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## Development of IoT Technologies for Air Pollution Prevention and Improvement

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## **ABSTRACT**

In order to mitigate the challenges of air pollution, a large number of Internet of Things (IoT)-related technologies have been developed to evaluate and monitor various parameters of air quality. Hence, this paper reviews the fundamental characteristics of IoT; compares and analyzes radio frequency identification (RFID), M2M, and sensor networks; and accordingly proposes an intelligent and multifunctional monitoring platform for reducing air pollution. Our results indicate that establishing systems for comprehensive network communication, cloud-based decision making, information tracking, and online management based on these technologies will improve the ambient air quality more efficiently. Furthermore, we examine several cases verifying the availability and performance of IoT ambient air quality management platforms.

Keywords: Internet of Things (IoT); Ambient air pollution; RFID; M2M; Sensor networks; IoT platform.

## INTRODUCTION

## Issues of Ambient Air Pollution and Instrumental Measurement

The World Health Organization (WHO) defines ambient air pollution as the potential air pollutants emitted from industries, households and vehicles. Those air pollutants include particulate matter (PM) and gaseous air pollutants. The fine particulate matter emitted from fossil fuel combustion process of vehicles, power plants, industry, households, or biomass burning has a severe effect on human health. The estimated 25% of lung cancer deaths, 8% of chronic obstructive pulmonary disease (COPD) deaths, and 15% of stroke deaths were caused by the fine particulate matter. Those particles can settle deep in the lungs resulting the decrease of lung function, chronic bronchitis and cardiac diseases. The gaseous air pollutants could also be the precursors of secondary particulate matters formation. Therefore, in order to control and assess the ambient air pollution emission, the development

of instruments measurement and monitoring system for ambient air quality is inevitable approach. In general, the instruments measure for critical regulatory air pollutants such as PM (i.e.,  $PM_{10}$  and  $PM_{2.5}$ ), sulfur oxide ( $SO_x$ ), nitrogen oxide (NO<sub>x</sub>), ozone (O<sub>3</sub>), carbon monoxide (CO) and volatile organic compounds (VOCs) can be monitored and real-time analyzed (Pan et al., 2018; Chen et al., 2019; He et al., 2020). For example, the aerosols and dust at the designated area are systematically monitored by different industrial proven PM technologies such as gravimetric sampling, light scanning, and inertial weighing tapered element oscillating microbalance (TEOM). The portable and personal instruments are the available options to monitor ambient air pollution in the specific workplace. The equipment can detect the presence of toxic substances to protect the people's safety. Consequently, the application of instrumental measurement for the existence of crucial air pollutants can prevent the health and respiratory problems. According to the U.S. EPA, the criteria of ambient air monitoring strategies include: (i) establishment of air pollution data to the general public; (ii) implementation of air quality standards; (iii) evaluation of the effective air pollution control; (iv) development of the predictive air quality models; and (v) long-term studies of air pollution on the health effects.

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## Concepts of IoT

The *Internet of Things* (IoT) generally refers to the goals achieved by following established network communication

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protocols, connecting items through various networks and using radio frequency identification (RFID) technology, various sensors, location recognition systems, and information processing mechanisms. Finally, information exchange and item identification, tracking service and real-time management are realized. These physical devices from IoT can achieve collaboration and interaction without human intervention, and provide people with intelligent, intensive, and fast-response services. The IoT plays a remarkable role in many application fields including healthcare, industry, entertainments, agriculture, environmental protection, and security. The pervasiveness of IoT eases some everyday activities and enhances the connection properties of people (Ammar *et al.*, 2018; Sai *et al.*, 2019).

From the technical level analysis, IoT can be divided into perception, network and application layers, as shown in Fig. 1.

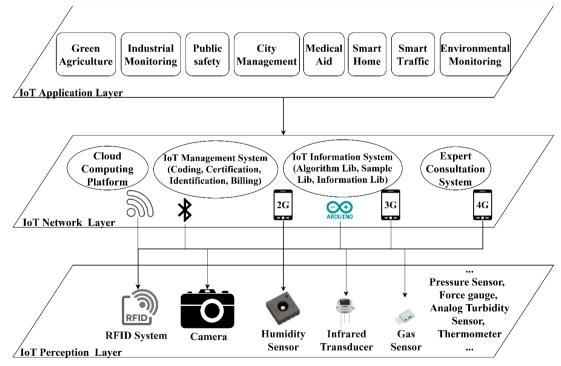
- 1) Perception layer includes diverse sensor nodes and gateways, such as various sensors, electronic tags, read/write devices, cameras, and GPS, whose main function is to identify, collect and transmit information of objects.
- 2) Network layer is composed of various internet, wireless communication networks, mobile air networks (3G/4G/5G), private networks, network management systems, cloud computing platforms, etc. Its main role is to carry out real-time transmission and fast various data information obtained by the perception layer.
- Application layer provides a convenient information interaction system for IoT and users according to the actual needs of users.

Fig. 2 presents the system model to gain an insight into the real meaning of IoT framework under the axial application development. The IoT framework is composed of a loop of real-time sensing, calculating, transmitting, and presenting data. For cost and safety reasons, not all IoT devices can directly connect to the outside world (e.g., the cloud). These devices must be connected to a hub or gateway to communicate. For the IoT frameworks considered in this survey, the cloud is the backbone, which offers databases for high-speed storage and reading of data, big data operations for analysis, and security encryption for preserving confidentiality and privacy. Customers use their smart phones, tablets, or laptops to interact with other IoT devices indirectly through Bluetooth, Wi-Fi, or mobile communication technology (Kim *et al.*, 2017; Benammar *et al.*, 2018).

## IoT Technologies for Ambient Air Quality Monitoring

IoT makes full use of next-generation IT technology in all aspects of life and integrates the existing Internet with IoT to achieve the integration of human society and physical systems, as shown in Fig. 3. In this integrated network, there are server platforms that can achieve real-time management and interact with people, machines, equipment and infrastructure components within the integrated network. Therefore, human beings can manage life cycle of production in a more refined and dynamic manner, reach a "smart" state, improve resource utilization and productivity levels, and strengthen the relationship between man and nature. Specific applications of IoT include the areas such as intelligent transportation, environmental protection, e-government, public safety, industrial monitoring, and safe home.

Regarding ambient air quality monitoring, developed countries such as some from Europe and the United States have carried out many related studies. The IoT-based air quality monitoring platform could perform online monitoring and real-time response, and realizes 24 hours of air condition



**Fig. 1.** Three layers of IoT.

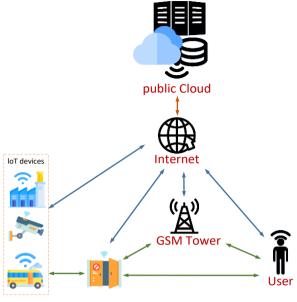


Fig. 2. IoT system model.

monitoring throughout the day (Postolache *et al.*, 2009). Pillai *et al.* (2010) proposed the method of using intelligent

sensor networks for monitoring. It was also proved that the air quality has a great impact on human health with monitoring indoor air conditions. Marinov et al. (2016) studied the air quality monitoring system that was applied in urban environments. The system consisted of sensor nodes, wireless routers, servers and terminals. The sensor node was connected to the router and sent the collected data to the server via Wi-Fi. The terminal could access the server to obtain sensor data. Telegram et al. (2017) proposed an air quality monitoring system based on ZigBee, and used LabVIEW to draw a graphical interface on the monitor, and finally tested it on a campus to obtain good results. Kim et al. (2014) implemented an integrated indoor air quality monitoring system that could collect multiple-gas concentration information simultaneously. The system was optimized to improve fault tolerance, reduce network congestion and system power consumption based on an algorithm calculation. Firdhous et al. (2017) proposed an indoor air quality monitoring system based on IoT, which collected and transmitted data to the gateway node with 5 minute intervals via a Bluetooth connection.

The gateway node communicated with the processor via Wi-Fi. The system met the requirement of tracking the ozone concentration near the photocopier. Yang and Li (2015) designed an intelligent sensor system for air quality

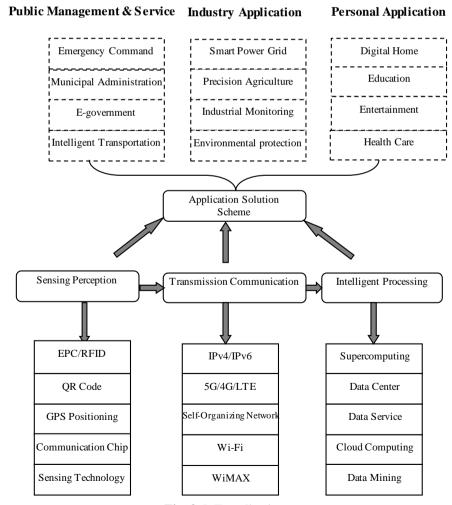


Fig. 3. IoT applications.

monitoring and made a lot of research on data sharing. The system used mobile phones as a middleware to implement data pre-processing, data display and positioning functions. The sensor unit was connected to the user's mobile phone via Bluetooth, and then the mobile phone was connected to the server, to complete the process of data interaction and sharing. As data providers and receivers, users could upload their own data and view other users' data as well. Based on a data transmission method, Phala et al. (2016) proposed to use the Global System for Mobile Communications (GSM) to transmit collected data to a base station, and developed a graphical user interface for users to interact with the system, which could finally measure the air pollution level in real time. Wonohardjo and Kusuma (2019) used mobile sensors and evaluated two different sampling methods, which can only detect carbon monoxide pollution. Since each of the previous studies had its own unique technologies and applications, it was required to develop an open and comprehensive air pollution monitoring platform throughout this research work.

#### **FUNDAMENTALS OF IOT**

IoT technology is a kind of network technology based on internet technology. In addition, it includes end equipment and facilities for information exchange and communication. Generally speaking, three key technologies of IoT are: RFID. M2M and sensor network.

## RFID

RFID is a non-contact automatic identification technology. It uses radio frequency signals to automatically identify target objects and to obtain related data. The identification work does not require manual intervention and can work in various harsh environments. RFID hardware consists of tags, readers and antennas. The reader sends an electronic signal through the antenna. After receiving the signal, the tag transmits the internally stored identification information. The reader then receives and recognizes the information sent back by the tag through the antenna. Finally, the reader sends the recognition results to a host.

Fig. 4 shows the working principles of RFID. When an electronic tag enters the magnetic field recognition range of a reader, the reader encodes the information, and then transmits it to the electronic tag through an antenna through a process of simultaneously releasing radio wave energy. Passive electronic tags or semi-active electronic tags within the working recognition range of the reader receive this pulse signal and use the magnetic field energy induced from the reader to convert the magnetic field energy into electrical energy to generate an induced current. The closed circuit performs a series of processing and reasoning on the received signal. The electronic tag sends a read-only command by extracting information from its own storage unit through the control logic circuit, and then sends this information to the reader after a series of processing. If the command sent by the reader is a rewrite command, the working voltage of the control logic circuit in the electronic tag is increased, and then the relevant content in the EEPROM is modified.

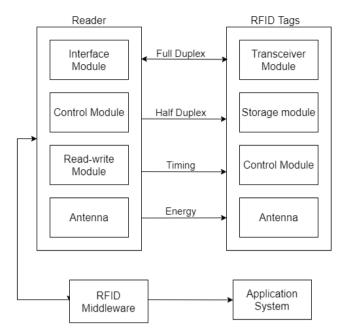


Fig. 4. Working principle chart of RFID.

The development of RFID technology can be divided into the following stages:

- 1) 1941–1950: RFID technology was proposed on the basis of the radar concept, which laid the theoretical foundation.
- 2) 1951–1960: Many RFID technology exploration projects were widely conducted in the research field of the laboratory.
- 3) 1961–1970: RFID technology had gradually shifted from theory to application attempts.
- 4) 1971–1980: RFID had been developing rapidly and some RFID applications emerged.
- 5) 1981–1990: RFID technology and derivative products entered into a commercial stage and various applications had appeared.
- 6) 1991–2000: The standardization of RFID technology began to be valued, and a series of RFID products began to be applied in people's daily activities.
- 7) 2001-present: The types of RFID products become more and more abundant, and the production costs of electronic tags have gradually reduced. Active, passive, and semiactive electronic tags are commonly used in different fields, and the issue of RFID standardization is receiving increasing attention.

## M2M

M2M is a general term for all technologies that enhance the communication and network capabilities of machines and equipment. As a natural extension of embedded control, it allows machines and equipment applications to share information with host information systems and among operators. It provides a means for the device to establish a wireless connection between systems, remote devices or/and individuals in real time to transmit data. M2M includes the domain of machine to machine, man to machine, machine to man, machine to mobile, and mobile to machine (Toma *et al.*, 2019).

As shown in Fig. 5, M2M's products include the wireless terminal, transmission channel and industry application center. Rather than the usual mobile phone or laptop, the wireless terminal refers to a special industrial application terminal. The transmission channel is the channel from the wireless terminal to the user's industry application center. The industry application center is a convergence point for uploading data from terminals, and keeps an eye on scattered industry terminals. The characteristic is that the industry has strong characteristics, users manage it by themselves, and it can be located at the end of the enterprise or hosted.

The M2M application market is growing rapidly worldwide. With more sophistication of related technologies including communication equipment and open-source software and protocols, the cost of M2M products has significantly dropped. The M2M industry will be gradually mature and low-cost with more standardized technologies (Zhang, 2011). At present, it has been applied in the fields of safety monitoring, mechanical services, maintenance operations, vending machines, public transportation systems, fleet management, industrial process automation, electric machinery, and urban informatization all over the world. Unlike traditional wired or wireless networks, M2M has no need for expensive cables and communication transceiver equipment; it only requires a system that is stable, cheap, efficient, and real-time under non-manual operation.

#### Sensor Network

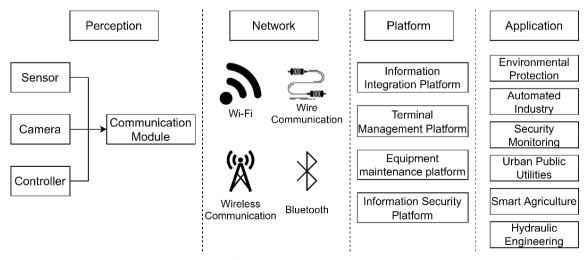
The sensor network is an important component of the IoT to recognize material world. It refers to a huge network formed by combining information sensors such as infrared sensors, global positioning systems, and laser scanners with the Internet. The sensor network allows all components connecting to the network for easy identification and management. It uses the sensors built in the node to measure various signals in the surrounding environment, where to detect material phenomena including temperature, humidity, noise, light intensity, pressure, soil composition, size, speed, and direction of moving objects.

The basic feature of a sensor network is dynamically self-

organizational, and user terminals can move freely within the network while maintaining communication. The dynamically self-organizational networks can use the routing and forwarding capabilities of mobile terminals to communicate without an infrastructure set-up. The main types of nodes are sensor nodes, aggregation nodes and management nodes. The various nodes in the system are primarily connected by dynamically self-organizing topology. Typically, the composition of network nodes includes the following four sensing mechanism, processing mechanism, communication mechanism and power supply. Other functional elements include: positioning system, motion system, and power generation device. In view of the characteristics of limited number of nodes and irreplaceable energy, technicians are trying to find a method that can control the number of nodes and can effectively use node energy to maximize the number of nodes and save energy. In addition, to extend the service life of nodes is another important research goal to effectively utilize each node. As for wireless sensor networks, an efficient network topology is the basis of network technologies. It can greatly improve the utilization efficiency of network communication protocols and extend the life cycle of the network. Under certain conditions, the network topology can be optimized by the node selection strategy for the network to avoid the emergence of redundant lines between nodes, and to maximize information transmission. Currently, there are two main methods of topology control:

 Hierarchical topology control: A clustering idea is adopted, first to select some nodes in the network as cluster head nodes, and then to connect these cluster head nodes to communicate with each other, and finally to constitute an optimized transmission system for information processing and transmission, as shown in Fig. 6.

Power-type topology control: The main idea is to adjust the actual power of each node in the network to achieve a dynamic adaptive balance of routing efficiency, number of neighboring nodes, and network energy consumption while ensuring network connectivity.



**Fig. 5.** Structure of M2M system.

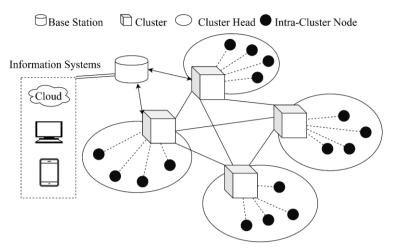


Fig. 6. Structure of hierarchical topology control.

# DEVELOPMENT OF 10T PLATFORM FOR AMBIENT AIR QUALITY MANAGEMENT

This IoT system used JavaScript library to write dynamic webpage program, and integrated Arduino Ethernet and jQuery UI to build up an interactive interface for the exchange of webpage information. The NPM (Node Package Manager) management module tool and Express framework are used to develop website application. The application ("apps") of cell phone and personal access devices (PADs) are developed by using HTML and JavaScript for the end users.

The current environmental monitoring technologies are mainly ground-based passive monitoring systems, which are still insufficient for real-time transmission and spatial distribution of pollutants, data collection, and real-time information integration. Therefore, the IoT technology is used in conjunction with relevant scientific advanced equipment to perform air quality monitoring, and provide real-time environmental information for policy planning, information advocacy, and real-time pollution inspection and prevention.

Table 1 presents comparisons of IoT technologies and applications which indicates that technologies of IoT can be classified into sampling technique, data processing, commutation method and system integration, which can be utilized in the area of indoor and ambient quality management. With the development of IoT technologies, in this research work, our IoT platform of ambient air pollution control was expected to monitor the pollution concentration in real time and identify the pollution type in a specific area by using open-path Fourier transform infrared (OP-FTIR) and miscellaneous gas sensors (MGSs). When the air pollution concentration is over the ambient standard, the Light Detection and Ranging (LiDAR) system is triggered to gather the information of pollution on different locations, both spatially and temporally, to understand the processes and trajectories of the atmospheric pollutants. The source of pollution traced by LiDAR will be monitored with miniature continuous emission monitoring systems (Mini-CEMSs) continuously. The scientific instruments use a variety of communication methods including the NarrowBand Internet of Things (NB-IoT) and Wi-Fi with terminals, i.e., mobile computers and phones, which are not utilized in conventional instrument and traditional technology. In addition, to adapt to different communication distances and device requirements, the appropriate method could be developed to make the system more robust, user-friendly, and inexpensive. The details of the environmental applications extended from the platform were described in the section "Application of IoT Platform."

## IoT Platform of Ambient Air Pollution

This environmental air pollution IoT monitoring system (shown in Fig. 1) is a network of multiple scientific instruments (LiDAR, OP-FTIR, mini-CEMSs, MGSs, anemometers) and a web connected by the NarrowBand Internet of Things wireless communication technology. The NB-IoT is a standards-based low-power wide area (LPWA) technology (Alliance, 2015), a unified standard for global telecommunications characterized by wide coverage with low power consumption and cost, and suited for IoT devices in radio interference environments. This monitoring platform (Fig. 7) is composed of NB-IoT networked scientific instruments (LiDAR, OP-FTIR, mini-CEMSs, MGSs, anemometers) and web application software to complete environmental air pollution monitoring network and to realize real-time monitoring around the clock. The monitoring system is composed of three layers of sensors, data transmission and application software. By utilizing the characteristics of NB-IoT's wide coverage, low power consumption and large connection, the system realizes the uploading of monitoring data and the sending of instructions. The system software mainly includes two parts: embedded software and server-side web application software. The embedded software is responsible for uniformly coordinating and integrating the hardware modules of the system to ensure the stable and orderly operation of the monitoring system. As for system server side, MySQL is used to complete the monitoring database design. The web application software implements the management of user information and the storage and query of monitoring data. At the same time, the geographic information system (GIS) is used to implement

Table 1. Comparisons of IoT technologies and applications.

G. 1.1	T1 1 CI.T	A 1'	D.C
Subjects	Technologies of IoT	Applications	Ref.
Reasoning for sensor data	The model for the	To utilize the sensor network together	Alirezaie and
interpretation: an	interpretation of time series	with high-level domain knowledge to	Loutfi (2015)
application to air quality monitoring.	signals of a gas sensor.	infer explanations for changes in the ambient air detected by the gas sensors.	
Sensor-based optimization	The specific modeling	To easily access the IoT system	Kim and
model for air quality	techniques for improving	through the Web or mobile applications	Hwangbo (2018)
improvement in home IoT.	air quality.	in air quality improvement model.	
A big data analysis of	The principal component	To analyze pollution from 50 air	Chen et al.
PM <sub>2.5</sub> and PM <sub>10</sub> from low- cost air quality sensors	analysis (PCA) for big data.	quality sensors in industrial and traffic emission.	(2019)
near traffic areas.		<b></b>	
Smart-sensor-network-	A ZigBee-based wireless	To collect and report real-time data on	Telagam et al.
based high-quality air	sensor network.	different gases from wireless network	(2017)
pollution monitoring		sensor nodes and to provide an alert	` ,
system using LabVIEW.		when the air quality characteristics	
		exceed acceptable levels.	
Air pollution mapping	A real-time carbon	To monitor the carbon monoxide	Wonohardjo and
using mobile sensors.	monoxide pollution	pollution levels on Google Maps.	Kusuma (2019)
_	monitoring system on the		
	IoT basis.		
IoT solution for smart	A real-time pollution	To mitigate health-threatening risks	Toma et al.
cities' pollution	monitoring system on the	and to raise awareness in relation to the	(2019)
monitoring and the	IoT basis.	effects of air pollution exposure.	
security challenges.			
Development of IoT	The smart ambient air	To introduce the network of multiple	This study
technologies for air	quality management	advanced scientific instruments for	
pollution prevention and	platform on the IoT basis.	pollution monitoring, transport, trace,	
improvement.		prevention, inspection, and	
		improvement.	

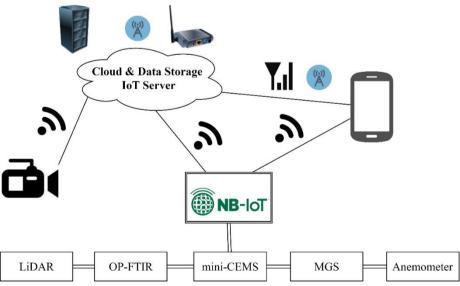


Fig. 7. Air pollution monitoring platform of Internet of Things.

the visual display of scientific instrument control and the monitoring data of environmental air pollution. The functions of automate, intelligent, network and systemize, data monitoring and tracking can be integrated into the communication technologies. The industrial operators can self-control through public information to achieve a robust air quality management.

The pollutants' real-time data and control target (industrial

zone factory)'s related information can be uploaded to the cloud database. The platform employs Eclipse software to develop mobile audit apps and provide relevant personnel the query and transport of the data. In addition, the platform applies two-way information protocol to compare and to analyze for the air pollution monitoring, location distribution, manufacturer information, configuration of equipment and waste storage facilities, and operating permits. Finally, the platform provides analysis of the potential pollution areas of environmental protection units, identifies the source of discharged pollution, and then assists on-site inspection and improves the efficiency of supervision and management.

## **Environmental Air Monitoring Sensors**

The gas sensor is a device that converts a specific gas concentration into an appropriate electronic signal, such as voltage, current, or resistance. Jones et al. (1987), in the Health and Safety Executive Laboratories of UK used a catalytic sensor to monitor the explosive mixture of methane and air. This device is prepared on the surface of platinum wire for high-temperature resistance. The catalyst layer and the heater are used to keep the catalyst at a high temperature to ensure the rapid combustion of flammable gas molecules. When the air and the combustible gas are mixed, the combustible gas is oxidized and contacts the catalyst to generate heat, which causes the surface temperature of the platinum wire to rise. The higher the temperature is, the greater the resistance is. As such, the concentration of specific gas can be identified by obtaining an electronic signal and measuring the change in the resistance value of the platinum wire.

In 2001, Vincenzi et al. (2001) employed the screen printing method by attaching palladium with tin oxide to distinguish gases such as carbon monoxide, methane and nitrogen dioxide. Nguyen et al. (2011) presented a 1-D tungsten oxide nanowire produced by electrospinning, which has a measurable minimum concentration of ammonia around 10 ppm. Mane et al. (2014) published the tungsten oxide thin film by solgel method for nitrogen dioxide measurement. It was found that the film has a fast response and the lowest concentration that can be measured is 5 ppm. Chinh et al. (2014) used thermal evaporation to produce a 1-D structure, and then applied yellow photolithography technology to produce electrodes and self-heating devices. It is possible to measure 10 ppm of nitrogen dioxide gas (Molenar, 2005). The typical gas sensors such as VOCs, CO,  $SO_x$ ,  $NO_x$  are based on metal oxide semiconductors (MOSs). The sensor component is a micro-electromechanical system (MEM) device using silicon wafer technology to implement in an approximately 1- $\mu$ m-thin silicon nitride membrane to achieve ultimate stability and lowest possible power consumption. The catalytically active material shows a gas-concentration-dependent resistance change.

Since the value of the gas sensor has drift due to longterm continuous working time or aging, the gas sensor needs to be calibrated by connecting the standard gas in the gas cylinder, adjusting the specified flow rate, and resistance value. In addition, some new sensors can possess self-correct function based on the relationships among the temperature, gas sensor values, the voltage, and current in the circuit.

As for the concentration of suspended particles, it is measured by using light-scattering theory. When the particles pass through the laser light, scattering and light attenuation would be generated. The measurement and analysis of different particle sizes are carried out by the Mie optical scattering theory algorithm.

#### Networked Device

The internal network of IoT platform includes LiDAR, OP-FTIR, mini-CEMSs, MGSs, and anemometers, as briefly described below.

### LiDAR System

As shown in Fig. 8(a), the Light Detection and Ranging system is a self-made air pollution optical telemetry instrument. It consists of a laser transmitter and a telescope as a receiver. The specific backscatter signals are measured by photomultiplier tube installed behind the telescope. The system is mounted on a vibration-isolated scanner with good structural stability for the pollution measurement at the vertical elevation. It has a wide-area and real-time feature for air pollution monitoring, which can break through the existing bottlenecks of passive monitoring instruments and measure hot zones, spatial concentrations, and diffusion ranges of air pollutant.

#### OP-FTIR

Open-path Fourier transform infrared is shown in Fig. 8(b). The volatile pollutants in the air are monitored, and the average concentration of the gas sample in the measurement path is obtained by spectral analysis.

#### Mini-CEMS

In order to reduce the monitoring misinterpretation of high-concentration pollution in costly pipelines, the miniature









Fig. 8. Networked device: (a) LiDAR, (b) OP-FTIR, (c) mini-CEMS, and (d) MGS.

continuous emission monitoring system (as shown in Fig. 8(c)) uses an automatic start-up device to dilute the standard air to a measurable range according to the concentration of VOCs extracted from the emission outlet of the blowdown piping by the aspirator of mini-CEMS, and automatically derives it. The concentration of native VOCs is obtained, and the measurement data is automatically and continuously uploaded to the cloud server. This system can be installed in the pipeline before/after prevention and control equipment to measure the concentration of pollution before/after the equipment. It can also be used to evaluate the effectiveness of the equipment and reduce the high-altitude operation of the chimney. Inspection can be performed directly with standard gases, ensure the accuracy of the instrument and upload measurement data in real time over the network to provide environmental-protectionrelated personnel's query reference.

## Miscellaneous Gas Sensor (MGS)

Hybrid gas sensors use metal oxide semiconductors to detect polluted gases and optical scattering to detect suspended particles (PM). These low-cost sensors have been widely used in real-time air quality monitoring. The self-developed composite gas sensor (Fig. 8(d)) integrates multiple sensors for measurement of VOCs, O<sub>3</sub>, CO, SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, temperature, humidity, etc. The specifications regarding concentration range, heater voltage, power and accuracy of sensors are shown in Table 2. The installed conditions of

MGSs are similar to that of the air quality monitoring equipment set by the Environmental Protection Agency. The MGS can upload a large amount of relevant continuous monitoring data to the cloud system in a real-time manner.

#### APPLICATION OF IOT PLATFORM

## **Pollution Monitoring and Transport**

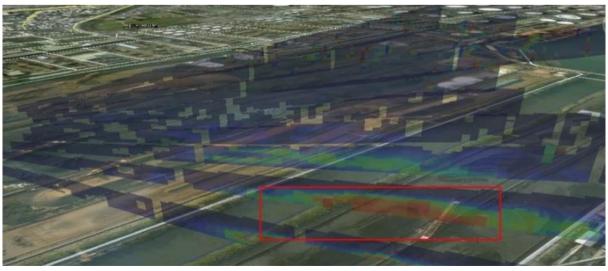
The Spatial Concentration of Dust Emissions

The tracking source and monitoring dispersion of dust are rather difficult, an IoT system makes an attempt for the transportation and flux estimation of particle concentration by using LiDAR and MGS to investigate the dynamical process of particle and their relationship with air quality. The results (Fig. 9) show that the material storage eroded by wind with speed about  $3.6~{\rm m~s^{-1}}$  could cause particle emission to the maximum height of 20 m above the material storage, and produce the flux of dust around 674 mg s<sup>-1</sup>. The flux of dust is also proportional to the dust mass concentration (PM<sub>10</sub>) measured by ambient particular monitors.

The transportation and diffusion of particles can be proved by using controllable particle generator under specific weather condition. The artificial particle measured by MGS settles every 5 m on the transmission path. The experimental results show that the average wind speed is between 1 m s<sup>-1</sup> and 3 m s<sup>-1</sup> when the prevailing wind is southwest (200–300°). The artificial particles can be flown to at least 60 m.

N	Items	Concentration range	Heater voltage (V)	Power (mW)	Accuracy
1	VOCs	1–50 ppm	5.0	350	±20%
2	$O_3$	10–1000 ppb	5.0	800	±20%
3	CO	10–1000 ppm	5.0	450	±10%
4	$\mathrm{SO}_2$	1–200 ppm	5.0	300	±10%
5	$PM_{10}$ , $PM_{2.5}$ , $PM_{1.0}$	$0-500 \ \mu g \ m^{-3}$	NA	700	±5%
6	Temperature	0–50°C	NA	250	±0.5°C
7	Humidity	20–90%	NA	250	±5%

**Table 2.** The specifications of sensors.



**Fig. 9.** Spatial variation of dust above the material storage. (Note: Inserted box shows the area of spatial variation of dust for the flux estimation of dust concentration.)

It is indicated that the distance where is the most floated dust settled. However, the fine particles diluted in atmosphere can be most likely dispersed more to 130 m in distance and 10 m in height from the outlet of particle generator measured by LiDAR before settlement. The results are further estimated by vertical wind speed 0.2–0.5 m s $^{-1}$  measured by the anemometer. The vertical wind speed is used to determine the time about 20–50 s when the particles rise 10 m. When the horizontal wind speed is 3 m s $^{-1}$  at this time, the particle can be dispersed about 60–150 m in theory, which is consistent with the experimental results.

## The Sediment Pollution from Refinery

The IoT technique will be useful to enhance the effectiveness of inspection and to strengthen the capability of the environmental monitoring by integrating information immediately. It is accomplished to use the 3-D scanning LiDAR system to track the path of air pollution emissions first, then monitor the range of pollution diffusion, and finally cooperate with the analysis of pollution components to confirm whether the polluted area is responsible for specific pollution emissions. The method and observation results are described as follows: The spatial distribution of pollution is monitored by LiDAR scanning monitoring operation. The observation shows that the pollution diffusion range is shown in Fig. 10, and the FTIR is set up at the pollution settlement denotes as \( \textstyle \) shown in Fig. 11 to analyze the pollution components which indicates that the situation of pollution-free settlement mainly occurs at 1-3 a.m.

The prevailing wind direction is southerly. When no settlement occurs, the concentration values of all pollutants measured by OP-FTIR are lower than the ones of their individual pollution. The average value of the objects indicates that the concentration of pollutants measured on the ground is low when no atmospheric settlement occurs.

The vertical distribution of pollution measured by LiDAR found that the settlement time more likely occurs from 8 p.m. to about 1 a.m. the next day. The main prevailing wind direction is northwest wind to northeast wind. When the pollution subsides and the northwest wind prevails, the *N*,*N*-dimethylformamide measured by OP-FTIR has a higher concentration (17–60 ppb). Furthermore, the vertical distribution of pollution measured by LiDAR has found that sometimes non-sedimentation may occur, which may originate from low-level transmission. The time, path and composition of the pollution can be used to trace the source of the pollution. It is worth mentioning that the pollution of the refinery in this case can affect the ambient air quality up to 3 km away.

#### **Pollution Trace and Prevention**

Another application example of this technology confirms the settlement position of the dust in the Zhuoshui River to facilitate the planting of vegetation and to abate wind erosion of dust. Zhuoshui River, the longest river running through central Taiwan, is about 186.6 km long and covers a basin area of 3,156.90 km<sup>2</sup>. As the river name suggested, its stream is entrained with a large amount of sediment and is turbid for many years. The annual precipitation of the mountain catchment area in the upstream reaches 2–3 m, and the strata of passing through are mostly slate, shale, and sandstone that are susceptible to erosion. Therefore, the sand content is high and the local residents have the saying "meal with sand disturbance." To this end, the technology can be used to monitor the dust in the vast field, so that the vegetation can understand the diffusion range and pollution concentration of the dust in the turbid water stream, and evaluate the contribution of the dust in the turbid water stream to the air quality.

By comparing the scanning LiDAR result about 15 m

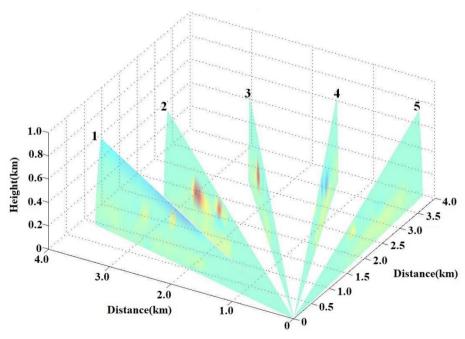


Fig. 10. Optical radar vertical scan pollution distribution diagram.

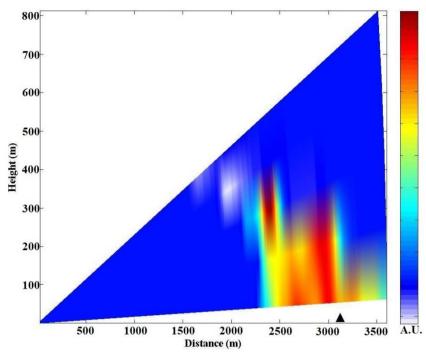


Fig. 11. Vertical scanning result of the second measuring line in Fig. 9. (Note: ▲ is the location of FTIR.)

directly above the ground station with the PM<sub>10</sub> value, the correlation coefficient  $r^2 = 0.55$ . It shows that the PM<sub>10</sub> concentration in the air has a similar trend to that of local stations. When sand is rising, the monitoring results of LiDAR scanning are shown in Fig. 12(a). The suspended particles appearing in the red circle in the figure cause the concentration of suspended particles in the air and ground stations to be  $36 \pm 12 \,\mu g \, m^{-3}$  and  $100 \pm 20 \,\mu g \, m^{-3}$ , respectively. If it is affected by sandstorms outside the country, a layered sand and dust distribution occurs between 300-600 meters above the ground (as shown in Fig. 12(b)), and the ground station also has a large range of suspended particulates concentration increase response, sometimes the wind speed is low  $(0.7 \pm 0.3 \text{ m s}^{-1})$  The surface air quality is poor. At this time, the boundary layer height is ~250 m, the diffusion is not easy, and a similar situation occurs. This monitoring result can not only distinguish the location and the impact range of the sand, but also decide whether it is affected by the outside or inside when the ground air is bad. Consequently, the relevant units can make a correct judgment and grasp the time limit to protect and protect people's health.

## Pollution Inspection and Improvement

## The Real-time Air Quality Improvement

A research was designed to apply IoT to collect relevant information to understand the air quality situation of the athlete village in Linkou area before the World Universiade 2017, and then analyze the possible sources and causes of pollution to prevent pollution and maintain air quality. Historical data show that the main prevailing wind field during the World Universiade (19–30 August 2017) is northeast wind (from the Linkou Industrial Zone to the player village). The scanning information of the LiDAR system was used to compare and analyze the combined gas sensor measurement

results and atmospheric wind field information provided between the Linkou Industrial Zone and the player village.

The results show that the main pollutants transmitted by the prevailing northeast wind in Linkou Industrial Zone were PM<sub>10</sub>, followed by pollutants such as VOCs and SO<sub>2</sub>, while pollutants such as CO and O<sub>3</sub> did not significantly affect the player village. The system flow chart is shown as Fig. 13 to set up scientific instruments and sensors on relevant pollution transmission paths, and to study and formulate the implementation plan of relevant inspection and control measures. Compared to before/after the World Universiade as shown in Fig. 14, the air quality of the player village during the World Universiade significantly improved when environmental protection personnel carried out inspection and control using online information of the air pollution.

#### The Pollution Prevention in Industrial Areas

Using networked scientific instruments; cloud information management systems and databases; long-term recording of monitoring data, air quality, and meteorological parameters; etc., statistically summarize and master air quality, atmospheric conditions, spatial distribution of pollution, and sources of emissions. Based on the relevant monitoring data, our research conducted a pollution inspection and prevention action plan (as shown in Fig. 13), installed an automatic continuous monitoring system (Fig. 14) for pollution sources, and monitored pollution emissions and plant prevention and control operations for a long time. The research also assisted relevant personnel to conduct real-time air pollution inspection and prevention measures. The staff of the Environmental Protection Agency used the statistical information provided by IoT to understand and strengthen the audit of abnormal air emissions which exceed the mean measured concentration with one standard deviation. The results provided real-time

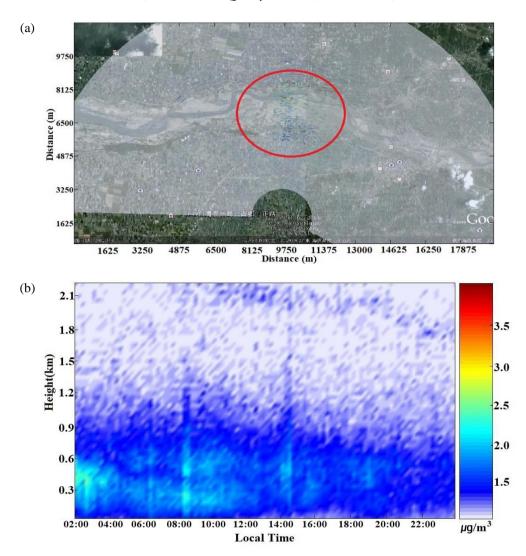


Fig. 12. (a) Light-scanning results of dust emission from turbid water stream dust. (b) Distribution of sand and dust under the influence of overseas sand and dust with height.

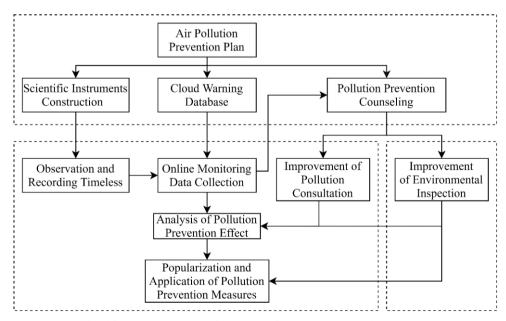
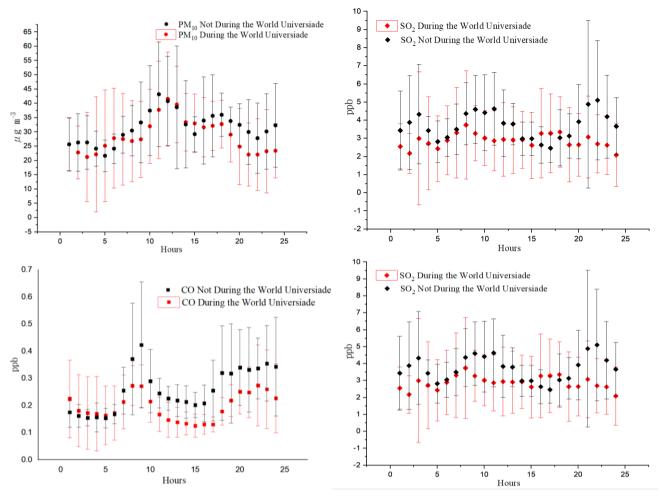


Fig. 13. Implementation flowchart of pollution inspection control.



**Fig. 14.** Distribution of PM<sub>10</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub> concentrations over time at the Linkou Environmental Station during the World Universiade.

public information to polluters that exceeded the standards and repeatedly persuaded them and to take the initiative to explain and respond to the situation during the time of exceeding the standards. Compared with the same period in 2018 (without related equipment setting and control), the current pollution impact situation is improved by about 7–16%, as shown in Fig. 15.

It was thus concluded that a large-scale IoT system was constructed with multiple applications such as pollution monitoring and transport, pollution trace and prevention, pollution inspection and improvement throughout this research work. With the development of IoT technologies, the results of this research can not only provide the law enforcement and policy formulation for the government and the public, but also improve the automation system of production for the manufacturers. Many advanced technologies and instruments are integrated into this system, including NB-IoT, LiDAR, OP-FTIR, mini-CEMSs, MGSs, and anemometers, for ambient air quality management.

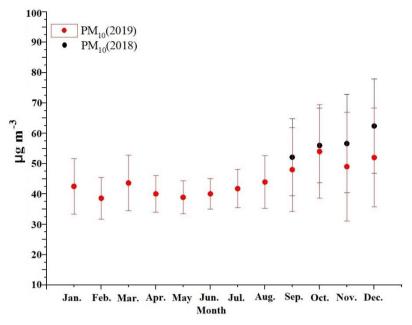
## CHALLENGES AND PROSPECTS

In developing IoT technologies for smart ambient air

quality management, the major challenge revolves around embedding intelligence into common electrical devices, thus enabling them to perform autonomously and reliably. A secondary challenge involves coordinating the heterogeneous platforms of multiple devices and their unique features so that they function as a unified network for a comprehensive goal.

Thus, this paper proposes a stable and efficient system for obtaining air monitoring data from various IoT devices and performing massive cloud-based calculations. The readability and maintainability of the programming enable highly extensible connectivity via software and hardware, and the system simultaneously assesses and controls environmental air quality by analyzing big data.

In greater detail, an intelligent air quality monitoring system that embodies *flexibility*, *reliability*, *effectiveness*, and *economics* (FREE) can be developed by integrating microcontrollers, wireless sensor networks (WSNs), cloud service, the Global Positioning System (GPS), and the Android platform. The Air Benefit and Cost and Attainment Assessment System (ABaCAS; www.abacas-dss.com), which provides decision support tools, including the International Cost Estimate Tool (ICET), Response Surface Model



**Fig. 15.** Monthly changes in suspended particulate concentration from 2018 (before implementation of related equipment and measures) to 2019 (after implementation of related equipment and measures).

(RSM), Software of Model Attainment Test (SMAT), and Environmental Benefits Mapping and Analysis Program (BenMAP), should be employed during project planning to configure different control scenarios and identify cost-effective strategies.

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