

Chapter 7

Air Quality Measuring Sensors



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7.1 Air Quality Measuring Sensors

In many cities, the air quality information is provided to public in the form of air quality index (AQI). Various air quality indices were developed worldwide to provide air quality information to the public. The AQI is estimated from fixed stations. In most epidemiologic studies, the ambient concentrations measured at fixed monitoring sites are also used as surrogates for human exposure assessment. As these fixed stations were unable to capture the air quality beyond certain radius (up to 500 m to 1000 m), the air quality index cannot represent actual personal exposure to air pollutants in the urban environment. Therefore, existing air quality measuring techniques having the limitations like lack of spatial-temporal variations, target-specific monitoring, personal exposure, location-specific measurement, real-time alertness, feedback and control mechanism and many more, of course, they are more accurate. With the negligible amount of compromise in the accuracy makes the availability of sensors for the measurement of air quality.

Measurement of air quality becomes easy and comfortable with the availability of sensors for all the criteria pollutants (particulate matter, NO₂, SO₂, CO, etc.) (Vincent 2007). Table 7.1 provides some of the commercial low-cost air quality measuring

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Table 7.1 Some of the low-cost air quality measuring sensors in the market

S. No.	Sensor	Measured	Range	Company	Technology
1	SDS011	PM _{2.5}	0.0–999.9 $\mu\text{g}/\text{m}^3$	Nova	Optical
2	OPC-N3	PM ₁ , PM _{2.5} , PM ₁₀	0–2000 $\mu\text{g}/\text{m}^3$	Alphasense	Optical
3	HPMA115S0-XXX	PM _{2.5} , PM ₁₀	0–1000 $\mu\text{g}/\text{m}^3$	Honeywell	Optical
4	Mics 2614	O ₃	10 ppb–1 ppm	Sensortech	Semiconductor
5	3SP-O3-20	O ₃	0–20 ppm	SPEC sensors	Electrochemical
6	A3OZ	O ₃	0–10 ppm	CITY Technology	Electrochemical
7	Mics 2714	NO ₂	50 ppb–5 ppm	Sensortech	Semiconductor
8	NO2 B43F	NO ₂	0–20 ppm	Alphasense	Electrochemical
9	ULPSM-NO2 968-047	NO ₂	0–20 ppm	SPEC sensors	Electrochemical
10	MQ-7	CO	20–2000 ppm	Hanwei Electronics	Semiconductor
11	CO-B4	CO	0–1000 ppm	Alphasense	Electrochemical
12	CO-A4	CO	0–500 ppm	Alphasense	Electrochemical
13	UL 2034	CO	1000 ppm	SPEC sensors	Electrochemical
14	SO2-B4	SO ₂	0–100 ppm	Alphasense	Electrochemical
15	ULPSM-SO2 968-006	SO ₂	0–20 ppm	SPEC sensors	Electrochemical
16	C03-0973-100	SO ₂	0–20 ppm	Honeywell Rare SYS	Electrochemical

sensors. The future technological advancements will make sensor measurements more accurate. In this chapter, we focused on the air quality measurement with sensors and their limitation in real time. A sensor is a device which senses (responds) a physical quantity (stimulus) and provides a measurable output. With the advancement of technology, most of the sensors provide electrical output, hence, the manipulation and controlling of other devices made simple. In order to provide the electrical output, the sensing element of a sensor is associated with an electrical signal conditioning circuit called as transducer. Today, the sensor and transducer resemble same (Neubert 2003). Figure 7.1a illustrates RTD (PT1000, temperature sensor) operation upon the wheat stone bridge to provide electrical voltage to the corresponding temperature. Nonlinearity in the temperature voltage relationship as shown in Fig. 7.1b of RTD can be improved by other linearization signal conditioning methods.

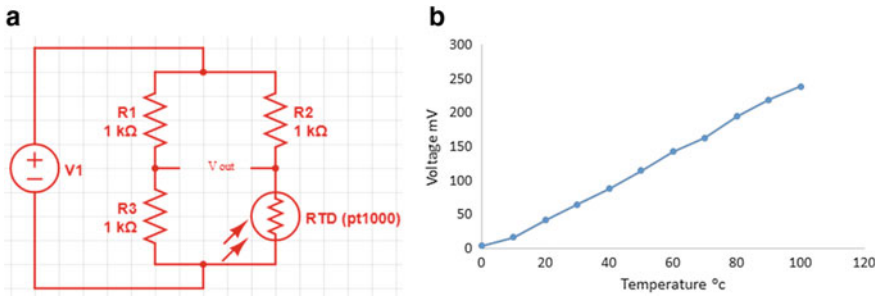


Fig. 7.1 Sensors with electrical circuit **a** RTD (Pt 1000) operation upon Wheatstone bridge, **b** temperature versus voltage graph

7.2 Types of Smart Air Quality Sensors

According to the external power requirement, the sensors are classified into two categories.

7.2.1 Active Sensors

Active sensors are those which do not require external source (voltage, current) to produce measurable output. Thermocouple and piezoelectric crystal are examples of active sensors. Thermocouple arrangement as shown in Fig. 7.2 for temperature measurement did not require any external supply. The EMF generated at the cold or reference junction is proportional to the temperature at hot junction.

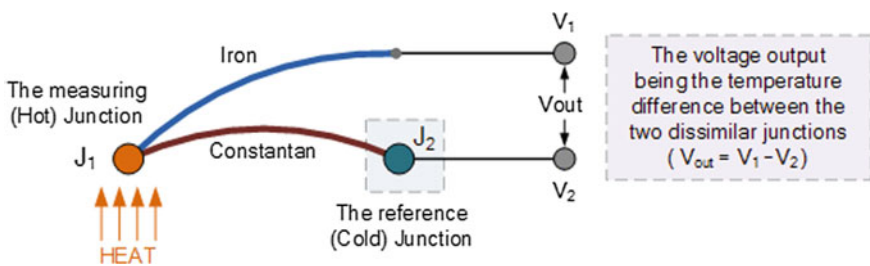


Fig. 7.2 Temperature measurements with thermocouple

7.2.2 *Passive Sensors*

Passive sensors are those which requires external source (voltage, current) for the transduction (input physical quantity to output measured) purpose. Thermistors, RTD and resistive strain gauges are the examples of passive sensors. RTD arrangement as shown in Fig. 7.1a requires external supply for the temperature measurement, hence, it is a passive sensor.

7.3 Specifications of Sensors

For the effective usage of sensors, the manufacturer provides the specifications in the form of a sheet called specification sheet. This sheet contains the detailed information about the sensor (Usher and Keating 1996). In general, all the specifications are brought into three categories. Apart from these sensors must be operated within the electrical specifications.

1. Static specifications
2. Dynamic specifications
3. Environmental specifications.

7.3.1 *Static Specifications*

Sensor characteristics when static input (input which is not changing continuously with respect to time) is applied to sensor are mentioned under static specifications. Accuracy, range, threshold, resolution, linearity, sensitivity, etc., fall into static specifications.

Range and Threshold: The minimum to maximum value measured by sensor is called as the range. Figure 7.3a shows the range specification of the SDS011 PM_{2.5} sensor. Threshold is the lowest concentration of a pollutant that a sensor can detect. This may or may not be provided by the manufacturer.

Resolution: Smallest input change that can produce a measurable output without ambiguity is called as the resolution. Figure 7.3b shows the resolution specification of SDS011 PM_{2.5} sensor.

Accuracy: The closeness of the measured value with the true value is called as accuracy. In general, the accuracy is specified in terms of full-scale error.

$$\text{Error} = \text{Measured value} - \text{True value} \quad (7.1)$$

$$\% \text{Error} = \frac{\text{Measured value} - \text{True value}}{\text{True value}} \times 100$$

No	Item	Parameter	Note
1	Measurement parameter	PM _{2.5} PM ₁₀	
2	Range	0.0-999.9 µg/m ³	
3	Rated voltage	5V	
4	Rated current	70mA±10mA	
5	Sleep current	<4 mA	Low&Fan sleep
6	Temperature range	Storage environment: -20 - +60°C	

a)

Nova Fitness Co., Ltd.		SDS011 sensor	
7	Humidity range	Work environment: -10 ~ +50°C	
		Storage environment: Max 90%	
8	Air pressure	86KPa-110KPa	
9	Corresponding time	1s	
10	Serial data output frequency	1Hz	
11	Minimum resolution of particle	0.3 µm	

b)

Fig. 7.3 Specification sheet of SDS011 PM_{2.5} sensor **a** range specification, **b** resolution specification

$$\text{Full scale error} = \frac{\text{Measured value} - \text{true value}}{\text{Full scale value}} \times 100$$

$$\% \text{Error (reading)} = \% \text{Full scale error} \times \frac{\text{Full scale value}}{\text{Measured value (read)}}$$

Example 7.1 1000 µg/m³ CO₂ gas sensor having scale error of ±0.5% is used to measure the 200 µg/m³ target concentration, then find the accuracy lies between?

$$1000 \times \frac{0.5}{100} = 5 \mu\text{g}/\text{m}^3$$

5 µg/m³ is the error in the reading measured by sensor.

∴ The accurate value between (200 and 5) µg/m³ and (200 + 5) µg/m³.

Sensitivity: The change in output to the change input ratio is called sensitivity. The sensitivity is the slope of the sensor characteristic graph.

Example 7.2 Figure 7.4 shows the improved linearization signal conditioning output of an RTD as shown in Fig. 7.1a, b. Find out the sensitivity of RTD characteristics as shown in Fig. 7.4.

$$\begin{aligned} \text{Sensitivity} &= \frac{\text{change in output}}{\text{chnage in input}} \\ &= \frac{601.9 - 406.9}{60 - 40} = 9.75 \end{aligned}$$

∴ Sensitivity = 9.75 mV/°C.

Example 7.3 An RTD having the specification like $R_t = 1000(1 + 0.00385 \pm \Delta T)$, here, 0.00385 will indicate the temperature sensitivity of RTD in Ω/°C.

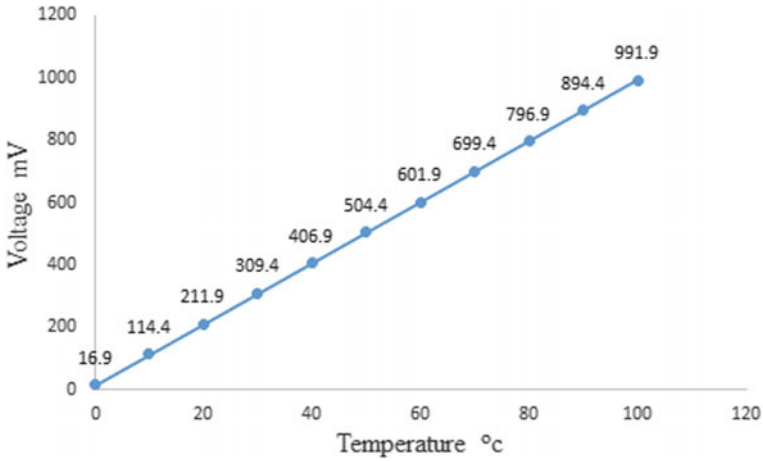


Fig. 7.4 Linearized characteristics of RTD

Precision: Precision refers to how well the sensor reproduces the measurement of a pollutant under identical circumstances. The sensor with precision and accurate is preferable.

7.3.2 Dynamic Specifications

Sensor characteristics when dynamic input (input which is changing continuously with respect to time) is applied to sensor are mentioned under dynamic specifications. Rise time, settling time, slew rate, etc.

Settling time: Time taken for the sensor output to reach and stay within the range of final value (steady state) is called settling time. In general, 2% or 4% is the considered range of the final value for settling time calculation.

Rise time: Time taken for the sensor output to rise from 10% of the steady-state value to 90% of the steady-state value is called rise time.

Slew rate: The maximum rate at which the output of sensor can change.

$$\text{slew rate} = \frac{\text{change in output}}{\text{change in time}} = \text{slope of the output.}$$



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Parameter	Conditions	Min.	Rec.	Max.	Units
Supply Voltage		2.7	3	3.3	V
Storage Temperature	Vapor sealed @ 50% RH	5	20	30	°C
Storage Humidity	Non-condensing, Vapor sealed	20	50	80	% RH
Storage Pressure	Vapor sealed	0.8	1	1.2	atm.
Storage Time	Vapor sealed	-	12	-	Months
Operating Temperature	< 10 hours	-40	-	50	°C
Operating Humidity	< 10 hours, Non-condensing	0	-	100	% RH
Operating Temperature	Continuous	-20	25	40	°C
Operating Humidity	Continuous, Non-condensing	15	50	95	% RH
Operating Pressure	Continuous	0.8	1	1.2	Atm.

Fig. 7.5 SPEC sensors and SO₂ sensor data sheet for environmental specifications

7.3.3 Environmental Specifications

Environmental specification tells about the performance of the sensors in the harsh environments, because the ambient atmospheric conditions will affect the output of the sensor. All the air quality sensors need to be operated under the rated temperature, humidity and pressure. Some of the manufacturers will indicate both the operating as well as storage environmental specifications. Different environmental specifications of SO₂ sensor under rated conditions manufactured by SPEC sensors are shown in Fig. 7.5.

7.3.4 Electrical Specification

Operating current, voltage and power, etc., are come under electrical specifications. If the sensor is having multiple pins/ports, each pin will be specified with the rated operating conditions. Electrical specification of SO₂ sensor manufactured by SPEC sensors is shown in Fig. 7.6. Before integrating the sensor in the real-time monitoring

Parameter	Conditions	Min.	Typ.	Max.	Units
Supply Current	V+ = 3.0 V	5	10	15	µA
Power Consumption	V+ = 3.0 V	15	30	45	µW
Vref			V+/2 + 0.1		V
Vgas Zero		(V+/2 + 0.1) - 0.005	(V+/2 + 0.1)	(V+/2 + 0.1) + 0.005	V
Vgas Span (M)	Room temperature	2.5	3.0	3.5	mV/ppm

Fig. 7.6 SPEC sensors and SO₂ sensor data sheet for electrical specifications

sensor board (PCB), the electrical compatibility with battery/line should be maintained. If source and sensor are not in the same range of electrical specifications, voltage/current regulators, etc., will be useful for electrical compatibility.

7.4 Development of Air Quality Sensors

Based on the physical, chemical and other important characters of air pollutants, the sensors will be developed (Maag et al. 2018). In general, particulate matter sensors are based on light scattering principles and gaseous sensors are utilizing semiconductor and electrochemical principles. Apart from these, other techniques like infrared radiation absorption, etc., are also popular.

7.4.1 Semiconductor

Metal oxide-based semiconductors such as ZnO and SnO₂ are highly sensible for both reducing gasses like H₂, H₂S, CO, ethanol, etc., and oxidizing gasses like O₂, NO₂. Whenever these gases exposed to the above-mentioned material-based sensors, the conductivity changes. Hence, the flow of current changes in the electrical circuit associated with sensor, by which we can measure target gas concentration. Most of the metal oxide semiconductor sensors are the passive sensors. Thermistor is the best example of this category.

7.4.2 Electrochemical

An electrochemical sensor consists of two electrodes, a working electrode and counter electrode in an electrolyte solution. When target gas is exposed to the electrochemical gas sensor the gaseous molecules either oxidized or reduced at working electrode, which causes charge generation or consumption. If we provide a closed loop, the current will flow. The amount of current flow is proportional to the targeted gas concentration.

7.4.3 Optical Principle (Light Scattering)

The pollution laden air is captured in a small chamber. When light passed into the chamber, i.e., either LED or laser, its gets scattered by the particulate matter. Depending upon the concentration and size of the particulates, the intensity of

scattered light will change. In general, visible light (~600 nm) is used in the light scattering instruments to measure particulate matter.

7.5 Calibration of Sensors

Adjustment of sensor readings against the standard measurement for a target concentration is called as calibration. Calibration is important, because sensor performance can change over time. As the air quality sensors can be used for different air pollution applications, their performance requirement will also be different depending upon the application (Artiola et al. 2004).

Currently, there is no Indian regulatory (Central Pollution Control Board, CPCB) guidelines and EPA (United States Environmental Protection Agency) also does not provide any guidelines for performance requirement of the indicative measurements using sensors for supplementary monitoring, as in USA, there is no defined role for supplementary sensor measurements in regulatory monitoring. However, European Union (EU) directive on “Ambient air quality and cleaner air for Europe” provides for the use of “indicative measurement” (Equivalence 2010). These measurements can be used to supplement “fixed” (or, “regulatory”) measurements to provide information on the spatial variability of pollutant concentrations. These supplementary measurements have less stringent requirements for data quality. The EU requirements specify a maximum uncertainty, and do not address precision and bias separately. Table 7.2 gives the EU performance requirements for the fixed and indicative measurements. Table 7.3 gives the suggested performance goals for each tier (Tier I–V) in comparison with regulatory monitoring requirements.

The studies shown that the calibration can be done in two ways

1. Pre-deployment calibration
2. Post-deployment calibration.

7.5.1 Pre-deployment Calibration

Calibrating sensor before deployment in the real-time environment is called as pre-deployment calibration. Generally, this calibration will be done under laboratory

Table 7.2 EU performance requirements for the fixed and indicative measurements

Type of measurement	Maximum uncertainty allowable in pollutant measurement			
	SO ₂ , NO ₂ , CO (%)	Benzene (%)	PM and lead (%)	Ozone (%)
Regulatory (fixed)	15	25	25	15
Supplemental (indicative)	25	30	50	30

Table 7.3 EU suggested performance goals for different application areas

Tier	Application area	Pollutants	Precision and bias error (%)	Data completeness (%)
I	Education and information	All	<50	≥50
II	Hotspot identification and characterization	All	<30	≥75
III	Supplemental monitoring	Criteria pollutants, air toxics (incl. VOCs)	<20	≥80
IV	Personal exposure	All	<30	≥80
V	Regulatory monitoring	O ₃ , CO, SO ₂ , NO ₂ , PM _{2.5} , PM ₁₀	<7 <10 <15 <10	≥75



Fig. 7.7 Pre-deployment calibration setup in air quality research laboratory, IITM

conditions for the gain and offset adjustment by drawing the calibration curve, which shows the relationship between input gas concentration and output values (Williams et al. 2017). Offset indicates the sensor response value when target gas is absent. Figure 7.7 shows the pre-deployment calibration setup for NO₂, CO, O₃ gasses in air quality research laboratory, IIT Madras.

7.5.2 Post-deployment Calibration

Calibrating sensors after deployment in the field is called as post-calibration. The frequent post-calibration will reduce the errors in the measurement (Maag et al. 2018). The duration for the post-calibration depends upon the technology used to manufacture sensors (in general, semiconductor sensors exhibit more drift with time), the real-time weather conditions, concentration at which we are measuring, etc.

The studies have been shown different post-deployment calibration techniques like liner regression, multivariate linear regression, artificial neural networks, machine learning, etc.

7.6 Data Acquisition

Data acquisition system for air pollution measurement starts with the identification of right sensor (measuring range, accuracy range, sensitivity, etc.) for the pollutant. Once the sensors identified, they should have to calibrate under the laboratory conditions (temperature, humidity, pressure, etc.) by exposing sensors to the known gas concentrations. Compare the calibrated sensors output with the standard measuring devices output. Check for the errors and correct them either by recalibrating or any controlled mechanism. Then, all the sensor used for pollutants measurement is placed on a board (in general, PCB) called sensor board, which is either battery powered, or line powered along with the necessary signal conditioning circuit for every sensor. At present, the manufacturer is providing inbuilt signal condition for most of the sensors. Inbuilt signal condition is beneficial to reduce errors. The output from the sensors is integrated into the microcontroller or processor (personal computer) through the digital interface (serial (RS232) or parallel (IEEE 1284)) for further processing and storage. If any sensor is giving analog output, then analog-to-digital converters (ADC) must use to convert the obtained response in digital format. By using the transceiver, the data can be transferred to the central server. Different wireless communication techniques used for data transfer in the wireless sensors network listed in Table 7.4. Finally, the obtained information is used by the end user to understand, control and policy making. Figure 7.8 shows the data acquisition system for single sensor node. It is possible to create a sensor network by integrating large number sensor nodes to a single server to monitor air pollution at large area with spatial and temporal variations. The flowchart of sensor data acquisition is shown in Fig. 7.9.

Table 7.4 Wireless communication techniques used in wireless sensor networks

Technology	WIFI	Bluetooth	Zigbee
Standard	IEEE 802.11b	IEEE 802.15.1	IEEE 802.15.4
Range	100 m	(10–100) m	10–100 m
Data rate	(10–100) Mbps	125 kbps–3 Mbps	(20–250) kbps
Operating frequency range	(2.4/5) GHz	2.4 GHz	2.4 GHz

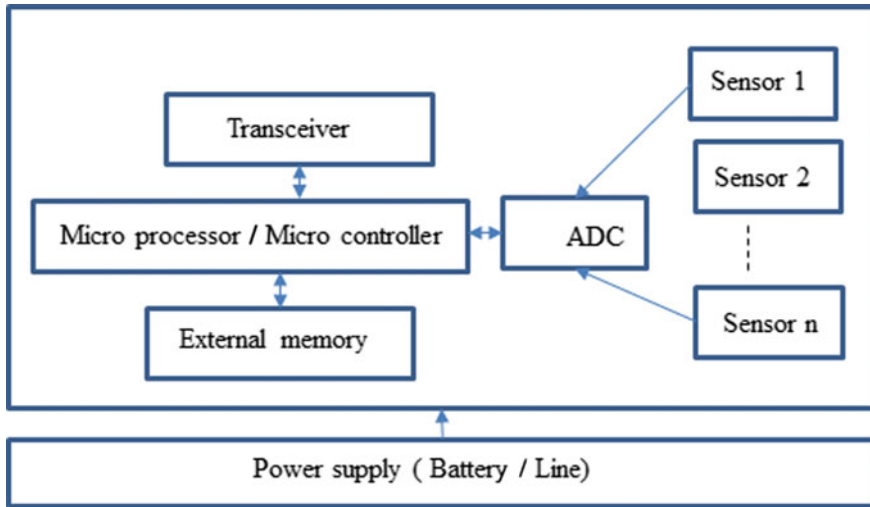


Fig. 7.8 Sensor node preparations

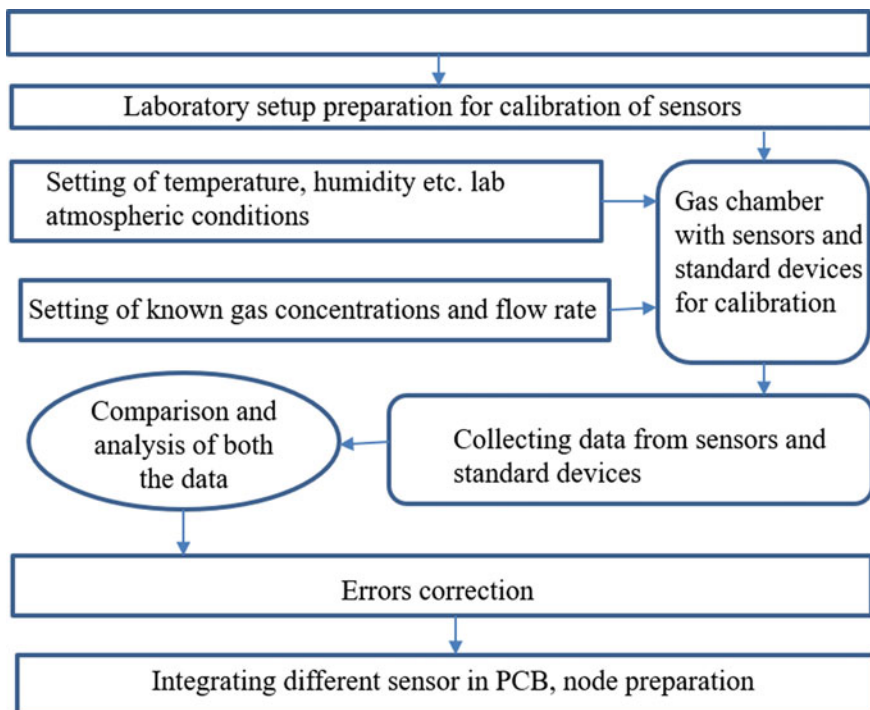


Fig. 7.9 Flowchart and data acquisition system preparation

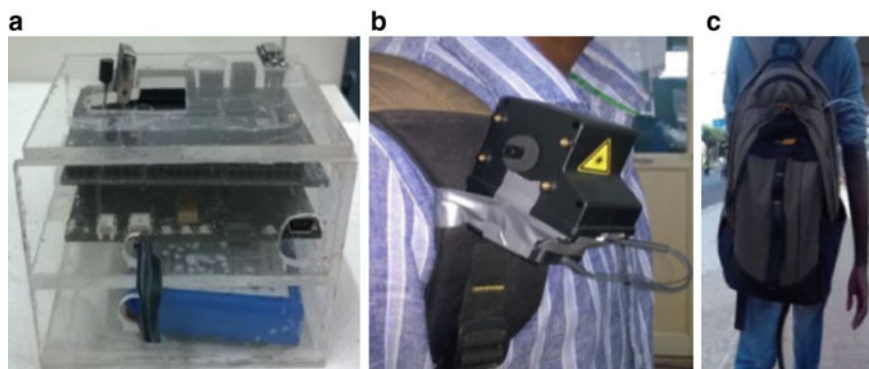


Fig. 7.10 Personal monitoring **a** personal monitoring sensor device, **b** attachment of device to a person, **c** pedestrian exposure monitoring

7.7 Smart Sensors for Mobile and Personal Monitoring

Personal exposure monitoring needs to take into consideration the individual exposure to air pollution (Ueberham and Schlink 2018). Personal monitoring can provide detailed insight into a person's individual short-term exposure in a specified area (SM et al. 2019). The recent studies showed the ways of personal exposure monitoring. The integrated sensor device with memory along with GPS device is carried out by the individual to get the personal exposure at different locations in different scenarios like inside the bus, pedestrian exposure with and without traffic scenarios. The miniaturization of the personal monitoring device will help in energy saving, hence, battery life, weight reduction, hence, carrying fatigue reduction, etc. Figure 7.10 shows the way of personal exposure monitoring.

7.8 Air Quality Maps

Air quality maps help us to visualize the air quality levels and spatial variation of pollutant concentrations in representative areas. With the advent of low-cost sensors measuring various air pollutants, there is significant potential for carrying out high-resolution mapping of air quality in the environment (Schneider et al. 2017). Real-time maps are prepared by using real-time air quality observations of pollutant concentrations from ground stations. Using historical data, spatial and temporal variations of pollutant concentrations can also be depicted through air quality maps. This can be done with the help of interpolation techniques and GIS. Monitoring represents air pollution level for a particular point. Thus, spatial interpolation techniques are used to create a surface grid or contour map (Fig. 7.11). Interpolation processes estimate concentrations in the study area using known concentrations at fewer points. The other methods are regression techniques and dynamic modelling.

Some of the interpolation techniques used are the inverse distance weighted method and the kriging interpolation method. Inverse distance weighted (IDW) interpolation determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable. This method assumes that the variable being mapped decreases in influence with distance from its sampled location (Wang et al. 2014). Kriging is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z -values. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface. Kriging is most appropriate when there is a spatially correlated distance or directional bias in the data.

Air quality maps can also be prepared with the help of dispersion models. But these models only provide estimates for known emission sources (Briggs et al. 1997). Even in urban areas, locally derived pollutants may make up only a small proportion of the total concentrations recorded at any site. It makes field validation difficult since what is monitored is not the same as what is modelled. Therefore, the modelled concentrations may represent only part of total exposures.

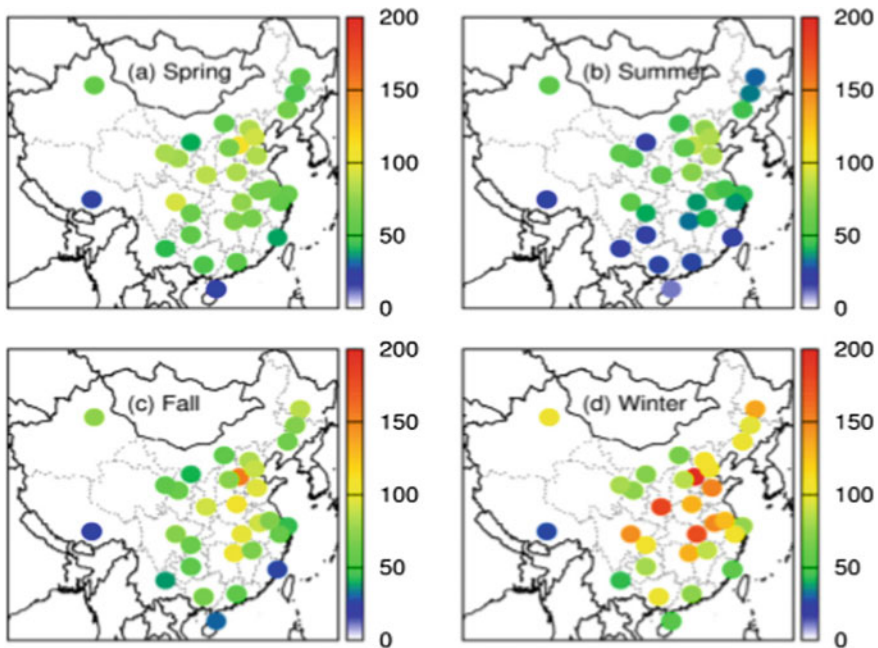


Fig. 7.11 Air quality maps showing temporal and spatial variation of pollutants generated using interpolation techniques. *Source* Wang et al. 2014

7.9 Limitations of Smart Air Quality Sensors

Sensor drift: Sensor drift refers to a gradual change in a sensor's response characteristics over time. Instruments drift may lead to wrongly conclude that concentrations have increased or decreased over time. Drift can be positive or negative, and it may occur due to a variety of reasons. One way to reduce drift is to calibrate the sensor frequently so that the instrument only drifts a small amount between each recalibration. The frequency of calibration needed will depend on how much drift occurs.

Accuracy limit: It is a known fact that the air quality sensors are not as accurate as standard instruments. But all the applications do not require cent percentage accuracy. Regular calibration will make sensors error-free and accurate.

Cross-sensitivity: Sensor response to other gases (which are not target gases) is called cross-sensitivity. The cross-sensitivity shows either positive (amplified value) or negative response (attenuated or reduced value) on the sensor performance. For example, CO sensor has positive response to the H₂ gas and SO₂ sensor has negative response to the NO₂ gas.

Apart from the above-mentioned issues, there exist software issues like data incompatibility, data interference, heterogeneous platforms, etc., and hardware issues like power failures, devices incompatibilities, network failures (for data transfer), etc.

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