Low-Cost Sensor Pod Design Considerations

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A look at the decision-making process used in the development of two unique low-cost air quality sensor pods.

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Public concern about air quality is growing in communities around the globe, as citizens learn more about the potential health effects of the air they breathe.[1] In the United States, air quality monitoring has often been restricted to organizations administering Federal Reference Method (FRM) or Federal Equivalent Method (FEM) equipment or other professional/academic institutions operating research-grade instrumentation.[2] The recent development of low-cost (< $2,500) air quality sensors has generated opportunities for communities to engage in citizen science to address air quality concerns on a local level, but many of these low-cost sensors have not been fully evaluated and may have undefined issues regarding performance characteristics and data quality.[3-5]

In an effort to gain perspective on sensor performance and support a wide range of interested stakeholders, the U.S. Environmental Protection Agency (EPA) has developed and deployed a variety of custom sensor pods in community settings to evaluate their performance under real-world conditions. These sensor pods were constructed by combining various low-cost original equipment manufacturer (OEM) component sensors and system integration technologies into a single unit in an effort to maximize ease of operation, while meeting a specific research requirement.[3,6] Many of the sensor components selected for these pods were chosen based upon research findings from direct reference monitoring comparisons. This approach provides the ability to leverage knowledge gained regarding sensor operational requirements and general performance capabilities with application needs.

Researchers at the EPA are often asked about how they develop sensor pods. Development is guided by project requirements to ensure adequate data collection to meet a specific purpose. This article describes some of the decision-making used in the development of two unique low-cost sensor pods as a means to share our generalized approach with users having some degree of technical expertise. Each example was designed to meet the specific needs of a unique user community, and therefore, the two had quite dissimilar requirements.

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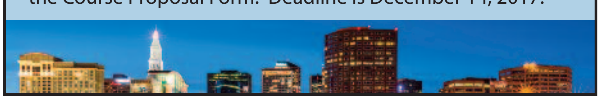

Key Parameters of Pod Development

Various decisions must be made during the design and development of a deployable sensor pod. These decisions must consider the technical abilities of the user, the length of the deployment, and the measurement goals of the deployment. The primary design decisions include:

1. Pod Enclosure and Ancillary Components
2. Ease of Use Features
3. Power Supply
4. Data Collection and Processing
5. Sensor Selection

Pod Enclosure and Ancillary Components

The design and level of sophistication of a sensor pod is influenced by the intended use in exploring environmental challenges. Regardless of application, all sensor pods reflect compromises among a number of competing factors affecting functionality. Materials for enclosures may range from metallic to plastic, and pods may be custom-built or use a commercially available enclosure.

A benefit of metallic enclosures is the flexibility to customize on the fly via drilling holes, cutting openings, and so forth. However, these cases are often heavier, can have inadvertent sharp edges, and may require special equipment to make modifications.

Plastic can be a less expensive alternative for enclosures and the rise of three-dimensional printing supports rapid prototyping and iteration of a custom case. A risk with plastic materials is potential interference; great effort should be made to ensure the material is inert and is non-reactive with the target pollutant.

A lightweight material is ideal for versatile and portable sensor pods. Such designs would allow for mobile measurements, where the sensor pod is being worn or carried by the user. To ensure the sensor pod is durable, internal components should be packaged in a weather-resistant, rugged enclosure to protect them from damage during transport and minimize interferences from environmental conditions. Depending on the performance specifications of the internal sensors, environmental conditions, such as sunlight, precipitation, relative humidity (RH), and temperature can influence response.[7-10]

To ensure that sensor pods are operated under proper conditions and measured values are representative of ambient concentrations, additional components, such as fans, active sampling inlets, temperature sensors, RH sensors, and non-reactive samplings lines, are factors we consider in the design of sensor pods. Appropriately positioned inlets and environmental sensors (e.g., temperature and RH) help ensure more representative sampling. Inadequate planning and testing of the design of a sensor pod can result in a device that produces results not reflective of true environmental conditions.

Ease of Use Features

Ease of use is a critical factor supporting successful operation of sensors pods by community members, who may have a diversity of backgrounds and level of comfort with new technology. User-friendly features help minimize the risk of user error and the amount of time required for training. The amount of operation time required to deploy a sensor pod and start data collection will often be dictated by the amount of tasks that are not automated via firmware. Firmware provides the instructions needed for the microprocessor to communicate with sensors and initialize required tasks.

A fully automated sensor pod can be designed to have a power switch to simultaneously power all components and, via an onboard programmed microprocessor, initialize sensors, perform self-checks, set timestamps, and begin logging data. Scripts can also be incorporated to provide quality assurance by performing checks and balances to alert users to a range of issues, such as low battery warnings, fluctuations in flowrates, sensor failure, and interruptions in data logging. Quality assurance scripts can direct a sensor pod to terminate operations to prevent further damage in the event of a failure.

Real-time data and alerts can be displayed on an interactive graphical user interface on a touchscreen or an external laptop to allow users to navigate through menus and configurations to monitor the status. This provides a visual method to clearly identify which components are operating and to communicate the cause of any potential issue. The complexity of sensor pod design and the experience of the user will vary across projects and should be considered when incorporating user-friendly features.

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Power Supply

Unlike traditional regulatory monitors, a sensor pod's low-cost internal components typically have low energy requirements (< 30 watts). This often allows sensor pod energy supply decisions to be a function of the location and duration of deployment. A sensor pod can be operated using various combinations of AC, solar, and battery power.

Sensor pods using AC power are more suitable for urban settings, where the electrical grid can supply AC power. The reliability of electrical grids varies by location, so sensor pods can also be equipped with an internal battery as a backup to protect against the event of a power failure. This allows for continuous measurements during momentary power outages and provides time to follow proper shutdown procedures if the primary power source is down for an extended period.

Solar-powered sensor pods are designed for outdoor deployments, where ideal conditions permit. However, a sensor pod dependent on solar panels as a main power source is at risk of failure during non-ideal weather conditions. Sensor pods that rely on solar panels must also be equipped with an internal battery and controller, which supports the ongoing charge/discharge of the battery and automatic shutdown of the pod to protect the battery under critical low-charge conditions.

Sensor pods powered only by battery are typically used for deployments with short durations or in rural areas that lack access to electrical connections. In these situations, additional batteries for periodic battery changes are required to maximize data collection, otherwise measurements will be interrupted for allocated recharge time.

A wide variety of batteries are available (e.g., lead acid, lithium ion, lithium polymer) with different advantages depending on application type. These trade-offs include, but are not limited to: safety, ease of use, and weight considerations. To determine the battery capacity or number of solar cells requires an energy budget to be performed to calculate the required operational watts of the internal components. The frequency at which batteries are exchanged will also influence the required capacity of the power source. The battery can be stored in a dedicated enclosure or the sensor pod can be designed to accommodate an internal battery bay. In either case, the internal battery should be easily accessible to accommodate routine battery recharge and/or replacement in a safe manner and to reduce the amount of time the sensor pod is offline.

All sensor pod designs should be reviewed by a qualified engineering team to ensure all integrated electrical circuits meet required standards of safety. Power requirement considerations are essential in ensuring proper operation of sensor pod components and maximizing performance.

Data Collection and Processing

Sensor pods are composed of a range of components that each require independent power and communication connections. To provide power and communication to these devices requires a simple computer (microprocessor) capable of: (a) collecting raw data and controlling major operations, (b) locally processing raw data to final reporting units or transmitting raw data to a server for post-processing, and (c) storing processed data. Major operations controlled by the microprocessor include powering the sensor and initializing the collection of data.

Once data collection is initialized, the microprocessor is responsible for controlling a range of tasks by running scripts. These tasks might include quality assurance checks and displaying values in real-time as a single value or graphically as a time series. If a sensor does not have a built-in processor that directly reports final measurements units, then the microprocessor is also required to convert a raw electrical signal to the final units or direct the raw electrical signal to be transmitted to a server via cellular, Bluetooth, or cloud communication.

Post-processing data on a server allows algorithm updates to be easily implemented across a network of sensor pods instead of reprogramming sensor pods individually, but sensor pods should still locally store data for quality assurance. Additional processing might be required if data need to be averaged over a defined time interval. The final major task a microprocessor is responsible for includes storing either processed or unprocessed data.

Data can be stored locally in real-time either temporarily on the processor or long-term on a secure digital (SD) memory card. The available capacity of flash storage on microprocessors is often very limited, so sensor pods that require data storage on the level of gigabytes (GB) or more should incorporate additional internal storage. Local data storage requirements are mainly determined by the number of sensors and parameters being measured and the frequency and duration of the sampling. Our experience would indicate 4–8-GB SD cards often provide months of data logging capacity. As an example, we have observed 1-minute data collections for 10 variables translates to a rate of ~ 0.1 MB per day.

Remote data storage also helps minimize power requirements because data do not have to be processed or stored locally.[11-12] Remote data storage can be redundant of locally stored data or data processing/storage can be entirely remote with the risk of communication failure potentially resulting in lost data. The appropriate selection of a microprocessor is critical to ensuring a sensor pod is capable of properly operating internal components, processing data to final units, and storing data.

Sensor Selection

When choosing an environmental sensor, it is important to define performance specifications considering the expected environmental conditions and the data quality requirements of the end-user. This requires understanding the target pollutant's expected range of concentrations during the duration of the project and the rate of fluctuation. The duration of the project affects the impact of diurnal and seasonal trends, as well as the potential drift in a sensor's response over time. Understanding these parameters is critical for proper sensor selection to ensure data are useful and appropriate.

The quality of the data collected by a sensor pod is a function of the performance specifications of the internal sensors. Sensors with a wide range of sampling frequencies are available and end-users need to define the specifications required to achieve the goals of the specific application. Important characteristics to consider during the design of sensor pods and the performance specifications of various low-cost sensors are covered in more detail in EPA's *Air Sensor Guidebook*.[13]

Sensor pods could include a combination of sensors to measure particulate matter (PM), and/or gas-phase species, and environmental conditions. Many low-cost PM sensors are nephelometers that size particles in real-time based on light scattering by an ensemble of particles at one or more specific wavelengths.[6] Particles are measured via either active (e.g., pump or fan) or passive (e.g., heated resistor or diffusion) sampling. The translation of the light scattering signal to mass is commonly done through a calibration against a mass standard or through collocation with a reference monitor.[14]

The second common PM sensor type is via an optical particle counter, which counts and estimates the size of individual particles as they pass through a laser beam. These sensors then translate the size-binned particle counts to mass by assuming the particles are spherical and applying an assumed density.

Generally, PM sensors lack a true physical impactor and therefore provide only estimations of size fraction concentrations.

Two common types of low-cost gas-phase sensors are electrochemical and metal oxide.[15,16] These sensors rely on chemical reactions that produce electrical responses proportional to the concentration of the target pollutant. Metal-oxide sensors have the advantage of high sensitivity across a wide range of concentrations relative to electrochemical sensors, but are influenced by cross sensitivity to other pollutants and are susceptible to drift.[17]

Measurements from both PM and gas-phase sensors have been shown to be influenced by changes in temperature and RH.[7-9,19] To monitor changes in a sensor's response, it is recommended that sensor pods incorporate ambient temperature and RH sensors to ensure the readings are truly representative of the environment being sampled. Besides air quality sensors, other options of sensors not covered in depth include accelerometers, GPS, noise, and so forth.

Examples of Developed Sensor Pods

EPA has been developing resources to help citizen scientists explore the air quality of their local communities and properly conduct research to address potential environmental issues. Two examples of low-cost, cutting-edge air sensor pods are described below: the Citizen Science Air Monitor (CSAM) and the AirMapper.

CSAM

EPA developed the CSAM, as shown Figure 1, for an environmental justice research study in Newark, NJ, involving the measurement of nitrogen dioxide (NO_2), fine particulate

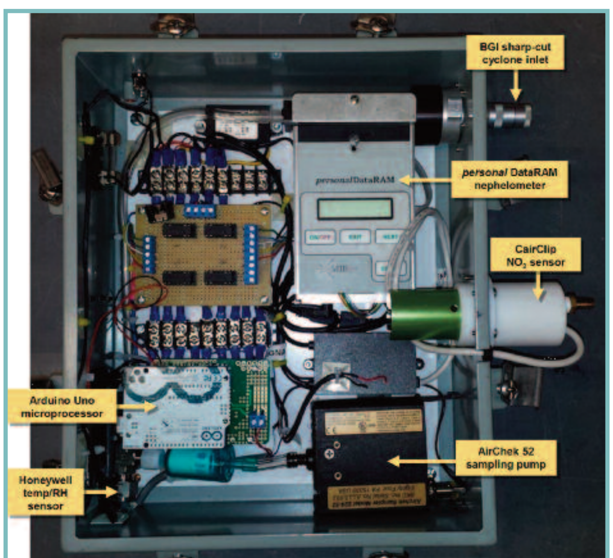

Figure 1. The Citizen Science Air Monitor (CSAM) showing the internal components.

matter ($PM_{2.5}$), temperature, and RH. A primary requirement of the CSAM was to be capable of operating indoors and/or outdoors on AC and/or battery (LiFePO4) power for one week unattended. For that reason, the CSAM units were designed to be fully automated by using a single-step keylock access door to operate all functions simultaneously.

All of the sensors in the CSAM communicated and relayed data through an Arduino Uno microprocessor via custom software that continuously stored all logged data to a SD memory card. The CSAM was designed to function in both outdoor and indoor environments with minimal modifications. When deployed indoors, the CSAM operated on AC power with inert Teflon tubing used to extend the sampling inlets through windows to sample ambient conditions. The sensors and battery were housed in separate National Electrical Manufacturers Association (NEMA)-approved boxes equipped with rubber gaskets and a rain cover to be fully weather resistant. Aluminum materials were used for the housing, tripod, and rain shield to minimize weight and to prevent rust.

The CSAM measured NO_2 in real-time in parts per billion (ppb) using a CairClip sensor, and $PM_{2.5}$ in micrograms per cubic meter (µg/m^3) using a Thermo Scientific personal DataRam (pDR) 1200 nephelometer. Sensors selected for inclusion represented those useful in establishing potential near-road environmental conditions. The pDRs were modified from their original design by making them active samplers and amending their control board to accept on/off initiation instructions from the CSAM. Air was actively sampled at a flow rate of 1.5 liter per minute (LPM) through a sharp-cut cyclone to exclude particles greater than 2.5 micrometers in diameter. Temperature and RH were measured inline by a Honeywell sensor (hih-4602-A/C series) to monitor environmental conditions.

Each CSAM unit included an embedded Microsoft Excel macro-enabled spreadsheet to allow for the processing of field data. Following data collection, the user executed the macro, which resulted in the conversion of the voltages recorded for each sensor to the appropriate reporting units. The resulting spreadsheet contained the raw data, calibration algorithm, converted data, and time series for each sensor to allow the data to be assessed for quality and usability in a user-friendly manner.

During deployment, a collocation study was performed at the NCore network site maintained by the New Jersey Department of Environmental Protection (NJDEP) to compare four CSAM units to Federal Reference Monitors. The internal NO_2 and $PM_{2.5}$ sensors were audited over a period of one week (April, 7–April 14, 2015) against a TECO 42i sampler and a R&P Tapered Element Oscillating Microbalance-Filter Dynamics Measurement System (TEOM-FDMS), respectively.

Each CSAM demonstrated good correlation with the reference monitors for temperature (R^2 > 0.92), RH (R^2 > 0.88), NO_2 (R^2 > 0.62), and $PM_{2.5}$ (R^2 > 0.61). Individual regression equations were derived for each CSAM to normalize the response between the reference monitors and the CSAM internal sensors. The deployment of the CSAM sensor pods at the study location from February 12, 2015, to July 30, 2015 demonstrated that they could be operated by citizen scientists in a manner to provide reliable air quality information with only minor technical issues reported.

Lessons learned from the development and deployment of the CSAMs have been reported in depth elsewhere.[3] These included miniaturization of the primary pod enclosure and use of pod-specific printed circuit boards designed to improve electrical architectural features. Overall, operation of the CSAMs and data recovery were effective. The operation of the CSAMs using the turnkey design allowed for minimal training and resulted in no issues with the citizen volunteers. Similarly, regularly changing batteries and switching to AC power was successful.

AirMapper

The AirMapper, as shown in Figure 2, was designed as a lightweight battery-powered portable sensor pod to measure PM_1/$PM_{2.5}$/PM_{10}, carbon dioxide (CO_2), temperature, RH, acceleration, noise, and location.[18] The focus of the AirMapper was to develop an environmental awareness sensor pod with a focus on ease of use to accommodate a wide range of end user ages, including elementary school participants. For this application, the data quality requirements were relaxed compared to a research application and a priority was high time resolution data (10 seconds) to support fast data retrieval while walking or biking.

The AirMapper was constructed by modifying a commercially available bicycle commuter bag to add an aluminum case enclosure. The lightweight design (< 2 kg) and size (25 cm x 20 cm x 25 cm) provided for the AirMapper to be either personally carried or used in a mobile fashion. Collected data were processed using two coupled Arduino (Arduino Uno and Arduino Mega 2560) microprocessors, which supported two components (touchscreen and PM sensor) that required a serial interface. The data were logged to an internal SD card and could also be viewed in real time through a touchscreen interface. Data were logged in 10-second intervals and automatically processed to report in a format compatible with the Real-Time GeOspatial viewer (RETIGO) data visualization tool,[20] which could be used to explore trends and changes in data. The AirMapper can run on battery for approximately 8 hours using a 7.2V rechargeable NiMH battery pack (recharge time of ~ 4 hrs).

On-board the AirMapper, PM was measured in units of μg/m³ using an AlphaSense OPC-N2 optical particle monitor, which pulled ambient air into the sensor via a fan. CO_2 was measured in units of parts per million (ppm) using a COZIR sensor (GC-0015) using nondispersive infrared sampling. Both temperature and RH were measured by an Adafruit sensor (DHT22). The AirMapper also measured noise (MAX9814 Chip), acceleration (ADXL326), and longitude and latitude coordinates (Ultimate GPS module).

EPA released the AirMapper for pilot testing by three EPA regional offices. Early feedback from community groups and EPA users indicated that the AirMapper is user-friendly and the immediate interactive data exploration via RETIGO provided an enhanced educational experience. When releasing the AirMapper to specific EPA regional offices, the agency also provided educational lessons directly to them, which aligned with national science standards. Such education materials are available upon direct request.

Future Considerations

To continue the advancement of emerging low-cost sensor pods, several key aspects must be addressed. A mechanism is needed to inform users of commercially available sensors that have been evaluated against Federal Reference Monitors to establish performance specifications. EPA's Air Sensor Toolbox[21] and South Coast Air Quality Management District's (SCAQMD) AQ-SPEC[22] program are examples of methods of communication useful in conveying performance specifications of low-cost sensors to end users.

Figure 2. The portable AirMapper with carrying strap and touchscreen.

Establishing benchmark performance criteria would provide a pathway for emerging technologies to achieve certification. This would create a clear means for users to identify sensors that meet defined performance standards. In addition, establishing data and metadata standards for low-cost sensors would improve interoperability, software, and databases. Many low-cost sensors currently lack an affordable and simplistic means of calibration. The most widely practiced method is to do a collocation study against a reference monitor prior in order to normalize sensor data relative to the reference monitor.[23,24] Field calibrations also allow sensor pods to be calibrated under real-world conditions rather than under factory and laboratory settings. This option helps address data quality concerns but is probably not feasible for inexperienced end users without support from third-party applications and custom field calibrations.

Based on the examples described here, multipollutant sensor pods can provide value to environmental air quality awareness studies. Key decisions about component selection are required early in the design process. Knowledge about the capabilities of the sensors of interest is vital in ensuring a device meeting its proposed use is developed. Understanding how the technology functions and then integrating the components into a functional design requires technical expertise often not available at the citizen or community level. **em**

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