A Literature Review of the Feasibility of a Low-Cost Portable Air Quality Sensor System with Smartphone Connection and Network

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1 INTRODUCTION

The quality of air that we breath directly affects our health, and the majority of the time that poor or harmful air quality is inhaled we do not realize it. There is a great need in the world for a low-cost portable air quality system [6]. Such a system might be made of a number of air quality sensors, each measuring a main quality of the air around to determine if the quality of air is safe (measurements of particulate matter, volatile organic compounds, carbon monoxide, temperature, humidity, barometric pressure, etc.). The system should be portable to monitor the air that the user is breathing wherever they are. The uses for such a system of sensors are life saving for the individual because the user can be alerted if the air surrounding them is harmful. Additionally, if the sensor systems can be networked through smartphones and servers for visual mapping, they can work to save all the lives around that do not have the system themselves as long as they have the app.

The practicality and feasibility of such a system and network is up for debate for a variety of reasons. This literature review will examine the differing reasons on whether a low-cost portable air quality sensor system and network can be deployed today or in the near future.

In the first section, I lay out the real need for such a system and network to exist. The second section is a review of the different kinds of sensors required for such a system to operate successfully, along with the shortcomings of each of the sensors. The third section dives into the networking applications required to make the system more effective for the general public. The review will conclude with my final thoughts on the present status and future of such a system and network.

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2 MOTIVATION

In the world that we all live in now, the effects of air pollution and climate change are a toxic duo. According to the World Health Organization (WHO), air pollution accounts for 1 in 8 deaths worldwide [9]. The vast majority of deaths linked to harmful air quality are from cardio-vascular diseases including ischaemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer, and acute lower respiratory infections in children [9]. These diseases are brought on and made worse by harmful air quality, the effects of pollutants are even stronger on children, the elderly, immune compromised people, pregnant women, and those who already have some respiratory illness [13]. The major pollutants that are commonly seen are:

- carbon monoxide from burning of fossil fuels, volatile organic compounds (VOCs, commonly emitted from industrial areas from the production of paints, pharmaceuticals, and refrigerants. compounds such as oxidants, by-products of water chlorination, and solvents [4]).
- ozone from the mixing of nitrogen oxides and VOCs [1].
- sulphur dioxides also from burning fossil fuels [3].
- particulate matter of sizes between 5 micrometers and less than 2.5 micrometers that come from any sources that produces smoke, dust, aerosol chemicals, or nitrogen oxides which combine in the atmosphere into hundreds of different dangerous aerosols [2].

A low-cost portable air quality sensor system is something that could be a lifesaver for millions of people if implemented because of its ability to warn users. If users are able to leave and avoid areas with harmful air quality, it would lessen their risks for diseases brought on by pollution and prevent already present diseases from worsening.

3 SENSORS

A variety of sensors would need to go into a system that would be able to detect all of the most common types of air pollutants.

- **Particulate Matter Sensor:** There would need to be a sensor that could detect particulate matter (commonly referred to as PM) of sizes down to 2.5 micrometers or lower. This is due to the fact that particulate matter of this size or smaller enters the lungs and is able to enter the blood stream easier than larger size particles and the size of the particle makes it impossible to detect by eye [2]. However, particulate matter makes up the smog and haze that you see over cities [2]. There are two main types of PM sensors:

Light Scattering Particle Sensors: They runs off of a small laser or some other light emitting source, such as an LED, that particulate matter floats through the beam of causing the light receptacle at the end of the laser beam to be able to sense the amount and size of particles if properly calibrated and adapted [5, 8, 10–12].

Diffusion Size Classifiers: They use a sensing surface and send electrical signals through the surface to identify changes on the surface. There is a multi-step process that the air goes through when it enters the sensor chamber. The air passes through a chamber called a diffusion charger that uses a corona wire to produce ions that them attach to particles in the air. The charged particles then pass through to an induction stage that measures their charge, which is a direct proportion to their concentration. The particles then pass into a diffusion chamber that precipitates the particles to produce an electrical charge that is proportional to their concentration. Large particles that do no precipitate then are measured for their charge and concentration at the end of the sensors measuring. The way that the particles pass through the sensor allows for their size to be determined [5].

In terms of which PM sensor is better suited for a low-cost portable air quality sensor system, there are pros and cons to each kind of PM sensor. Some advantages of the light scattering particle sensors are that they are small, low-cost, and require low power [5, 8, 10–12]. Although, it has shown in studies that temperature and humidity affect the accuracy of the sensor as the sensor detects water vapor as particulate matter [5, 8, 10–12]. Other than the effects of temperature and humidity on the accuracy of the light scattering particle sensor, the sensor is opted for in all studies reviewed for this literature review. The advantages of the diffusion size classifier is that is has a higher accuracy than its competitor, however, the cons of the sensor are its high production cost and the frequency of having to clean the sensor surface [5].

- **Gaseous Pollutant Sensor:** A gaseous pollutant sensor is another key sensor for the system. This kind of sensor is different than a particulate matter sensor because it is detecting a gas rather than an aerosol, meaning the gas is in a mixture in the air rather than small particles suspended in gases in the air. [5] This causes the gases to not be detectable in the same way as the particulate matter is. There are multiple different sensor techniques when it comes to gaseous sensing:

Metal Oxide Semiconductor: Commonly known as MOS or MOX, this kind of sensor works by having a heating element and a metal oxide sensing element. The heating element heats up the sensing element to operating temperature (300-500 degrees F) where the gases coming in contact with the sensing element to chemically react. The reaction causes the change in the electrical conductivity on the sensing surface which is read by a external circuit to determine gas levels and type. Usually MOS sensors can detect carbon monoxide (CO), carbon dioxide (CO2), non-methane hydrocarbons (NMHCs), nitrogen oxides (NOx), ozone (O3), and many combination of NOx and O3 [5, 11].

Electrochemical: Commonly known as EC, this kind of sensor works by having at least two electrodes near each other. One of the electrodes is working and the other is the counter. As gasses pass by the working electrode, they cause a chemical reaction on the surface of the working electrode that causes an electrical charge to be formed. The charge is directly proportional to the gas concentration. EC sensors usually detect NOx, CO, CO2, O3, and sulphur dioxide (SO2) [5, 11].

Non-Dispersive Infrared: Commonly known as NDIR, inside the sensor there is a chamber where infrared light is shined onto a receptacle where gasses pass through the beam. The gasses absorb some of the energy from the light and changes the frequency of the light as it hits the sensor surface. The frequency is sent out in electrical current. This determines the gasses by detecting how much energy has been absorbed and how much gas concentration there is. NDIR sensors usually detect CO2, but can detect other gasses by the wavelength of the light that is received if tuned and calibrated properly [5].

Photo-Ionization Detector: Commonly known as PID, UV light shines through the gasses as pass by, this ionizes the gasses. The gasses can be read as electrical current when they collide with a detecting surface inside the sensor. The resulting current detected measures direct proportional to the amount of gas, the PID sensor can detect any gas whose photo-ionization potential is lower than the UV light hitting it - this means that it is not specific to any particular pollutant [5].

There are pros and cons to each type of gaseous sensor. From the literature about the MOS sensor, it is the best suited for a low-cost portable air quality sensor system [5, 11]. This is because of its high sensitivity, resistance to environmental effects such as temperature and humidity, and short response time creating high frequency of data. The cons are its power-draw and accuracy drift causing bad data. The power-draw will most likely be fixed through future sensor development and better battery technology. Additionally, the accuracy drift can be fixed by regular calibration - which requires the system to have humidity and temperature sensors [5].

As for the EC sensor, this is a sensor that is also commonly used because of its high sensitivity and low cost, but it is used less often than the MOS sensor. In terms of pros, they have less power-draw and are less affected by humidity and temperature than the MOS, but they have a slower reaction speed and other gasses affect the measuring abilities of EC sensors more than MOS sensors [5].

The NDIR sensor is a good quality gaseous sensor that is small, reliable, and have little power-draw. However, the cons of the NDIR sensor is that they are not sensitive to low concentrations of gas and are very susceptible to water vapor and accuracy drift as well as costing multitudes more than both the MOS and EC sensors [5].

The PID sensor is similar in pros and cons to the NDIR sensor. The PID pros are that it is small, has low power-draw, is very sensitive to gas levels and has a fast response time. And the cons are that the sensor needs to be re-calibrated more often than the EC sensor, it is prone to accuracy drift, it is susceptible to high humidity and water vapor levels, and it costs multitudes more than the MOS or EC sensors [5]. Besides the sensors that are required to detect harmful pollutants in the air, there are needed sensors that can determine qualities of the air in order to better optimize the sensor system's function.

- **Humidity Sensor:** A sensor that would be able to detect humidity concentration is another crucial part of the sensor system because humidity has been shown in studies to have a major effect on the accuracy of PM sensors and other air quality sensors in high levels [5, 8, 10, 14]. If calibrated correctly and with a sufficient algorithm, knowing the precise humidity at the sensor system can help the other sensors be more accurate in measurements.
- **Temperature Sensor:** A temperature sensor would be needed for the sensor system. This is due to the temperature having a direct affect on the ability of the sensor system to calibrate and maintain calibration. Extreme temperatures have been shown in studies to have a direct affect on the accuracy of sensors while operating and their ability to re-calibrate. [5, 7, 10, 14, 15].

4 NETWORK AND CALIBRATION

The sensor system would not be nearly as effective for users and non-users without a proper connection to a smartphone and server-side network system that re-calibrates and gathers air quality data. The network applications would be to take in the data from the smartphone connected to the sensor system and then apply it to a map that would track the location of dangerous air quality levels in real-time. The sensors themselves would need to be re-calibrated within certain time intervals (weekly, bi-weekly, or monthly), this could be done through varying calibration techniques that have been researched so far:

Pairwise Calibration: This calibration technique uses two different sensors (nodes), a reference sensor and another node. This technique is also referred to as **collaborative calibration, collaborative multi-hop calibration, rendezvous calibration, and opportunistic calibration**. The calibration is done to the node using the reference sensor to make calibration adjustments off of. This technique can use normal nodes as reference nodes if they are calibrated accurately off of a reference node, or it can use a stationary sensor that is pre-calibrated to be the reference sensor. Then the mobile nodes that are within close vicinity of the now calibrated mobile reference node, would calibrate off of the node and become reference nodes themselves [5, 7, 11].

Macro Calibration: For this calibration technique, all sensors on the network would be calibrated at once using an advanced algorithm without the nodes interacting with each other. This is also referred to as **blind calibration** as the nodes are blind of one another when being calibrated. Macro calibration is not commonly used if the amount of sensor systems is large or if they are spread far apart in different climate areas [5, 7, 11].

Group Calibration: This calibration technique is an in-between of the pairwise and macro calibration techniques. The sensor nodes would be grouped based on categorical qualities, such as location or if there exists sensors that detect specific things rather than the usual, and then a macro calibration would be applied to all nodes in the group. This is also considered to be **partially blind calibration** because the groups are blind to one another while those nodes inside each group are not blind to each other [7].

Transfer Calibration: Transfer calibration is a technique that has been implemented inside factories where electronic noses are used to detect gasses and chemicals in the air. The technique is to develop a calibration function that uses data from typically one control sensor that is in proximity to the other sensors in a factory to calibrate all nodes [5, 11]. In order to adapt this to for general use, the calibration function would be developed so the nearby nodes are calibrated off of the control sensor calibrated with a neural net function that has been built off of years of air quality data from stationary ground sensors. For the neural net function, it would continue to be build and adapted so that the future calibrations for that area would be easier and already have a good base to go off of and need less data moving forward to make changes to the calibration. This kind of neural net machine learning technique is called transfer learning and it is theorized that it can be adapted to general outdoor use for sensor systems [5, 11].

With a proper calibration technique (most likely using a neural network working with transfer learning/calibration), it is possible for a sensor system to be able to determine the gases and particles that it is sensing in the air from the interactions between all sensors in the system - similar to an electronic nose (e-nose) [11]. However, as it is now, there are some major short comings of the transfer calibration technique that still need to be ironed out:

(1) Transfer calibration generally assumes that the accuracy drift in nodes is equal to the accuracy drift of the control sensor. In real world applications, this is most likely not to be the case for nodes because of the variety of micro-climate shifts [11].
(2) Environmental interactions are assumed to be equal across different nodes. This could be the case if all the sensor system nodes were created the same, but most likely there will be some interactions with the environment that are different between exactly the same nodes. This could be due to age of the sensor system, or it could be due to the user not cleaning the sensor if it needs it, or some other standard condition that happens with time [11].

There are other shortcomings of the other calibration techniques (pairwise, macro, and group), for the pairwise calibration:

(1) Pairwise calibration can propagate errors across nodes. Because of the way that the referencing system works within pairwise calibration, errors made by one node can propagate to the next nodes that calibrate off of the erroneous reference. This can cause a wave of errors that would need to be fixed manually through some other calibration form [7, 11].

(2) Another disadvantage to pairwise calibration is that the nodes need to be in close vicinity in order for the calibration to happen, this can cause nodes that are farther away from the others to go uncalibrated by this method. This could be mitigated if there were a large enough amount of nodes for rendezvous points to occur frequently for calibration [7, 11]
(3) The last big hurdle for pairwise calibration is for sensors is non-linear calibration. This means that sensors that are not the same build or have a different environmental interaction would be more challenging to accurately calibrate using pairwise calibration because of how they differ in interacting with environmental stimuli and could propagate more errors or cause the node calibrating to become less accurate than before calibration [7, 11]

The macro form of calibration comes with the disadvantages:

(1) One of the main drawback to macro calibration is the lack of fidelity to environmental differences between sensors. For a macro calibration technique to work, it would require a large amount of data from a large amount of densely populated sensor systems to create the calibration function that would be applied to all sensors equally [5, 7, 11]
(2) In the papers reviewed for this literature review, it is discussed that macro calibration is only really successful using a function that would adjust for data offset in the sensor systems [5, 11]. Although, it should be possible, if combining calibration techniques, to use macro calibration as a distribution form rather than the basis of creating the calibration function [7].

For the group calibration technique, the main disadvantage is:

(1) Basically, because group calibration is a combination of pairwise and macro, the disadvantages of both strategies are taken into account. Group calibration requires sensor systems to be near each other in some form of relatively similar environment for the macro calibration to have a positive effect. However, because the group calibration technique uses interactions between sensor systems to determine the calibration function, it diminishes the disadvantage of small environmental changes between the sensor systems [7]

From all the studies reviewed for this literature review, it seems like the best way for a low-cost portable air quality sensor system to be implemented is for a calibration and network technique that uses pairwise, group, and transfer forms of calibration in different situations where the best calibration option can be chosen based on the users environment and the systems nearby.

5 CONCLUSION

From the all the literature reviewed for this literature review, it seems to me to be very plausible for a low-cost portable air quality sensor system with smartphone and network connection to be made and put into production for the general public. This kind of system would require a lot of back-end processing on the network/server side, meaning that the biggest hurdles, beyond the physical size of the system, is the sensor calibration from the network that would need to happen on a semi-regular basis depending on the sensors involved in the system. Just judging off the studies reviewed and the rising prominence of this field in the last five years, the development for this kind of system should rapidly accelerate in all directions (sensor hardware, calibration techniques using neural networks and other machine learning techniques, and field studies for how to expand systems to more rural areas) - I would honestly say this kind of system will most likely be on the market in developed nations in less than ten years.

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