Electronic circuits of measuring modules of air pollution monitoring system based on low-cost sensors

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Abstract. Currently, the state system for monitoring atmospheric air pollution in Ukraine is obsolete both in terms of technical and methodological support. In Ukraine, air pollution measurement standards have not been updated for more than 30 years, which led to gradual degradation of the monitoring system. Although relatively new technical means for measuring the concentration of various pollutants are partially used in certain industrial cities, the data they generate do not allow to make a full conclusion about the level of local pollution, the full range of pollutants, the localization of pollution sources, etc. This led to the need to create modern measuring modules of the air pollution monitoring system capable to generate large data sets and solving a number of modern methodological problems of the monitoring system. The hardware complex of the measuring module of the atmospheric air monitoring system based on low-cost sensors has been implemented. It is designed to receive, process, accumulate data, transmit and visualize the necessary information of the air pollution monitoring system. Connection diagrams of various hardware elements of the measuring module of the air pollution monitoring system (STM32F103C8T6 microcontroller, HC-12 module, SIM800C module) are shown. Printed circuit board in Altium Designer CAD, the drawings and the layout of the printed circuit board also are shown. The proposed technical prototype of the measuring modules of the monitoring system can become an addition to an existing monitoring system, or, in the case of creating a large-scale network of such tools, completely replace it.

1. Introduction
Atmospheric air is one of those natural environments that have a significant impact on the state of well-being and human health. In modern conditions of vigorous activity of industrial enterprises and urbanization of territories, the impact on the environment is increasing [1–5].
One of the factors of this impact is appeared in increasing the volume of harmful substances emissions into the atmospheric air from stationary and mobile sources. Since today most of the population of Ukraine lives in urban areas, the problem of urban air pollution has become extremely urgent and requires an immediate solution [6, 7]. The existing monitoring system has a number of disadvantages, is technically and morally outdated, does not correspond to the appropriate level of providing the governing bodies with detailed information for them to make effective management decisions in order to reduce the level of atmospheric air pollution [8–12].

To ensure the implementation of the basic principles of the functioning of the state system for monitoring environmental air pollution, it is necessary to involve the existing potential of all subjects of monitoring, primarily on the basis of consistency and progressiveness of the technical, regulatory, legal and methodological support of observation networks.

Each developed monitoring system should contain the following main components: observation of both distant and short-term trends; assessment of compliance with air quality standards; assessment of public health and negative impact on the environment; planning; approval of dispersion models using mathematical modeling approaches to predict air pollution levels; effectiveness of management measures.

As a result of atmospheric air monitoring, the following is obtained: primary data on monitoring and monitoring the state of pollution; generalized data on the level of pollution in a certain area for a certain period of time; generalized data on the composition and volumes of pollutant emissions; assessment of the levels and degree of danger of environmental pollution and the life of the population; assessment of the composition and volumes of pollutant emissions.

The purpose of this work is to obtain qualitatively new data by developing new measuring modules for an air quality monitoring system with a high update rate.

2. Modern state of the air pollution monitoring network in Ukraine

Atmospheric air monitoring is an integral part of the state environmental monitoring system, which is carried out in order to obtain, collect, process, store and analyze information on the state of atmospheric air and develop scientifically based recommendations for making decisions in the field of atmospheric air protection [13–16].

Atmospheric air monitoring subjects place observation posts, monitor concentrations of pollutants. Enterprises, institutions and organizations whose activities lead or may lead to deterioration of the atmospheric air may establish observation posts and monitor the concentrations of pollutants [17–19].

The number of observation posts and their location for assessment are determined in the program of state monitoring in the field of atmospheric air protection for each zone and agglomeration.

To ensure the accuracy of measuring devices, all subjects of atmospheric air monitoring that monitor the concentration of pollutants, assess the quality of atmospheric air, provide calibration and maintenance of measuring equipment used for monitoring atmospheric air.

According to [6], in Ukraine there were 162 posts in 53 cities, among them: 16 – in Kyiv; 10 – in Kharkiv; 8 – in Odesa; 6 – in the Dnipro, 5 – in Zaporizhzhya, Mariupol, Kryvyi Rih. In other regional centers, the number of observation posts did not exceed 4.

The mandatory air pollution monitoring program includes seven substances: suspended dust particles, sulfur dioxide, nitrogen oxides, carbon monoxide, formaldehyde, benzo(a)pyrene and lead [20, 21]. Some observation posts may monitor other pollutants. This depends on local or regional emissions as well as the industrial potential of the area.

In general, the quality of atmospheric air is determined by 33 indicators, according to the approved list for each of the 53 cities of Ukraine. Other substances may be included in the monitoring program in accordance with the decision of local authorities.
At 81 stationary posts, such heavy metals are monitored: iron, cadmium, copper, zinc, lead, nickel, manganese, chromium.

Sampling is carried out at certain time intervals according to one of 4 observation programs: complete, incomplete, reduced or daily. The full program provides for 4 measurements during the day: 01:00, 07:00, 13:00, 19:00; incomplete involves 3 measurements: 07:00, 13:00, 19:00; the reduced program provides 2 measurements: 07:00; 13:00; the daily program implies continuous observations. As measuring instruments on the observation network, such types of stationary observation posts of domestic production as “POST-1”, “POST-2”, “POST-2a” are used.

The development of the environmental monitoring system in Ukraine in recent years has led to the development in large industrial regions of networks of monitoring posts for the state of atmospheric air using automated monitoring posts. They complement the existing monitoring network. Such automated observation posts are already operating in the city of Kryvyi Rih, projects have been developed for the Nikopol and Kharkiv cities.

At present, a large number of software has also been developed for processing measurement results and forming specialized educational complexes for ecologists, engineers, scientists, and various specialists on their basis.

Since the control of atmospheric air pollution and emissions from industrial enterprises is one of the main elements of the environmental monitoring system, the creation and development of local networks using automated observation posts should be the main direction in the development of the atmospheric air quality monitoring system.

This article is devoted to the development of hardware for measuring modules of the atmospheric air pollution monitoring system, which will allow obtaining up-to-date information on the level of air pollution using modern microprocessor technology.

3. Electronic circuits of measuring modules

As a microcontroller, a microcircuit of the STM32F10x family (STM32F103 series) was chosen, which provides the best 32-bit efficiency in the class of microcontrollers (figure 1). The microcontroller has a high-performance RISC core with a frequency of 72 MHz, fast memory, extended I/O ranges and peripherals connected to APB buses. The STM32F103C8T6 is equipped with a 12-bit A/D converter, a timer, standard and advanced communication interfaces: up to two I2C and SPI, three USART, USB and CAN. Power saving mode allows to use it in low power devices.

The 32-bit microcontroller is made according to the Harvard architecture (program and data memory are separated), has several separate buses and a 3-stage pipeline and more than 10 general-purpose registers, which allows to perform operations in parallel and (most) in one cycle. The instruction set is Thumb-2 (a mix of 16-bit and 32-bit instructions, targeted at C/C++ compilers).

Microcontroller connection is typical:

- power is supplied through capacitors C7-C11, respectively, to each foam VBAT, VDD and VDDA;
- boot through the resistor is brought to the ground;
- restart button is programmable;
- quartz QZ1 with a frequency of 32.768 kHz.

The measurement module also includes SIM800C, HC-12 transceivers and BME-280, DHT-22, MQ-9, PMS7003, ZE08-CH2O, GP2Y1010AU0F, DS18B20 sensors.

The device is powered by a Li-Pol battery with standard size 54×34×10 mm, nominal voltage 3.7 V, capacity 2 Ah, operating temperature -20...60 °C. The device is charged via a Micro-B USB connector.
Figure 1. Microcontroller electrical diagram of STM32F103C8T6 connection.

The HC-12 module was selected as a transmitter for peer slave modules, which is a wireless half-duplex UART module that allows to transmit and receive data in the frequency range from 433.4 MHz to 473 MHz at a speed of 1200 to 115200 Bd, has the ability to select channels from 1 to 100, has the ability of choice of 8 transmitter power options from -1 dBm to 20 dBm. At the same time, the transmission distance can reach 1000 meters in the open area at a data speed of 5000 bps. The module connection diagram is shown in figure 2.

The module is built on the basis of the SI4463 chip, a 30 MHz quartz resonator is connected to the same chip, which is necessary for operation. This chip has an SPI interface, but the module is connected via UART. The fact is that there is another microcontroller on the module – STM8S003F3, it acts as an interface converter. In addition, the STM microcontroller simplifies interaction with the SI4463. The STM microcontroller implements all necessary commands and simplifies the configuration and control of the HC-12 module using native AT commands. The role of the master is played by the SIM800C transmitter module, this is a model of a full-featured quad-band GSM/GPRS module from SIMCOM figure 3. The module is a semi-finished product with 16x18mm size, designed for surface mounting on a printed circuit board. The module contains interfaces for connecting a SIM card, analog audio circuits, USB, UART, and general-purpose digital inputs/outputs. Power is supplied from a stable voltage source of 3.5–4.2 V, which can be a standard lithium battery. The current consumed from the power supply is on average 100–200 mA (several milliamps in standby mode), but pulsed currents can reach 2 A, so to prevent a short-term drop in the supply voltage, it is necessary to use low-impedance blocking capacitors, placing them in close proximity to the module. The antenna circuits of the module have an impedance of 50 ohms in the operating bands of 900 and 1800 MHz.

The data exchange interface with the module is represented by two functions: a function for reading data from the driver intended to be sent to the module, and a function for sending
data to the driver received from the module. The latter function can be safely called with the microcontroller’s interrupt handler and is capable of passing 1–255 bytes of data to the driver. This makes it easy to implement a “module-driver” channel using an interrupt from UART RX or from DMA microcontroller, transferring 1 byte or variable length data blocks at once. The reverse data channel “driver-module” must be implemented depending on the platform used, for example, using UART TX or DMA interrupt. The driver can generate a data block up to 600 bytes long (MTU+ headers), so the user must provide an appropriately sized buffer to store the data during its byte or block output.

The exchange interface with the user program is represented by two groups of functions: reading and writing (control). The functions of the first group should be called by the user when certain events occur in the driver. They are designed to receive data from the driver (for example, SMS text or data received via TCP). The functions of the second group can be called if the driver is free (not busy processing the previous command) and are used to control the module and transfer data. Figure 4 shows the printed circuit board in Altium Designer CAD, the drawings (used to design the VM case) and the layout of the printed circuit board (to check the compliance of the manufactured printed circuit boards with gerbera files).

Figure 5 shows the wiring boards of the measurement module (3D model in Altium Designer CAD and manufactured at the JLCPCB factory). Figure 6 shows a working prototype of the measurement module as an element of an air pollution monitoring system.
4. Information-measuring channel and system sensors

Sensors of various physical quantities can be included in the air quality monitoring system. Depending on the needs, up to 15 analog sensors, and 256 digital sensors via the 1-WIRE bus and up to 127 via I2C can be connected to the base module, including:

- particulate sensor: PMS 5003 and/or GP2Y1010AU0F;
- meteorological sensors: BME 280, DHT-22, DS18b20;
Figure 5. Measurement module board: (a) 3D model of the board; (b) PCB manufactured by JLCPCB factory.

Figure 6. Working prototype of the measuring module of the air pollution monitoring system: (a) 3D model; (b) appearance of the studied sample of the module

- sensors for monitoring the concentration of the following substances: formaldehydes ($CH_2O$); carbon monoxide ($CO$); carbon dioxide ($CO_2$); nitrogen dioxide ($NO_2$); ozone ($O_3$).

Table 1 shows the parameters and characteristics of the sensors. Table 2 shows parameters of the measuring module.

Thanks to the provided wide range of sensors, it is possible to expand the range of use of
Table 1. Parameters of sensors of the measuring modules of air monitoring system.

| Name       | Parameter       | Unit     | Measuring range | Resolution | Error       | Reaction time |
|------------|-----------------|----------|-----------------|------------|-------------|---------------|
| SDS011     | PM10, PM2.5     | µg/m³    | 0-1000          | 0.1        | ±15%        | 1 s           |
| BME280     | Temperature     | °C       | -40...+85       | 0.01       | ±0.01 °C    | 1 s           |
|            | Humidity        | %        | 0-100           | 0.01       | 3%          | 1 s           |
|            | Pressure        | hPa      | 300-1100        | 0.01       | ±0.01 hPa   | 1 s           |
| MH-Z19     | CO₂             | ppm      | 0-5000          | 1          | 50 ppm±5%   | <60 s         |
| ZE08-CH2O  | CH₂O            | ppb      | 0-5000          | 1          | <10 ppb     | <60 s         |
| MICS-6814  | NH₃             | ppm      | 0.1-300         | 0.001      | ±20%        | 1 s           |
|            | CO              | ppm      | 0.1-1000        | 0.001      | ±20%        | 1 s           |
|            | NO₂             | ppm      | 0.02-20         | 0.001      | ±20%        | 1 s           |
| RadKit     | Radiation       | µR/h     | 0-999           | 1          | ±10%        | 60 s          |
| ZE03-SO2   | SO₂             | ppm      | 0-20            | 0.1        | <0.1 ppm    | <90 s         |
| ZE25-O3    | O₃              | ppm      | 0-10            | 0.1        | <10 ppb     | <90 s         |

Table 2. Parameters of the measuring module of air monitoring system.

| Parameter     | Value                                                                 |
|---------------|------------------------------------------------------------------------|
| Power supply  | 5 V, USB compatible battery (3.7V, 2000 mAh)                           |
| Connection    | GSM and 433MHz module                                                  |
| Dimensions    | 60x60x70 mm                                                           |

measuring modules and the system as a whole.

Figure 7 and figure 8 show graphs of PM2.5 dust concentration and radiation background obtained as a result of the operation of the measuring module for 7 days. The location of the measuring module is shown in figure 9. The measurements were carried out within one week – from April 5, 2022 to April 12, 2022. Significant excess of these parameters was not recorded. The measurement range of sensors was 20 minutes. Thus, a data base of more than 500 measurements was formed. Compared to the existing monitoring system, the network built on the developed measuring modules is able to increase the amount of received data by 18 times.

5. Conclusions
The current state of the existing air pollution monitoring system in Ukraine is shown. The features of air pollution monitoring in different cities of Ukraine are presented. The actual task of creating a modern information-analytical system for monitoring atmospheric air pollution, based on low-cost sensors, is considered. The electronic circuits of the measuring modules of the air pollution monitoring system implemented on the basis of modern microprocessor technology are proposed. The features of connecting individual components (STM32F103C8T6 microcontroller, HC-12 module, SIM800C module) as elements of the measuring module are presented. The use of a number of meteorological parameters (temperature, humidity, pressure) and pollutants (PM10, PM2.5, CO₂, CH₂O, NH₃, CO, NO₂, SO₂, O₃, radiation) as the basis of the monitoring system is proposed. Experimental data were obtained from measuring the concentration of PM2.5 dust and the radiation background of the area where the measurements
Figure 7. PM2.5 dust concentration during April 5-12, 2022.

Figure 8. Radiation background during April 5-12, 2022.
Figure 9. Location of the measuring module.

were made. In comparison with the existing system, the information base of the developed module has been increased by 18 times.

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