# Real time machine olfaction for mobile robot applications

A. Holloway*, G. Chliveros and A. Nabok

Materials and Engineering Research Institute
Sheffield Hallam University
Sheffield S1 1WB, UK

**Abstract.** The detection and classification of vapours/gases by the electronic nose can be complex and time consuming even in stationary mounted sensors. The application of an electronics nose to a mobile robotic platform, results in additional variables which must be accounted and compensated for. This paper discusses the difficulties, limitations and design implications which must be taken into consideration in mobile electronic nose applications.
*Keywords*: Sensors: QCM, MOS; Hazardous Chemicals, Contamination.

## 1 Introduction

The concept of the electronic nose has now been in existence for approximately 30 years and is defined by Gardner [1] as "*... an instrument which comprises an array of electronic chemical sensors with partial specificity and an appropriate pattern recognition system, capable of recognising simple or complex odours*".

The range of transduction mechanisms in use is vast. Examples include acoustic wave devices such as the Quartz Crystal Microbalance (QCM) and Surface Acoustic Wave (SAW), optical methods based around spectroscopic and evanescent field measurements, and electrical sensors such as Metal Oxide Semiconductors (MOS) and Conducting Polymer Sensors (CPS) where the chemical sensitivity is related to the conductivity of the device. Several commercially available electronic noses also exist, some using an array of one particular type of sensor, others combining two or in some cases several types sensor [2]. While some of the electronic noses such as the MOSES II® from Lennartz Electronic(Germany) and the Agilent 4440A are inherently stationary sensors, several manufactures are now producing portable hand held devices primarily for the detection of Volatile Organic Compounds (VOC's) such as VOCCheck® from AppliedSensors (Germany/Norway) and VaporLab® from Microsensor Systems Inc. (USA). These allow rapid detection of VOC's in the atmosphere, and are particularly suited to in field leakage detection. In must be noted that even the small portable units cost in the region of $10000 and in many cases the data obtained must be compared to previously measured reference samples.

The most common alternative to the electronic nose method defined earlier for gas/vapour detection is Gas Chromatography/Mass Spectrometry (GC/MS). The technique is reliable and accurate and is often seen as the golden standard for environmental monitoring. However it is restricted in application due to its physical size, complexity, lengthy sample times and high cost [3]. The GC/MS system is currently used by fire and rescue services in the UK for detection and monitoring of potentially hazardous substances[1].

The Viewfinder and Guardians projects employ the use of mobile robots to assist search and rescue operations in potentially hazardous environments where, under normal circumstances human presence would be risky. An example would be entry to a fire at a factory or warehouse where flammable or toxic chemicals may be stored; we will be referring to this case as Scenario 1.

* Corresponding author: A.F.Holloway@shu.ac.uk
[1] See paper in this conference by Neil Baugh, SyFire UK.

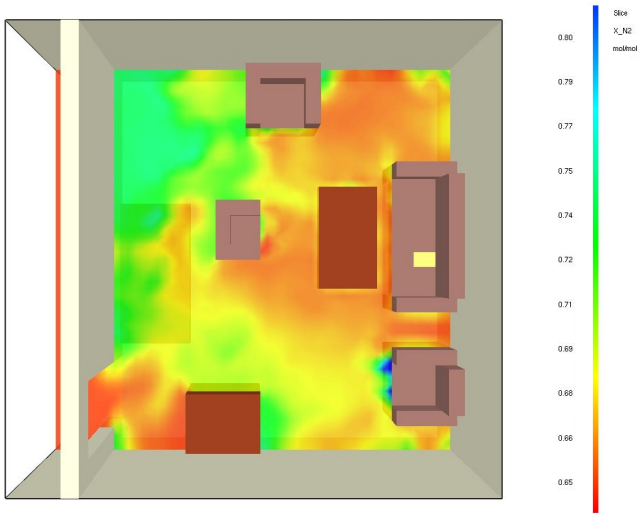


**Fig. 1.** Example 2D plot of a room with chemical sensor data superimposed. The colour-bar denotes the volume fraction of $N_2$ in the mixture fraction of other chemical components

In such an instance the deployment of a mobile robot which could via autonomous or remote control enter the building and sample the environmental conditions would be of significant benefit for search and rescue services. Additionally superimposing the environmental data obtained onto a two dimensional map of the area will give unprecedented amounts of information to the user. Such an environmental data mapping can be seen in Figure 1. This example is from simulation with realistic values; for further details see [4] as well as Section 3. The colour bar denotes the relative proportion (mole fraction) belonging to Nitrogen $N_2$ to those (components) of the mixture. For further details on the simulator's measured quantities and the mixture fraction model employed see [5].

The application of the electronic nose to a mobile robot as described above inherently adds an additional dimension of difficulty to the acquisition and interpretation of the data obtained. This paper highlights some of the key points which must be taken into account when an electronic nose is utilized in such an environment. A brief overview of the sensors, hardware, and practical techniques used is also given within context of the Viewfinder, as well as the Guardians project.

## 2 Practical aspects of chemical sensing

It is a common misconception that a single sensor(s) may be readily purchased to detect and give an accurate concentration of a particular target analyte in its local environment. The above statement will only hold true if

- The sensor(s) are completely specific reacting only to the target analyte or only a single analyte is present in the atmosphere
- The sensor samples fast enough to give an accurate reading of the current concentration
- The concentration of target analyte is evenly distributed throughout the surrounding environment and remains constant.

In real world applications such a sensor does not exist and the likelihood of a single (unique) analyte being present and has a uniform spatio-temporal concentration distribution is remote. The following sections discuss practical implications caused by non-ideal sensor responses.

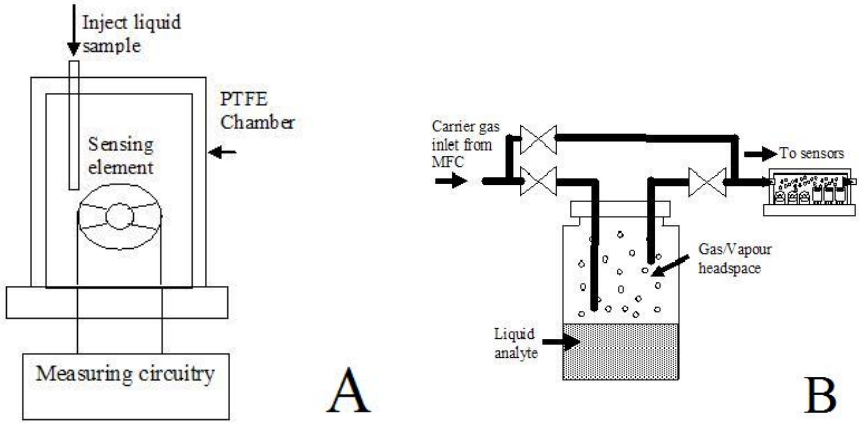


**Fig. 2.** Basic schematic of Static (A) and Flow (B) basic exposure systems

### 2.1 Chemical Sample delivery in the laboratory

In laboratory testing of chemical sensors two methods are primarily used: the static and flow systems. Figure 2A depicts the basics of the static system. A small volume of liquid analyte typically in the micro litre range is injected into the chamber. Evaporation takes place until equilibrium is reached inside the chamber. The sample measurement is then taken. Figure 2B illustrates the flow system, where the headspace above a liquid sample is utilized and a carrier gas then transports the headspace analyte to the sensors. Computerized control of the valves allows automatic switching between pure carrier gas and the target analyte. The flow rates may be precisely set using mass flow controllers (MFC) allowing a range of concentration to be delivered to the sample. Alternative arrangements for the flow based system include, the diffusion method and the sampling bag approach [6, 7]. The above classification applies to vapours rather than gases. Gases that do not have a liquid phase at room temperature and atmospheric pressure can be supplied in certain concentrations at high pressure and could be further diluted with a carrier gas and MFC's.

### 2.2 Sensor Selectivity

The selectivity between different types of sensor varies significantly, typically some cross sensitivity is always observed. Figure 3 demonstrates the response of a QCM sensor; it is clearly evident that the sensor responds to a range of gases/vapours. In general a sensor(s) may be optimized for a particular analyte and in the case of QCM by application of different sorbent membranes [10] or in the case of MOS devices through the use of different doping catalysts [9]. Inevitably some cross sensitivity still occurs. This is particularly evident amongst groups of similar chemical compounds, e.g. for alcohols.

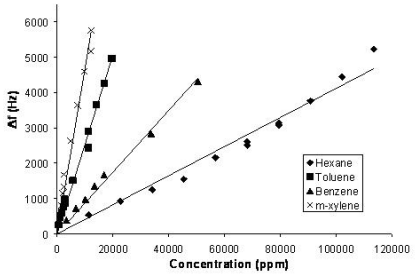


**Fig. 3.** QCM response to a range of VOC's.

To detect and discriminate between analytes it is therefore necessary to have an array of sensors each having partial specificity to a single or group of anayltes. The collective sensor responses must then analyzed and pattern recognition techniques applied. If suitable variance between the responses exists, then identification of a specific analyte is possible. This forms the basis of the electronic nose.

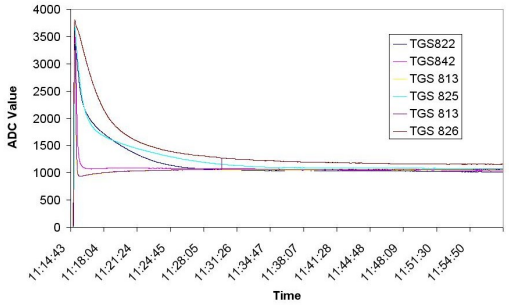


**Fig. 4.** Startup / initial action of several MOS sensors

In the viewfinder and Guardians projects two types of sensor, namely QCM and MOS are used to construct the array. QCM coated with a range of calixarene derivatives provide very fast and fully reversible responses to the majority of VOC's, while commercial MOS sensors from Figaro (Japan) are designed to detect a range of oxidizing and reducing gases. The combination of these sensors provides suitable recognition of a range of gases and vapours in their pre-explosive vapour concentrations.

### 2.3 Sensor start-up time

Preceding the application of power to many sensors an initial action or start-up time is required to establish a baseline from which all further sensor readings are relatively measured. Figure 4 shows the observed start-up responses of several MOS sensors from Figaro (Japan). As is clearly evident a start-up time of greater than 30 minutes may be required, such factors must of course be accounted for on deployment of such sensing equipment in field use.

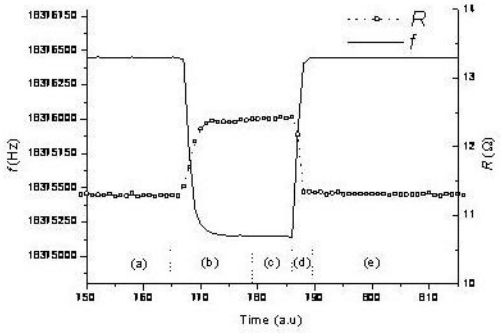


**Fig. 5.** Dynamic response of a QCM exposed to hexane vapour.

### 2.4 Sensor sample times

An ideal sensor would produce an instantaneous response directly proportional to the target analyte, and when flushed with air, immediately return to its original baseline. From basic thermodynamic principles, high sensitivity and selectivity are typically accompanied with slow response and poor recovery, and vica versa fast responses and complete recovery are attributes of low sensitivity and selectivity. In practice a response as shown in Figure 5 is typically observed. Several distinctive regions are apparent: a) the initial measured baseline in air b) vapour exposure, the sensor responds in approximately $3-10$ seconds c) steady state, the sensor response has saturated d) flushing of chamber with air e) the recovered response where the sensor should return to its original baseline. The sensor measurement is taken within region (c) where a stable steady state response is observed. The response time is proportional to the concentration, higher concentrations most often producing larger response therefore increasing the response time. It must be noted that in some cases sensor poisoning may also occur. Effectively the sensor becomes irreversibly contaminated and does not return to its original baseline value. This can have significant consequences and in the worst cases results in an unusable sensor.

Within context of the Viewfinder and Guardians projects, the required sensor sample times obviously place several limitations on the advancement speed of the robots into the warehouse/factory, described earlier as Scenario 1. In review, factors such as the detail and quality of the chemical mapping with respect to the time permitted must be considered in such applications.

## 3 Sensing in a dynamic environment

The collection of data from an array of sensors each offering partial specificity to an individual analyte has no real benefit, unless the combined resultant data allows classification and quantification of a specific analyte or group of analytes [8]. To achieve this, further processing/pattern recognition of the sensor data is required. The topic of sensor processing and data analysis is vast and cannot be reviewed within the scope of this paper. The subject is however covered extensively in literature [11–15]; Table 1 gives several examples indicating the analysis method used and the number of sensors within the array.

The laboratory based exposure methods described earlier provide a suitable method for measuring the performance of chemical sensors within a controlled environment. Real life situations however add much additional complexity: this is especially evident if for example a turbulent environment surrounding a fire must be monitored.

| Target odours | Analysis method | Number sensors | Reference |
|---|---|---|---|
| Organic solvents | ANN, PCA | 16 | Kalchenko et al 2002 [16] |
| Organic compounds | Fuzzy clustering | 4 | Barko et al 1999 [17] |
| Volatile sulfur compounds | PCA | 8 | Ito et al 2004 [18] |
| Blended fragrance | ANN, Fuzzy logic | 8 | Nakamoto et al 1996 [19] |
| Apple flavor | Unknown | 8 | Nakamoto et al 2001 [20] |
| Food products | PCA | 7 | Pardo et al [21] |
| Organic compounds | ANN, Decision tree | 6 | Polikar et al 2001 [13] |

**Table 1.** Examples of several QCM based arrays using a range of sensor processing techniques.

Figure 6 (A to D) depicts results for Nitrogen ($N_2$) concentrations at horizontal and vertical planes from simulations obtained using the NIST fire dynamics simulator [22]. In this simulation a room of dimensions $4 \times 3 \times 2.5$m is populated with three items of upholstery furniture (couch), two wooden tables and one carpet. To simulate the air flow we have placed 'vents' just above the couches on the left wall.

A fire is simulated as to have started at one of the couches with a heat release rate per unit area of 900kW/m$^2$. The initial burning area on the couch is set at 0.05m$^2$ resulting in a heat release rate of 45kW. All material data for the fire and gas mixture model are realistic and have been taken from Babrauskas [23]. The fuel for the fire spread is assumed to be polyurethane foam ($C_3H_8N_2O$) and results in the release of carbon dioxide, water vapour, nitrogen and an assumed constant yield of carbon monoxide and soot.

Figure 6 (A to D) snapshots of the simulation[2] are at 300, 392, 504 and 767 seconds and depict nitrogen concentration on two planes showing the spatial density distribution at given time frames. It is clear that the distribution of $N_2$ concentration changes rapidly and dynamically, and that the concentration may differ significantly depending on where the sample point is taken. Figure 6A also demonstrates that the sensor(s) should be mounted as high as practically possible, since until reaching simulation time 300 seconds virtually no analyte was observed in the lower section (horizontal plane) of the room.

It must be concluded that to establish even a basic representation of the analytes present, and their relative concentrations, multiple sample points must be taken. Consequently, for effective spatio-temporal search with respect to the visual representation, appropriate search algorithms [24, 25] for analyte detection must be employed. Finally, due to the time delay from data acquisition to sensor response and analyte recognition, localisation of the sensor-array, hence the mobile robot, is vital for a valid spatial representation of analyte concentrations in the 2D map.

## 4 Conclusions

The application of chemical sensors to mobile robot applications as demonstrated within the Viewfinder and Guardians projects potentially adds a new dimension to the amount of information which may be presented to fire/search and rescue teams entering risky environments. However, as established within this paper the implementation is not trivial, and many factors must be taken into account if accurate and reliable results must be obtained.

– Sensor selectivity: A suitable number and type of sensors must be used which respond to the target analyte(s) in question

[2] NIST visualisation package Smokeview version 5 has been used

– Sensor Start up: an appropriate length of time must be allowed for the sensors to stabilize and reach there baseline value
– The sampling time of sensor may be in the order of several seconds, this must be accounted for when setting the progress speed of the robot
– The dynamics of the sensing environment must be considered. Environmental conditions change rapidly and may be localized to a small area. An appropriate number of samples must therefore be taken to give a valid representation

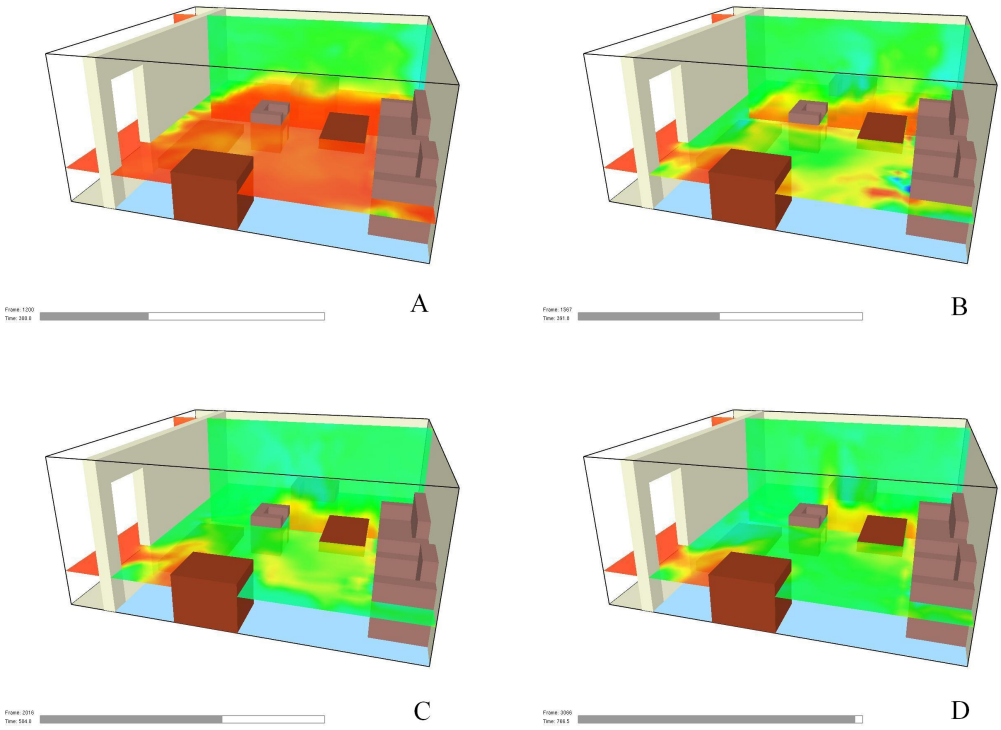


**Fig. 6.** Snapshots from a polyurethane (foam) fueled fire for horizontal and vertical planes. Note that for clarity only nitrogen concentrations are depicted indicating its dynamic nature. Colour-bar is identical to the one in Figure 1.

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