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Volatile Organic Compound (VOCs) Monitoring and Alerting for Indoor Settings with MOS Sensor and Wireless Sensor Nodes

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ABSTRACT

Volatile organic compounds (VOCs) are carbon based pollutants included in the Kyoto protocol and in its updated versions. They are responsible for great and dangerous air pollution. This paper explains the issues, infrastructure and challenges in designing and implementing an integrated sensing system for real time monitoring of VOCs in indoor settings. The system is developed with an objective to detect VOCs in surrounding air and provide automated alerts to users. The system uses miniature MOS gas sensors to detect VOC in 1-30 ppm range and a GSM module to send SMS alerts to users. Two identical sensor nodes are implemented which connect themselves to control side through ZigBee transceiver kits. The system is aimed to be easily deployable, so that more data on VOCs can be collected as data on levels of VOCs in developing countries, including India, are lacking. The system is tested in the urban environment in the suburbs of Mumbai and applications include residential homes along with small scale industries indulging in chemical based operations.

Keywords: Air Quality, air sampling, indoor air, monitoring, pollutants, VOCs, wireless sensor networks, ZigBee.

1. INTRODUCTION

Volatile Organic Compounds or VOCs are organic chemicals that easily vaporize at room temperature. They are called organic because they contain the element carbon in their molecular structures. These volatile carbon-containing compounds quickly evaporate into the atmosphere once emitted. While coming from certain solids or liquids, VOCs are released as gases. In India, these have become a major issue due to gigantic vehicle population and weak monitoring framework. The Environmental Protection Agency (EPA) identifies indoor air pollution as a greater risk to human health than outdoor air pollution, the reason being that people spend 80-90% of their times indoors [1]. VOCs (Volatile Organic Compounds) are a major source of pollutants in indoor air. VOCs are harmful organic chemical compound that can significantly vaporize under conditions of normal atmospheric temperature and pressure. They are also defined by European Union as organic compounds with boiling points below or equal to 250 ◦C (482 ◦F) measured at a standard atmospheric pressure of 101.3 kPa [2]. There are thousands of volatile organic compounds and only a few are regulated, but it does not mean that others are not harmful. Hence there still is a vast unexplored area in the field of VOCs.

VOCs are released from burning fuel such as gasoline, wood, coal or natural gas. They are also emitted from oil and gas field and diesel exhaust as well as solvents, paints, glues, nail polish, perfumes, hair sprays, dry cleaned clothes, PVC cement, moth balls, air fresheners, cosmetics, pesticides, plywood, furniture, carpets etc. [3].

Health effects of VOC are known to vary greatly according to the compound, level and length of exposure and can range from being highly toxic to having no obvious health effects at all. According to a report published by the National Toxicology Program, benzene and formaldehyde are human carcinogens perchloroethylene and styrene are "reasonably anticipated to be human carcinogens." Long term exposure to volatile organic compounds can cause damage to the liver, kidneys, and central nervous system. Short term exposure to volatile organic compounds can cause eye and respiratory tract irritation, headaches, dizziness, visual disorders, fatigue, loss of coordination, allergic skin reactions, nausea, and memory impairment [4]. Besides being dangerous to human health, VOCs can also damage plants, destroying their natural processes, if exposed for long periods. Higher concentrations of VOCs can form an explosive mixture in air and can become a concern when they exceed the Upper Explosive Limit described by chemical specifications. According to the UK Environment Agency, total VOC emissions peaked in 1989 and fell by 38% by 2000. Road emissions fell by 55% over the same period, mainly as a result of the introduction of catalytic converters for petrol cars. Fuel switching from non-catalyst cars to diesel cars has also had a small beneficial effect. However, emissions from solvent use have changed little over the past 25 years. In Western countries, monitoring VOCs are required by law in most cases.

2. RELATED WORK

Several researches have devoted effort to address research issues related to indoor air quality monitoring. Some important developments are discussed in this section.

Manes, G., et al. developed a Wireless Sensor network for monitoring Volatile Organic Compounds which consisted of WSN platform whose nodes were equipped with climatic sensors and VOC detectors [25]. The End node unit comprised of an ARM Cortex-M3 32-bit Microcontroller, Transceiver and an integrated antenna which was connected to a VOC detector unit using RS485 serial interface. The VOC sensors used were PID sensors and the VOC sensor energy budget was predominant compared to that of the computational/communication unit. The PIDs used for reading the VOC concentration were kept continuously on to operate efficiently. The sensors registered current draw of around 30mA, corresponding to 720mAh a day, which was reported to be more than twice the amount the communication/computational units, with their power consumption of some 360mW a day. The authors found two major issues which affected efficient use of the PID in their system. The first was that in the low ppb range the calibration curve of the PID showed a marked nonlinearity which would require an individualized, meticulous multipoint calibration involving higher costs and complexity. The second issue was that when PID was operated in diffusion mode at low ppb and after a certain time in power-off, the detector required a stabilisation time of several minutes, hence it was not able to operate at small intervals.

Tsow, F., et al. have described an integrated volatile organic toxicants sensor with a Bluetooth device interface in their paper [17]. The sensing elements employed by the authors are enclosed in a sensing cartridge which is an array of modied tuning fork sensors. A different cartridge allows the sensor to detect different molecules or to improve sensitivity and response time by using different tuning fork sensors. Tuning fork crystals are mechanical resonators that have a resonant frequency (typically in the 32 to 33kHz range with a typical spring constant of 20 kN/m) given by the following equation:

$$f = (1/2\pi)\sqrt{(k/m)} \qquad \text{....(1)}$$

where f is the resonant frequency of the tuning fork, k is the effective spring constant, and m is the effective mass. The authors tested their devices ability to discriminate benzene from BTEX (benzene, toluene, ethylbenzene and xylenes). The results showed that the device was able to discriminate benzene from BTEX, its responses were reproducible and the sensing mechanism was reversible. The system also used tuning fork sensors as temperature and humidity sensor by coating the sensor with different materials.

In general terms, the two most widely used technologies to measure total VOCs are Flame Ionisation Detection (an example of this is the Casella Eti / M&A Flame Ionisation Detector) and Photo Ionisation Detection (an example of this is the Casella CEL VocPro). Both technologies rely on the principle that when most organic vapours burn they produce positively charged carbon ions

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as an intermediate product of combustion. These positively charged ions are then collected on an electrode and an electrical current corresponding to the amount of carbon ions present is produced. If the instrument has been calibrated against a known source of carbon / VOCs a reading of the total carbon as parts per million (ppm) can be taken. Further calculations can then be performed to infer the actual VOC concentration, assuming the proportions of VOCs being measured is known e.g. 80% xylene, 20% isopropyl alcohol and assuming these proportions haven't changed as part of the process.

3. TECHNIQUES USED IN MEASURING VOCS

Sampling and measurement of VOCs can generally be done in three different ways depending on the information required and the legislation in place, these are:

- Periodic measurements
- Continuous emissions monitoring (CEMs)
- Screening

Periodic measurements describe a measurement regime that is carried out at specific intervals, every six months, for example. The information is then extrapolated to reflect the general operating conditions for the periods between monitoring. The monitoring equipment is usually brought to the site of interest only when the monitoring is required. Continuous emissions monitoring describes automatic continuous measurements taken with very few gaps in the data. The sampling equipment is therefore located at the site of interest permanently. Screening is done using easily portable measuring equipment, traversing a large area looking for incidences of high VOCs (hotspots) that may prove a problem either in the workplace or for example, at the boundary of a landfill site.

It is essential that the sample taken when performing the periodic and continuous monitoring techniques is representative of the overall VOC Detection process emissions. The usual location for a representative sampling port is just prior to the VOCs exiting the process / factory boundary, in most cases via an exhaust stack, to enable measurement of emissions to atmosphere. There are several techniques that can be applied to ensure representative samples are taken, these are generally much less onerous when dealing with VOCs compared with monitoring particulates.

Prior to performing a periodic sample, a sweep of the duct should be carried out. This is simply taking VOC measurements from a point diametrically opposite the sample point located in the exhaust/duct and drawing the measuring equipment back across to the opening/ sample port, noting the concentrations at several points. The variation in concentrations should not exceed 15% - if this is the case, then the gas being sampled can be considered homogeneous and therefore any samples taken should be representative. Once sampling begins in earnest, it is recommended that the tip of the measuring probe be placed between one-third and half of the diameter into the stack. If the gas is found to not be homogeneous, then a sweep across the duct should be performed at several predetermined intervals and the samples combined to provide an average value.

4. DESIGN OF THE MONITORING SYSTEM

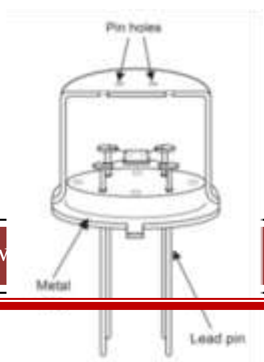
The monitoring system consists of two identical sensor nodes, which report to a sink node which is connected to a computer. The computer can be a desktop or laptop with a USB port. Sensor node consists of Microcontroller unit, the TGS2602 VOC sensor, 16x2 LCD display, transform, relay circuit and power supply circuit. The purpose of the system is to detect VOC levels in real time, log the data and initiate actions dependent on different events.

4.1 Sensor Node

Sensor node is an integration of VOC sensor, LCD and relay interconnected around microcontroller PIC16F883. The circuit for the sensor node hardware is designed using Proteus application. It also consists of GSM module which is connected externally to the PIC16F and serves the purpose of sending an event triggered SMS to the registered users.

4.1.1 TGS 2602 VOC Sensor

The system uses TGS 2602 for sensing VOC levels



in the surrounding air.

Fig. 1: TGS2602 Sensor structure.

It is a miniature thick film metal oxide semiconductor, screen printed gas sensor developed by Figaro Sensors. Using thick film techniques, the sensor material is printed on electrodes (noble metal) which have been printed onto an alumina substrate. The main sensing material of the sensor element is a metal oxide semiconductor. Figure 2 shows the relative sensitivity of TGS2602 to various gases. The Y-axis shows the ratio of the sensor resistance in various gases (Rs) to the sensor resistance in clean air (Ro) taken at standard test conditions of 20^{o}C/65% RH.

It works on 5V DC/AC supply and provides a detection range of 1-30 ppm for VOCs. The sensor requires two voltage inputs: heater voltage (VH) and circuit voltage (VC). The heater voltage (VH) is applied to the integrated heater in order to maintain the sensing element at a specific temperature which is optimal for sensing [26]. A common power supply circuit is used for both VC and VH to fulfil the sensor's electrical requirements. It is connected to a pin on Port A of the PIC.

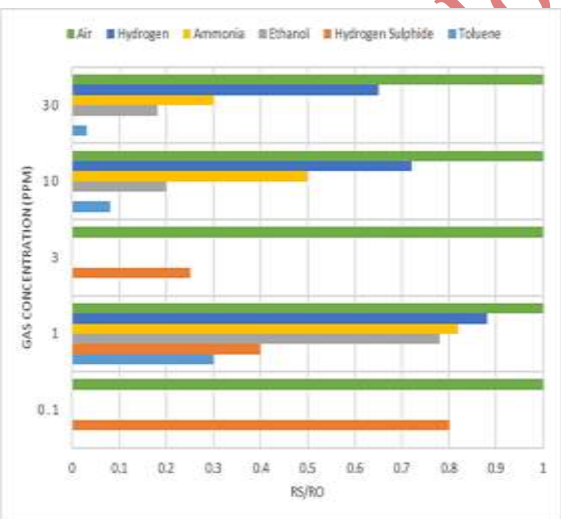


Fig. 2: TGS2602's sensitivity to various gases (Rs/Ro).

4.1.2 PIC 16F883

It is an 8-bit, 28-pin, CMOS FLASH-based microcontroller. The PIC16F883 features 256 bytes of EEPROM data memory, self-programming, an ICD, 2 Comparators, 11 channels of 10-bit Analog-to-Digital (A/D) converter, 1 capture/ compare/PWM and 1 Enhanced capture/compare/ PWM functions, a synchronous serial port that can be configured as either 3-wire Serial Peripheral Interface (SPITM) or the 2-wire Inter-Integrated Circuit (I2CTM) bus and an Enhanced Universal Asynchronous Receiver Transmitter (EUSART). The program for the PIC is written in C language and compiled using MPLAB developed by Microchip. The system uses no external ADC as the PIC has an internal 10bit ADC, which is used to convert 2602s readings to discrete steps. 10-bit ADC gives a resolution of 210 i.e. 1024 which is divided by 10 to display VOC values in percentage form.

4.1.3 ZigBee Module

The ZigBee module is a Chipcon developed, IEEE 802.15.4 compliant, ZigBee-ready radio frequency transceiver integrated with the microcontroller. ZigBee is a wireless network protocol that is owned by the ZigBee Alliance and is adapted from the IEEE 802.15.4 standard, which denes the media layer and objective layer. ZigBee provides a low transmission speed at low cost, low power consumption, and high security and supports a large number of web node operations. It transmits/receives over a distance of few tens of meters and is especially suitable for low data rate, low power applications. Tx and Rx pins of ZigBee module are connected to Rx and Tx pins of PIC respectively. The module has additional circuits for voltage conversions requires when connecting to serial devices. As there are two sensor nodes, the number of ZigBee modules is also two. Each byte is divided into two symbols, 4 bits each. The least significant symbol is transmitted first. For multi-byte fields, the least significant byte is transmitted first, except for security related fields where the most significant byte it transmitted first. Each symbol is mapped to one out of 16 pseudo-random sequences, 32 chips each. The chip sequence is then transmitted at 2 MChips/s, with the least significant chip (C0) transmitted first for each symbol. The chips current consumption as specified by the manufacturer is 18.8mA for Rx and 17.4mA for Tx respectively, and it has 128 bytes of data buffering (for both Rx and Tx).

4.1.4 GSM Module

A GSM module is necessary to establish a communication between a computer and a GSM system. Global System for Mobile communication

(GSM) is an architecture used for mobile communication in most of the countries. GSM module consists of a GSM modem assembled together with power supply circuit and communication interfaces (like RS-232, USB, etc.) for computer. It requires a SIM (Subscriber Identity Module) card just like mobile phones to activate communication with the network. Also, they have IMEI (International Mobile Equipment Identity) number similar to mobile phones for their identification. GSM module can perform the following operations: receive, send and delete SMS messages in a SIM, read, add and search phonebook entries of a SIM, make, receive or reject a voice call. The system uses a GSM module to send a warning SMS to users whenever VOC levels rise above pre-specified threshold values. This eliminates the need to continuously monitor the VOC readings and makes the system more user-friendly.

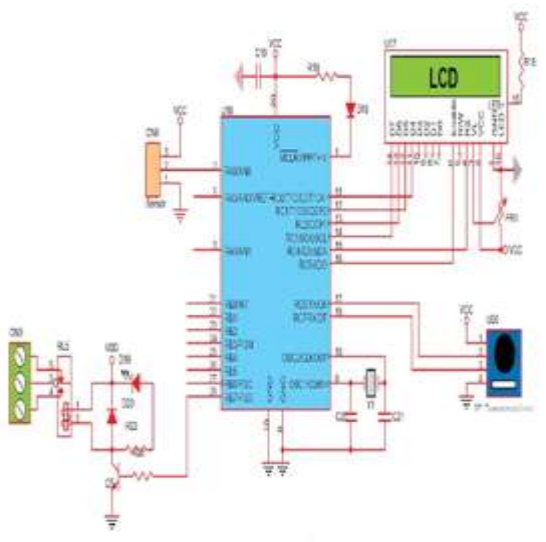
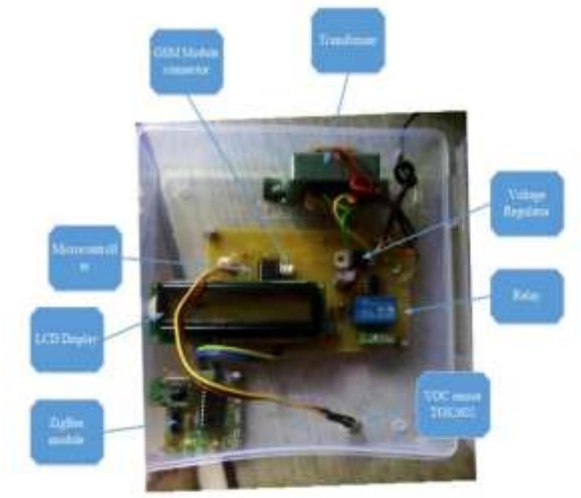


Fig. 3: Circuit diagram of sensor node.

The circuit diagram for the sensor is shown in figure 3. The GSM module (not shown in diagram) is connected to an I/O pin on the PIC through a 2-pin connector. A clock signal of 4 MHz is provided by external source i.e. crystal oscillator.

4.2 Controller side

Both the sensor nodes transmit data over the ZigBee protocol to a sink node which is connected to a computer. The USB TTL adapter is needed on the computer side to communicate with the PIC16F. We will be using a computer to configure the sensor node and to send and receive data directly from desktop or laptop. Several different ZigBee USB adapters are available from third-party manufacturers. The controller side has a sink node which receives VOC data from the sensor



nodes. The system has a User Interface designed to control some aspects of the sensor node, which is explained later.

Fig. 4: Sensor node hardware.

The control signals from the UI are also sent through the sink nodes to the respective nodes in order to execute the command.

4.3 System software

The programming code for PIC was written in C language and compiled using HI-TECH Compiler in MPLAB. The system uses ADCON0 register of PIC to control Analog to Digital conversion operations. PIC16F883s ADC is 10bit providing 1024 resolution, which is rounded to indicate percentage of VOCs which is shown below.

```
Read_ADC:   //Read_ADC subroutine
     ADC_val[0] = ADIn 0
     ADC_val[1] = ADIn 0
     ADC_val[2] = ADIn 0
     ADC_val[3] = ADIn 0   //Read 10 bit
value in Adc
     ADC_val[4] = ADIn 0
     ADC_val[5] = ADIn 0
     ADC_val[6] = ADIn 0
     ADC_val[7] = ADIn 0
     ADC_val[8] = ADIn 0
     ADC_val[9] = ADIn 0
     DelayMS 5

     ADC_val = ADC_val/10 //Divide ADC
value by 10
     If ADC_val > 100 Then ADC_val = 100
Return
```

The output of TGS2602 ranges from 0-5V which is indicated as a percentage on the LCD display in real time and simultaneously transmitted to the controller side to be displayed on the UI. Any commands from the UI are treated as interrupts by the microcontroller. This is done by setting the GIE (Global Interrupt Enable) and PEIE (Peripheral Interrupt Enable bit) of the Interrupt control register. A relay circuit is also integrated on the PCB which is connected to a port pin on the PIC. This relay can be used to control external components such as exhaust fans or alarms etc. We have connected a computer cooler fan for presentation, which is turned on when VOC levels reach above 70%. It can also be turned on from the UI. GSM modem SIM300 is used to send SMS automatically as well as on user demands. It is controlled by sending AT commands from microcontroller. AT+CMGS command is used to send SMS command from an I/O pin on the PIC.

The UI is designed as a VB form in SharpDevelop. SharpDevelop is a free and open source integrated development environment (IDE) which supports Visual Basic and .NET. UI was developed as a Windows application with WiX (Windows Installer XML) Toolset that builds Windows Installer packages from XML code. The button press on the form is sent with AT prefix to the ZigBee modules connected to sensor nodes. The sensor nodes can operate in two modes: Automatic and Manual. These modes can be controlled from the UI. Also, the SMS can be send and relay can be turned on manually from UI irrespective of the VOC level. In this sense, the system is fully flexible and user configurable. SharpDevelop creates an application which can be installed on Windows platform and does not need Visual Basic preinstalled on the system, thus making the system independent. The UI was tested successfully on Windows 7 Professional and Ultimate versions.

The USB adapter is a type of protocol converter which is used for converting USB data signals to and from other communications standards which generally include conversion of USB data to standard serial port data and vice versa. The USB processor sends the processed USB signals to a serial driver chip which applies the correct voltages and sends the processed data signals to the serial output.

For the computer to be able to detect and process the data signals drivers must be installed on the computer. When the USB to serial adapter is connected to the computer via the USB port, the drivers on the computer creates a virtual COM port which shows up in Device Manager. The baud rate at both ends is set at default 9600 bits per second.

Fig. 5: User Interface form designed with SharpDevelop.

The sensor node communicates with the sink node using half duplex mode. Data is transmitted with a predefined delay of 12 seconds, which is configurable. The data is logged on the user's computer itself as a Notepad file which provides the advantage of small size along with date and time logging for both the nodes.

5. EXPERIMENTAL RESULTS

The system is designed to keep track of total VOC concentrations in homes and buildings and such a real-time. The sensor node is switched on when the power plug is connected to the switchboard and power is indicated by a glowing LED on the node. The system is programmed to perform following operations based on VOC concentrations.

1. When VOC levels rise above 70% and the mode is set to auto, then relay will go on as well as an SMS will be sent to the registered user along with the VOC level reading.

2. When the levels drop below 50% and mode is set to auto, the relay will go off and no action will be taken until levels rise again.

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3. As stated above, there are some buttons provided on the UI to control sensor node that is namely SMS, RLY on or off and Mode select button. In Auto mode SMS is sent and relay made on automatically when VOCs rise above 70%. If the user wishes to control these actions, he can either toggle the mode by pressing Mode button on the UI or control these options with SMS and RLY buttons. When in Manual mode, the sensor node will not send SMS and neither will the relay go on no matter what the levels of VOCs persist.

The general flow of the system is shown in figure 6 below.

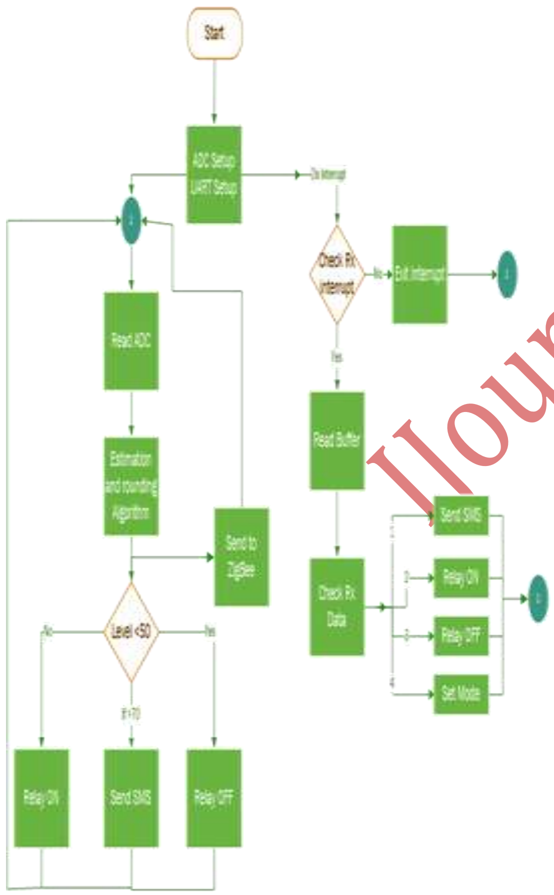

Fig. 6: System flow diagram.

The VOC monitoring system was tested for about three hours in an enclosed area of about 200 sq. feet located in the Mumbai suburban region. The setting of the room is as illustrated in figure 7. Humidity range for the normal operation of TGS sensor is 65% and humidities in Mumbai region ranges from 69 to 75 with the highest values observed in July and August months. High humidities can affect the performance of the sensor and hence it is adviceable to use dehumidifiers. The climatic conditions of the area tested were: temperature27◦C, humidity-80%. Testing was conducted for about 3 hours in an isolated condition. For higher VOC levels, the system was successful in sending SMS to the specified mobile number along with the VOC level. The relay also turned on and off at 70% and 50% VOC levels respectively.

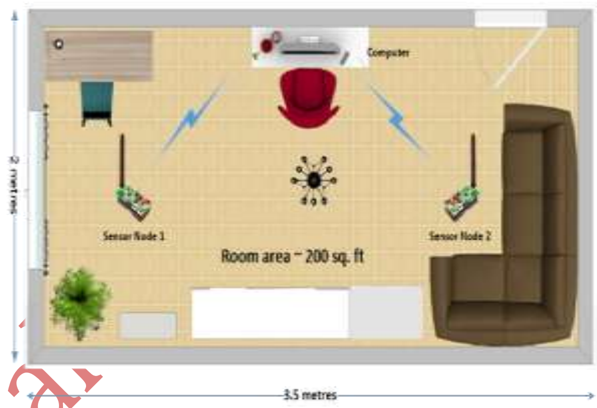

Fig. 7: Room setup for testing of the system.

This highly relieves the user of the need to continuously straining his eyes by keeping strict watch on levels which may be necessary in sensitive zones as different patterns of VOCs have been correlated with various diseases with cancer among them.

As the power supplied to sensor nodes does not depend on batteries, power consumption is not an issue and the system can be kept on continuously for hours at length and has potential to last for years if no glitch appears. The readings provided by the system are extracted from the log file and are illustrated in the graph.

Fig. 8: Graph showing VOC readings from system.

The first peak that can be seen in the graph occurred when a body deodorant was sprayed near sensor node 1. As the level reached 76%, an SMS was sent and relay was turned on automatically for sensor node 1. The peak soon died out and values of both the sensors were nearly at about 20% for normal room condition. At around 9 am, four cans of paint thinner, each 250ml, were placed in the room at random spots with their caps open. Because of this, the readings went up above 40% for both the sensor nodes at around 9.15 am. This showed that the sensor nodes operated normally and were sensitive to the changes in VOC levels in the surrounding air. The thinner cans were removed from the room at 10 am and the readings returned to about 20% after that which showed that normal VOC concentrations in the room were 20%. A reading of 20% corresponds to 6 ppm of VOCs, which is general in urban homes.

The same room was simulated for VOC concentrations using Indoor Air Quality Emission Simulation Tool (IA-Quest) which is a free application that provides a database of materials and their measured emissions allowing materials to be selected for different environments. The room parameters were selected using Room Setup tab where room volume, ventilation rates (optional), ventilation schedule (time period over which simulation is to be done) and materials. IA-Quest has a wide range of materials under headings of Carpeting, Ceiling, Finishes, Flooring, Furnishing Materials, Installation Materials, Interior Panels and Structural Materials. The ventilation rates for the simulation were set as: Minimum=3, Normal=4 and Maximum=5 m3/h. The materials selected were Flooring (Vinyl Tile; Commercial 12in x 12in x 1/8in), Wood (Solid Maple) and Adhesive. These selections closely represented the room interior setup. The simulation result is shown in figure 9.

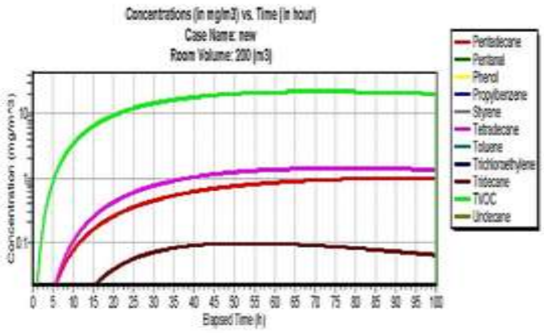

Fig. 9: IA-Quest Simulation results.

It can be seen that IA-Quest provides TVOC levels in mg/m^3. However, it can be converted into ppm value by using the formula provided by Canadian Centre for Occupational Health and Safety department. The formula needs the gram molecular weight of VOC which is complex but many studies show it to be 78.9156 grams. Therefore,

$$TVOC\ (ppm) = (24.45\ X\ 20 mg/m^3) / (78.9516) \quad ..(2)$$

$$TVOC\ (ppm) \simeq 6.2\ ppm$$

The VOC level obtained by simulation is close to the ppm levels detected by the system and it shows values close to that obtained by the system.

6. CONCLUSION

An important advantage of the system developed is that, in case of failure of the controller side, the overall system will not come to a halt but instead still function as it is in Auto mode. The only loss will be that the user can no longer control the actions of SMS and relay toggle. On failure of controller side, the sensor node will still monitor VOCs and send SMS as and when required alongside with displaying live values on LCD display. The aim of the system is to robustly monitor VOC concentrations in indoor settings with special emphasis on being non-obtrusive. Flexibility of the system is enhanced in the sense that the system is configurable in almost any of its parameter. Different organisations such as ASHRAE, WHO and EPA have their own guidelines regarding recommended levels of VOCs in the air. These values can be chosen by the user and set in PICs program code to alert on particular levels as per the needs. The sensor nodes are small measuring just 18x14 cm and require nothing besides a constant power source. This makes them easily transportable and deployable in any environment. The UI on the other hand is also independent because of the fact that it has been developed as an application that can be installed without any additional software needed. Thus the system can serve the purpose of gathering VOC relevant information in different backgrounds and serve as a source to expand VOC related knowledge in future.

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