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Fine-Granularity Urban Microclimate Monitoring Using Wearable Multi-Source Sensors

Jinjing Ren [1], Runfa Li [2], Fengshuo Jia [2], Xinhao Yang [2], Yusheng Luo [2], Chenglin Wu [2], Wei Wang [3] and Yuan Yang [2,*]

1 Research Center for Electromagnetic Environment Effects, Southeast University, Nanjing 211189, China; renjj@seu.edu.cn
2 Key Laboratory of Micro-Inertial Instrument and Advanced Navigation Technology, Ministry of Education, School of Instrument Science and Engineering, Southeast University, Nanjing 211189, China; 220213660@seu.edu.cn (R.L.); 220213592@seu.edu.cn (F.J.); 213182135@seu.edu.cn (X.Y.); 213180132@seu.edu.cn (Y.L.); 213181385@seu.edu.cn (C.W.)
3 School of Architecture, Southeast University, Nanjing 210096, China; weiwang@seu.edu.cn
* Correspondence: yangyuan@seu.edu.cn

Abstract: With the development of urbanization, the environment is the key to the safety of residents' life and health and the United Nations' Sustainable Development Goals (SDGs). Urban environmental changes and microclimate problems have attracted widespread attention. For the SDGs, monitoring the urban microclimate more accurately and effectively and ensuring residents' environmental health and safety is particularly important when designing applications that can replace the traditional fixed-point urban environment or pollution monitoring. Based on the BeiDou Navigation Satellite System platform, this paper proposes a fine-granularity urban microclimate monitoring method using wearable multi-source ($PM_{2.5}$, PM_{10}, and other air pollutants) sensors innovatively, which includes the satellite position function by adopting the satellite pseudo-range differential positioning technology, environmental data perception through the embedded system and wireless transmission, as well as the GIS data processing and analysis system. The wearable sensor acquires position and service information data through the satellite positioning system and acquires environmental parameters through integrated mobile multi-source sensors. The data are cached and wirelessly transmitted to the cloud server for digital processing. The urban microclimate is evaluated and visualized through algorithm and map API. Mobile monitoring can be flexibly applied to complex and diverse urban spaces, effectively realizing all-weather, all-directional, and accurate microclimate monitoring of urban environmental quality.

Keywords: BeiDou Navigation Satellite System; wearable mobile monitoring; urban microclimate; position-based service; spatio-temporal analysis

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1. Introduction

1.1. Research Background

With cities now being home to the majority of the global population, their importance for global development is undisputed. "Building cities and human settlements that are inclusive, safe, adaptable and sustainable" (SDG11) is considered the minimum requirement for sustainable urban development in the 2030 Agenda. The ambient air quality has a significant impact on human health [1], but the inefficient economic growth model has triggered serious air pollution, which poses a threat to people's health [2]. Not only that, but serious air pollution can also cause large economic losses [3,4]. Therefore, it is imperative to monitor and control the urban air environment and advance the achievement of transformative air quality related SDGs. The methodology for calculating the Sustainable Development Goal Indicator 11.6.2 "Annual mean levels of fine particulate matter (e.g., $PM_{2.5}$ and PM_{10}) in cities (population weighted)" is based on the methodology proposed by the UN, the main goal of which was to collect best practices to promote the concept of the "smart city" and use it for as many cities as possible by integrating satellite observations to increase the resilience of the environment and society to urban impact. Because there are many cities in China, although the technical research on ambient air quality monitoring networks has been carried out, the monitoring network is only accessible to those cities [5], and the monitoring network cannot cover every corner of the city [6]. The main reason is that the traditional fixed-point monitoring method cannot make people only consider the number of data sources without considering the cost of installing ambient air quality monitoring devices. The smaller the range of ambient air quality monitoring in the city, the higher the cost becomes. A city needs to design equipment and systems that can replace the equipment and systems for fixed-point environmental quality monitoring and mobile monitoring of pollutant concentration and position.

For the fixed-point monitoring of urban gaseous pollutants, foreign developed countries and regions have successively established relatively complete monitoring networks and adopted statistical analyses, such as correlation analysis and cluster analysis, to optimize the monitoring layout [7]. In China, it was not until the 1970s that the environmental quality monitoring network began to be set up, and the national environmental quality monitoring network was initially put into place in the early 1990s. However, there are still various problems that challenge China's environmental quality monitoring network, one of which is the lack of research on the optimization of environmental quality monitoring network layout, and the unreasonable layout of monitoring stations in each region, resulting in insufficient monitoring coverage and representativeness [8].

Traditional environmental monitoring methods need base stations and a wired power supply, while traditional monitoring and evaluation approaches are limited by how the monitoring work is carried out and incur such problems as having monitored blind spots. Therefore, designing a device and relevant system that can replace the fixed-point monitoring station and accurately locate and monitor the environmental quality in motion is the key to solve the problem of the resolution and real-time performance of urban environmental quality monitoring [9]. In this context, mobile monitoring is flexible and intelligent, which can help overcome the above shortcomings.

With the development of wireless positioning [10], mobile platforms, and sensor technology, mobile terminal applications are emerging in all areas of people's lives and are widely used thanks to their flexible advantage and other advantages which can benefit productivity, product quality, and the labor environment [11]. Mobile sensing is a technology-intensive agent integrating environmental monitoring, dynamic decision-making, intelligent identification, and other functions, which greatly reduces the work intensity of workers and improves their job safety. Mobile monitoring is a frontier topic in robot application engineering in recent years [12]. Potential applications of the mobile monitoring system will release the labor force and make environment monitoring much easier and provide finer granularity. Intelligent mobile monitoring has broad application prospects.

1.2. Research Significance

The quality of the environment seriously affects people's health. The World Health Organization reported in 2009 that the burden of disease caused by environmental pollution and other factors in China registers 21% every year, while air pollution is the main factor to blame for this result. Excessive concentrations of various pollutants in the air can easily make people suffer from diseases or even die. It is worth mentioning that the excessive concentration of $PM_{2.5}$ can easily cause respiratory diseases. Besides, the excessive concentration of PM_{10} can weaken the human immune system. According to the relevant report issued by the Ministry of Ecology and Environment in 2018, 70.7% of the 338 cities in China in 2017 have not met environmental quality standards, which means that 239 cities have failed to reach the environmental quality standards. To sum up, at present, the air pollution problem in China has not been effectively addressed, which indicates that relevant control measures and more efforts should be made to quickly and effectively monitor and resolve the air pollution problem in China.

Therefore, the monitoring of urban microclimate [13] has great significance for urban environmental quality control, residents' travel, urban planning, and people's life quality improvement [14]. The wireless, wearable, mobile, crowd-sourced and multi-sourced environmental monitoring system based on the BeiDou Navigation Satellite System proposed in this paper solves the problem of the monitoring range, because the traditional monitoring system is not wide enough. At the same time, typical regional pollutants are taken into account when the environmental evaluation method is formulated [15], which greatly improves people's dynamic, real-time, comprehensive and detailed ability for monitoring the urban environment.

1.3. Research Description

This paper studies location-based mobile sensing of urban microclimate and proposes that it can realize non-fixed-point air environmental quality monitoring. To be specific, the environmental monitoring system including the BeiDou positioning module is installed on buses, dockless shared bicycles, and other travel tools using mobile sensing, thus realizing the diversification of data sources. Compared with fixed-point environmental quality monitoring, mobile monitoring greatly expands the number of environmental quality monitoring stations and reduces the cost incurred by environmental quality monitoring. Moreover, the system can adjust the time interval of data transmission according to achieve real-time and dynamic monitoring of air quality. At the same time, it can play the role of national supervisor and discourage tampering and falsifying ambient air quality data. The results of mobile environmental monitoring are sent to the PC through the 4G-DTU module, and the PC can obtain a detailed distribution map of urban air quality, which plays an extremely important role in the supervision and control of the urban air environment.

2. Device and Methods

The location-based mobile monitoring of urban microclimate can be divided into four parts: the data acquisition system, the data transmission system, data processing, and data visualization. The monitoring terminal of the mobile monitoring system obtains the environmental quality parameters and geographical position through the sensor and BeiDou positioning module and stores them in the memory of a microcomputer. Then, the data is transmitted to a PC through 4G communication technology. After that, the PC directly inputs the data into the model for processing, using an algorithm to a certain extent. A heat map of air pollutant concentration is generated using the processed data. The overall design of the system is shown in Figure 1.

The system includes several sensor modules, a wireless data communication module, and a cloud server which helps communicate in sequence. The sensor module includes a ground environment monitor and an aerial mobile sensor; the environmental monitoring sensor can be installed on a hand-held object, a ground vehicle, or a low-altitude unmanned aerial vehicle. The remote monitoring and early warning module have the functions of real-time monitoring and statistical analysis of many parameters, such as $PM_{2.5}$/PM_{10}/TSP/noise/temperature/humidity. At the same time, the GNSS positioning module can realize the functions of real-time return of monitoring points, trajectory drawing of mobile carriers, real-time display of environmental parameter values along the trajectory, and warning prompts of exceeding the standard. It is mainly used in digital urban management, smart cities, construction sites, demolition sites, garbage dumps, wharves, industrial parks, communities, and other places, focusing on areas where uncertainties are compared in terms of mobile monitoring areas and short-term construction sites, which is also an effective supplement to areas that cannot be covered by fixed monitoring points. The implementation of the system can be summarized as the following points:

(1) Installation positions

The mobile environmental monitoring terminal can be installed on mobile carriers, such as public transport vehicles (taxis, buses, private cars, and/or bicycles), personal equipment, and unmanned aerial vehicles, etc. The data communication can be interconnected with existing servers by wireless communication technology and share GPS information and GIS information with those servers.

(2) Data processing

The system software can collect a massive amount of data, which needs to be processed quickly and effectively. The system software has a strong capability to process data, and can calculate the collected original data according to the calculation formula provided by customers, engineering conversion method, project coefficient, audit rules [16], national or industry regulations, etc. After calculation, the original data and the calculated data are stored in different tables of the database at the same time. If data that is not qualified or reflects abnormal quality code appears, the system will sound an alarm.

(3) Data storage

The software has writing functions of various databases and can seriously treat the fault tolerance of the system when conducting operations, such as connection, insertion, and queries related to the database. Thus, if the circumstances of disconnection and reconnection, blocking the signal abnormally, database deadlock, and other abnormal phenomena appear, the system can handle them.

The system uses multi-thread and multi-connection modes to operate the database in order to ensure the insertion, query, and update of massive data.

(4) Microclimate classification

Urban microclimate classification reflects the spatial and temporal differences of the environment, and its evaluation on the environment is based on the development density, topography, and meteorology of the city [17,18].

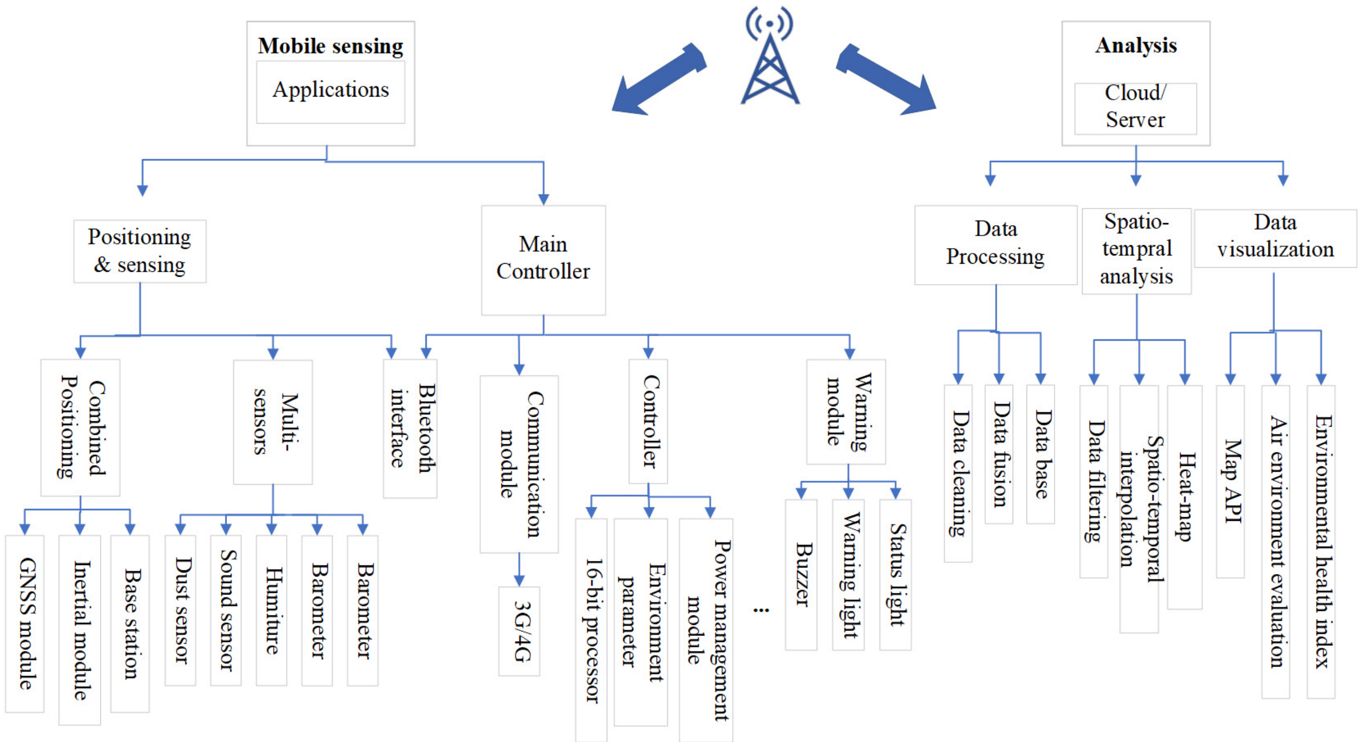


Figure 1. Structure of mobile monitoring for urban microclimate.

2.1. Pseudo-Range Differential Positioning of BeiDou Navigation Satellite System

BeiDou Navigation Satellite System uses pseudo-range differential positioning technology [19,20]. At a certain moment, the receiver generates a distance measurement signal which is the same as the satellite signal according to its clock. The time for moving is indicated by Δt. The pseudo-range between the satellite and the receiver can be obtained by multiplying the relative time difference between the satellite and the user and the propagation delay of the signal from the satellite to the user by the propagation speed of light.

The equation of pseudo-range is:

$$\rho = r + \delta t_u - \delta t^{(n)} + I + T + \varepsilon_p \quad (1)$$

Among the terms in the equation, r represents the linear distance between the receiver and the satellite transmitting the signal; δt_u represents the clock error corrections of the receiver; $\delta t^{(n)}$ represents the clock error corrections of the nth satellite; I and T represent ionospheric and tropospheric corrections respectively; and ε_p represents other error corrections.

If a receiver performs a pseudo-range measurement on the nth visible satellite at a specified time, the following equation can be obtained:

$$\rho^{(n)} = r^{(n)} + \delta t_u - \delta t^{(n)} + I^{(n)} + T^{(n)} + {\varepsilon_p}^{(n)} \quad (2)$$

The equation of pseudo-range measurements corrected by troposphere, ionosphere, and clock difference is as follows.

$${\rho_c}^{(n)} = \rho^{(n)} + \delta t^{(n)} - I^{(n)} - T^{(n)} \quad (3)$$

Therefore, the following equation can be obtained:

$$r^{(n)} + \delta t_u = {\rho_c}^{(n)} - {\varepsilon_p}^{(n)} \quad (4)$$

As for the terms in the above equation, $r^{(n)}$ represents the geometric straight-line distance between the receiver and the nth satellite. At present, this pseudo-range differential positioning technology is the most widely used. After pseud-range correction, the mobile station can largely eliminate the ionospheric delay, tropospheric delay, satellite clock difference, and other unfavorable consequences that cause large errors in the measurements.

In Figure 2, S1, S2, and S3 are satellites, M1, M2, and M3 are independent reference stations, and B1 is a mobile station within a certain range with the reference stations.

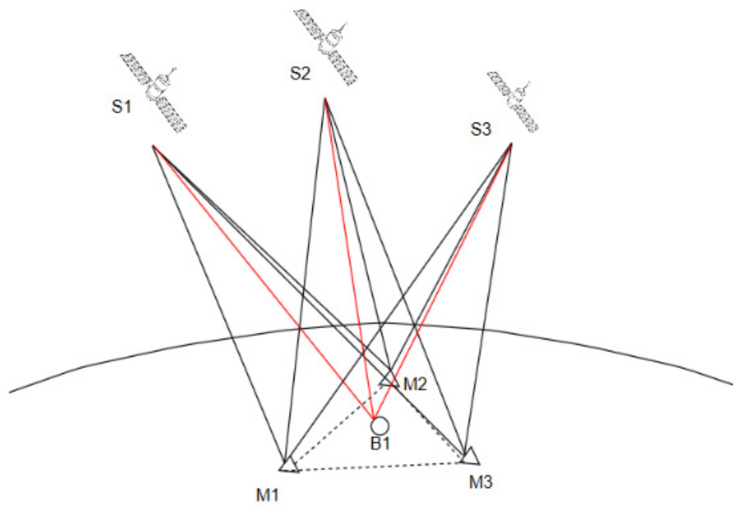


Figure 2. Schematic diagram of separate satellite pseudo-range network.

2.2. Wearable Monitoring Device

The data acquisition system mainly collects information on urban environments by sensors and the location information from the BeiDou positioning module. The data acquisition system of the urban environmental movement perception in BeiDou can be divided into three parts: the BeiDou positioning module, the sensor acquisition module, and the microcomputer processing module. In the BeiDou positioning module, we use pseudo-differential positioning technology to improve positioning accuracy. In the sensor acquisition module, we have innovatively designed multi-source environmental mobile sensing monitoring and pattern recognition methods based on BeiDou location information, which provides new ideas for protecting the urban environment. The design of the wearable monitoring device is shown in Figures 3 and 4.

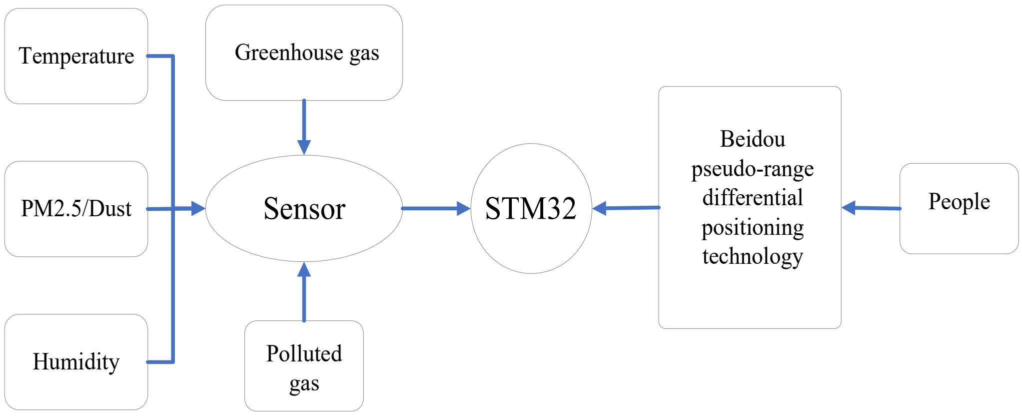


Figure 3. Hardware construction of the wearable monitoring device.

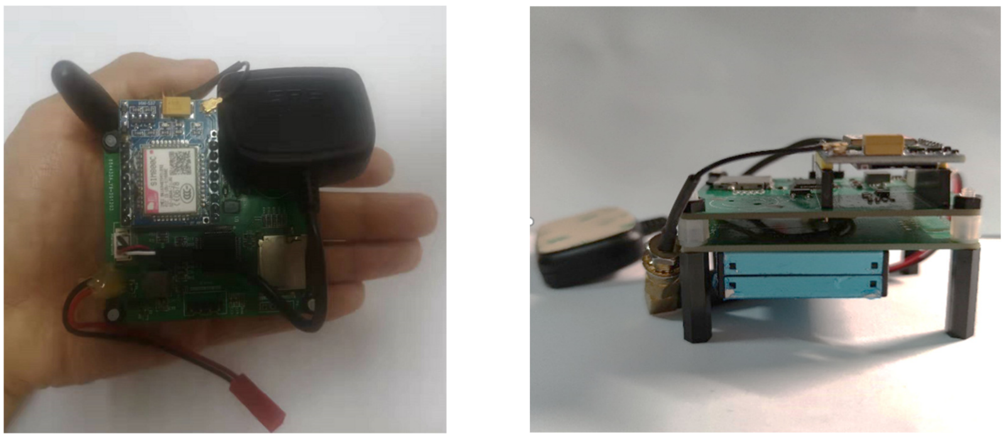


Figure 4. Photo of the wearable monitoring sensor node.

2.2.1. Microcomputer Module

The microcomputer module is the processor of the data acquisition system, which receives the urban environment information collected by the sensor and the position information sent by BeiDou positioning module through the serial port and transmits the information to the 4G-DTU module through the serial port, thus realizing the transfer function of data receiving and sending. In order to maximize the performance of the system and easily realize multiple data control processing, we have used an STM32F103ZET6 enhanced chip. It adopts a CM3 core CPU, has the highest main frequency of 72MHz and 256KB SRAM, and has a variety of peripherals with flexible functions. Besides, it is rich in extended functions and can easily cope with the work of multiple modules.

2.2.2. Sensor Module

Sensors are the core part of the environmental monitoring system, and the data collected by sensors hold the key to establishing an environmental monitoring system. In this design, our sensor is PTQS1005, which is an all-in-one gas sensor module. Specifically, this sensor can be used to measure various gas indexes at the same time. The built-in laser particle sensor, non-dispersive infrared carbon dioxide sensor, and the latest sensor combining electrochemistry and the semiconductor principle are used to obtain particle concentration, carbon dioxide concentration, and toxic gas concentration, respectively.

The sensor module also has a built-in temperature and humidity sensor chip. Various parameters will be output in the form of a digital interface. By optimizing the internal structure of the sensor module, the path of air in the module is better combined with the sampling interface of each sensor, which not only reduces the size of the module, but also ensures the sensitivity of each sensor.

2.2.3. Positioning Module

The positioning module is the key part to data collection. Only when accurate location information is measured can an accurate GIS map be drawn after data processing. In the aspect of positioning, we will adopt the pseudo-range differential positioning technology based on the BeiDou Navigation Satellite System to solve the problem of inaccurate positioning in cities.

In the system design, we choose the AKT-S1216F8-BD BeiDou module, which is a high-performance BeiDou positioning module. The module adopts S1216F8-BD, as shown in Figure 5. The module can set various parameters through a serial port, and the parameters can be stored in internal FLASH, which is convenient to use. The module has its IPX interface and can be connected with various active antennas. The module is compatible with 3.3 v/5v level, making it convenient to connect with the microcomputer system.

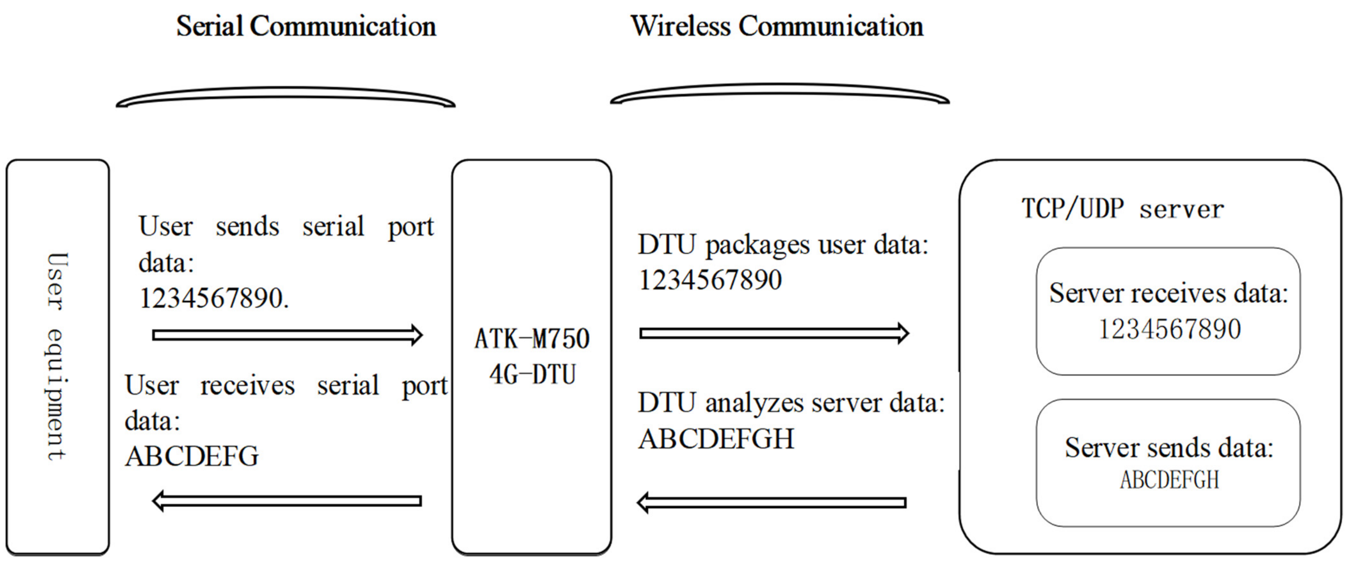


Figure 5. Mode diagram of data transmission system.

The positioning data obtained by the ATK-S1216F8-BD BeiDou module in this system adopts NMEA-0183 messaging protocol, and its $GNRMC format is as follows.

With regard to $GNRMC, (1), (2), (3), (4), (5), (6), (7), (8), (9), (10), (11), and (12), their meanings and descriptions are as Table 1.

Table 1. The meaning of abbreviations.

Serial No.	Meaning	Description
(1)	UTC Time	hhmmss (hour minute seconds)
(2)	Positioning state	A = effective positioning, V = invalid positioning
(3)	Latitude	ddmm.mmmmm (degree minute)
(4)	Hemisphere (latitude)	N (Northern Hemisphere) or S (Southern Hemisphere)
(5)	Longitude	ddmm.mmmmm (degree minute)
(6)	Hemisphere (longitude)	E (East Longitude) or W (West Longitude)
(7)	Speed Kn	Speed over ground, knots
(8)	Track true	Track made good, degrees True
(9)	Date	Date: dd/mm/yy
(10)	Mag variation	Magnetic variation, degrees
(11)	Var direction	Magnetic variation direction E/W
(12)	Mode indicator	Positioning system mode indicator

2.3. Data Transmission System

The data transmission system is mainly composed of a STM32 microcomputer and 4G-DTU module. As the core system for processing information, the STM32 microcomputer transmits the acquired environmental information to the PC through the 4G communication system, as shown in Figure 5.

To process the environmental information obtained by the microcomputer from the sensor and positioning module, we need to transmit the environmental and position information to the PC through the communication module. In this design, we use ATK-M750, i.e., the 4G-DTU communication module. ATK-M750 supports TCP/HTTP protocols, cloud server connection, TCP/HTTP data transparent transmission, automatic timing acquisition, base station positioning, configuration parameters of upper computer /AT instruction/SMS/transparent transmission instruction, and RS232 and RS485 serial interfaces. It can be widely used in wireless data transmission, power industry, industrial control, water conservancy industry, environmental protection industry, agricultural application, centralized reading systems, and smart building.

In the experimental design, our 4G-DTU module is connected to an STM32 microcomputer through the serial port, receives the sensor and BeiDou data from the microcomputer, and transmits the data to the cloud server, thus realizing the long-distance transmission from data collection to the cloud server. We can process and visualize the data transmitted from DTU to PC.

2.4. Mobile Environment Data Processing

2.4.1. Environment Data

Because of the local emission and regional transmission characteristics of air pollution sources [21], air pollutants in the environment can usually change rapidly in a relatively small time and space. For complex air conditions, a large number of deployed low-cost sensors can be used to achieve high temporal and spatial resolution monitoring. According to different monitoring purposes, gas sensors can be applied to different application scenarios, and the ways to effectively monitor the environmental quality of a certain area are mainly divided into fixed monitoring and mobile monitoring.

The fixed sensors can be gridded and arranged in a specific area of the city, which is used for monitoring the environmental quality with high spatial and temporal resolution. Mobile sensors can be installed on corresponding mobile carriers. Compared with fixed sensors, mobile sensors can provide more flexible spatial data, and can realize stereoscopic monitoring of environmental quality and pollution sources. Given portability and practicality, mobile environment monitoring equipment can be installed on mobile tools, such as wearable devices, bicycles, automobiles and unmanned aerial vehicles to monitor the concentrations of PM_{10}, $PM_{2.5}$, and other air pollutants in real-time.

Based on the microcomputer module, BeiDou positioning module and all-in-one sensor module in the above-mentioned data acquisition system, different areas are selected as outdoor environment test scenes in the experiment, and multiple groups of environmental data such as temperature, humidity, $PM_{2.5}$, and CO_2 are measured using walking, cycling and unmanned aerial vehicle flight. Records of the experimental environment are shown in Table 2.

Table 2. Records of the experimental environment.

Experiment No.	Mobile Tool	Monitoring Location	Monitoring Height	Moving Speed
1	People	Campus A	About 1 m	1 m/s
2	Bicycle	Campus A	About 1 m	2.5 m/s
3	Unmanned aerial vehicle	Campus B	20 m	10~20 m/s
4	Bicycle	Urban area (morning)	About 1 m	2.5 m/s
5	Bicycle	Urban area (evening)	About 1 m	2.5 m/s

2.4.2. Data Processing

In the process of data collection, there may be occasional errors in hardware or errors in data transmission, which may lead to the wrong values, missing values, and repeated records of the collected sensor data. Therefore, we need to establish data evaluation rules according to the sensor data format to clean, adjust, and discard some unreasonable data. After the data cleaning, the concentrations of $PM_{2.5}$, PM_{10}, and other air pollutants are extracted from the sensor data, which are correlated with BeiDou positioning data to establish a data set. Finally, cluster analysis is carried out on the data set so that the similarity of air pollutant concentration data objects in a certain place is maximized, and the target data set is obtained. The flow chart is shown in Figure 6.

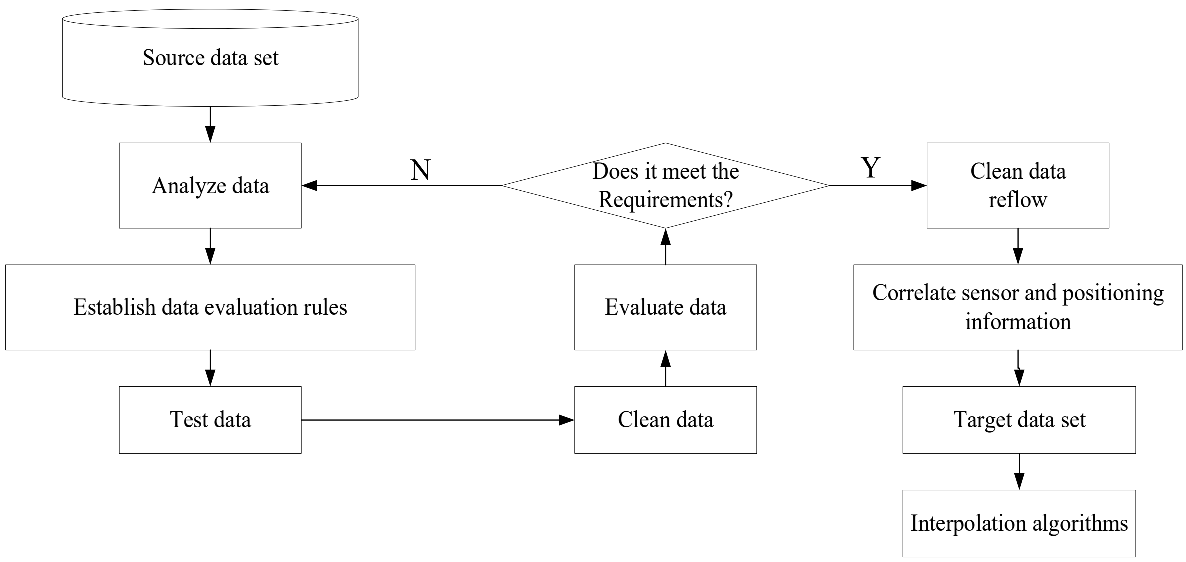


Figure 6. Flow chart of air and time-spatial data processing.

The wearable sensor node moves along a planned trajectory, then it acquires position and service information data through the satellite positioning system and environmental parameters through integrated multi-source sensors. The data are cached and wirelessly transmitted to the cloud server for digital processing. For spatial analysis and visualization, we use the Kriging interpolation algorithm to estimate the whole area [22,23]. The first law of geography states that geographical attributes are spatially correlated, and the degree of correlation is affected by distance. Based on this principle, the Kriging interpolation method is proposed to calculate the unknown point data by weighted sum of all known point data. Its general form is as follows:

$$\widehat{z_0} = \sum_{i=1}^{n} \lambda_i z_i \tag{5}$$

Among the terms in the equation, $\widehat{z_0}$ represents the estimated value at the interpolation point (x_0, y_0), $z_1, z_2 \ldots\ldots, z_n$ are values at the interpolation nodes. $\lambda_1, \lambda_2 \ldots\ldots \lambda_n$ are the weights of each interpolation node. The weight coefficient is a set of optimal coefficients which can satisfy the minimum difference between the estimated value $\widehat{z_0}$ and the true value z_0. The mathematical notation is shown as follows:

$$\min_{\lambda_i} D(\widehat{z_0} - z_0) \tag{6}$$

There are many variations of the Kriging interpolation method, depending on the assumptions. The simple ordinary Kriging interpolation method is adopted in this study, and its assumptions are as follows:

The space attribute Z is homogeneous. For any point (x, y) in the space, its attribute value Z has the same expectation and variance:

$$E(z_1) = E(z_2) = \cdots = E(z_n) = E(z_0) = c \tag{7}$$

$$D(z_1) = D(z_2) = \cdots = D(z_n) = D(z_0) = \sigma^2 \tag{8}$$

Assume Equation (7) into the unbiased constraint $E((Z_0){-}z_0) = 0$, that is:

$$E\left(\sum_{i=1}^{n} \lambda_i z_i - z_0\right) = 0 \tag{9}$$

Thus, the constraint conditions of this set of weight coefficients can be obtained:

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{10}$$

2.4.3. Evaluation Model

According to the Environmental Quality Standard (GB 3095—2012), there are six basic pollutants in the ambient air, and they are O_3, $PM_{2.5}$, PM_{10}, NO_2, CO, and SO_2, and the corresponding concentration limits of each item are shown in Table 3.

Table 3. Concentration limits of basic items of ambient air pollutants.

Serial No.	Main Pollutants	Duration	Concentration Limit		Unit
			Level I	Level II	
1	SO_2	Annual mean concentration 24 h mean concentration 1 h mean concentration	20 50 150	60 150 500	μg/m^3
2	NO_2	Annual mean concentration 24 h mean concentration 1 h mean concentration	40 80 200	40 80 200	
3	CO	24 h mean concentration 1 h mean concentration	4 10	4 10	mg/m^3
4	O_3	8-h daily maximum concentration 1 h mean concentration	100 160	160 200	μg/m^3
5	PM_{10}	Annual mean concentration 24 h mean concentration	40 50	70 150	
6	$PM_{2.5}$	Annual mean concentration 24 h mean concentration	15 35	35 75	

In order to objectively evaluate the environmental quality of the urban environment and understand the actual situation of urban environmental quality, the above six basic pollutant indexes can be used as evaluation factors. Based on the environmental quality standards in Table 3, the evaluation standard set and weight set of each pollution factor are established, and then the fuzzy comprehensive evaluation method is used to objectively and comprehensively evaluate the urban atmospheric environmental quality [24,25].

2.5. Data Analysis and Visualization

To realize the visualization of the flow chart of data processing, we activate the call_map function of the heat map of the Baidu map API with the help of a web browser and realize the correlation of the BeiDou module positioning data, sensor module data, and Baidu map through Python programming [26,27]. Baidu map API can provide functions such as map display, search, and positioning, and thus it is suitable for the application and development of this system.

The WGS coordinate system adopted by the satellite positioning system is different from the BD09 coordinate system adopted by the Baidu map. After extracting latitude and longitude information from the above data, it is necessary to convert BeiDou latitude and longitude into the Baidu latitude and longitude format. If you register in Baidu Map API and get the corresponding AK value, you can manage to activate the call_map function via Baidu Map Static Map API, complete the coordinate conversion, and draw a heat map. By displaying the data information of measuring points with different controls and the pollution degree of measuring areas with different colors, the heat map can be drawn on a Baidu map. Embedding Baidu maps into web pages in the form of pictures can not only browse the basic map information, but also accelerate web page access speed.

The general flow chart of the heat-map is shown in Figure 7.

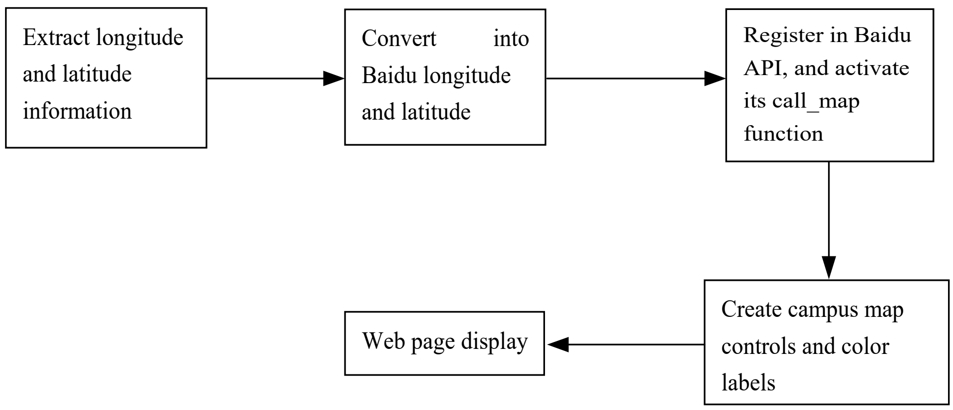
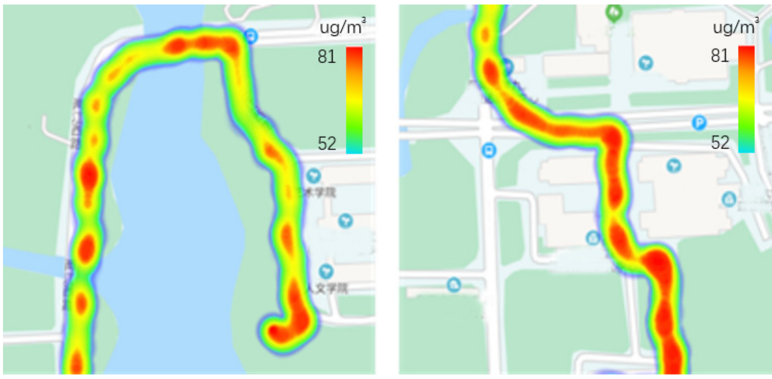


Figure 7. Flow chart of heat map drawing.

After processing a large amount of experimental data, environmental data, such as temperature, humidity, CO_2, and $PM_{2.5}$ in different places can be obtained. Considering the programming needs, several groups of data are converted into the JSON text format, which is easy for people to read and write. Then, a city map is created, the map level is set, and the longitude and latitude coordinates are taken of markers as the center coordinates of the map, and different color gradients are set for different measurement objects, and finally the heat map of urban environmental monitoring data is obtained.

3. Result Analysis

For the data acquired on campus, taking the data of the $PM_{2.5}$ level, CO_2 level, humidity, and temperature measured in Experiment 1 as examples, the heat maps in Figure 8 are drawn respectively. It can be seen from the figure that the content changes of each measured object in different areas are obvious, which is consistent with the actual environmental conditions. For example, the temperature in sunny areas is higher, the humidity in areas near water is higher, the CO_2 level in areas near forests is higher, and the $PM_{2.5}$ level near dust emission areas is higher.



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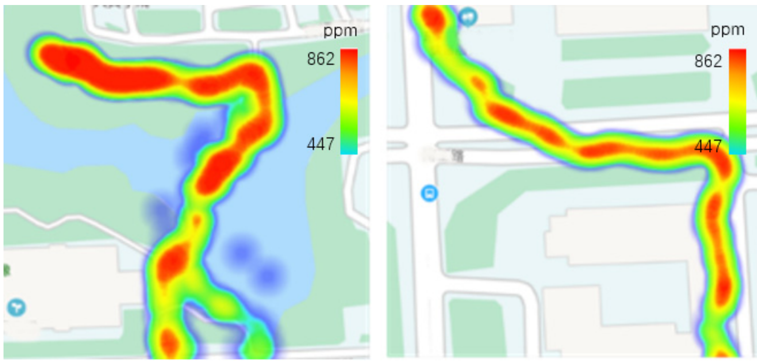

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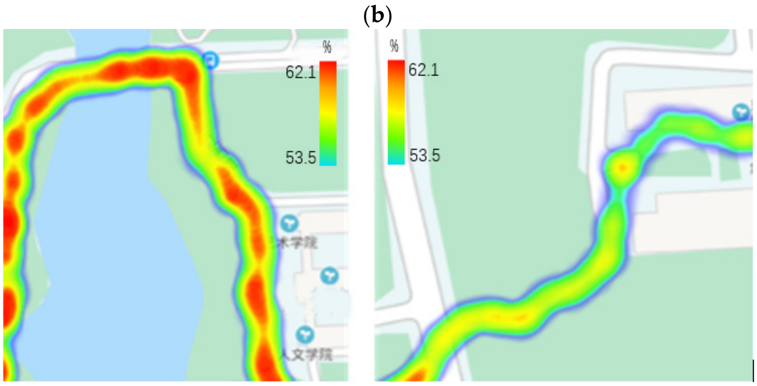
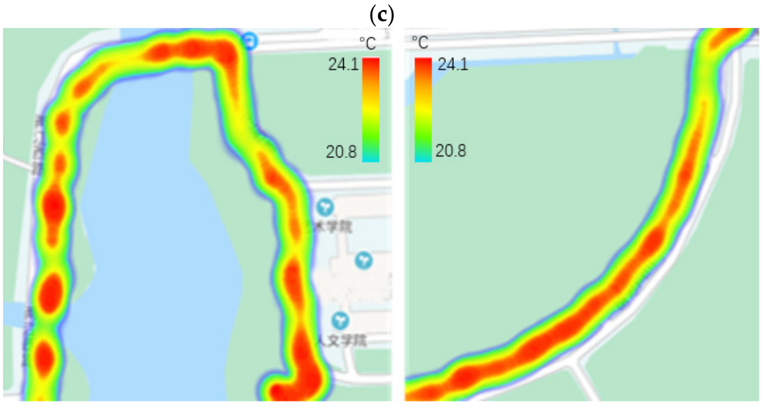


(**c**)



(**d**)

Figure 8. Maps in Experiment 1. (**a**) Experiment 1 Map of $PM_{2.5}$ level; (**b**) Experiment 1 Map of CO_2 level; (**c**) Experiment 1 Map of environmental humidity; (**d**) Experiment 1 Map of environmental temperature.

Taking the $PM_{2.5}$ level measured in Experiment 2 and Experiment 3 as an example, the heat maps of Figures 9 and 10 are drawn respectively. After comparing with Figure 8, it is known that walking and riding affect the moving speed of the monitoring device, and thus affect the monitoring accuracy. The $PM_{2.5}$ levels at different heights on the ground vary considerably.

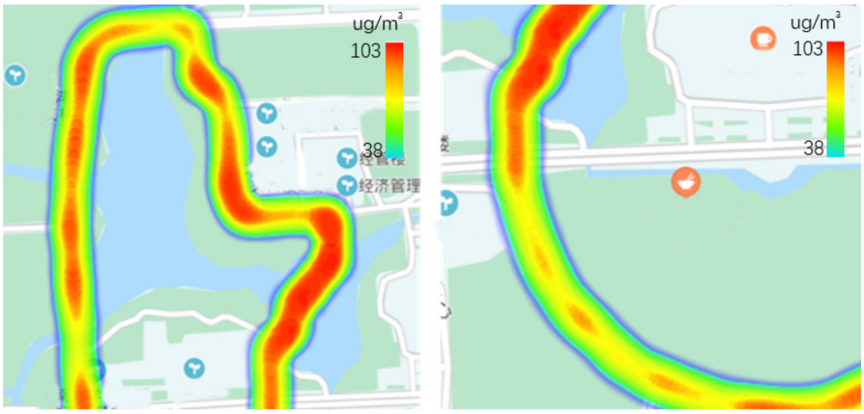


Figure 9. Experiment 2 Map of $PM_{2.5}$ level.

Figure 10. Experiment 3 Map of $PM_{2.5}$ level.

For Experiment 4 and Experiment 5, the route was selected as Figure 11 shows. Specifically, Experiment 4 was conducted at 10:00 am, while Experiment 5 was conducted at 7:00 pm. As the collection range of these two experiments is larger, the Kriging interpolation method is used to interpolate in the two-dimensional grid to generate a two-dimensional thermal map after filtering. Thus, the graph can represent more information. Take carbon dioxide as an example; the heat maps of each are presented in Figure 12. The content of carbon dioxide in Experiment 5 is higher than that in Experiment 4 because there is more emission of CO_2 after a whole day of social operation. Additionally, the peak area of carbon dioxide remains the same from the morning to the evening, which indicates that the heat map of gas can be used to source the original emission location.

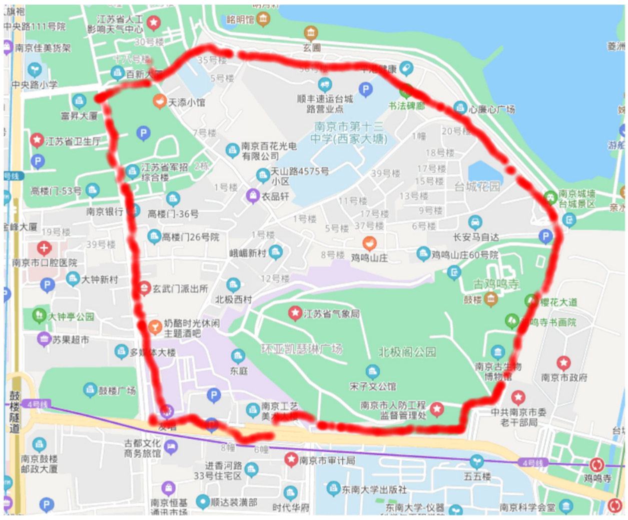
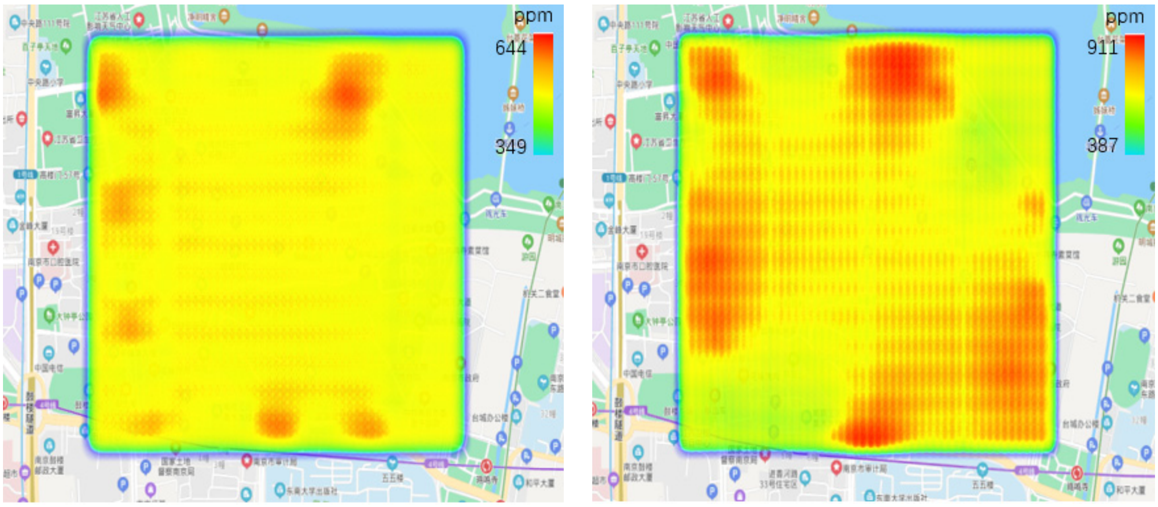


Figure 11. Mobile trajectory carried out by our students of Experiments 4 and 5.



(**a**) (**b**)

Figure 12. Heat maps of Experiments 4 and 5. (**a**) Experiment 4 heat map; (**b**) Experiment 5 heat map.

4. Conclusions

The mobile monitoring system includes meteorological and environmental quality monitoring stations in the wide area of blocks in cities. Those monitoring stations can communicate with the cloud server, obtain data released by the official monitoring stations in real-time through the cloud data server, and link with the monitoring data obtained by the mobile monitoring platforms. In addition, they can automatically find out the nearest data for online checking and precision correction, and regularly correct the sensor's zero drift to realize three-dimensional monitoring and dynamic checking in the urban area. It is conducive to establishing the mobile monitoring system for spatial distributed urban environmental quality with a large database of environmental data, which can be used in some citizen science (CS) projects specifically focused on tackling air pollution and contributing to the SDGs [28].

1. Compared with the existing environmental data monitored by meteorological environment monitoring stations which rely on fixed positions, the data monitored by three-dimensional monitoring stations in the wide area of the blocks in cities is more accurate because three-dimensional monitoring stations can achieve multi-point measurement covering a radius of 1000 m and a height of 200–300 m.

2. Dynamic checking and high accuracy: This invention can synchronously obtain the officially released high-accuracy monitoring data of meteorological and environmental monitoring stations in the monitoring areas and build a mathematical model to dynamically check the high-frequency sensors, which helps to improve the monitoring accuracy and regularly corrects the zero drift. Thus, people can acquire massive amounts of high-accuracy information at a low cost.
3. Conducive to the establishment of a large database of environmental data: It can integrate the mass data acquired via mobile and fixed monitoring covered by this system to build a large database and provide more valuable data services for the evaluation of SDG indicator 11.6.2 [29].

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Informed Consent Statement: Not applicable.

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