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View: implementing low cost air quality monitoring solution for urban areas

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Abstract

Background: Air pollution represents non uniform trends particularly in dense urban areas which arises the necessity for pollution monitoring at finer resolution. Since recent advancements in electrochemical technology have made it feasible to deploy economical wireless sensor nodes for environmental monitoring, we present a bed of cost effective referential sensors which replace the role of traditional weather stations. The system is intended to target lower income nations like Pakistan, where air pollution monitoring and regulation is a crucial issue, not receiving appropriate attention.

Results: The project is specifically designed to be cost effective, compact, energy efficient and possesses the ability to be deployed in large numbers to overcome the limitations of conventional static environment monitoring sites. We have developed a system which aims at increasing awareness to the average citizen and policy makers regarding the prevailing environmental conditions. We go on to investigate the feasibility, reliability and accuracy of the project when deployed in an urban setting. Here we provide a brief summary on the calibration techniques we employed to achieve accurate results, along with providing details on the future research and development with respect to the project.

Conclusion: The model proposed, was used to pilot a venture in Lahore, Pakistan and is deployed successfully.

Keywords: Air pollution, Low cost, Sensor networks, Environmental monitoring, Sensor calibration

Background

Urban air pollution is an essential environmental issue due to its direct effect on human health. It is fast becoming a grave threat as levels of toxicity in urban centers increase beyond safe limits. This is especially true for many low and middle income nations, where the rapid pace of industrialization and development coupled with fast growing urban population are leading to increased environmental constraints. Due to the trans-boundary nature of airborne pollutants, a single organization cannot seek to control or take responsibility for international pollution issues. Therefore, the control of air pollution is entirely inter-country dependent and relies heavily on the local legislation. The passing of new legislation can only take place once accurate figures on current pollution trends are in place and may only be effectively executed if the airborne compounds can be monitored accurately.

Many organizations and countries around the world have set up urban environmental monitoring systems to provide the data needed to maintain or improve air quality. In Paris, AIRPARIF (2012), an organization tasked by the French government to monitor air quality is operating a network of 42 automated monitoring stations spread over a 100-kilometre radius. Likewise, in Australia, the Office of Environment and Heritage (OEH) (Environment Protection Authority of New South Wales 2012) is responsible for monitoring and reporting air quality. OEH collects data on real-time concentrations of ambient air pollutants from over 30 monitoring sites within the Air Quality Monitoring Network, located around the metropolitan areas. It aims on informing the public about prevailing environmental conditions by updating the regional air quality index on an hourly basis, i.e. providing 24-hour, monthly and annual reports. On a larger scale, the United States Environmental Protection Agency manages the nationwide air quality monitoring program called AIRNOW (2012), which monitors a specific set of air pollutants, called criteria air pollutants

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across the United States. AIRNOW offers daily AQI (Air Quality Index) forecasts as well as real-time AQI conditions for over 300 cities across the United States. Pakistan however, like most lower-income countries, lacks an urban air pollution monitoring infrastructure as it is difficult for the public sector to dedicate the resources necessary for this. What is required is a system that is comprehensive in terms of spatial and pollutant coverage and is relatively inexpensive and autonomous.

Furthermore in order to effectively tackle the detection of pollution distribution and production, it is also required that trends specific to a region over time are observed. Pollution distribution is not only affected by the source of pollutant but also by the changing aspects of the atmosphere. Therefore to understand the dynamics of pollution distribution, we require data that can highlight the diffusion of pollutants with respect to time and prevailing atmospheric conditions.

The project we have proposed distinguishes itself from existing modes of air pollution detection and representation, as adopted by other countries, by providing a cost effective, easy to deploy and relatively accurate method of ambient air pollution detection which is also able to highlight prevailing trends/dynamics of pollution distribution.

VIEW (Volunteer Internet-based Environment Watch) (Ikram & Akram 2007) retains its name from the previous version of the project which involved volunteer input for the collection and representation of environmental data. The effort has been seamlessly automated in the subsequent versions of the project, to feature real time representation of data.

Objectives and goals

We have aimed to build a system that is economical, not only to manufacture but to operate and maintain as well. The project deployment costs are intended to be nominal with the minimization/elimination of physical limitation such as spatial and external power requirements. The proposed project should overcome the constraints of singular static monitoring sites by achieving distributed, high resolution air pollution detection. Our objective therefore is to propose and test a system that is comprehensive and achieves its intended purpose economically, without the loss of functionality or accuracy. The project is intended to serve the needs of two groups:

- The first group is environmental policy makers, workers and activists, and they will be able to:
- Create policies and act according to the information they acquire. They will have the ability to deploy resources more efficiently and effectively with respect to the prevailing air pollution statistics.
- Monitor the effects of their policies and actions on the urban environment and fine tune their policies accordingly.
- The second group is ordinary citizens, who are empowered through the knowledge they acquire regarding the environmental conditions they live in and consequently can act upon that knowledge.

Design attributes

Ease of deployment

The individual sensor nodes (A complete VIEW air quality sensing unit capable of generating and transmitting various sensor readings) are completely self sustainable. The sensor node to server communication is handled through a wireless connection therefore no communication infrastructure set up is required. Furthermore each node is powered via solar batteries and no wall power is required for prolonged sustainability of the nodes. They have been specifically designed to be compact in size. All the above mentioned factors make the project deployment as simple as dropping of the sensor nodes at the area of preference.

Low cost of deployment

Nodes have been designed to be cost effective so they can be effectively mass produced. A number of design choices have been made to specifically cater to this idea reducing the cost of each node down to 200 dollars. The cost estimate is reasonable considering that a single mobile air quality analyzing unit used by the Pakistani Environmental Protection Department costs approx $80,000 (Research Triangle Park NC27711 1993), while a complete View network can be dispatched in a fraction of this cost (Figure 1).

Flexibility

VIEW is flexible in the sense that any kind of pollutant can potentially be measured. Nodes can easily be modified to include different kinds of pollution sensors. This allows for a comprehensive analysis of the air pollution spectrum to take place.

Use of existing infrastructure

VIEW relies on the Internet which confers two immediate benefits. First, the Internet is a well-established medium of communication thus VIEW would ride on a

Component	Quantity	Cost(USD)
Sensors	4	100
Solar Cells	15	25
Gel Battery	1	30
Circuitry (PCB + PICs)	1	25
GSM Modem	1	15

Figure 1 Cost Estimate for a single VIEW sensor node.

very reliable and proven infrastructure. Second, because the Internet infrastructure already exists, cost of VIEW is relatively low as no new communications infrastructure is required.

Finer resolution for monitoring
Since the nodes are economical and easy to deploy, they can be dispatched in large numbers over a specific region to allow higher resolution for monitoring.

Hardware architecture
VIEW uses a series of electrochemical sensors to measure the environment variables at real time. The data gathered by sensors is received at the respective sensor node. The sensor node after autonomously collecting the data encapsulates it into a GSM (Global System for Mobile Communication) text message and sends it to the server via the GSM modem. The server plays the role of reading, filtering and organizing the received data and making it available to the World Wide Web. The data is readily available on the Internet, from raw to plotted/analyzed form (Figure 2).

Sensors
Electrochemical sensors are fuel cells composed of noble metal electrodes in an electrolyte, which is normally an aqueous solution of strong inorganic acids (Electrochemical Sensors – Sensor Technology 2012). The gas diffuses into the sensor, through a porous membrane to the working electrode where it is oxidized or reduced. When a gas is detected, the cell generates a small current proportional to the concentration of the gas. Amplification and signal processing functions are applied to the detected signal which can then be translated into an absolute value. The calibration of electrochemical sensors tends to be more stable over time and so electrochemical sensor based instruments require much less maintenance than some other detection technologies.

The VIEW electrochemical sensors have been chosen on the basis of the availability, range, functionality for calibration and cost of the sensors. Currently, the following sets of sensors are being utilized:

- Temperature, Humidity and Dew Point are measured using the Sensirion SHT11 (2012) humidity and temperature sensor. Dew point is calculated using temperature and humidity readings on the go.
- SO2 – using the AeroQual SM50 (Aeroqual 2012) module with SO2 sensor head.
- Ozone (O3) – using the AeroQual SM50 module6 with O3 sensor head.
- Carbon Monoxide (CO) – using the Membrapor CO/CF-200 (Membrapor Gas Sensors - CO-CF-200 Module 2012) Carbon Monoxide sensor.

This list of sensors is not definite and the project has been designed to easily add, remove or replace sensors as per requirements. Table 1 shows the detailed analysis of the above mentioned sensors.

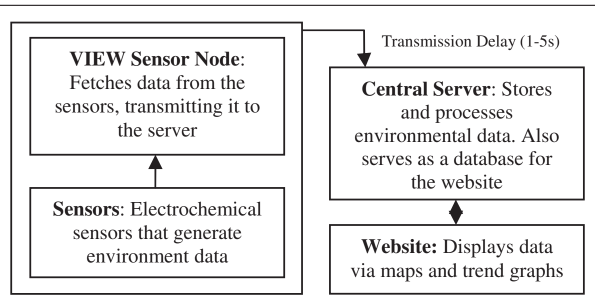

Figure 2 Overall Architecture of the project.

Wireless capability
VIEW maintains wireless connectivity through a GSM MODEM. The SIM300D modem is used for this purpose. The modem is connected on main serial bus of the micro-controller, to have access to the hardware interrupts, preventing any unwanted time delays. The SIM300D is a one-chip GSM Modem with serial interface and variable Baud Rate. The power consumption of SIM300D is relatively high so it is powered on selectively, only when data is being transmitted.

Self sustaining capability
To make the architecture stand-alone a 15 watt solar panel has been incorporated. An 8.6 Ah Gel battery provides backup power for the solar panel and enables the sensor node to remain powered for long hours without sufficient light. The charge controller is added to monitor the battery voltage and manage charging intervals. An 8-pin DIL MCU PIC makes the unit provides the functionality for programmatically adjusting charging/power controls. The sensor node automatically shuts down when the charge controller detects the voltage is less than the specified range.

Sensor node
The Sensor Node is part of the VIEW hardware that is responsible for collecting data from VIEW sensors and transmitting it to the server via the GSM modem. The device is capable of storing up to one month of sensor data on board and maintains an accurate system clock. It can effectively be hooked up with a personal computer through the serial port, using a telnet client for adjusting node settings. The module includes features to enable

Table 1 VIEW Electrochemical Sensor Specifications

Sensor	Model	Range	Sensitivity	Cost
Ozone (O3)	SM50	0-0.5 ppm	<+/− 0.008 ppm	30 $
Sulphur Di Oxide	SM50	0-10 ppm	<+ − 0.5 ppm	30 $
Carbon Monoxide	CO/CF200	0-200 ppm	<+/−0.1 ppm	20 $
Temp/Humidity	SHT11	−40-123 c T/ 0–100 H	+/0.4 T/ + − 3 H	20 $

modification of the sensor data transmitting interval, adjusting sensor calibration and system time and includes hardware system check features. Other minor features such as basic air filtration were also set up to avoid any damage to the electrochemical sensors through deposition of dust.

The module uses PICTM 18 F series, 8-bit controllers including on chip 10 bit ADC with 4.8 mV accuracy. Using this PIC enabled us to program the device using an efficient RTOS while decreasing the energy consumption and hardware size. Four EEPROM chips have been interfaced to store on board sensor data. The component level design of the hardware can be seen in Figure 3.

Software

The software deals with management of sensor data and representation of this data in a useful manner for statistical interpretation. Software component of the project consists of the web server supported by Google GIS technologies and Databases. The software has been divided into two basic categories:

Communication API

An Application Programming Interface (API) based on GSM network is utilized to facilitate the communication between the sensor nodes and the web interface. Currently this is a one way communication channel and is limited to sensor nodes transmitting sensor data to the web server. The API is independent of the web-interface and is purpose built from scratch. Streams of sensor readings arriving from sensor node devices is distributed narrowly in time domain. We have created a layer between the API and database to filter-out outliers in real-time from the data stream. As we had all required parameters in hand, we employed Statistical Methods for Multivariate Outlier Detection to remove unwanted sensor readings (Figure 4).

Outliers are determined by Mahalanobis (Xiaoqiao et al. 2006) distance. There can be some outliers caused by communication/hardware anomalies, though very seldom but a malfunctioned reading can be received. If it does, it usually has an extreme value - disrupting average. Therefore Mahalanobis distance algorithm aims to remove the sensor reading which are two standard deviation away from the mean readings, in a particular time frame. This time frame moves forward as sliding window so events which have a jerk influence on reading can also be kept accountable. A prime example of such an event is smoke from a fire. As size of the sliding window is finite (limited to 10 readings in current implementation), spikes in readings are held for processing.

Web Graphical User Interface (GUI)

The website interface acts as central point for all user activities. We have used industrial standard user experience design techniques to evaluate readings from all sensors in a productive manner, and make a user friendly GUI. We have used various graphing techniques and algorithms to make data presentable in an as useful way as possible. We have also created a GIS (Geographical Information System) aware sensor reading spatial interpolating algorithm (Kurt 1999), which is used to estimate the value of variables at an un-sampled location from measurements made at other sites. A convex gradient hull is created on the map through positive spatial auto-correlation, based on the notion that points which are close together in space tend to have similar value attributes, as seen in Figure 3 (bottom). Furthermore the website provides non-restrictive access to users for downloading raw sensor node data. A separate interface

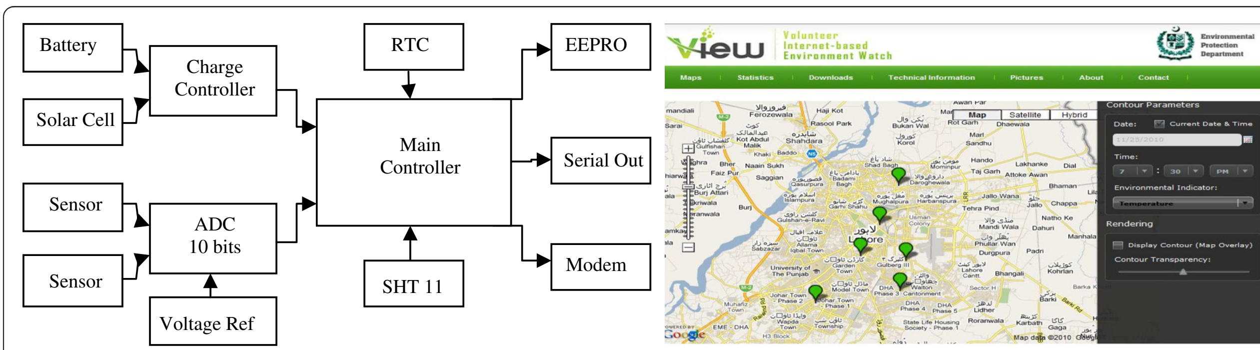

Figure 3 Left: Component level design of sensor node; Right: Map depicting locations of sensor nodes.

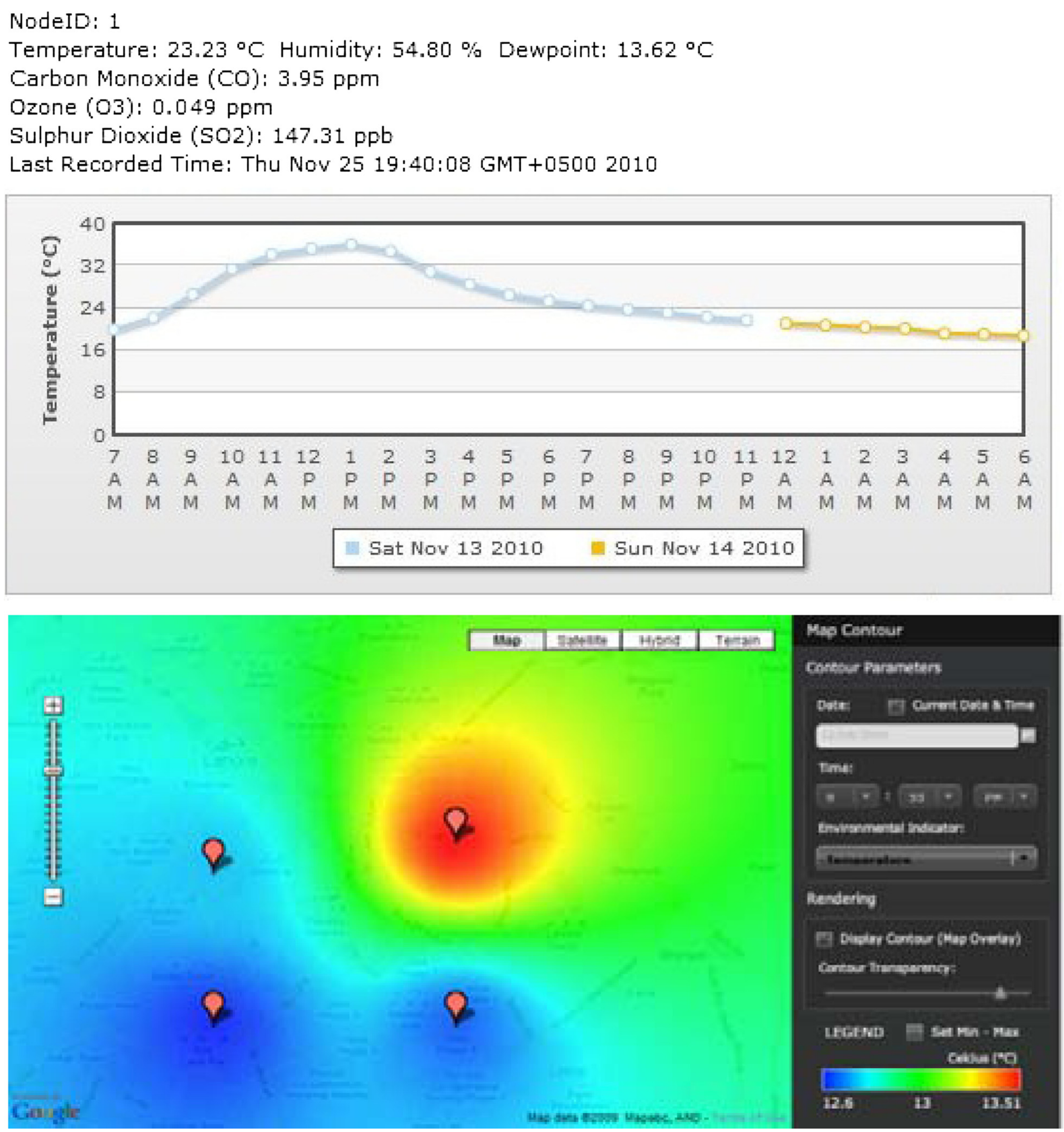

Figure 4 Top: Temperature vs. Time graph as recorded by an individual node; Bottom: Interpolation of nodes.

is also provided to generate trend graph charts (Motion Chart, Annotated Time Line Chart, and Bar Chart) for an indicated node, during a given time frame.

Calibration and testing

With the utilization of electrochemical sensors the project loses a degree of accuracy as compared to conventional standardized sensing systems. In order to get accurate readings, the VIEW sensor nodes were calibrated with internationally standardized environmental pollution sensor equipment.

The calibration was performed in two phases. In the first phase the sensors were calibrated with the sensors of HORIBA (Pakistan Environmental Agency 2012) and in the second phase to ensure complete accuracy, the sensors were calibrated with the SUPARCO (Pakistan Space and Upper Atmosphere Research Commission 2012) sensor readings. This was done to measure the

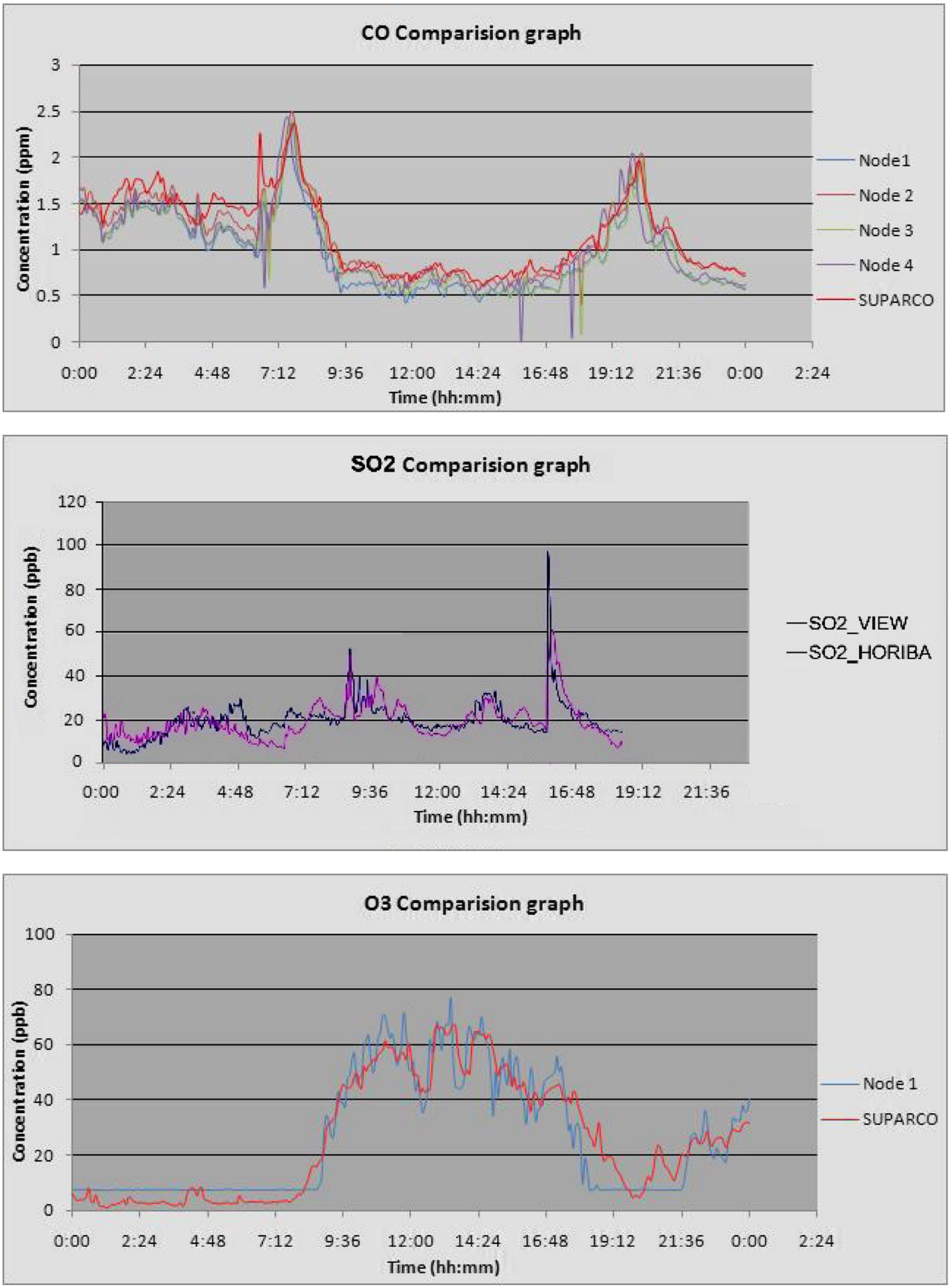

Figure 5 Calibration results in comparison to standardized sensor equipment (Horiba/Suparco).

adaptability and accuracy of the project in comparison to two different set of apparatus.

Calibration was performed by calculating the mean and standard deviation of the range of readings from the VIEW and HORIBA/SUPARCO sensors as follows:

- $\mu 1$ = Mean of Reference sensor readings
- $\sigma 1$ = Standard Deviation of reference sensor readings
- $\mu 2$ = Mean of VIEW sensor readings
- $\sigma 2$ = Standard deviation of VIEW sensor readings

$$\alpha = \sigma 1/\sigma 2 \tag{1}$$

$$\beta = \mu 1 - (\mu 2 * \alpha) \tag{2}$$

$$\text{Calibrated reading} = \alpha * (\text{un} - \text{calibrated reading}) + \beta \tag{3}$$

Our approach allowed us to use already calibrated, precise and accurate sensors of HORIBA and SUPARCO to calibrate our electrochemical sensors; this gave us huge cost savings. Alternatively if we used a standard calibration procedure, we would have to use Zero Gas (air without any CO, SO2, NOX and O3) along with Span Gases (air with known concentration of specified gases) (Anderson Gerald & Hadden David 1999) for calibration procedure. Using these gases would have meant utilizing more than the project's entire allocated budget for calibration alone, let alone the fact that most span gases are not available in Pakistan locally and have to be imported.

The Horiba/Suparco air quality monitoring equipment was placed in the vicinity of VIEW sensor nodes for the purpose of eliminating any reading congruities caused due to environmental variations. Figure 5, below shows the calibration results, i.e. graphs of environmental readings of View sensor nodes after being calibrated with high end sensors. Comparisons of readings over a 24 hour period are shown for clarity of representation of data .It can be seen that VIEW calibrated readings coincide with the readings from highly precise sensors. SO2 and CO sensors achieved an accuracy of approximately 96 percent while Ozone concentrations were accurate to 93^{th} percentile primarily due to the sensors high cut off value, which makes it difficult for the sensor to measure low levels of ozone concentration in the atmosphere.

Results and discussions

VIEW was deployed in an urban setting to ensure its reliability i.e. ensuring proper functionality over an extended period of usage. A total of 10 to 15 nodes were operational at a time covering a variable locality. Reading intervals of 5 min per node were set to obtain a high density and variability of readings as per prevailing environmental conditions. It was noted that the nodes are able to function without any maintenance for a prolonged time when placed in the vicinity of busy urban centers. Since each node is completely independent and self-sufficient in terms of energy, the nodes were placed in remote locations, where human accessibility was limited and tested. Pakistan receives a high annual average of sunlight therefore we did not face any power related issues. The device also features an external power hookup as a backup power source, in case the solar panels do not produce sustainable power, depending on the climactic conditions.

In order to increase the life expectancy of the electrochemical gas sensors and electronic equipment, a fan component along with an air filter has been introduced to prevent accumulation of high temperatures and deposition of dust particles. We have also considered adding a dehumidifier to prevent any damage that can be incurred from prolonged exposure to a damp atmosphere and can consequently increase sensor life. However if a sensor component malfunctions, the affected sensor can be easily identified by comparison of readings with other sensor nodes in the locality and by ensuring the results remain within the expected range.

The hardware was tested in extreme conditions, without facing any major issues. The server and the website module were tested to process large amount of information and handle high user requests without the loss of performance or functionality.

VIEW is currently operational and the online air pollution statistics website can be accessed at http://view.lums.edu.pk.

Conclusions and methods

Urban air pollution monitoring at high granularity is highly infeasible due to high costs. We have proposed a cost effective method of measuring air pollution constituents at dense granularity in an urban setting. We have shown that we can calibrate low cost electrochemical sensors with expensive chemical sensors to produce near accurate environmental pollution readings.

The model proposed, was used to pilot a venture in Lahore, Pakistan and is deployed successfully. In near future, we plan to develop in-house Black Carbon (pure Carbon particles suspended in air) sensors and deploy them through VIEW sensor nodes. For researchers in the field of environmental monitoring, our model could serve as a basis for a low cost distributed air pollution monitoring system, which can be easily extended with new sensors, analysis algorithms and approaches.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions

JI provided insight, supervised and arranged for the project funding. AT proposed contouring algorithms and developed the front end for the project website. HK developed the communication protocol, SMS libraries and application software. ZK was responsible for the database administration and management. RJ carried out sensor calibration procedures, project testing/maintenance evaluations and drafted the manuscript. UM designed and implemented the hardware. All authors read and approved the final manuscript.

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