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Evaluation of Precalibrated Electrochemical Gas Sensors for Air Quality Monitoring Systems

Saeed Malky
Department of ECE
Florida Institute Of Technology
Melbourne, FL, United States
smalky2008@my.fit.edu

Dr. Ivica Kostanic
Department of ECE
Florida Institute Of Technology
Melbourne, FL, United States
Kostanic@fit.edu

Khalid Altheiab
Department of ECE
Florida Institute Of Technology
Melbourne, United States
Kaltheiab2006@my.fit.edu

Waleed Alharbai
Department of ECE
Florida Institute Of Technology
Melbourne, United States
Walharba@my.fit.edu

***Abstract*— Harmful atmospheric pollutants have been attributed to causing adverse weather conditions and health problems, which are particularly prevalent in more populated global regions such as in megacities. Nongovernmental and international agencies likewise throughout the world have called for increased awareness and action in effectively countering the increased rates of air pollution of which the consequences seem ominous. Meanwhile, in several major urban landscapes such as Saudi Arabia, no modern apparatus or efficient systematic mechanisms for qualitative detection of dangerous pollutants and gases exist. The current counterparts for hazardous gas measurements are expensive, bulky and cumbersome to set up. Thus, sensor devices that are portable and prompter in ambient air measurement are desired for filling the current gap in effective air pollution monitoring. Our objective in this research was to better understand and explore relatively cost-effective, flexible and dynamic sensors in real time monitoring that can efficiently function in modern day environments and regions. The suitability of these new-age sensors were analyzed for gases such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particle pollution ($PM_{2.5}$, PM_{10}), and ozone (O_3). The study area was urban cities.**

Keywords*— *Air Quality Monitoring, Wireless Sensor Network (WSN), Air Quality Index, Air Pollution, Electrochemical gas sensors, Temporal Resolution.

I. INTRODUCTION

Air pollution affecting both indoors and outdoors is a severe crisis in many areas throughout the world. It has garnered public attention by triggering adverse health impacts on people who are sensitive to environmental factors. Conditions such as bronchial asthma, emphysema, and pneumonia have been commonly associated with air pollution. Epidemiological research has reported an alarming risk of heightened and graver heart problems related to both short-term and long-term exposure to present-day levels of air particle contaminants such as PM2.5 and PM10 and gaseous contaminants such as ground-level ozone and nitrogen oxides [1]. Booming metropolitan areas, a rising influx of inhabitants in megacities, and large-scale industrial progression are in many ways responsible for the production of new contaminants that in the long term may be gradually destructive to the global environment and global community wellness [2].

Conventional air pollution monitoring systems are mainly based on bulky, heavy, and sophisticated instruments. This equipment tends to apply complex statistical methods and complex supporting tools such as temperature and relative humidity controllers, air filters or sensors for particulate matter and gases along with built-in calibrators guaranteeing the precision and performance. Therefore, this equipment is typically expensive, large, and uses an excessive amount of energy [3]. It also results in a deficiency in systematic networks of real-time monitoring equipment, inducing ineffectiveness in the tracking of sharp gradients in pollutant concentration both spatially and temporally [4]. The deficiency or rather the absence of a useful strategy thus leads to the inability to comprehensively understand the effects of such pollutants on human health and the environment. In a situation in which air pollution is progressively severe, ambient sensors that are of low cost, small size, and fast response time are incredibly desirable [3]. The concept and potential for such devices are well recognized in the public industrial arena. However, low-cost sensors have not been commonly used in communities partly because it is extremely challenging, even under ambient conditions, to collect a particular gas measurement with high data accuracy; in addition, to attain stability over time, they still need to be compared to traditional monitoring equipment [5],[3]. Furthermore, detailed published measures of efficiency are relatively rare, particularly for analytical technologies that are already used by the general public. In Saudi Arabia, which is now among the most polluted countries in the world, no such effective real-time monitoring equipment is commonly used. Our purpose in this study was to offer an opportunity to apply relatively low cost, convenient, and real-time monitoring sensors that we hope to use more of in the forthcoming future, along with studies that will eventually aid in the detection of air quality with a higher accuracy and precision and shorter response time. We analyzed and validated the effectiveness of

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the sensors in monitoring outdoor air pollutants, such as CO, Ozone, NO2, SO2, and PM, in urban cities to provide a foundation for later use.

II. Related work

Research findings from other case studies where 21st century wireless air pollution monitoring systems have been implemented were reviewed as part of the preliminary analysis before undertaking the project in Saudi Arabia.

The first study of this technology to be discussed here is 'Real Time Pollution Monitoring Using Wireless Sensor Networks' by Movva Pavani and P. Trinatha Rao. The paper mentions the high operating costs and the reported difficulty in terms of stationing and transportability of conventional bulky air pollutant measurement systems and the relatively low pay-off for larger-scale applications. However, the effectiveness of recent innovative technology within this scientific area of study, i.e., wireless capable gas sensors, was highlighted and demonstrated to show its versatility. Among the greatest advantages is its scalability that allows the setup size of the wireless sensor network to be adapted based on the level of application demand. Its basic design is composed of three parts: a libelium wasp mote that houses the different gas sensors, a middleware component for back-up and graphical data transmission, and a base station whereby information is received that also connects to other users throughout the network. This wireless air monitoring technology was set up in an industrial zone of Patancheru in Hyderabad, India. Results from this research showed the consistency in adoption of such a mode of wireless network in air pollution measurement over different durations. Technically, it was also able to verify the calibration of sensors and that their deployment on the wasp mote proved an effective strategy for installation of an air pollution monitoring system that would otherwise be arduously met in a heavily industrialized locality [6].

The next reviewed and discussed here is 'Air Pollution Monitoring in Lemesos using a Wireless Sensor Network' by Theofylaktos Pieri and Michalis P. Michaelides. The study location was the city of Lemesos, Cyprus. This literature provided some interesting discoveries pertaining to the utilization of an air pollution monitoring system that is wireless. The architectural design proposed for this study consisted of 10 sensor nodes or "waspmotes." There were also 2 gateways or "meshliums" and a computer for data computation that included a web interface for dynamic interactions with the data. Gas sensors and particulate (PM) sensors were deployed. An XBee device was supported by the meshlium that communicated data to other mediums. Among them was a MySQL database for additional data processing. The challenges encountered with the Libelium wireless sensor technology were communication gaps resulting from spatial obstructions. In localities that are far from ideal, Libelium air pollution monitoring components, although wireless, showed downgraded performance capabilities such as possessing a range ceiling of slightly greater than 1 km as opposed to the 7 km in an open nonclustered civil space. The latter scenario is less likely to occur using technology that is meant for application in urbanized locations. Generally, the optimal setting was found to be meshlium and waspmotes positioned at 15 m and 4 m, respectively, above the ground level resulting in a communication range ceiling of 1050 m. Installation of the waspmotes was on light poles 300 cm above ground level [7]. The entire installation of the Libelium WSN technology required approximately two weeks, a subtle indicator of addressing miscellaneous issues of waspmote deployment in a heavily populated downtown setting such as Lemesos, Cyprus. Communication problems were witnessed between the waspmotes and gateway only 60 m apart because of the constrictive structural environment within the city. One such example was leaves from bulging tree stems that caused a line-of-sight hindrance between the gateway and one of the nodes. The need for precalibrated sensors was also highlighted as part of this research in which calibration techniques were not able to robustly equate the characteristic patterns of the sensors with the ambient conditions. More refined algorithms in program software were therefore stressed pertaining to negation of calibration discrepancies in the Libelium sensors. Overall, however, the technical feasibility of the Libelium WSN as an air pollution monitor showed room for further improvement [7].

Another paper reviewed was 'SAQnet: Experience from the Design of an Air Pollution Monitoring System Based on Off-the-Shelf Equipment' by Sebastian Bader, Mathias Anneken, Manuel Goldbeck, and Bengt Oelmen. This was conducted in a simulated laboratory depicting real environmental settings, as well as at external physical locations in Sundsvall, a Swedish city. The proposition that implementation of a wireless sensing system in air pollutant detection offers a broadly viable solution in comparison to conventional technology was extensively investigated. The authors of this work dissected their system into sensing, data storage, and data access layers. The sensing portion contained the waspmote housing on an Atmel controller with its quality of low power consumption as the most important reason cited for its use in addition to other capabilities. The gases and pollutants that were considered for measurement were CO, Pb, PM, SO_2, NO_2 and O_3, but because of constraints in terms of measurement capacity, all of these could not be simultaneously monitored [8]. Under the sensing layer, the operational frequency of the transceiver was 2.4 GHz, while the protocol stack was bought from Digi International Inc. The power source for the sensor nodes was lithium batteries, and the software side of waspmote was complemented with API functionality. The sensor node was awoken from an energy preservative mode periodically every 15 minutes. Regarding the middle layer of data storage, it was responsible for collection or quantification of sensor inputs and enabling access to measurements of external components; this was incorporated with a meshlium design commercially sourced from Libelium. The third layer of data access facilitated the high-level management of air pollution monitoring functionality, which included tools for various network configurations as well as adaptation of sensor nodes and the graphical presentation or illustration of values into user-friendly data. Evaluation of sensor nodes showed that those powered by batteries lasted up to 34 days and their operational duration varied based on displacement from the sink. However, those charged via solar panels had an operational duration of a few months before powering off. The conclusions from the off-the-shelf WSN air pollution monitoring system were many. First, power drainage of the system was observed to not be merely a byproduct of radio communication, but the sensing of the sensors themselves contributed most to power drainage that exceeded 1000% of that of communication activities. Second, in terms of cost-data output metrics, the ratio was not sufficiently low to suggest or convince that the wireless sensor nodes utilized were a significantly better economical alternative as opposed to conventional counterparts using nonwireless traditional technology. Third, wireless sensors that are not already precalibrated are susceptible to producing less than satisfactory output in terms of data quality and subsequent data interpretation. Thus, as per the authors, commercial-readiness and viability of WSN air monitoring for mass-industrial use still needs improvements addressing the discussed disadvantages [8].

III. WSN APPLICATION IN AIR QUALITY MONITORING

The proposal for a Wireless Sensor Network implementing the Alphasense sensors in Middle Eastern countries for air quality and pollution level monitoring offers a revolutionary approach. This becomes all the more significant for a region that has arguably witnessed the most rapid infrastructure development and most extensive landscape changes during the latter 20th and early 21st centuries. If the usability and application purpose of a dynamic atmospheric pollution monitoring system needs to be explored and investigated at all, the Middle East justifiably offers an archetypal research model. In terms of urbanization rates, tourism influx, and global warming effects, countries such as Saudi Arabia, United Arab Emirates, and Qatar can be rated as among the top countries to be environmentally influenced by these aforementioned factors [9]. Specifically, regarding the subject of air quality index variances over the years in these countries, the need for greater administrative vigilance in informing its mass public of air quality levels has high precedence. Particularly in light of 'oasification' or artificial reforestation and industrialized urbanization by which the region's tourism sector has boomed, the regulatory and monitoring measures for atmospheric air-related measurements therefore must be exceptional. Such a scenario necessitates the latest technological means for real-time air pollution detection in the Middle East that can keep up with the increasing pressure and constraints imposed upon its urbanized landscape. A wireless air sensor network monitoring system thus presents a promising approach to address this particular challenge in the region, with Saudi Arabia as a representative example to gauge and assess the performance parameters of this relatively new form of air pollution sensor technology. WSN as shown in Figure 1, consists of a set of nodes that can measure information from the environment, process and relay them to the base station and that, through particular nodes called gateways. The use of WSN for air pollution monitoring may have a great interest which can be mainly ascribed to the cost reduction, the node autonomy, the fine spatial and temporal granularity and to the self-organization and self-healing of the network without heavy infrastructure.

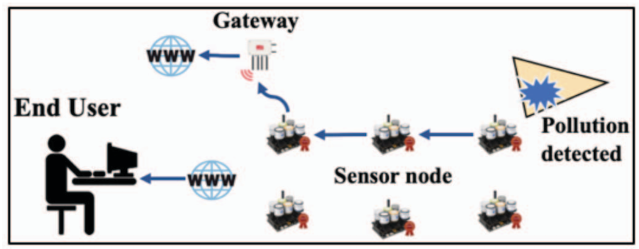

Figure 1: WSN in Air Quality Monitoring.

IV. IMPACT OF AIR POLLUTION ON HEALTH

The Air Quality Index (AQI), as the term suggests, offers an index of classification for determining the qualitative levels of air pollution and their plausible health impacts on humans. The emphasis of the AQI is borne primarily out of concern for the general well-being of the public that may be vulnerably exposed to any type of aerial condition, which is why classifying air quality type becomes all the more significant. The area of focus for the AQI by the Environmental Protection Agency (EPA) in the United States is on aerial pollutants that may be the most severe in causing negative health impacts to the exposed masses, whether over the short term or long term. As established by the Clean Air Act, the 5 dangerously harmful gases are nitrogen dioxide, sulfur dioxide, carbon monoxide, surface ozone, and particulate matter. Each has a level defined by the EPA in outdoor or indoor air that can be termed as more or less dangerous to the exposed masses. In particular, surface ozone and particulate matter are the most potent of all threats to human health impacts. The ceiling of the AQI is 500, while zero is the lowest rating on the index scale. Higher AQI numbers are indicative of greater percentages of pollutant-inflicted ambient air and thus a greater risk to the health of individuals or the public in the area. Conversely, lower numbers on the index scale are representative of safer air quality. An AQI score of 50 has a little to nearly zero possibility of causing any adverse health impacts on humans, whereas a score of 300 is definitely dangerous for anyone exposed to such aerial conditions [10].
Color codes have been ascribed to provide ranges of air quality levels that possess attributes of either good and relatively safer air quality levels or increasingly poor and unhealthy air quality levels that the public should avoid.

Table 1: Pollutant - Specific Sensitive Groups[10].

Numerical Value	AQI	Meaning
I_{low} - I_{high}	**Category**	
0-50	Good	**Air quality is considered satisfactory, and air pollution poses little or no risk.**
51-100	Moderate	**Air quality is acceptable; however, for some pollutants, there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.**
101-150	Unhealthy for Sensitive Groups	**Members of sensitive groups may experience health effects. The general public is not likely to be affected.**
151-200	Unhealthy	**Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.**
201-300	Very Unhealthy	**Health alert: everyone may experience more serious health effects.**
301-400	Hazardous	**Health warnings of emergency conditions. The entire population is more likely to be affected.**
401-500		

Table 2: Effects of an AQI higher than 100 on people [10].

When this pollutant has an AQI above 100…	**Reported Sensitive Groups.**
Ozone	People with lung disease, children, older adults, people who are active outdoors (including outdoor workers), people with certain genetic variants, and people with diets limited in certain nutrients are the groups most at risk
PM2.5	People with heart or lung disease, older adults, children, and people of lower socioeconomic status are the groups most at risk
PM10	People with heart or lung disease, older adults, children, and people of lower socioeconomic status are the groups most at risk
CO	People with heart disease is the group most at risk
NO2	People with asthma, children, and older adults are the groups most at risk
SO2	People with asthma, children, and older adults are the groups most at risk

Notes: Statements may be combined such that each group is mentioned only once.

V. DATA COLLECTION AND VALIDATION

The data points for the research were collected from metropolitan Riyadh in Saudi Arabia. The sensors utilized had the manufacturer's approval of precision calibration as measured against conventional calibrating standards. When inspected for their repeatability under distinctly different environmental conditions in Riyadh compared to the original production site, the expected discrepancies were shown in the sensory readings. Requisite adjustments were therefore mandatory for alignment of the sensor accuracy with the expected performance parameters under operating conditions of the research location. In our application of the chosen sensors for the purposes of our research in Riyadh, Saudi Arabia, the data output showed the direct sensor variability with humidity or its inverse relation with temperature. Thus, pertaining to the location for air pollution measurement, recalibration of the sensors must be performed for enhancing sensor precision to the desired degree of accuracy, which would then result in idealized data outputs as per the research objectives. The quiddity of electrochemical sensors is such that they adversely react to appreciable variations in ambient environmental conditions. This entails calibration of the electrochemical sensors for all seasons in multiple designations where they are expected for application. This would enable data repeatability of these precalibrated electrochemical sensors in similar environments corresponding to test locations within a minimal standard deviation. The algorithm derived from executing these calibrations facilitated the applicability of our electrochemical sensors to a wider range of areas globally and avoided susceptibility to otherwise expected data errors.

The manufacturer had calibrated the sensors in Serbia, but data were collected in Saudi Arabia. The pronounced differences in environmental conditions between these two countries thus necessitated calibration.

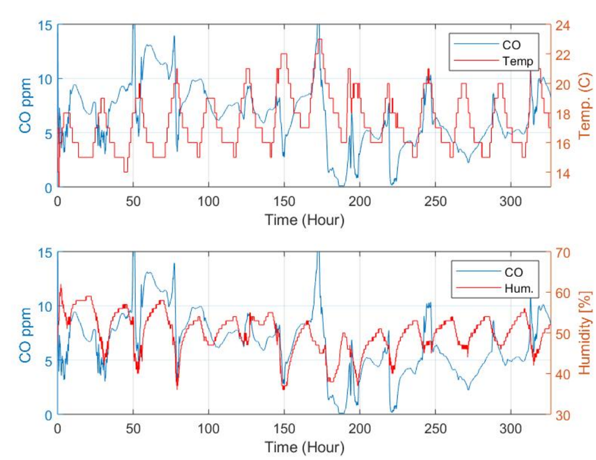

Figure 2: Measured CO.

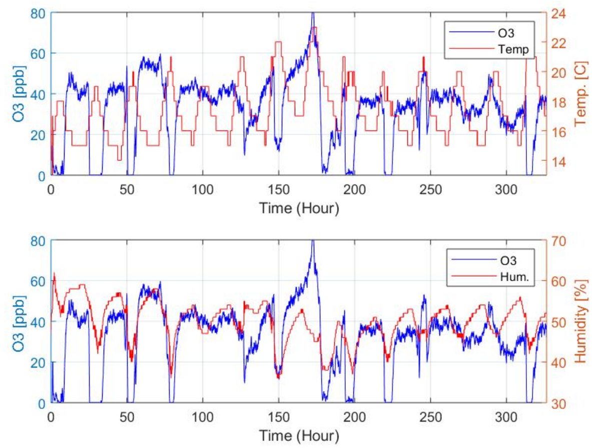

Figure 3: Measured Ozone.

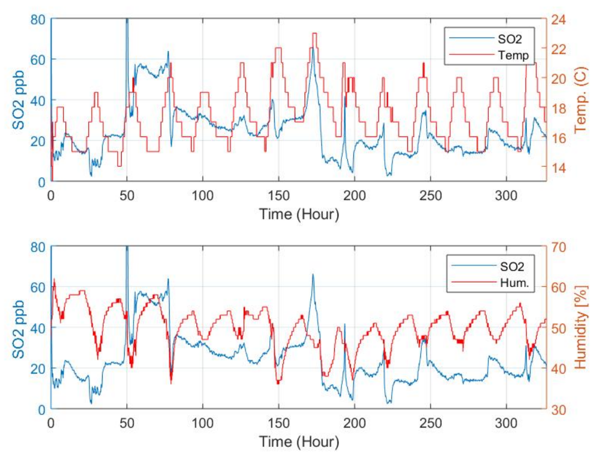

Figure 4: Measured SO2.

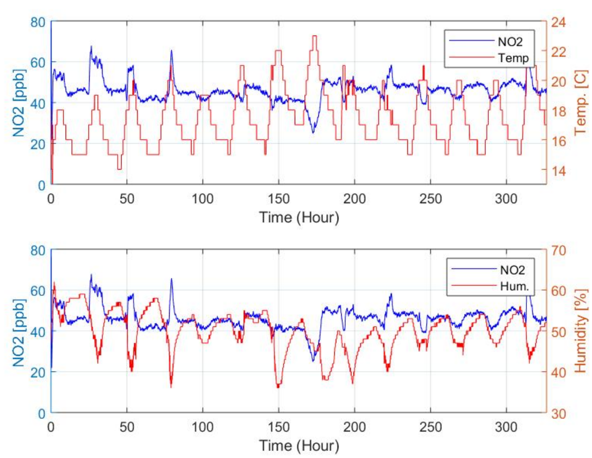

Figure 5: Measured NO2.

A. Factors Affecting Sensor Accuracy

Variations in general aerial conditions such as moisture content and temperature can influence the gaseous sensory devices such as its sensitivity to measurement [11]. To understand to what extent ambient environmental changes can influence or alter the normal performance characteristics of these sensing devices, metrics of temperature, moisture level, specific timeframes, and concentration of certain chemical compounds were studied. Their significance in influencing sensor performance and whether they are to be considered for initial sensor calibration were assessed.

B. Temperature

The electrochemical gas sensor devices definitely responded to aerial temperature changes. Numerically, this sensitiveness was between one-tenth to three-tenths of a percent per Kelvin as a general characteristic of such sensors. Meanwhile, the grounded or '0' electric-current of the sensor remained stable under aerial conditions not exceeding 30 degrees on the Celsius scale. As for the overall range of general temperature recordings typically between 10-40 degrees Celsius such as during the summer season, sensor sensitiveness varied between 95 and 110% [12].

The relation of CO, O3, and SO2 concentrations to temperature was verified with positive connections between the sensors and temperature in all measurements as shown in Figures 2, 3 and 4. Regarding the effects of temperature, it was essential to assess whether the accuracy of the sensors would decrease with an increase in temperature and whether we should include the temperature as an independent variable in multilinear regression to calibrate the sensor data. Errors were determined as the difference between the sensor and reference data (sensor data – reference data) observed at the same time. Errors were presented as an indicator of how much the sensor data differed from the reference, which, to a certain extent, indicated the accuracy of the raw sensor data before calibration.

C. Humidity

The technicalities of these sensors as per their manufacturing company disclose that they are highly adaptable to a wide range of ambient conditions. A key characteristic that enables such a feature in the sensors is in its containment of sulfuric acid as an ionized solvent aiding in the ionized flow of diminutive charged particles because of relative ambient air changes [12]. To maintain stability in the sensor measurements, the ionized solvent drains liquid at low moisture levels while seeping in liquid at times of high moisture. Figure 6 shows how the sensor loses weight at a low humidity and gains weight at a high humidity at a room temperature of 20 °C. The sensory devices are reported to optimally function between the 15th and 90th percentiles of relative humidity. Also, within this range, the gaseous sensors may lose a maximum of one-quarter of a gram while gaining a maximum of one-fifth of a gram in terms of mass. The sensitiveness of these devices was greater than 80% even at the zero percentile of hydration levels, thus demonstrating the reliability and repeatability of sensor performance as highlighted by its manufacturing company [12]. A problem may still persist, however, for accuracy and sensitivity of the sensing devices under time-variant humidifying factors whereby excessive moisture may be absorbed. Thus, it is helpful for us to carefully examine how discrepancies pre- and postcalibration vary under the given pretext.

Similar to CO, O3, and SO2 changes with moisture levels, erroneous discrepancies of the sensory devices preceding calibration are proportional to the humidity of the aerial conditions. The more humid the air, the greater is the offset and vice-versa. Once the sensors have been calibrated and adjusted, the differences are zeroed out similar to those for the calibrating effect on the sensors with respect to temperature.

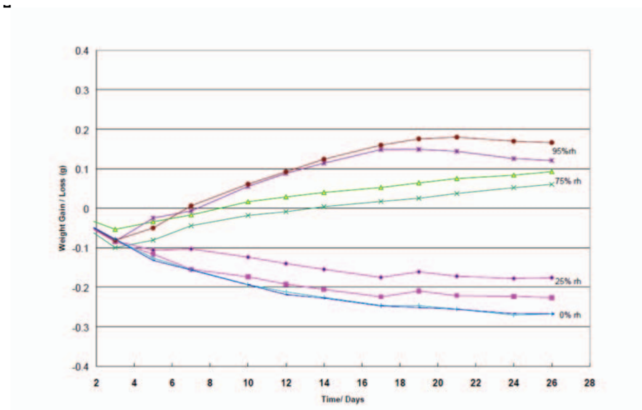

Figure 6: Sensor weight gain/loss when subjected to humidity extremes [12].

D. *Gas Ambient Concentration*

Sensor measurements of ambient air concentration may be influenced by the concentration of other gases in the aerial vicinity. An optimally functioning sensor necessitates the zeroing out of erroneous discrepancies as much as possible. For this, the regression squared magnitude of erroneous values in the calibration as well as of all individual gaseous concentrations need to be near 0. The calibrating objective would then be fulfilled once any extraneous gaseous concentration is rendered ineffective at influencing measurement of the target gas for which the particular sensor has been designed. Numerically, in terms of postcalibration correlation, this translates to all coefficient factors for errors and external gaseous concentrations adjusted to be nearly null.

E. *Time*

There is definitely a probability that the accuracy of the sensors would be subject to its durational cycles, or in other words, how long it has been in a continuous mode of operation. It is also probable that the frequency of erroneous measurements may increase with a sensor's time continuity of nonstop operation. The observance, however, has been that erroneous measurements highly oscillated while the sensors were continuously engaged for two weeks. Part of this could be because of the general volatility in aerial conditions pertaining to local temperature, moisture variation or diffusion or effusion of any random gaseous concentration. Nevertheless, further investigative study is necessary for establishment of error coefficients related to time-centric analysis and the causes of such time-centric erroneous measurements under monitored variables.

F. *NO2 Concentration*

Nitrogen dioxide can be considered as being among the primary contributors to surface or tropospheric ozone besides ultraviolet radiation and other volatile organic compounds. Nitrogen dioxide can also easily combine with ozone chemically producing nitrate ions and oxygen [13]. The concentration of nitrogen dioxide near the surface is reported to adversely affect ozone-specific gas sensor measurements. Moreover, nitrogen dioxide can explicitly alter ozone concentrations whereby the arduous nature of obtaining a robust trend between nitrogen dioxide and ozone is quite apparent. However, it is obvious that the NO2 concentration is not well correlated with the O3 concentration as shown in Figures 3 and 5 . The primary reason is that nitrogen dioxide can have a chemical reaction with ozone whereby the ozone products can produce more nitrogen dioxide from nitrogen monoxides in the air. Consequently, these reactions can spin-off in gigantic proportions. Therefore, deriving relational coefficients between nitrogen dioxide and surface ozone abounds in outright complexity.

VI. Conclusion and Future Work

Data collection and monitoring related to air pollution measurements were performed in Riyadh, Saudi Arabia, via precalibrated electrochemical gas sensors. After executing these sensors to meet the research-related deliverables, the need for collocation calibration became apparent. This surfaced as a key requirement to improve upon the data measurements and corroboration at a given location. For our research purposes, algorithm derivations were ensconced via comparison of real-time measurement values to calibration of known standards of accuracy under all possible seasonal conditions of the given region. This significantly mitigated the probability of erroneous data readings from the electrochemical gas sensors. It is expected then that the results of the measurement outputs are within the allowable limits of standard deviancy based on the mathematical model of the derived algorithm.

As for the ontological function of the algorithms addressed in this research, they should serve to solidify data validation and confirm calibration outputs. The methodology lies in the categorization of the typical variant seasonal conditions around the globe under which the electrochemical gas sensors are to be physically assessed. Comparison with local environmental parameters, along with sensor regression analyses under each of these scenarios, shall then yield algorithms for each seasonal category. Calibration schemas determined via the derived algorithms will allow the sensors to be simulated for reliable performance in any region based on its particular ambient inputs. The objective of doing so is to efficiently discretize the spatial resolution related to air pollution measurements to effectively enable the large-scale utilization of low-cost sensing stations over a wider territorial domain. Besides being available for prompt use anywhere in the world, sensors with such a calibration configuration would greatly aid in providing more accurate information to local authorities with minimal delay. The impact would be substantial in terms of allowing engineers, scientists, policy makers, politicians, and planners to take the requisite steps and make informed decisions for managing and improving the overall air quality of their environment.

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