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SUBSYSTEM FOR MONITORING ATMOSPHERIC AIR QUALITY IN THE CYBER-PHYSICAL SYSTEM "SMART CITY"

The task of designing and developing a cyber-physical system "Smart City" is currently relevant for Ukraine. This study is devoted to the development of a method and subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City".

The article develops a method for monitoring atmospheric air quality, which forms the basis for effective monitoring of atmospheric air quality in the cyber-physical system "Smart City" and allows making informed decisions on warning residents about the danger with recommendations for protecting their health.

The developed subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City" collects data from the installed sensors of air humidity, air temperature, dust content in the air, including particles PM2.5, PM10, air radiation background, air pollution level by nitrogen oxides, air pollution level by sulfur, air pollution level by carbon compounds, air pollution level by greenhouse gases CO, CO2, NH3, NO, real-time transmission of the collected data to the data processing server, real-time processing and analysis of the received data using various analytical methods, visualization of the air quality monitoring results in the form of a city map with n districts displaying all air parameters. The user can select the air parameters of interest in the mobile application of the cyber-physical system. After selecting such parameters, the visualization of the air quality monitoring results is adapted to the user's needs: the measured value of the parameter selected by the user is displayed on the image of the district on the city map, and the mobile application displays a sound signal in the background and a flashing sign on the image of the district on the city map in the application, which signals a danger in this area of the city; clicking on this sign displays a notification on the screen about the indicator for which there is a danger and recommendations for protecting the health of residents in this case.

Keywords: cyber-physical system "Smart City", atmospheric air parameters, air quality monitoring, air humidity sensor, air temperature sensor, air dust content sensor, including particles PM2.5, PM10, air radiation background sensor, sensor for air pollution level by nitrogen oxides, sensor for air pollution level by sulfur, sensor for air pollution level by carbon compounds, sensor for air pollution level by greenhouse gases CO, CO2, NH3, NO.

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ПІДСИСТЕМА МОНІТОРИНГУ ЯКОСТІ АТМОСФЕРНОГО ПОВІТРЯ У КІБЕРФІЗИЧНІЙ СИСТЕМІ «РОЗУМНЕ МІСТО»

Задача проєктування та розроблення кіберфізичної системи «Розумне місто» є наразі актуальною для України. Дане дослідження присвячене розробленню методу та підсистеми моніторингу якості атмосферного повітря у кіберфізичній системі «Розумне місто».

У статті розроблений метод моніторингу якості атмосферного повітря, який становить основу для ефективного моніторингу якості атмосферного повітря у кіберфізичній системі "Розумне місто" і дозволяє приймати обґрунтовані рішення щодо сповіщення мешканців про небезпеку із наданням рекомендацій щодо захисту їх здоров'я.

Розроблена підсистема моніторингу якості атмосферного повітря у кіберфізичній системі "Розумне місто" виконує збір даних з встановлених датчиків вологості повітря, температури повітря, вмісту пилу у повітрі, в т.ч. частинками PM2.5, PM10, радіаційного фону повітря, рівня забруднення повітря оксидами азоту, рівня забруднення повітря сіркою, рівня забруднення повітря вуглецевими сполуками, рівня забруднення повітря парниковими газами CO, CO2, NH3, NO, передачу зібраних даних в реальному часі до сервера обробки даних, обробку та аналіз отриманих даних в реальному часі з використанням різних аналітичних методів, візуалізацію результатів моніторингу якості повітря у вигляді карти міста з n районів із відображенням всіх параметрів повітря. Користувач в мобільному додатку кіберфізичної системи може виконати вибір параметрів повітря, які його цікавлять. Після вибору таких параметрів відбувається адаптація візуалізації результатів моніторингу якості повітря під потреби користувача – відбувається виведення виміряного значення обраного користувачем параметру на зображенні району на карті міста, а також відбувається виведення звукового сигналу мобільним додатком у фоновому режимі та миготливого знаку на зображенні району на карті міста в додатку, який сигналізує про небезпеку в даному районі міста; натискання на цей знак виводить на екран сповіщення про те, за яким показником існує небезпека та рекомендації щодо захисту здоров'я мешканців в такому випадку.

Ключові слова: кіберфізична система «Розумне місто», параметри атмосферного повітря, моніторинг якості повітря, датчик вологості повітря, датчик температури повітря, датчик вмісту пилу у повітрі, в т.ч. частинками PM2.5, PM10, датчик радіаційного фону повітря, датчик рівня забруднення повітря оксидами азоту, датчик рівня забруднення повітря сіркою, датчик рівня забруднення повітря вуглецевими сполуками, датчик рівня забруднення повітря парниковими газами CO, CO2, NH3, NO.

Introduction

The "Smart City" is a concept of urban development that involves the use of innovative technologies and the integration of digital solutions to improve the quality of life of residents and the efficient management of urban infrastructure. The main goal of a smart city is to create a viable, environmentally friendly, efficient, and innovative environment for people to live in [1-3]. Smart cities and the Internet of Things have made it possible to integrate communication devices for effective decision-making [2]. Given that, according to the UN, more than 72% of the world's population is expected to live in cities by 2050, effective decision-making and efficient organization of city residents using the concept of "Smart City", a new approach to urban planning that uses data and technology to improve the quality of life of residents while reducing the impact of urbanization on the environment, is more relevant than ever [3].

The main characteristics of "Smart City" [3-5] are:

1) integrated communication network and the Internet of Things – the installation of sensors and other devices that collect data on various aspects of urban life, such as transportation, energy, water, waste, security, etc;
2) digital technologies and data analytics – the use of data analysis to make informed management decisions and optimize various processes in the city;
3) efficient resource management – the use of technology to optimize the use of energy, water, transportation and other resources to reduce consumption and improve efficiency;
4) infrastructure for mobility – development of infrastructure to encourage environmentally friendly modes of transportation, such as bicycles, electric vehicles, and public transport, in order to reduce congestion and air pollution;
5) active community participation – involvement of city residents in the decision-making process using digital platforms and feedback mechanisms;
6) security and data protection – ensuring the protection of personal data and cybersecurity in the context of widespread use of digital technologies.

The implementation of the smart city concept contributes to the creation of cities that are more viable, competitive, environmentally friendly and comfortable to live in.

The cyber-physical system “Smart City” is an innovative integrated platform that combines data collection and analysis technologies, communication systems, and information technologies to improve the quality of life of city residents, optimize the management of urban infrastructure, and increase the efficiency of various areas of city life. Such a system allows collecting large amounts of data from various sources, analyzing them in real time, and making decisions based on this information [6-8]. Smart cities are seen as catalysts for transforming the socio-economic environment of a city into a more knowledge-intensive and environmentally friendly one [7].

The main components of the cyber-physical system "Smart City" are [9, 10]:

1) sensors – installation of sensors throughout the city to collect data on various parameters such as air pollution, traffic, noise, humidity, temperature, etc.;
2) communication network – deployment of communication networks (e.g., wireless, mobile networks, Internet of Things, etc.) to enable real-time data transmission between sensors and a centralized data processing system;
3) data processing and analysis – development of algorithms and software for processing and analyzing large amounts of data received from sensors and other sources in order to identify patterns, trends and forecast events;
4) integrated management system – the creation of a centralized management system includes an interface for city administrators, dispatch centers, control panels and data visualization tools;
5) infrastructure automation and management systems – the use of data to automate the management of various city systems, such as lighting, water supply, transportation, waste, security, etc. to optimize their operation and efficiency;
6) community feedback and interaction systems – providing opportunities for feedback and interaction with city residents through mobile applications, web platforms, and other tools to report problems, feedback, and suggestions for improving services and infrastructure.

The cyber-physical system "Smart City" has great potential to improve the management of urban resources, reduce negative environmental impacts, and improve the quality of life of city residents.

The cyber-physical systems "Smart City" are constantly evolving, integrating new technologies that allow cities to become even more efficient and environmentally friendly, such as the use of artificial intelligence for data analysis, the development of autonomous vehicles, the introduction of smart energy supply systems, and much more [11-13]. The cyber-physical systems "Smart City" can include intelligent analytical tools that allow cities to collect, process, and analyze large amounts of data to make more informed management decisions, such as analyzing traffic flows to optimize traffic, forecasting demand for utilities, identifying congestion and taking measures to eliminate it, and analyzing air quality to identify sources of pollution and take measures to reduce it [14-16]. Such cyber-physical systems are a key tool for achieving modern urban development goals and improving the quality of life of their residents. They make cities more efficient, safe, environmentally friendly, and comfortable to live in.

Air pollution is a serious environmental problem in our daily lives. Deteriorating air quality has a negative impact on public health and the environment. Environmental pollution and air quality are becoming increasingly important topics in the areas of Smart City and government regulation. Air quality monitoring in a cyber-physical system "Smart City" plays a key role in ensuring the health and comfort of residents, as well as in preserving the environment. A real-time air quality monitoring subsystem helps to track sudden changes in the atmosphere [17-19]. Solving pollution problems is one of the main challenges faced by cities today, since cities are the main sources of pollutant emissions and, on the other hand, are areas where the impact of pollution on human health (especially on the respiratory tract, cardiovascular system, and nervous system) is quite significant. Therefore, monitoring of air quality in cities is crucial, as it is a preliminary and necessary step for the development and further implementation of measures aimed at reducing pollution in order to preserve the health of citizens [20].

Air quality monitoring in the cyber-physical system "Smart City" is performed by placing sensors throughout the city to measure various air quality parameters, such as humidity, temperature, dust content, including particles PM2.5, PM10, radiation background, pollution levels with nitrogen oxides, sulfur, carbon compounds, greenhouse gases such as CO, CO2, NH3, NO etc. and other harmful substances. The data from the sensors are analyzed and processed, as a result of which alerts can be sent to city residents in case of severe air pollution and advice on how to protect their health [20-22]. Air quality monitoring in the cyber-physical system "Smart City" is an important tool for ensuring the safety and comfort of residents, improving the quality of life and preserving the environment [23-25].

Online collaborative platforms for sensor data management are services with online databases that allow sensor owners to register and connect their devices to submit data to the database online for storage, and allow developers to connect to the database and create their own applications based on this data [26].

The European Union is making ongoing efforts to develop a strategy for achieving smart urban growth for the largest cities and regions [27]. The EU has developed a number of programs as part of the "Europe Agenda" [28]. "Arup" estimates that the global market for smart city services was worth $400 billion per year in 2020 [29]. Examples of smart city technology have been implemented in Milton Keynes [30], Southampton [31], Amsterdam [32], Barcelona [33], and Stockholm [34]. An important cluster of smart city tech companies exists in Israel, where Tel Aviv was awarded the 2014 World Smart City Award [35].

Let's consider the known examples of the implementation of the smart city concept, which demonstrate the variety of approaches and innovative solutions used by cities to improve the quality of life and create a sustainable, efficient and comfortable urban infrastructure [5].

Launched in 2009, Amsterdam's Smart City initiative currently includes more than 170 projects jointly developed by local residents, government, and business. These projects are developed on the basis of wireless devices that serve to increase the city's ability to make real-time decisions. The projects aim to reduce traffic, save energy, and improve public safety. To stimulate the efforts of local residents, the city holds an annual Smart City competition, accepting proposals for improvements that fit into the city's structure. An example of an app developed by city residents is Mobypark, which allows owners of parking spaces to rent them out to people for a fee. The data obtained from this application can then be used by the city to determine parking demand and traffic flows in Amsterdam. In addition, smart energy meters have been installed in a number of buildings, and incentives are provided for those who actively reduce energy consumption. Other initiatives include flexible street lighting, which allows municipalities to control the brightness of streetlights, and intelligent traffic management, where traffic is monitored in real time and information about the current traffic on certain roads is broadcast to allow motorists to determine the best routes [32].

According to the Smart Cities study conducted by Juniper Research in 2015, Barcelona ranks first in the world in the ranking of "smart cities". Every year, Barcelona hosts the international conference Smart City Expo World Congress, where the authorities of the largest cities and technology companies present their solutions in the field of smart city development. Barcelona is implementing smart solutions to optimize its transportation system, water, energy and waste management. The city is also developing smart applications and platforms to interact with residents and ensure their participation in city management [33].

Copenhagen is considered one of the smartest cities in Europe. It is actively implementing innovative technologies to improve the transportation system, use renewable energy sources, and promote green initiatives [36].

The English city Milton Keynes has made an attempt to turn itself into a "smart city". Currently, the mechanism for achieving this goal is the "MK: The Smart Initiative" [30, 37], a collaboration of local authorities, businesses, academia, and organizations. The focus of this initiative is to rationalize the use of energy, water, and transportation while promoting economic growth in the city. Central to this project is the idea of creating an advanced "MC Data Hub" that would support the collection and management of a huge amount of information relevant to the city system from various sources. This includes information on electricity consumption and water consumption, traffic flows, satellite data, social and economic data, and crowdsourcing received through social media or specialized applications.

Singapore is considered one of the most advanced smart cities in the world. The city is implementing technologies to manage its transportation system, water supply, energy, and waste. It also actively uses digital solutions to ensure security and monitor the health of residents [38].

Toronto is launching the Sidewalk Toronto project, together with Sidewalk Labs, to create a smart district on the city's coastal territory. This project involves the use of innovative technologies to optimize transport infrastructure, energy, construction, and housing [39].

Kyiv has also launched the Kyiv Smart City initiative, which aims to create favorable conditions for the city's evolution. The concept lays down the basic principles of the city's infrastructure, technological, and social development, and identifies areas for transforming urban space [40]. To date, Kyiv has implemented the Kyiv Card project, which is the "access key" for city residents to innovations implemented in the city.

The city Santander in Cantabria, northern Spain, has 20000 sensors connecting buildings, infrastructure, transportation, and communication networks, offering a physical space for experimentation and testing IoT functions such as interoperability and management of protocols, technological devices, and ancillary services such as detection, identity management, and security [41]. In Santander, sensors monitor pollution, noise, traffic, and parking.

Sydney is actively implementing a smart city in many areas, such as transportation, energy, healthcare, and culture. The city uses information technology to optimize public transport, introduce smart traffic lights, energy-efficient lighting, and air pollution monitoring systems [42].

These examples demonstrate that the smart city concept is widely used around the world and has significant potential for creating sustainable, efficient, and comfortable urban environments. Currently, this concept is not widely used for the development of Ukrainian cities, mainly due to its high cost, although it has a huge potential for them, especially during post-war reconstruction.

So, the task of designing and developing a cyber-physical system "Smart City" is currently relevant for Ukraine. This study is devoted to the development of a method and subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City".

Subsystem for Monitoring Atmospheric Air Quality in the Cyber-Physical System "Smart City"

Before proceeding to the development of a method for monitoring atmospheric air quality and the design of the subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City", we will define the purpose and objects of air quality monitoring among following purposes: measuring various air parameters and current air quality monitoring, identifying pollution sources and their location in different parts of the city, identifying the impact of air pollution on the health of city/district residents, identifying trends in air quality, and further For this study, the specific goal will be to measure various air parameters and ongoing air quality monitoring.

The method of air quality monitoring consists of the following steps:

1) setting a set of normal values of air parameters: air dust content (*adcth*), PM2.5 content (*apmmth*), PM10 content (*apmtth*), air radiation background (*arbth*), air pollution level by nitrogen oxides (*anoth*), air pollution level by sulfur (*asth*), air pollution level by carbon compounds (*accth*), air pollution level by greenhouse gases CO (*acoth*), CO2 (*acooth*), NH3 (*anhth*), NO (*anaoth*): $APTH = \{apth_1, apth_2, \ldots, apth_{11}\} = \{adcth, arbth, anoth, asth, accth, acoth, acooth, anhth, anaoth, apmmth, apmtth\}$, when exceeded, the city residents are notified of the danger and recommendations are given to protect their health;
2) selection and placement of sensors - selection of appropriate sensors for measuring key air quality parameters, such as air humidity, air temperature, dust content in the air, including particles PM2.5, PM10, air radiation background, air pollution level by nitrogen oxides, air pollution level by sulfur, air pollution level by carbon compounds, air pollution level by greenhouse gases CO, CO2, NH3, NO, as well as the systematic placement of sensors in different areas of the city to ensure representativeness and coverage of the entire city; if there is a need to measure air parameters in hard-to-reach places, drones or robots can be equipped with appropriate sensors;
3) collecting data from installed sensors connected to the Internet of Things network:
   - 3.1) forming a set of air humidity values $AH = \{ah_1, ah_2, \ldots, ah_n\}$ based on data obtained from *n* air humidity sensors located in *n* city districts;
   - 3.2) forming a set of air temperature values $AT = \{at_1, at_2, \ldots, at_n\}$ based on data obtained from *n* air temperature sensors located in *n* city districts;
   - 3.3) forming a set of values of dust content in the air $ADC = \{adc_1, adc_2, \ldots, adc_n\}$ based on data obtained from *n* dust content sensors located in *n* city districts;
   - 3.4) forming a set of values of the level of the content of PM2.5 particles in the air $APMM = \{apmm_1, apmm_2, \ldots, apmm_n\}$ based on data obtained from *n* sensors of content of PM2.5 particles in the air located in *n* districts of the city;
   - 3.5) forming a set of values of the level of the content of PM10 particles in the air $APMT = \{apmt_1, apmt_2, \ldots, apmt_n\}$ based on data obtained from *n* sensors of content of PM10 particles in the air located in *n* districts of the city;
   - 3.6) forming a set of values of air radiation background $ARB = \{arb_1, arb_2, \ldots, arb_n\}$ based on data obtained from *n* air radiation background sensors located in *n* city districts;

3.7) forming a set of values of the level of air pollution by nitrogen oxides $ANO = \{ano_1, ano_2, \ldots, ano_n\}$ based on data obtained from *n* sensors of air pollution by nitrogen oxides located in *n* city districts;
3.8) forming a set of values of the level of air pollution by sulfur $AS = \{as_1, as_2, \ldots, as_n\}$ based on data obtained from *n* sulfur air pollution sensors located in *n* city districts;
3.9) forming a set of values of the level of air pollution by carbon compounds $ACC = \{acc_1, acc_2, \ldots, acc_n\}$ based on data obtained from *n* sensors of air pollution by carbon compounds located in *n* city districts;
3.10) forming a set of values of the level of air pollution greenhouse gas CO $ACO = \{aco_1, aco_2, \ldots, aco_n\}$ based on data obtained from *n* sensors of air pollution greenhouse gas CO located in *n* districts of the city;
3.11) forming a set of values of the level of air pollution greenhouse gas CO2 $ACOO = \{acoo_1, acoo_2, \ldots, acoo_n\}$ based on data obtained from *n* sensors of air pollution greenhouse gas CO2 located in *n* districts of the city;
3.12) forming a set of values of the level of air pollution of greenhouse gas NH3 $ANH = \{anh_1, anh_2, \ldots, anh_n\}$ based on data obtained from *n* sensors of air pollution of greenhouse gas NH3 located in *n* districts of the city;
3.13) forming a set of values of the level of air pollution of greenhouse gas NO $ANAO = \{anao_1, anao_2, \ldots, anao_n\}$ based on data obtained from *n* greenhouse gas NO air pollution sensors located in *n* city districts;

4) transfer of the collected data in real time using the Internet of Things network to the data processing server;
5) processing and analysis of the obtained data in real time using various analytical methods – either for the purpose of current monitoring of air quality, or to identify sources of air pollution and their location in different parts of the city, or to identify the impact of air pollution on the health of city residents / city district, or to identify trends and further forecast air quality, etc.; for this study, given the chosen goal of air quality monitoring, the processing and analysis of the data obtained will be carried out exclusively for the purpose of ongoing air quality monitoring;
6) visualization of the results of air quality monitoring – in the form of a map of the city with *n* districts with a graphical display of all air parameters using color schemes or symbols indicating the intensity of air pollution, in the form of graphs and/or diagrams for easy perception and analysis by city authorities, researchers and city residents;
7) selection of air parameters by the user – selection of air parameters of interest to the user (the user can select from 1 to 11 of the above parameters);
8) adaptation of the visualization of air quality monitoring results to the user's needs – in the form of a city map of *n* districts with a graphical display of the air parameters of interest to the user using color schemes or symbols indicating the intensity of air pollution, in the form of graphs and/or diagrams for easy perception and analysis by city authorities, researchers and city residents:

8.1) if in step 7 the user selected the "air humidity" parameter, the user is provided with a city map of *n* districts, each of which shows the corresponding air humidity value of the given district from the set of air humidity values $AH = \{ah_1, ah_2, \ldots, ah_n\}$;
8.2) if in step 7 the user selected the "air temperature" parameter, the user is provided with a city map of *n* districts, each of which shows the corresponding air temperature value of the given district from the set of air temperature values $AT = \{at_1, at_2, \ldots, at_n\}$;
8.3) if in step 7 the user selected the "dust content in the air" parameter, the user is generated a city map of *n* districts, each of which shows the corresponding value of dust content in the air of the given district from the set of values of dust content in the air $ADC = \{adc_1, adc_2, \ldots, adc_n\}$; if in the *i*-th district of the city $adc_i \geq adcth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The dust content in the air exceeds the norm" and recommendations for protecting the health of residents in this case;
8.4) if in step 7 the user selected the parameter "level of content of PM2.5 particles in the air", the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the level of content of PM2.5 particles in the air of the given district from the set of values of the level of content of PM2.5 particles in the air $APMM = \{apmm_1, apmm_2, \ldots, apmm_n\}$; if in the *i*-th district of the city $apmm_i \geq apmmth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a

notification screen: "The level of content of PM2.5 particles in the air exceeds the norm" and recommendations for protecting the health of residents in this case;

8.5) if in step 7 the user has selected the parameter "level of content of PM10 particles in the air", the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the level of content of PM10 particles in the air of the given district from the set of values of the level of content of PM10 particles in the air $APMT = \{apmt_1, apmt_2, \ldots, apmt_n\}$; if in the *i*-th district of the city $apmt_i \geq apmtth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of content of PM10 particles in the air exceeds the norm" and recommendations for protecting the health of residents in this case;

8.6) if in step 7 the user selected the "air radiation background" parameter, the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the air radiation background of the given district from the set of air radiation background values $ARB = \{arb_1, arb_2, \ldots, arb_n\}$; if in the *i*-th district of the city $arb_i \geq arbth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The radiation background of the air exceeds the norm" and recommendations for protecting the health of residents in this case;

8.7) if in step 7 the user selected the parameter "level of air pollution by nitrogen oxides", the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the level of air pollution by nitrogen oxides of the given district from the set of values of the level of air pollution by nitrogen oxides $ANO = \{ano_1, ano_2, \ldots, ano_n\}$; if in the *i*-th district of the city $ano_i \geq anoth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of air pollution with nitrogen oxides exceeds the norm" and recommendations for protecting the health of residents in this case;

8.8) if in step 7 the user selected the "sulfur air pollution level" parameter, the user is shown a city map of *n* districts, each of which shows the corresponding value of the sulfur air pollution level of the given district from the set of values of the sulfur air pollution level $AS = \{as_1, as_2, \ldots, as_n\}$; if in the *i*-th district of the city $as_i \geq asth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of sulfur air pollution exceeds the norm" and recommendations for protecting the health of residents in this case;

8.9) if in step 7 the user has selected the parameter "level of air pollution by carbon compounds", the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the level of air pollution by carbon compounds of the given district from the set of values of the level of air pollution by carbon compounds $ACC = \{acc_1, acc_2, \ldots, acc_n\}$; if in the *i*-th district of the city $acc_i \geq accth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of air pollution with carbon compounds exceeds the norm" and recommendations for protecting the health of residents in this case;

8.10) if in step 7 the user has selected the parameter "level of air pollution by greenhouse gas CO", the user is shown a map of the city with *n* districts, each of which shows the corresponding value of the level of air pollution by greenhouse gas CO of the given district from the set of values of the level of air pollution by greenhouse gas CO $ACO = \{aco_1, aco_2, \ldots, aco_n\}$; if in the *i*-th district of the city $aco_i \geq acoth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of air pollution with greenhouse gas CO exceeds the norm" and recommendations for protecting the health of residents in this case;

8.11) if in step 7 the user has selected the parameter "level of air pollution of greenhouse gas CO2", the user is shown a map of the city with n districts, each of which shows the corresponding value of the level of air pollution of greenhouse gas CO2 of the given district from the set of values of the level of air pollution of greenhouse gas CO2 $ACOO = \{acoo_1, acoo_2, \ldots, acoo_n\}$; if in the i-th district of the city $acoo_i \geq acooth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of air pollution with greenhouse gas CO2 exceeds the norm" and recommendations for protecting the health of residents in this case;

8.12) if in step 7 the user has selected the parameter "level of air pollution of greenhouse gas NH3", the user is generated a city map of n districts, each of which shows the corresponding value of the level of air pollution of greenhouse gas NH3 of the given district from the set of values of the level of air pollution of greenhouse gas NH3 $ANH = \{anh_1, anh_2, \ldots, anh_n\}$; if in the i-th district of the city $anh_i \geq anhth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of air pollution with greenhouse gas NH3 exceeds the norm" and recommendations for protecting the health of residents in this case;

8.13) if in step 7 the user has selected the parameter "level of air pollution greenhouse gas NO", the user is shown a map of the city with n districts, each of which shows the corresponding value of the level of air pollution greenhouse gas NO of the given district from the set of values of the level of air pollution greenhouse gas NO $ANAO = \{anao_1, anao_2, \ldots, anao_n\}$; if in the i-th district of the city $anao_i \geq anaoth$, the mobile application running in the background emits a sound signal, and a flashing sign  appears on the image of the district on the city map in the application, signaling the danger in this area of the city; clicking on this sign displays a notification screen: "The level of greenhouse gas NO air pollution exceeds the norm" and recommendations for protecting the health of residents in this case.

The developed method for monitoring atmospheric air quality forms the basis for effective monitoring of atmospheric air quality in the cyber-physical system "Smart City" and allows making informed decisions on warning residents about the danger with recommendations for protecting their health. The use of this monitoring method allows cities to obtain accurate and up-to-date information on air quality, which is an important step in making strategic decisions to reduce pollution and improve environmental quality. Moreover, the data provided by the method can be used to develop and implement effective programs and projects in urban planning, transport infrastructure, energy efficiency, and other aspects of urban life.

Let's design the architecture of the subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City" based on the developed method – Fig. 1.

So, the developed subsystem for monitoring atmospheric air quality in the cyber-physical system “Smart City” collects data from the installed sensors of air humidity, air temperature, dust content in the air, including particles PM2.5, PM10, air radiation background, air pollution level by nitrogen oxides, air pollution level by sulfur, air pollution level by carbon compounds, air pollution level by greenhouse gases CO, CO2, NH3, NO, real-time transmission of the collected data to the data processing server, real-time processing and analysis of the received data using various analytical methods, visualization of the air quality monitoring results in the form of a city map with n districts displaying all air parameters. The user can select the air parameters of interest in the mobile application of the cyber-physical system. After selecting such parameters, the visualization of the air quality monitoring results is adapted to the user's needs: the measured value of the parameter selected by the user is displayed on the image of the district on the city map, and the mobile application displays a sound signal in the background and a flashing sign  on the image of the district on the city map in the application, which signals a danger in this area of the city; clicking on this sign displays a notification on the screen about the indicator for which there is a danger and recommendations for protecting the health of residents in this case.

Thus, the subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City" plays an important role in ensuring the health and comfort of residents, as well as in preserving the environment. The main goal of this subsystem is to collect, analyze, and visualize air quality data in the city to make informed management decisions and take measures to reduce pollution and improve air quality. It is also important to ensure that this data is accessible and open to a wide range of stakeholders, including city authorities, researchers, NGOs, and city residents. This will help to raise awareness of air pollution problems and facilitate joint efforts to address them. This approach to monitoring air quality in the cyber-physical system "Smart City" allows to create an effective toolkit for sustainable development and ensuring the health and comfort of residents.

The developed subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City" can be developed by identifying sources of pollution and their location in different parts of the city, identifying the impact of air pollution on the health of city / city district residents, identifying trends in air quality and further forecasting air quality in order to develop a strategy for improving air quality, etc. Continuous improvement of the monitoring subsystem is necessary to ensure maximum accuracy and efficiency of air quality monitoring. In addition, it is highly desirable to integrate air quality data with other Smart City systems, such as transport management systems, energy systems, water management systems, etc. for a comprehensive approach to addressing environmental pollution and creating an environmentally friendly living environment, as well as to ensure effective management of the urban environment and take measures to improve it.

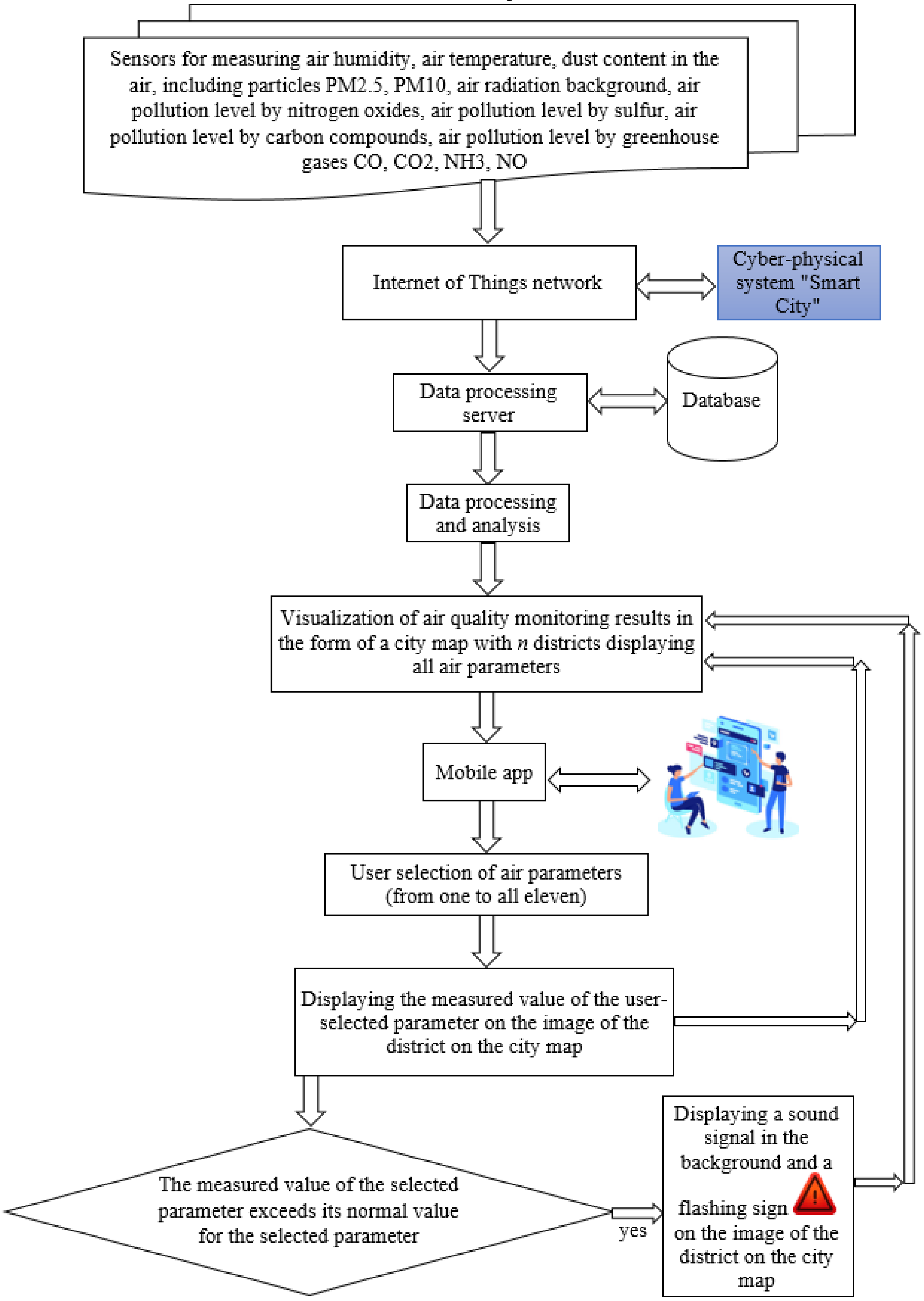

Fig. 1. Architecture of the subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City"

Conclusions

The developed subsystem for monitoring atmospheric air quality in the cyber-physical system "Smart City" collects data from the installed sensors of air humidity, air temperature, dust content in the air, including particles PM2.5, PM10, air radiation background, air pollution level by nitrogen oxides, air pollution level by sulfur, air pollution level by carbon compounds, air pollution level by greenhouse gases CO, CO2, NH3, NO, real-time transmission of the collected data to the data processing server, real-time processing and analysis of the received data using various analytical methods, visualization of the air quality monitoring results in the form of a city map with n districts displaying all air parameters. The user can select the air parameters of interest in the mobile application of the cyber-physical system. After selecting such parameters, the visualization of the air quality monitoring results is adapted to the user's needs: the measured value of the parameter selected by the user is displayed on the image of the district on the city map, and the mobile application displays a sound signal in the background and a flashing sign on the image of the district on the city map in the application, which signals a danger in this area of the city; clicking on this sign displays a notification on the screen about the indicator for which there is a danger and recommendations for protecting the health of residents in this case.

References

1. A new framework for assessment of park management in smart cities: a study based on social media data and deep learning / S. Liu et al. Scientific Reports. 2024. Vol. 14, no. 1.
2. A vehicular network based intelligent transport system for smart cities using machine learning algorithms / J. Prakash et al. Scientific Reports. 2024. Vol. 14, no. 1.
3. CSR and smart city progress: a proposed model for urban development / K. Singh et al. Letters in Spatial and Resource Sciences. 2023. Vol. 17, no. 1.
4. Hovorushchenko T. O., Aleksov S. V., Talapchuk S. I., Shpylyuk O. V., Magdin V. V. Overview of the Methods and Tools for Situation Identification and Decision-Making Support in the Cyberphysical System "Smart House". Computer Systems & Information Technologies. 2022. №4. Pp. 20-26.
5. Sustainable open data ecosystems in smart cities: A platform theory-based analysis of 19 European cities / M. Lnenicka et al. Cities. 2024. Vol. 148. P. 104851.
6. Ji C., Niu Y. A hybrid evolutionary and machine learning approach for smart city planning: Digital twin approach. Sustainable Energy Technologies and Assessments. 2024. Vol. 64. P. 103650.
7. Kim J. S., Feng Y. Understanding complex viewpoints in smart sustainable cities: The experience of Suzhou, China. Cities. 2024. Vol. 147. P. 104832.
8. Chen C., Li S.-E., Wang L. Can smart cities reduce labor misallocation? Evidence from China. Technological Forecasting and Social Change. 2024. Vol. 201. P. 123264.
9. Experts and intelligent systems for smart homes' Transformation to Sustainable Smart Cities: A comprehensive review / N. U. Huda et al. Expert Systems with Applications. 2024. Vol. 238. P. 122380.
10. Zheng X., Li M., Guo J. Task scheduling using edge computing system in smart city. International Journal of Communication Systems. 2020. P. e4422.
11. Shiu S. C.-o. Ageing in a smart city poses concerns on sustainability from a model perspective. Aging and Health Research. 2024. P. 100179.
12. Concept of Intelligent Measuring System for Analyzing the Energy Consumption of IoT Modules / A. Sachenko et al. Computer systems and information technologies. 2022. No. 4. P. 101–105.
13. Active smart switchable glazing for smart city: A review / A. Ghosh et al. Journal of Building Engineering. 2024. P. 108644.
14. Pavlova O., Kovalenko V., Hovorushchenko T., Avsiyevych V. Neural network based image recognition method for smart parking. Computer Systems and Information Technologies. 2021. №1. Pp. 49-55.
15. Kesar P., Ache (Peter) P. M. Past, present and future of the Smart City in India: An institutional perspective. Cities. 2024. Vol. 146. P. 104775.
16. Smart cities and sustainable development goals (SDGs): A systematic literature review of co-benefits and trade-offs / A. Sharifi et al. Cities. 2024. Vol. 146. P. 104659.
17. Air Quality Hotspot Monitoring with Trajectories of IoT in Smart City Implementation / S. C. Bhangale et al. 2023 3rd International Conference on Pervasive Computing and Social Networking (ICPCSN), Salem, India, 19–20 June 2023. 2023.
18. Holubčík M., Jandačka J., Nicolanská M. Improvement of Emission Monitoring System Accuracy in Aims of Increasing Air Quality of Smart City. Mobile Networks and Applications. 2023.
19. Das S., Alzimami A. Bayesian Optimization based Hyperparameter Tuning of Ensemble Regression Models in Smart City Air Quality Monitoring Data Analytics. 2023 1st International Conference on Advanced Innovations in Smart Cities (ICAISC), Jeddah, Saudi Arabia, 23–25 January 2023. 2023.
20. Designing Air Quality Monitoring Systems in Smart Cities / A. Marini et al. Communications in Computer and Information Science. Cham, 2022. P. 3–20.
21. Verma H., Prabhu S. Implementation Of IoT and Applications in Smart City in Achieving the Smart Environment. 2023 Second International Conference on Augmented Intelligence and Sustainable Systems, Trichy, India, 23–25 August 2023.
22. Smart and Portable Air-Quality Monitoring IoT Low-Cost Devices in Ibarra City, Ecuador / V. E. Alvear-Puertas et al. Sensors. 2022. Vol. 22, no. 18. P. 7015.
23. Tancev G., Toro F. G. Towards a Digital Twin for Air Quality Monitoring Networks in Smart Cities. 2022 IEEE International Smart Cities Conference (ISC2), Pafos, Cyprus, 26–29 September 2022. 2022.
24. Performance Analysis of LoRaWAN in an Air Quality Monitoring Applications for Smart Cities / A. F. da S. Veloso et al. 2021 6th International Conference on Smart and Sustainable Technologies (SpliTech), Bol and Split, Croatia, 8–11 September 2021. 2021.
25. Jiang X. Large Scale Air-Quality Monitoring in Smart and Sustainable Cities. Smart Cities. Hoboken, NJ, USA, 2017. P. 725–753.
26. Boyle D. E., Yates D. C., Yeatman E. M. Urban Sensor Data Streams: London 2013. IEEE Internet Computing. 2013. Vol. 17, no. 6. P. 12–20.
27. Paskaleva K. A. Enabling the smart city: the progress of city e-governance in Europe. International Journal of Innovation and Regional Development. 2019. Vol. 1, no. 4. P. 405.
28. Shaping Europe's digital future: Commission presents new initiatives for digital infrastructures of tomorrow. URL: https://digital-strategy.ec.europa.eu/en.

29. Smart cities: Digital technologies make smart cities more liveable, sustainable and prosperous. URL: https://www.arup.com/services/planning/smart-cities.
30. MK Data Hub. URL: https://datahub.mksmart.org/.
31. SmartCities card. URL: https://www.southampton.gov.uk/roads-parking/travel/smartcities-card/.
32. City of Amsterdam: Digitalization & Innovation. URL: https://amsterdamsmartcity.com/organisations/digitalization-innovation.
33. Barcelona Digital City. URL: https://ajuntament.barcelona.cat/digital/en.
34. Stockholm Smart City. URL: https://nscn.eu/Stockholm.
35. How Tel Aviv Became One of the World's Smartest Cities. URL: https://www.iotworldtoday.com/smart-cities/how-tel-aviv-became-one-of-the-world-s-smartest-cities.
36. Puttkamer L. City Portrait: Smart City Copenhagen. URL: https://www.beesmart.city/en/smart-city-blog/copenhagen.
37. Help make Milton Keynes a smarter, greener city. URL: https://ourmk.org/.
38. Singapore: the world's smartest city. URL: https://www.thalesgroup.com/en/worldwide-digital-identity-and-security/iot/magazine/singapore-worlds-smartest-city.
39. Toronto's Smart City: Our Fight For Privacy. URL: https://ccla.org/major-cases-and-reports/torontos-smart-city/.
40. Kyiv Smart City. URL: https://smartcitykyiv.com/.
41. Smart city case study: Santander, Spain. URL: https://www.rcrwireless.com/20170116/fundamentals/smart-city-case-study-santander-tag23-tag99.
42. Sydney a smart city? URL: https://www.arup.com/perspectives/sydney-a-smart-city

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