PRIMENA LOW-COST SENZORA I SISTEMA ZA MONITORING AEROZAGAĐENJA

USING LOW-COST SENSORS AND SYSTEMS FOR AIR POLLUTION MONITORING

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<https://doi.org/10.24094/mkoiee.017.5.1.11>

Naučno je dokazano da izlaganje aerozagađenju može izazvati kardiovaskularne bolesti, astmu, rak pluća kao i druge respiratorne bolesti. U cilju ublažavanja posledica aerozagađenja na ljudsko zdravlje vlade mnogih zemalja pokušavaju da poboljšaju nacionalne sisteme za praćenje aerozagađenja. Klasični sistemi za praćenje aerozagađenja zasnivaju se na stacionarnim monitoring stanicama i uređajima. Merni instrumenti ugrađeni u stacionarnim stanicama za monitoring kvaliteta vazduha su najčešće velikih dimenzija i skupi za održavanje. Monitoring aerozagađenja u gradovima kojim bi se obuhvatile velike oblasti i postigla visoka vremenska rezolutivnost još uvek je tehnički veoma zahtevan i skup zadatak. Jedan način za rešavanje ovog zadatka je korišćenje monitoring sistema za rad u realnom vremenu koji koriste low-cost senzore. Low-cost senzori zahtevaju posebnu selekciju i kalibraciju pre primene u sistemima monitoringa kvaliteta vazduha. U cilju boljeg razumevanja primenljivosti low-cost senzora i sistema za monitoring aerozagađenja u ovom radu prikazana su praktična iskustva u primeni low-cost senzora za merenje koncentracija suspendovanih čestica.

Ključne reči: aerozagađenje; monitoring; senzor; mikrokontroler

It is well known that air pollution causes cardiovascular diseases, asthma, lung cancer and other respiratory diseases. In order to mitigate the impacts of air pollution on human health, the governments of many countries in the world try to improve air pollution monitoring. Conventional air quality monitoring systems are based on a limited number of fixed monitoring stations with stationary monitors. Such monitoring instruments are large, heavy and expensive for maintenance. Monitoring of air pollutants in the cities with high spatial and time resolution is still technically demanding and expensive task. One of the possible solutions of this task is using the monitoring systems with low-cost solid-state gas and PM sensors that are able to operate in real-time. Such low-cost sensors require proper evaluation and calibration prior to their implementation. In this paper, practical experiences in the implementation of low-cost sensors and systems for PM monitoring will be presented with the aim of better understanding of their applicability in the air quality monitoring systems.

Key words: air pollution; monitoring; sensor; microcontroller

1 Introduction

The adverse effects of exposure to airborne particulate matter on human health are now well established. The air pollution causes cardiovascular diseases, asthma, lung cancer and other respiratory diseases[1-3]. As a consequence, the governments of many countries in the world established air quality standards and has implemented policies in order to reduce concentrations of particulate matter in ambient air. High temporal and spatial resolution is an imperative to obtain reliable data that could be used to setup policies and measures that would protect the health of the citizens [4]. Current air quality monitoring methods are costly and time-consuming with the limitations in sampling and analytical techniques. Most of the monitoring networks that are currently in use consist of a limited number of stationary monitoring stations with monitoring instruments that are large, heavy and expensive for maintenance. These ambient PM and gaseous monitoring units do not capture spatial gradients in the

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areas for which they are representative, and cannot provide data with high spatial and temporal resolution [4, 5].

To monitor air pollution levels in urban streets, as well as indoors, with high spatial and time resolution, a network of small and cheap monitoring devices equipped with sensors could be a reasonable and cost-effective alternative. Wireless Sensor Networks (WSN) has been successfully applied in a wide range of areas for real-time monitoring in the smart city environments. Such systems use low-cost, commercially available sensors [4-6]. Data collecting from the WSN nodes is easy and their automatic operations allow widespread implementation in the ambient as well as in a built environment.

National Air Quality Monitoring (AQM) networks that strictly follow the prescribed QA/QC procedures allows comparability across instruments and networks. Similar to that, the characteristics of low-cost air quality sensors should be assessed prior to their implementation in the AQM networks. In this paper, some practical experiences in the implementation of low-cost sensors and systems for particulate matter (PM) monitoring will be presented with the aim of better understanding of their usability in the AQM systems.

2 Automatic monitoring of PM mass concentrations in the Republic of Serbia

In accordance with the Law on Air Protection (Official Gazette of RS, No. 36/09 and 10/13) authority over the national network for the AQM in the Republic of Serbia has the Serbian Environmental Protection Agency (SEPA). AQM is carried out in accordance with the Regulation on establishing programs for the control of air quality in the state network (Official Gazette of RS, No. 58/11) and Regulation on conditions and requirements for monitoring of air quality (Official Gazette of RS, No. 11/10, 75/10, and 63/13). Gravimetric methods are the basis of the European and US reference methods for PM_{10} and $PM_{2.5}$ for outdoor monitoring purposes. In comparison with automatic monitors, gravimetric monitoring methods are labor-intensive, as they require pre/post-conditioning and manual weighing of filters, and therefore such methods are not ideally suited for routine compliance measurements. In addition, due to the time-consuming gravimetric procedure, results are available several days after sampling, while automatic on-line monitors provide real-time PM measurements.

Besides the established gravimetric reference methods, other PM monitoring techniques which can provide equivalent results to the reference method may be used. However, such equivalent automatic PM monitors are still expensive (cost tens of thousands of euros). The coverage area of these PM monitoring systems is limited, so that, they are usually unable to present actual situation of PM pollution in the wider area. A particle sensing system with low manufacturing cost and high mobility is therefore needed to be developed to compensate the shortcomings of such PM monitoring systems.

2.1 Stationary PM monitoring devices

Fig. 1. GRIMM EDM 180

SEPA has started automatic air pollution monitoring in the Republic of Serbia in 2006. Nowadays, SEPA operates with more than 30 automatic AQM stations. Most of AQM stations (28) have been equipped in the framework of Europe Aid/124394/D/SUP/YU “Supply of Equipment for Air Monitoring” project and started to operate in 2009 and 2010. According to data presented at SEPA [www](http://www.sepa.gov.rs) site (www.sepa.gov.rs), there are 16 AQM stations in the Republic of Serbia that are equipped with the automatic PM (PM_{10} and $PM_{2.5}$) monitors which are located in Belgrade (7) and in towns of Pančevo (3), Novi Sad (2), Smederevo (1), Niš (1), Subotica (1), and Beočin (1). Spatial coverage of the Republic of Serbia with the stationary automatic PM monitors is still uneven as most of

the automatic PM monitors are concentrated in Belgrade and towns in its surrounding [7]. So that, the density of automatic PM monitoring instruments is inadequate and do not always reflect personal health risk. The GRIMM EDM 180 is a gravimetric equivalence PM monitor that is used as automatic

PM monitor in the AQM stations operated by SEPA (see Fig.1.). GRIMM EDM 180 calculates PM_{10} and $PM_{2.5}$ mass concentrations by counting and sizing particles optically [8]. This is the first and only optical monitor that is fully approved in the USA by EPA and in Europe by EN. The GRIMM EDM 180 can also supply the corresponding particle size distribution in the measurement range from 0.25 to over 30 μm in over 30 different size ranges.

2.2 Portable PM monitoring devices

Commercially available portable PM monitoring devices usually work on the light scattering principle. Their dimensions are much smaller compared to stationary PM monitors, and their prices are in the range from few hundred up to few thousands of euros. These devices, in fact, calculate the mass concentration based on the intensity of light scattered from particles so that they have to be calibrated for each environment using the reference gravimetric method. The optical scattering efficiency per unit mass is not constant with respect to the particulate size and composition. Therefore, these instruments deliver an accurate PM mass concentration only if particle size distribution and composition is not very different from the calibration standard. Biases in PM exposure estimates may also be due to an incomplete capture of the particle size ranges [9]. Moreover, PM mass concentrations measured with any light scattering instrument increase with the relative humidity due to an increase of the average particle size associated with the condensational growth of its hygroscopic components.

The portable Dust Trak Model 8520 aerosol monitor (TSI) are widely used to monitor PM concentrations in the indoor and outdoor environments [9]. This is a real-time, small and portable monitor that use orthogonal light scattering (reflected light) technology. The OSIRIS (Turnkey Instruments) and HAZ-DUST EPAM-5000 (SKC Inc.) have also been used for the assessment of indoor and outdoor PM levels as well as personal exposure in a number of studies [9, 10]. OSIRIS monitor, shown in Fig. 2, is

Fig. 2. OSIRIS PM monitor

designed for indicative measurement of PM (PM_{10} , $PM_{2.5}$, and PM_1) concentrations in the range of 0.5 - 20 μm [9]. EPAM-5000 (SKC Inc.) uses the reflection of light from the particles to calculate PM concentration per unit volume, in contrast to the OSIRIS monitor which uses the diffraction of light from the particles. EPAM-5000 is suitable for measuring PM concentrations in the range of 0.1 - 100 μm [11]. The Dylos Air Quality Monitor (Dylos Corporation), is also widely used in homes and offices to monitor particle number concentrations [7]. The Dylos reports particle numbers in two size fractions: $PM_{0.5}$ which measures particles sized 0.5 μm and greater, and $PM_{2.5}$ which measures particles sized 2.5 μm and greater. The comparability between such portable PM_{10} monitors and instruments that are equivalent to reference measurement method has been tested also [7, 9, 10]. AQM systems in the form of compact and handheld devices also have space and time limitations, since the measuring is performed manually. The number of portable AQM stations in the national AQM network is also limited because of its maintenance

costs. So it comes to that suitable tools to quantify PM concentrations need to be developed. On account of these, the researchers have started developing systems with easily available sensors, which have low price and quick response time.

3 Low-cost PM sensors

The review of commercially available low-cost sensors utilized for PM detection that works on the light scattering principle was very well presented in the reference [4]. The sensors are based on the same operation principle. The photodiode emits a light beam in the measurement cavity, and a phototransistor captures the reflected light as shown in Fig. 3b. When the particles enter the measurement cavity and scatter the reflected light, the voltage over the phototransistor changes because of the blocked light by the particle. Such low-cost sensors are usually able to detect and count particles larger than 0.5 μm . The cheapest sensors, Sharp GP2Y1010 [12] and Shinyei PPD42NS [13] costs less than 10 euros, but they have to be connected to an external microcontroller and display. If the sensors have an inbuilt microcontroller, and USB port, such as NOVA SDS011 [14], the price increases up to a few hundreds of euros.

Fig. 3. (a) The Sharp GP2Y1010 dust sensor, (b) operation principle [15]

3.1 Low-cost PM sensors validation

Before use, low-cost sensors should be tested in the laboratory conditions and in the field in order to verify their characteristics. The aim of laboratory and field validation is to define sensor response and to demonstrate good linearity with the reference methods, reference equivalent methods or other PM monitors that are in use [4]. Sharp GP2Y1010 sensor (shown in Fig. 3a) has been frequently used in a number of PM monitoring projects [15-17] because it is cheap, small, low-power, and easily available. For the calibration of GP2Y1010 sensors, Budde et al. [15] were used a self-made dust dispenser and the TSI DustTrak DRX 8533 as the reference device. In this study, the evaluation of such calibrated sensors was performed both in the laboratory and in the field using the Arduino [18] and TECO Envboard [19] sensor platforms. After the calibration, a strong correlation was detected between the sensors readings and the reference devices.

The usability of GP2Y1010 sensors for $PM_{2.5}$ measurements in the laboratory was also investigated in [17]. The temperature and relative humidity of air in the laboratory were maintained in the ranges of 24-29 °C and 50-60 % respectively, in order to reduce their influences on measurement results. In that study, OSIRIS monitor (Turnkey Instruments, Model 2315) was used as the reference instrument. In addition to that, OSIRIS monitor has been calibrated weekly with the reference gravimetric method. Two independent low-cost measurement systems were formed as shown in Fig. 4. One consisted of the Arduino platform to which are connected a GP2Y1010 sensor and temperature and humidity sensor module DHT22 [20], while the second consisted of the Arduino platform to which are connected two GP2Y1010 sensors.

Fig. 4. Sharp GP2Y1010 sensors connected on Arduino platforms[17]

Correlation analysis of the measurement results shows a strong positive correlation ($0.74 < r < 0.95$) between the mean 15-min $PM_{2.5}$ levels obtained with GP2Y1010 sensors and OSIRIS monitor.

4 Low-cost PM monitoring devices

Arduino platform [18] is a low-cost platform that has been used in many $PM_{2.5}$ monitoring projects. In order to obtain a low-cost PM monitoring device, an Arduino platform was equipped with LCD1602 Arduino shield, temperature, and humidity sensor module DHT22, and GP2Y1010 sensor

which has previously been calibrated in the manner described in [17]. In this way, a low-cost PM_{2.5} data logger (which costs less than 100 euros), or real-time PM_{2.5} monitor was obtained. Arduino Software (Integrated Development Environment - IDE) is an open source environment that was used for writing the measurement program that provides I/O signals required for GP2Y1010 operation and to send the measurement results to PC via USB port [17].

At the PC side, the program written in Processing 3 [21] was used to read the results from Arduino and write them into text files. Processing 3 is also an open source environment, a flexible software sketchbook and a language for learning how to code within the context of the visual arts.

There are 5 such monitoring devices that were tested during 2016. They were used to measure the concentration of PM_{2.5} particles in the apartments in Bor, in the offices at the University of Belgrade, Technical Faculty in Bor (as shown in Fig. 5) and in the laboratories at the Mining and Metallurgy Institute Bor, and at the University of Belgrade, Vinča Institute of Nuclear Sciences.

Overall, the low-cost PM_{2.5} instruments used in this study was proved to be reliable for assessing indoor PM_{2.5} concentrations and for providing temporal variability profiles for PM_{2.5}. In order to improve the accuracy of such PM_{2.5} monitors, it is necessary to perform the calibration procedure on daily basis, by comparing their readings with the reference methods [9], reference equivalent methods or other PM_{2.5} monitors that are in use.

Further investigations in this area will be focused on examining the effects of the temperature and air humidity changes on the measurement results. Also, the inter-sensor differences will be further explored and evaluated in detail.

Fig. 5. PM_{2.5} concentrations measured in an office at the Technical Faculty in Bor

5 Local Area Network (LAN) for indoor PM_{2.5} monitoring

In order to reduce costs for the establishment of a local AQM networks in the interior of public institutions (schools, institutes, faculties) and business buildings it is possible to use the existing network infrastructure. Such an approach was used to establish a LAN for PM_{2.5} monitoring at the Mining and Metallurgy Institute Bor. The network consists of 1 Raspberry Pi [22] and 5 Arduino PM_{2.5} monitors (3 Arduino Yun + 2 Arduino Uno with Ethernet shields). The Raspberry Pi has the host role. It works under the Raspbian Linux [23] operating system with the SQLite database [24] and the Apache web server [25] installed. A Python [26] script that runs every 5 minutes (another time can be set as needed) was used for the data collecting from the Arduino PM_{2.5} monitors and to records them into the SQLite database. Python script also generates files with the data needed for the graphical presentations on the web page, as shown in Fig. 6. Web pages are created by using PHP [27] and JavaScript [28]. Arduino PM_{2.5} monitors, running measuring programs, act as measuring nodes with sensors. They also work as web servers, waits for HTTP requests from the host and responds to them by sending measured values from the sensors.

Fig. 6. $PM_{2.5}$ concentrations measured in an office at the Mining and Metallurgy Institute Bor

6 Wireless sensor networks (WSNs)

Using the WSN for detecting, measuring and gathering information from the real world and transferring them to end users is very widespread nowadays. Some of the advantages of these networks are: self-configuration, possibility of expansion, high sensibility, low price, exclusion of cables, effectiveness in hard working conditions, large surfaces covered, and small energy consumption [29].

As stated above, the conventional AQM systems are limited in terms of time, costs, and space coverage, so that, WSN can be used as an alternative for collecting data on air pollutants in real time.

The rapid development of WSNs has led to developing AQM systems which are cost effective, with low energy consumption. The development of AQM systems with WSN technology also lead to the minimization of installation and maintenance costs and enable quick and easy reconfiguration of those systems. The devices for wireless networking of small range (Bluetooth and ZigBee) are especially suitable, as well as mobile phone systems for greater range, such as GSM/GRPS [30].

WSN consists of a large number sensor nodes. Wireless sensor nodes represent a group of one or more sensors, of different sizes, control units, memories, transceivers, and power sources, as shown in Fig. 7.

Fig. 7. Basic components of the sensor node[31]

The sensor generates electrical signals, that microcontroller unit processes, and stores. The transceiver receives commands from and transfers data to the host computer. In addition to the required number of sensor nodes, WSN also should contain basic stations which connect sensor nodes to other networks (see Fig. 8).

IEEE 802.15.4/ZigBee represents a global open standard for WSNs, which is used for their monitoring and control. By developing this standard, the following requirements were fulfilled [33]: low price, low energy consumption, usage of unlicensed band, cheap and easy installation, flexibility and wide network. The basic advantage of ZigBee is that it can work at several frequency ranges: 2.4

GHz, 868MHz. ZigBee standard IEEE 802.15.4 is applied primarily in sensor systems, where the transfer of a large amount of data is not necessary, and where it is important that the consumption is so small that sensor batteries can last up to few years. It is very suitable for monitoring, control, and automation.

Fig. 8. Wireless sensor network [32]

6.1 IEEE 802.15.4 /ZigBee protocol

ZigBee networks consist of several types of devices: coordinators, routers and end devices. Coordinator forms a network root through which a connection with other ZigBee networks can be established. Since the network is initiated by this device, there can only be one coordinator in one ZigBee network. ZigBee router acts as a mediator in communication between coordinators and other devices in the network. ZigBee end device (sensor node) possesses sufficient functionality which enables communication with the superior node (any coordinator or router) by their inquiry [30]. The topology of these networks is as follows: Star typology, Mesh topology, and Tree topology which is considered a special type of Mesh topology (see Fig. 9).

Fig. 9. ZigBee network topologies [34]

7 Conclusion

The conventional method of AQM is based on a limited number of stationary and mobile stations. Also, this method is very expensive and the collected data do not cover large areas. The coverage area of such PM monitoring systems is limited, so that, they are usually unable to present actual situation of PM pollution in the wider area. As an alternative to the conventional method, PM monitoring system with low manufacturing cost and high mobility is therefore needed to be developed to compensate the shortcomings of such PM monitoring systems.

The presented PM_{2.5} monitors, based on Arduino platform and GP2Y1010 sensors, are small, cheap, and can be distributed in large numbers. PM monitoring network based on such PM low-cost monitoring devices can surely provide additional data needed for the exposure assessment and health impact studies. But, prior to that, the appropriate quality assurance and control protocols should be implemented.

Sensor networks are largely applied and represent a new field of research which is growing intensively at the moment. Based on large number of studies, it has been proved that the system of WSN, is the alternative to the conventional method of environmental monitoring. Because of its low

energy consumption and simple net configuration, ZigBee is considered the most perspective wireless sensor technology. Therefore, the system integration for air pollution monitoring with WSN technology may reduce the installation expenses and enable quick and easy system reconfiguration for data acquiring and control.

Acknowledgements

This work is supported by a grant from the Ministry of Education, Science and Technological Development of the Republic of Serbia, as a part of the project No. III42008: "Evaluation of Energy Performances and Indoor Environment Quality of Educational Buildings in Serbia with Impact to Health."

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