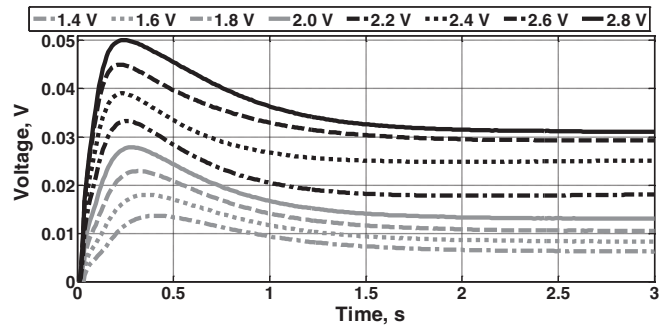


Fig. 8. Wheatstone bridge (sensor) response in volts at 0.26% CH₄ and 20 °C w.r.t. applied heating voltage (1.4–2.8 V).

Fig. 7 demonstrates the average values of sensor temperature in standby mode with respect to the heating voltage supplied from MCU. The curve is derived experimentally.

Figs. 8 and 9 show the response voltage of sensing circuit at room temperature of 20 °C in the presence of 0.26% CH₄ and 2% CH₄, respectively. Fig. 9 demonstrates higher amplitude of response voltage than the one shown in Fig. 8 due to higher concentration of CH₄ in the environment. The response voltage for both cases is stabilized between 1 and 1.5 s after the start of heating. The first critical point in the range of 0–0.5 s (see Fig. 9) appears when the sensor temperature reaches the value at which methane began the burning on the catalyst.

The points of local maximum observed in Figs. 8 and 9 are related to the mass difference of sensing and reference sensors that result in different heating speed.

4.2. Power consumption and lifetime estimation

The heating voltage of 2.8 V is used to heat the sensor(s) up to 450 °C operational temperature.

The heating time for the sensors in the Wheatstone circuit is 1.3 s (see Fig. 10). The average constant current flowing through R₄ (see Fig. 2) during heating is 81 mA that results in 227 mW of power consumption in continuous measurement mode. Under these conditions and power supply specification provided in Section 3.1 the sensor node can support approximately $(7.2 \text{ V} \times 15000 \text{ mAh}) / 227 \text{ mW} = 475 \text{ h}$ of continuous operation.

We estimate the battery lifetime for gas measurement once per 15 s. Since one measurement cycle is 1.3 s (excluding transmission, which takes place only in the case of emergency), the total estimated lifetime of the sensor node is $(7.2 \text{ V} \times 15000 \text{ mAh}) / (227 \text{ mW} \times 1.3 / 15 \text{ s}) = 5490 \text{ h}$ (228 days). A user can further increase the sensor node lifetime by making

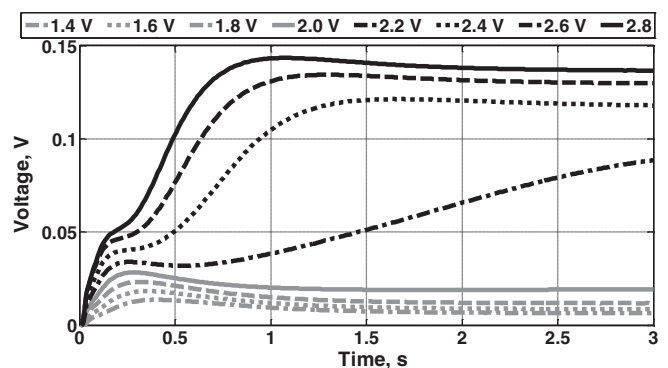


Fig. 9. Wheatstone bridge (sensor) response in volts at 2% CH₄ and 20 °C w.r.t. applied heating voltage (1.4–2.8 V).

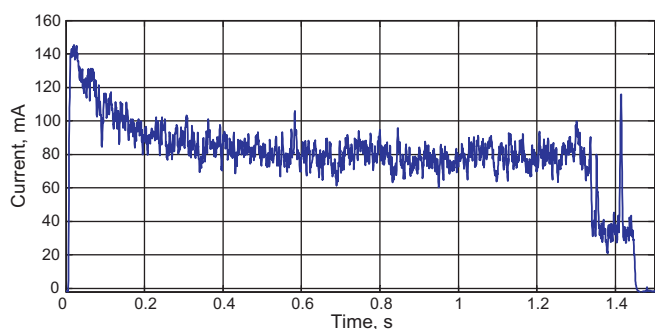


Fig. 10. Current consumption diagram for the Wheatstone circuit (sensing: 0.02–1.32 s, data transmission: 1.35–1.44 s).

measurements once per 120 s as it is specified in Ref. [6]. In this case the lifetime will be theoretically around five years.

4.3. Actuation time estimation

In this section we estimate the wireless sensor–actuator system actuation time necessary to react on a gas leak. For correct time estimation we synchronize both the sensor node and the actuator with computer.

In this experiment we install the sensor node in gas chamber and emulate the gas leak by using 2% CH₄. Sensor node is programmed for environmental scanning every 15 s. This interval is a viable trade-off between the long time operation of wireless sensor node and safety requirements for combustible gas detection. The sensing takes 1.3 s. Time required to send a request from the wireless sensor node to the wireless actuator is 0.1 s. The response of actuator includes the time for node request receiving and processing (0.1 s) and the time of valve closing (50 ms). Therefore, the total time of system reaction on gas leak is less than 17 s.

In parallel, the sensor node can send an alert message to a WSN operator and/or inform an appropriate civil service to put in place the necessary remedial measures. This alerting, however, is out of scope of this work.

5. Conclusion

In this work we have demonstrated a wireless sensor–actuator system for hazardous gas detection. The sensor node is based on a Wheatstone sensing circuit with a catalytic sensor. The sensing circuit consumes 227 mW that significantly improves relevant state-of-the-art solutions and meets safety requirements. Upon detection of a dangerous gas in the environment the sensor node communicates to a remote actuator wirelessly relying on ZigBee/IEEE802.15.4 standard and BACnet protocol. The actuator blocks the valve and sends an acknowledgement to the sensor node: the total time required is up to 17 s.

Acknowledgment

The authors would like to acknowledge the Russian Federal Program “Development of Electronic Components and Radio Electronics” Grant No. 14.427.11.0007.

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Biographies

Andrey Somov received his BS degree in Electronic Engineering and the diploma of Electronics Engineer from Moscow State Aviation Technological University, Russia in 2004 and 2006, respectively. Before starting his PhD, Andrey worked as an electronics engineer in space technology for two years. He subsequently undertook research in the area of wireless sensor networks in which he gained a PhD degree from the University of Trento, Italy in 2009. In the fall 2008 Andrey was a visiting

scholar at the University of California, Berkeley, USA, where he conducted research in energy efficient sensor networks. Dr. Somov holds the position of researcher at CREATE-NET, Italy. His work is focused on the internet of things and wireless sensor networks.

Alexander Baranov is a Professor at Moscow State Aviation Technological University, Russia. He received a PhD in Phys. and Math. in 1994 from Moscow Institute of Electronics & Mathematics (Technical University) and the Doctor of Technical Science degree in 2003 from Moscow State Aviation Technological University. Prof. Baranov is the project leader on several research projects, some with

international partners. His current research interests include the development of thin film nanocomposite catalysts for gas sensors by plasma deposition methods, catalytic and semiconductor sensor characterisation, and wireless sensor networks.

Denis Spirjakin is presently a PhD candidate at the Department of High Tech Radio-Electronics of Moscow State Aviation Technological University, Russia. He obtained his BS and MS in Electronics in 2005 and 2007 both from Moscow State Aviation Technological University, Russia. His research interests are in digital signal processing, data transmission system, and wired/wireless sensor networks.