USAGE OF MICROELECTROMECHANICAL SENSORS FOR THE MONITORING OF CRITICAL PARAMETERS IN THE ATMOSPHERE OF AN OPEN PIT

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ABSTRACT. During industrial blasting, large amounts of toxic gases are released, which often form high concentrations at workplaces in mining sites. This poses potential risks to workers and requires strict control of the atmosphere after blasting, which is most often done with the aid of portable and stationary devices equipped with precise but expensive electrochemical sensors. This article discusses the features and applications of low-cost microelectromechanical sensors for monitoring critical gas levels in the working atmosphere of mining sites. It also discusses the calibration of CO and NO_2 sensors as part of a multi-gas module, optimised for implementation using a microcontroller. The aim of the presented work is to study the possibility of building a mobile platform for atmospheric research and to increase safety when working in open pits and quarries.

Key words: atmospheric monitoring, blasting works, microelectromechanical sensors, safety

ИЗПОЛЗВАНЕ НА МИКРОЕЛЕКТРОМЕХАНИЧНИ СЕНЗОРИ ЗА НАБЛЮДЕНИЕ НА КРИТИЧНИ ПАРАМЕТРИ В АТМОСФЕРАТА НА ОТКРИТ РУДНИК

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РЕЗЮМЕ. При извършване на промишлени взривни работи се отделят големи количества токсични газове, които често формират високи концентрации на работните места в минните обекти. Това крие потенциални рискове за работниците и налага стриктен контрол на атмосферата след взривяване, който се извършва най-често чрез преносими и стационарни уреди, снабдени с прецизни, но скъпоструващи електрохимични сензори. Настоящата статия разглежда особеностите и приложението на микроелектромеханични сензори с ниска себестойност за наблюдение на критични нива на газовете в работната атмосфера на минни обекти. Дискутирано е калибрирането на сензори за CO и NO_2 като част от мултигазов модул, като е направена оптимизация за реализация с помощта на микроконтролер. Целта на представения труд е проучване на възможността за изграждане на мобилна платформа за изследване на атмосферата и повишаване на техническата безопасност при работа в открити рудници и кариери.

Ключови думи: мониторинг на атмосферата, взривни работи, микроелектромеханични сензори, техническа безопасност

Introduction

Mining is an energy-intensive and dirty process that involves moving large masses of ground. The most effective and cheap way to do this is to carry out blasting operations. They are characterised by a sudden and drastic release of a large amount of energy accompanied by high temperature and the release of gases. This is followed by the removal of the resource-rich blast mass for processing, which still requires human intervention and carries the risk of exposure to highly toxic gases. As a result, both relatively mild symptoms, including irritation of the eyes, nose, and throat, cough, dizziness, headache, and shortness of breath, as well as severe intoxication leading to death can occur. (Mainiero 2007, Özmen 2015). The American Industrial Hygiene Association – AIHA (AIHA 2020) defines some international public exposure guidelines, such as AEGLs (Acute Exposure Guideline Levels), ERPGs (Emergency Response Planning Guidelines), TEELs (Temporary Emergency Exposure Limits), each of which is subdivided into three tiers of exposure values. The National Institute for Occupational Safety and Health (NIOSH 2007) defines the IDLH (Immediate Danger for Life and Health) which specifies the maximum level of exposure to a given hazard to which a healthy person can be exposed for 30 minutes without having irreversible health consequences. In mines, due to the specifics of the mining process and in order to protect human health and life, it is more suitable to monitor critical values of the concentrations of gases formed after blasting instead of taking into account precise numerical values. (Dinchev 2014; MSA, 2022). Among these gases, the carbon oxide (CO) and the nitride dioxide (NO_2) are of a particular interest in the current research. Based on the above, the emergency values of the monitored hazards are given in Table 1.

Table 1. *Critical values of the monitored hazards*

Gas	Concentration, ppm			
	ERPG-1 ≤60 min	ERPG-2 ≤60 min	ERPG-3 ≤60 min	IDLH ≤30 min
CO	200	350	500	1200
NO_2	1	15	30	20

The International Labour Organization’s (ILO 1991) “Safety and health in opencast mines” instructions specify:

- 18.3.4. A person should not be permitted to enter the vicinity of a working face after shot firing until the gaseous products of the blast have dissipated.
- 18.3.5.2. The supervisory official, before allowing persons to enter such a locality, should ensure that it has been thoroughly ventilated and freed from water, if practicable, and that the atmosphere within has been tested to ensure its purity.

All this emphasises the importance of the problem under consideration and shows that monitoring of the atmosphere after the explosion is necessary.

Motivation of the research

A general idea of the scale of the blasting works can be obtained from what is shown in Fig. 1.

Fig. 1. Blasting works in a real open pit

The figure shows the dissipation of hazardous gases after blasting in a real open pit. Confirmation of safe concentrations of toxic gases in the atmosphere is required before the site is visited by workers. This necessitates the monitoring of the atmosphere after the explosion.

Problems with the stationary installations

At the moment, a small part of the open pits has stationary gas monitoring systems, and usually, their efficiency is not high. Modernising in this area is an upcoming task. A known problem is that in the process of mining, the workplaces change their location dynamically within the open pit mine. This requires that the measuring devices be positioned in new locations near the site of the explosions. Stationary installations have a high price, and the possibility of being damaged by blasting at any moment is high. An additional risk is represented by factors such as the temperature, humidity, and dustiness of the work environment. In addition, the high concentrations of noxious gases immediately after the explosion could lead to sensor saturation, which would disable them or render them inoperable for a prolonged period. This affects their reliability and poses a risk to mine personnel.

Problems with the mobile installations

While portable devices have a number of advantages, they also have disadvantages. When using portable devices and frequently changing the location in the mine cup, it is difficult to predict the trend of changes in the measured gas concentrations. They have problems related to the working environment in terms of response time and leaving the gas zone. The time to travel in the mine to a safe place can be very long, implying the risk of high doses of ingested harmful substances. Last but not least, passing near mobile machinery can lead to higher concentrations of the measured gases, which means an increased risk of making incorrect decisions regarding the evacuation of personnel.

In (Dinchev 2014), modernising the Assarel open pit through a set of stationary monitoring installations is considered. In (Ionascu 2021,) the use of electrochemical sensors that could be used to control the mine atmosphere is discussed. They have a high price and a limited shelf life. In the present study, an experiment with micro-electromechanical sensors has been carried out, which aims at the future construction of a remotely controlled mobile station offering a significantly higher level of reliability and more flexible measurement methods.

Gas concentration measurement using electromechanical sensors

The gas sensors used in this work are based on the micro-electromechanical system (MEMS) technology which has the advantage of being small in size. MEMS is a concept used to create tiny (chip-level) integrated devices or systems that combine mechanical and electrical components (Samotaev 2021). These sensors have significant measurement stability and are more suitable for qualitative rather than quantitative measurement.

The general overview of the electrical connection for every of the MEMS sensors used in the present work (Winsen, 2019) is given in Fig. 2.

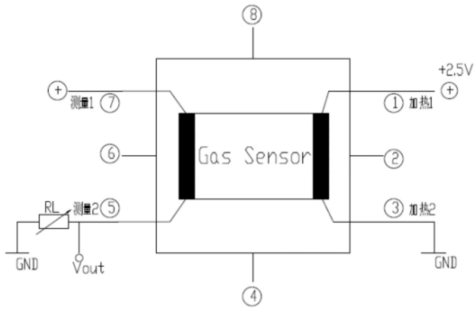

Fig. 2. Electrical connections and test circuit of the MEMS sensor

From an electrical point of view, the sensor can be seen as a two-resistor device. The resistive component between pins 1 and 3 has a resistance of about 80 Ohms with very low accuracy (+/- 20%). It acts as a 50mW heater used to preheat the module before starting measuring gases. The resistor between pins 5 and 7 is the sensitive component. Connecting it in a voltage divider configuration allows measuring the voltage drop across the resistor RL and then convert it to digital code with the aid of an analogue to digital converter (ADC).

The calibration curve is non-linear, so it must be interpolated or approximated mathematically. The polynomial for the NO_2 sensor (Winsen GM-102B) is given by (1).

$$y = a + b.x + c.x^2 + d.x^3 + e.x^4 \quad (1)$$

It is a 4-th order polynomial with coefficients:
a=0.3884834806, b=0.8232244906, c=8.124691449, d=6.623357975, and e=2.1753927.

The polynomial obtained for the CO sensor (Winsen GM-702B) is different in two measurement intervals. For the range (0.2V to 2.13V), it coincides with (1) and for the range (2.13V to 2.4V), it is given by (2).

$$y = a + b.x + c.x^2 + d.x^3 + e.x^4 + f.x^5 + g.x^6 \quad (2)$$

For the range (0.2V to 2.13V) it is a 4-th order polynomial with coefficients:
a=17.79251443, b=-121.7237072, c=269.7256284, d=-214.6489452, and e=60.53236018.

For the range (2.13V to 2.4V) it is a 6-th order polynomial with coefficients:
a=1176266431, b=-3259312339, c=3760050587, d=-2311641410, e=798788991.2, f=-147098079.5, g=11278154.95.

Although the elaborated polynomial approximations are quite accurate, with an error way below 10%, they pose a computational challenge when a small embedded microcontroller is considered as a measurement processing device.

Device implementation

Most small microcontrollers (MCU) do not support the floating-point (FP) standard IEEE-754 (IEEE Std 754, 2019). Even if they are equipped with FP math hardware, they usually perform integer math much faster. In the proposed device, the ATmega328P MCU is chosen. It is an 8-bit MCU with no built-in support for FP numbers. Although the "float" and "double" data types are supported, both of them occupy 4 bytes of memory. In order to use data types larger than 8 bits, the compiler needs to generate a sequence of code or link an external library. The use of FP arithmetic negatively impacts the code size and the speed of execution.

Due to the above drawback, the coefficients in the polynomial approximation need to be fixed-point or integer numbers. This is done by first upscaling them by a factor that is a power of two and then downscaling the final result by the same factor (Baron 2006). This allows for using left-shift operation for the multiplication and right-shift operation for the division which is much faster.

The block diagram of the proposed gas sensor device is given in Fig. 3.

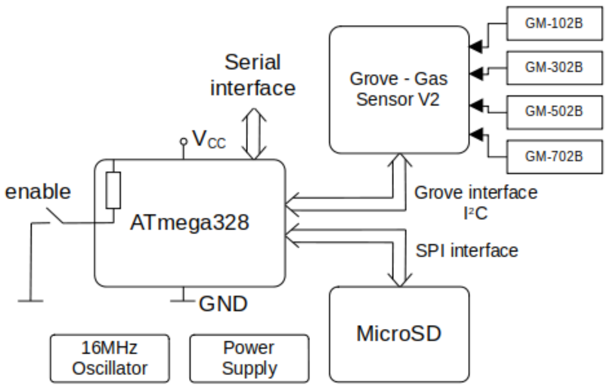

Fig. 3. Block diagram of the gas sensor device

The prototype consists of an Atmel (now Microchip) ATmega328P 8-bit MCU equipped with a 16MHz oscillator, a micro-SD card for data logging, and a button to enable or disable the logging process, and the Grove Multichannel Gas Sensor module made by Seeed Studio (Liu 2021). The latter is populated with four MEMS sensors, namely GM-102B (NO_2, 0.1~10ppm), GM-302B (C2H5OH, 1~500ppm), GM-502B (combined C2H5OH, 1-500ppm; C7H8, 1-500ppm; CH2O, 1-100ppm), and GM-702B (combined CO, 10-5000ppm; H2, 10-500ppm). Although all the sensors have been verified, the ones that are the subject of the experiment in this research are the GM-102B and GM-702B since the hazardous impact of the NO_2 and CO gases is most significant.

The physical view of the prototype is shown in Fig. 4.

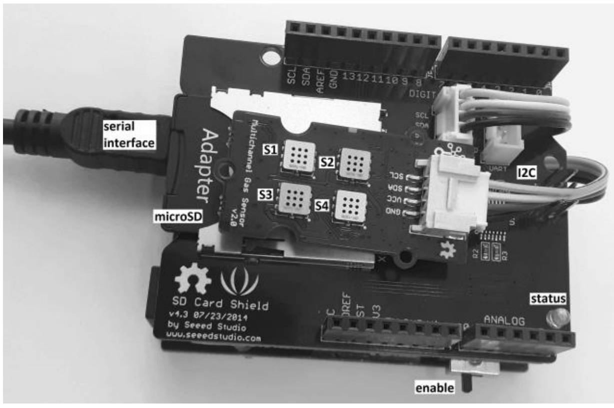

Fig. 4. Physical view of the prototype

In the figure, S1 is the GM-702B, S2 is the GM-502B, S3 is the GM-702B, and S4 is the GM-702B. The communication between the MCU and the sensors is done over an I2C bus. The status LED blinks when the device is in an idle state and it is constantly lit when in data logging mode.

The control algorithm is shown in Fig. 5.

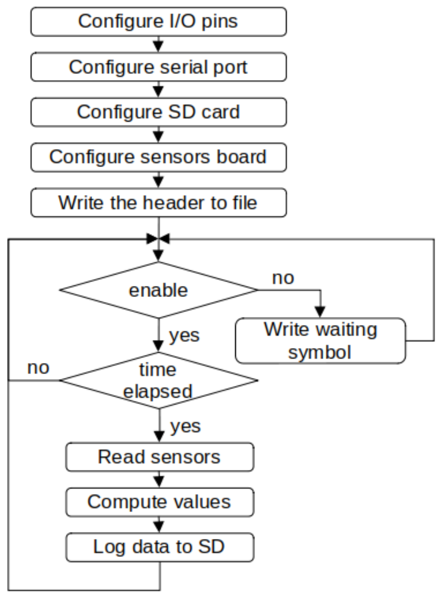

Fig. 5. Operational algorithm

On power-up, the controller periphery, such as the GPIO, serial port, SD card, and the sensor board, is initialised. Next, the main loop is entered. While waiting for the enable signal, the algorithm outputs the '.' character in the serial console indicating an idle state. When enabled, the sensors are read and processed, and the data is stored on the SD card. This is done in a pre-defined time frame that uses a non-blocking mechanism. The program flow guarantees that the SD card will always be written and the file will not remain open under any circumstances.

The comparison between the computed result for the static characteristic of the NO_2 sensor and the original curve given by the manufacturer is shown in Fig. 6. In the same figure, it can be seen the plot of the error varies within the maximum range of -6.8% to 6.6%. The error increases for smaller gas concentrations and decreases for higher ones which in fact benefits the quality of measurement in the area of interest, namely the hazardous concentrations.

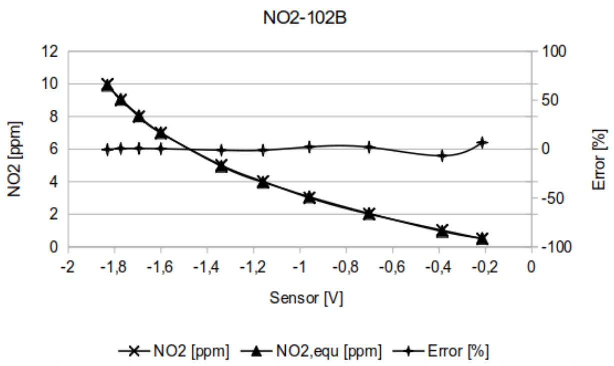

Fig. 6. NO_2 gas concentration plot versus sensor voltage drop. The "equ" index denotes the approximated curve. The error (horizontal line) fluctuates between -6.8% and 6.6%. The scaling factor is 2^{10}=1024

The comparison between the computed result for the static characteristic of the CO sensor and the original curve given by the manufacturer is shown in Fig. 7.

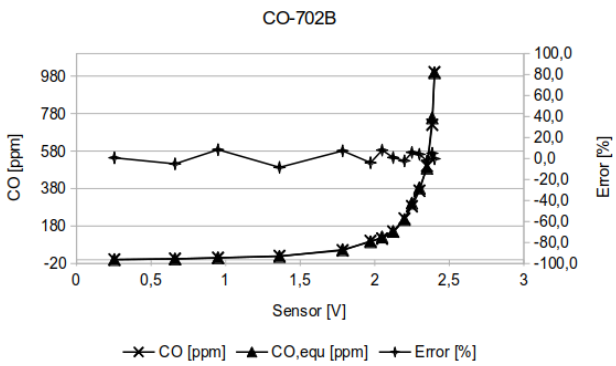

Fig. 7. CO gas concentration plot versus sensor voltage drop. The "equ" index denotes the approximated curve. The error (horizontal line) fluctuates between -8.4% and 0.7%. The scaling factor is different for two ranges – in the range 0.2V to 2.13V, it is 2^{10}=1024, while in the range 2.13 to 2.4, it is 2

The scaling factor for the polynomial description is 1024 for sensor voltages between 0.2V and 2.13V, and it is 2 for the range 2.13V to 2.4V. It can be seen that the plot of the error varies within the maximum range of -8.4% to 0.7%. The error for this sensor is evenly distributed and is within acceptable bounds.

As a result of the experiment, it can be seen that the approximation of a high-order polynomial with fractional coefficients by using integer coefficients does not change the validity of the data. The results obtained from the manufacturer's calibration curve almost fully coincide with the experimental ones, with a negligible error.

Future work

The satisfactory results of the study point out that the work should be continued until a finished and autonomous device is obtained. To achieve this, future efforts should focus on power autonomy, increased mobility, remote real-time data transfer, real-time measurement processing, and the development of a simplified sensor calibration procedure. This includes adding a battery and designing a small printed circuit board (PCB) that would contain all the necessary components in a compact design. In addition, research should continue to explore the possibility of using an autonomous self-propelled or flying device (drone) and finding a means of wireless communication over long distances with low energy consumption. The wireless LoRa (long-range) network seems to be a suitable candidate for this purpose.

Conclusions

The development of modern technology makes it more and more affordable to build reliable mobile devices that can increase the level of safety in the field of mining. In the presented study, the problems related to the control of the atmosphere in an open pit from the point of view of monitoring the critical values of toxic gases after blasting are considered. A mobile measuring device was built with the help of which measurements were carried out and micro-electromechanical sensors were calibrated. Optimisation of the computational process was carried out, allowing the efficient use of a small microcontroller. The conducted experiments provide a good basis for the future construction of a complete mobile station to replace the stationary mine atmosphere control equipment.

References

AIHA. 2020. *The AIHA Handbook for ERPG and WEEL*. American Industrial Hygiene Association, AIHA Press, Fairfax, Virginia, ISBN978-1-950286-06-5

Baron L., O. Ferguson. 2006. What Can Be Approximated by Polynomials with Integer Coefficients? - *The American Mathematical Monthly, 113*, No. 5, Taylor & Francis, Mathematical Association of America, 403-414, ISSN 00029890, https://doi.org/10.2307/27641948

Dinchev Z., M. Michaylov, E. Vlasseva, A. Krilchev. 2014. Open pit mine atmosphere remote control system. - *Annual of the University of Mining and Geology "St. Ivan Rilski", 57*, Part III, Mechanisation, electrification and automation in mines, 27-34, ISSN 1312-1820

IEEE Std 754-2019, IEEE Computer Society. 2019. IEEE Standard for Floating-Point Arithmetic IEEE STD 754-2019, 1–84, ISBN 978-1-5044-5924-2

ILO Code of practice. 1991. Safety and health in opencast mines. International Labour Organisation, ISBN 92-2-107103-0

Ionascu M., N. Castell, O. Boncalo, P. Schneider, M. Darie, M. Marcu. 2021. Calibration of CO, NO2, and O3 Using Airify: A Low-Cost Sensor Cluster for Air Quality Monitoring. *Sensors*, 21, issue 23, https://doi.org/10.3390/s21237977

Liu K. 2021. *An Arduino library for Grove Multichannel Gas Sensor V2.0*. Seeed Studio, https://bit.ly/3vJwDqr

Mainiero R., M. Harris, J. Rowland. 2007. Dangers of toxic fumes from blasting, *Proceedings of the 33rd Annual Conference on Explosives and Blasting Technique*, *Nashville, Tennessee, January 28-31, 2007*. The National Institute for Occupational Safety and Health, NIOSHTIC2 Number 20032444, 1-6

MSA (Mine Safety Appliances Company) 2022. *Gas Detection Handbook* 5th ed., MSA Instrument Division, P.O. Box 427, Pittsburgh, PA 15230, USA

NIOSH Pocket Guide to Chemical Hazards. 2007. National Institute for Occupational Safety and Health. Publ. No 2005-149, ISBN 978-0160727511

Özmen İ., E. Aksoy. 2015. Respiratory Emergencies and Management of Mining Accidents. *Turkish Thoracic Journal*, Suppl. 1, doi:10.5152/ttd.2015.005, 18-20

Samotaev N., P. Dzhumaev, K. Oblov, A. Pisliakov, I. Obraztsov, C. Ducso, F. Biro. 2021. *Silicon MEMS Thermocatalytic Gas Sensor in Miniature*

Surface Mounted Device Form. *Chemosensors, 9*, issue 340, https://doi.org/10.3390/

Winsen. 2019. *MEMS NO2 Gas Sensor*. Zhengzhou Winsen Electronics Technology Co. Ltd., https://bit.ly/3LirHQe