INVESTIGATING THE VIABILITY OF MEMS VAPOR SENSORS FOR DETECTING LAND MINES

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Abstract-- This paper reports the design specification and process for constructing a gas identification instrument using MEMS technology for the purpose of detecting buried land mines. The aim is to design an instrument to detect and identify gases that leak from buried land mines using an array of sensors and a pattern recognition/signature identification system. This report focuses on the design of the sensor array. The principal component of the sensors is a conducting polymer that is reversibly physically altered when exposed to different chemical compounds. Physical changes experienced by the polymer in the presence of the gas molecules are detected and converted into electrical signals by two kinds of transducers. Crystal oscillator-microbalances with MHz oscillating frequencies detect changes in the polymer's mass via the shift in frequency in one type of sensor. In the other sensing configuration, current traveling through the polymer for a fixed voltage source is measured to detect the changes in the polymer's resistance. The first type of sensor is a miniaturized version of the quartz crystal microbalance (QCM) which is based on the mechanical principle that resonant frequency decreases with increased mass. The second type of sensor uses carbon black-polymer composite films, which swell reversibly when exposed to a variety of gases and thus induce a resistance change. In order to allow this sensor to be reproduced accurately, high aspect ratio wells are constructed using an SU-8 photoresist, and the polymer solvent liquid is injected into these wells. The response of the sensor array to different gases, and also different concentrations of the gases, provides a signature by means of which the identity and concentration of a variety of gases can be recognized.

Index Terms-- Electronic Nose, MEMS, Chemical Sensor, Detecting land mines

I. Introduction

Vapor sensors have been in use for many years now. Their applications range from monitoring the concentration of dangerous chemicals in industrial environments to quality assurance of food and even beer. In the past few years, many experts have hailed vapor sensors as the most promising candidate for the ideal landmine detection sensor (see [19] and [23]). The success of using canines to sniff out land mines has been the primary reason for the hope that vapor sensors will be effective mine detectors. When a landmine is buried, TNT – trinitrotoluene (or DNT – dinitrotoluene) leaks out from the mine into the surrounding environment. Detecting these small traces of TNT could be the key to safely detecting the millions of abandoned landmines around the world. The principal drawback of most other sensing techniques is the large number of false positives, which cause a lot of extra work. Vapor sensors are likely to outperform all other sensors in this task since they are seeking the key element in the land mine – the explosive substance. Hence, the probability of a vapor sensors making a false detection is very low.

The following section highlights the motivation for humanitarian demining. Related work in the field of mine-detection sensors and vapor sensors is presented in section III followed by an outline of the theory of vapor sensing in section IV. Next, design and fabrication details, followed by performance analysis of a varistor based vapor sensor and a crystal-oscillator based vapor sensor are detailed in sections V-VIII. The issues of integrating many of these sensors into a single sensor array are presented in section IX. A discussion of the limitations of these sensing techniques is presented in section X, followed by a brief summary of the key elements presented in this work in section XI. This report concludes with a brief description of future work to be accomplished in this field (section XII).

II. Motivation

Current estimates indicate that approximately 125 million landmines are buried in over 60 countries around the world [15]. (In Angola it is estimated that there is a buried landmine for every living man woman and child). 250 million more landmines are estimated to be stored in different warehouses around the globe, ready to be used. The International Red Cross published that landmines claim a victim once every 20 minutes. A recent study showed that woodcutting, grazing livestock, planting or harvesting and plowing, land or ditch clearing, walking on tracks, fishing and collecting water, playing, scavenging (for food and scrap metals), driving (especially overtaking on verges of the road), and recovering dead or injured relations or friends from minefields are the 10 tasks most vulnerable to land mines [15]. Thus, it is no surprise that sometimes up to 80% of land mine victims are children since they aren't as careful about looking for the warning signs. There are also more long-term effects of landmines such as starvation due to lack of land safe for agriculture and shutdown of communication and transportation to some areas. [15].

Most existing minefields are in poor areas of developing countries. Hence, very little funding can be allocated to clearing the mines and therefore most of the landmine detection work is done manually (deminers are paid to probe the area – prodding with a stick – and search for buried objects). This is a highly dangerous and time-

consuming process since large areas need to be covered in this manner. Some of the wealthier nations (or nations that receive foreign aid) have successfully used dogs to sniff out areas where landmines are buried. The dogs are able to localize danger zones to within a few meters and hence the area to be covered by human prodders is vastly reduced. This is currently the most successful means of detecting buried mines.

Bringing canines into the demining effort however, does not drastically reduce the danger to human deminers. The U.N. estimates that 1 deminer is killed for every 1000 mines detected. Moreover, dogs are prone to illness and fatigue, and don't work well in different weather conditions. Therefore, several dogs need to examine the same area before it is declared safe. In addition, breeding and training these dogs is very expensive, and ultimately the dog's use is limited by the skill of its human handler. If the dog's nose could be successfully mimicked using a low-cost electronic sensor, millions of innocent lives could be saved.

III. Related Work

The development of sensors to aid humanitarian demining has become the focus of many research interests within the past few years. A variety of sensing techniques including automated prodding, metal detection, ground penetration radar (GPR), infra-red (IR) imaging, magnetic and electro-optical sensing, biosensing, microwave radiometry, radar, shock impulses, nuclear magnetic resonance spectroscopy, gas chromatography, and chemical sensing are currently being investigated as means of detecting buried mines[1].

Of these sensing techniques, chemical vapor sensing appears to be the most promising. However, in order to effectively detect buried mines using chemical vapor sensors (or any other form of sensor), characteristics such as materials used in different types of mines, and migratory behaviors of TNT vapor in the minefields, environmental effects on the migration of TNT must be known. Some research efforts have focused on studying these characteristics of mines and minefields[2], although very little data has been published yet since these efforts were only initiated recently.

Many different research groups are currently investigating the design of chemical vapor sensors that mimic the mammalian nose. These sensors are in high demand in a variety of applications including illegal-drug detection, quality assurance of food and drugs, medical diagnosis, environmental monitoring, safety and security, and of course land mine detection. A variety of sensing mechanisms has been investigated for "electronic nose" design. While some research efforts have focused on understanding the biological mechanism of the mammalian nose[3], others have focused on different materials that will react to a variety of vapors in some detectable manner[4].

A summary of some research efforts carried out in vapor sensing follows. Please note that this is by no means a comprehensive list of research carried out in this field of study. Howe, in some early work in this area, designed a Silicon electromechanical vapor sensor that was based on detecting a frequency shift corresponding to the change in mass due to the absorption of vapor molecules by a polymer coating on a micro-bridge [14]. More recently, Freund and Lewis designed a chemically diverse conducting polymer-based electronic nose [8]. Gas identification, using Tin Oxide sensors, is explored by Marco et al. [22]. Design of an electronic nose using gas chromatography is investigated by Staples [35]. Emmenegger et al., probe the issues involved with thermomechanically actuated gas sensors [6]. Baltes et al. look into designing MEMS capacitance and mass-frequency based sensors [1]. A means of fabricating MEMS conducting polymer-based chemical gas sensors is presented by Zee and Judy [41]. Yang and Swager introduce a means of using fluorescent porous polymer films as chemosensors [40]. Taking a different approach, Vig et al. discuss the design of a chemical sensor based on Quartz micro-resonators [37].

Analysis of detected signals is also an important part of sensing systems. Supportive work to allow better analysis of crystal-oscillator based vapor sensors has been published by many groups including [27], [28], [31], [32], [38], and [39]. Other groups have created new polymer combinations for enhanced vapor detection [5]. Nakamoto et al. present an active odor sensing system to enhance sensing capability [26]. Important work has also been carried out by some groups to investigate effective use of conducting polymers for vapor sensing (see [12], [21], and [33]).

IV. Theory of Vapor Sensors

An electronic nose, or vapor sensor, essentially attempts to mimic the principle components of a mammalian nose. The essential processes that must occur for a mammalian nose to detect and identify an odor can be summarized as follows: (1) sniffing, (2) reception and binding, (3) stimulus, (4) transmission, (5) identification, (6) action, and (7) cleansing. The parallel mechanisms in an electronic nose would be the following: (1) drawing in some gas from the environment, (2) allowing the vapor molecules to react with an array of sensors, (3) detecting signals indicating the reaction of the sensors to the vapor, (4) transmitting these signals to a neural network or some other pattern recognition mechanism, (5) matching the signal pattern with signatures of known chemical vapors and thus identifying the chemical composition of the vapor,

[1] Information about research in most of these sensing techniques can be found in the conference publications of the biannually held "International conference on the detection of abandoned land mines" (1996, 1998). Also see [10], [10], [29], [30], [34], and [36].

[2] See [2], [7], [13], [18], and [24].

[3] See [9] and [17].

[4] A survey of techniques used in the design of the electronic nose is presented in [25].

(6) taking some form of action based on the identification, and (7) cleaning the sensor array so that detection can occur again. The mechanisms of a biological nose and the corresponding mechanisms in an electronic nose are illustrated below:

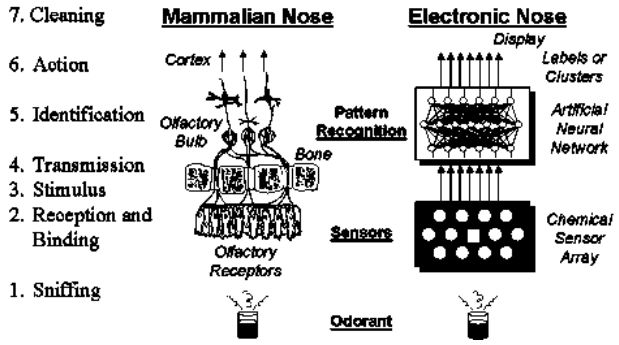

Figure 1: Parallel mechanisms in biological and electronic noses. (Illustration provided by courtesy of Paul E. Keller [16]).

It is estimated that humans have 10-40 million olfactory receptors while dogs can have up to 1 billion receptors. Furthermore, mammals are presumed to have between 1,000-10,000 distinct olfactory receptor types [17]. Thus, in order to build sensing arrays that can match the performance of a dog in sniffing out land mines, all indications are that MEMS technology is vital so that large numbers of sensors can be built into a single system.

In order to design a vapor sensor that will be useful for mine detection, the following constraints must be taken into consideration:

1. The sensor should easily transduce environmental information into some conveniently monitored signal while minimizing energy consumption and the number of hardware components.
2. The sensor's reaction must be reversible and reproducible with minimal baseline drift.
3. It is advantageous if the sensor can be tuned to respond in a predictable manner to small concentrations of selected chemical compounds.
4. The sensors should be easily and cheaply fabricated, preferably using well-established techniques and easily available materials (so that the sensors can be produced in mass quantities and thus be economically feasible).
5. Fabrication methods and design parameters should allow for miniaturization so that large numbers of sensors can be integrated into a single sensing system in a compact manner.
6. Finally, the sensors should be robust to changes in environmental conditions, and respond in a predictable manner in a variety of different weather conditions.

The viability of two types of transducers was investigated for mine detection. The design, fabrication, and analysis of these sensors are presented next.

V. Design and Fabrication of a Varistor-Type Vapor Sensor

One method of detecting chemical vapors is to use a thin-film of conducting polymer that swells predictably due to adsorption of the vapor molecules. When the polymer swells, the quotient of carbon molecules per unit volume decreases causing a change in resistance, which can be detected.[5] An array of sensors that produces a variety of responses when exposed to different vapors can be built by using different polymers and varying film thickness.

A. Fabrication Process

Fabrication of these sensors using standard MEMS techniques is relatively simple. The fabrication process is illustrated below in Figure 2. First, gold leads are deposited onto the surface of a silicon wafer coated with silicon nitride (or silicon dioxide), using an e-beam evaporation system. The leads are patterned using a lift-off process. These leads act as electrical contacts for the sensors. An SU-8 photoresist (MicroChem Corp.) is used to build high aspect ratio wells covering approximately half of two gold leads as shown in Figure 2 (a). Next, the carbon black composite conductive polymer is dissolved into a solvent mixture and injected into the wells using an automated syringe as illustrated in Figure 2 (b). The solvent mixture evaporates leaving behind a thin sensing film inside the well – see Figure 2 (c). Once evaporation is complete, the photoresist can be stripped off as illustrated in Figure 2 (d). This process allows the carbon-polymer film to be deposited reproducibly in a specific, well-constrained area. Since the polymer needs to be deposited in liquid form, containing the film to a small area can be difficult. This problem is overcome by building the high aspect ratio photoresist wells. Note these wells can be post-processed onto silicon CMOS chips, thereby allowing for integration of on-chip electronics for measurement and signal processing.

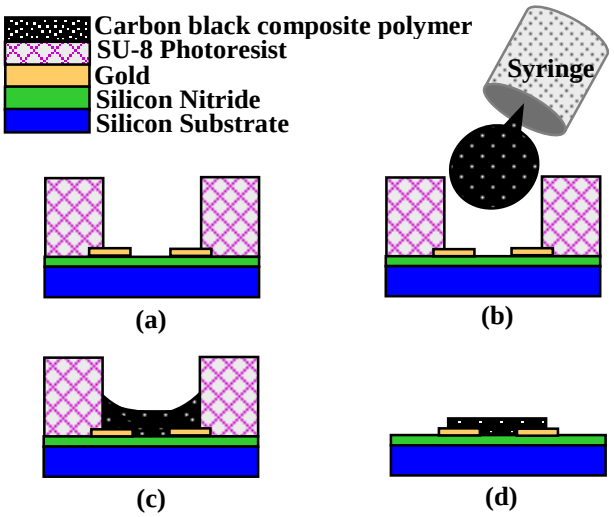

Figure 2: Fabrication process for varistor-based vapor sensor. (a) Build wells using SU-8 photoresist (b) Inject carbon black composite polymer into the wells (c) Allow the liquid to evaporate leaving behind a thin film (d) Strip off the photoresist

[5] The design of this sensor is primarily based on work done by Lonergan et al. [20] and [21], Freund et al. [8], and Zee and Judy [41].

B. Instruments and Materials

1) Automated Syringe:

An automated syringe that can be used in the fabrication process is Nanojet II, by Drummond Scientific Company. Nanojet II is capable of injecting nanoliter volumes in a reproducible manner. The tip of the syringe is a disposable, pulled-glass capillary with 10 μm diameter. Thus, the tip can be changed when depositing different polymer composite films.

2) Photoresist:

SU-8 is an epoxy-based negative imaging resist that is resistant to harsh conditions during fabrication, and allows high aspect ratio structures to be built due to its compatibility with thick-resist applications. A key factor in this process is the use of a photoresist developed for thick-resist applications because relatively large volumes of liquid need to be contained within the wells. Zee and Judy [41] report 200μm thick resist walls using SU-8 photoresist.

3) Carbon Black - Polymer Composites:

Black Pearls 2000, a furnace black material, can be used in the composites. Some organic polymers that can be used as the insulating portion of the carbon black composites are poly(styrene), poly(vinyl acetate), poly(sulfone), poly(methyl methacrylate), and poly(ethylene oxide). For other polymers that can be used see [20] and [21]. Instead of a carbon black composite, a conducting polymer such as poly(pyrrole) can also be used. However, the long-term stability of carbon black composite is much greater than that of the conducting polymers. Depending on which polymer is used, solvents such as THF, benzene, or dichloromethane can be used to allow injection of the carbon polymer composite in liquid form. To prepare the liquid, the polymer is first dissolved in an appropriate solvent and agitated in an ultrasonic bath. The carbon black is added once the polymer is fully dissolved, and the mixture is sonicated further to allow uniform dispersion of the carbon in the solution.

VI. Performance Analysis for the Varistor

The output of resistance of the sensor is measured using a Wheatstone bridge configuration. Harris et al. [12] suggest the use of ac techniques to improve the S/N ratio and also facilitate low voltage measurements (where self-heating does not occur and the polymer characteristics are most linear) more easily.

Percolation theory provides a means of determining the resistivity (ρ) of a carbon black-organic polymer composite[6]:

$$\rho = \frac{(z-2)\rho_c\rho_m}{A+B+\sqrt{(A+B)^2+2(z-2)\rho_c\rho_m}}$$

Where

$$A = \rho_c[-1+(z/2)(1-(v_c/f))]$$

$$B = \rho_m[zv_c/2f)-1]$$

In this equation, ρ_c is the resistivity of the carbon black, ρ_m is the resistivity of the polymer matrix, v_c is the volume fraction of carbon black in the composite, z is the coordination number of the carbon black particles, and f is their total packing fraction. The volume fraction of carbon black in the composite at the percolation threshold (v_p) is given by:

$$v_p = 2f/z$$

When the percolation threshold is crossed a large change in resistivity can be observed. Therefore, the polymer-carbon black composite should be mixed such that v_c is just slightly less than v_p so that the percolation threshold is crossed when the composite is exposed to TNT or DNT vapor.

Since no experimentation data could be found for the composite response to TNT or DNT, sensitivity and smallest detectable concentrations are calculated based on data presented for benzene vapor by Lonergan et al. in [20]. Note, the molecular weight of TNT ($C_7H_5N_3O_6$) = 227.13, DNT ($C_7H_6N_2O_4$) = 182.14, and Benzene (C_6H_6) = 78.11. The concentration of benzene vapor is presented as a partial pressure (P) measurement where P^* is the saturation partial pressure and P^* = 114 parts per thousand (ppt) benzene under ambient conditions. The largest, maximum relative differential resistance signal, observed in response to a change in partial pressure (ΔP) of a test vapor will occur when a composite has its stoichiometry poised such that the slightest swelling will pass the composite through the percolation threshold. Thus, the sensitivity would be measured as the partial pressure dependence of the maximum relative differential resistance response. Lonergan et al. report a factor of five increment in resistance corresponding to an increase in P/P^* from 0.81 to 0.84 (i.e. the introduction of an additional 3.4 ppt of benzene). Thus, if we assume linear resistance vs. swelling response over the range of swelling, this scales to a sensitivity of greater than 100% per ppt.[7]

Another important aspect to consider is the minimum detectable signal. Shurmer et al. [33] present a means of calculating the ultimate sensitivity attainable with resistance-based vapor sensors in the limit of Johnson noise. In this calculation, a signal to noise ratio of 10:1, a standard temperature of 290K, a 1kΩ gas-sensitive varistor, and a bandwidth of 100Hz for the noise filter was assumed. Thus, the minimum detectable r.m.s. voltage was calculated to be 4.0E-7V. Then, additionally assuming an audio frequency of 1kHz for the a.c. amplification source, a change in varistor resistance proportional to the gas concentration, and using measurements relevant to tin oxide sensors, Shurmer et al. calculated that a gas concentration of 1 part per billion (ppb) should lead to a signal sufficient

[6] See equations (6a), (6b) and (6c) in [20].

[7] Note, these calculations assume that the swelling occurs only in the polymer and not in the carbon.

to be detected by an electronic nose.[8] Making the same assumptions as Shurmer et al., and applying the results for the carbon black-polymer composite response to benzene presented by Lonergan et al., a minimum detectable concentration limit of 0.25 ppb results.[9] It should be noted that the canine nose is estimated to be able to detect vapor concentrations on the order of 1 ppb. Hence, the varistor-based vapor sensor seems capable of matching canine performance based on initial calculations!

VII. Design Considerations for a Quartz Crystal Microbalance Vapor Sensor

A second promising type of vapor sensor design was briefly investigated.[10] Once again, the key element of the sensor is a thin film of polymer that adsorbs vapor molecules when exposed to certain chemical compounds. The transduction method however is different in that the detected signal is a shift in frequency rather than resistance. The basic principle of a quartz crystal microbalance (QCM) is that a resonant oscillating system will experience a shift in resonant frequency if its mass is changed. Thus, a crystal oscillator coated with a thin film of polymer will experience a shift in resonant frequency when the polymer adsorbs the vapor molecules and thereby causes a shift in the mass of the system. The basic structure of a QCM is illustrated below in Figure 3:

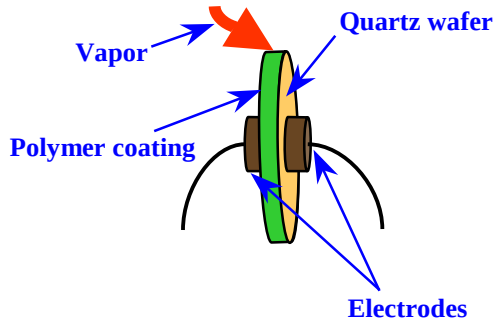

Figure 3: Illustration of the principal components of a quartz crystal microbalance.

A QCM generally consists of a resonating quartz wafer disk (usually a few millimeters in diameter) with metal electrodes on either side of the disk connected to lead wires. The device is excited with an oscillating signal and resonates at a characteristic frequency (usually in the 10MHz to 30 MHz range). The resonance frequency is determined by the cut (i.e. the angle at which the quartz is cut) and the thickness of the resonating disk. For example, the a 4.1μm thick AT-cut quartz disk has a resonant frequency of 400MHz, while a 166μm thick crystal cut along a certain axis will resonate at 10MHz.

QCM sensors produce a linear response over a wide dynamic range. The QCM can be tailored to detect TNT by choosing an appropriate polymer coating. Reducing the size and the mass of the device and also the thickness of the polymer coating can minimize the response and recovery times of the sensor. However, the larger the surface to volume ratio, the greater the noise in the device, so care must be taken when fabricating these devices with MEMS techniques. Variations occurring during manufacturing processes do not cause large errors since a normalized frequency change is usually measured.

VIII. Performance Analysis for the QCM

Mass changes occurring at the surface of a QCM result in frequency changes (Δf) that can be calculated according to the Sauerbrey equation:

$$\Delta f = \frac{-2 f_0^2 \Delta m}{A\sqrt{\mu_Q \rho_Q}}$$

In this equation, f_0 is the resonant frequency of the quartz resonator, Δm is the change in mass, A is the active vibrating area, μ_Q is the shear modulus of quartz, and ρ_Q is the density of quartz. In practice, the frequency shift (Δf) caused by a small change in resonator mass Δm or thickness Δd can be calculated using the equation:

$$\frac{\Delta f}{f} = \frac{-\Delta d}{d} = \frac{-\Delta m}{m}$$

Since the density of quartz is known, one can readily calculate the shift in mass resulting from exposure to vapor by measuring the shift in frequency. Because frequency can be determined with very high accuracy, it is possible to measure very small changes in mass. Vig et al. provide the example of a 5 MHz fifth overtone SC-cut resonator. The frequency noise of this resonator is 1E-13 at the optimum measurement time. Taking into account the thickness and area of the resonator and the density of quartz, the mass of the sensor can be computed to be 0.13g. Thus, the noise is equivalent to a mass shift of 1E-14g.[11] Therefore, the minimum detectable signal will be below the picogram range for this sensor![12]

Nagle et al. provides an example of the sensitivity of these sensors. A 166μm thick quartz crystal with a 10MHz resonant frequency produces a 1kHz shift in frequency when its mass is shifted by 0.01% of its mass. Walls and Vig [38] found that the two significant fundamental limits to stability of a quartz crystal oscillator are Johnson noise of the resonator and phonon scattering within the resonator.

[8] Experiments carried out by Shurmer et al. were only able to detect a minimum gas concentration of 10 ppb.
[9] If the percolation threshold is not crossed when exposed to vapor, the minimum detectable signal is 25 ppb.
[10] Details of the QCM are primarily based on work published by Nagle et al.[25], Vig et al.[37], and Ward [39].
[11] The Bofors Schnauzer [3] which is specifically catered towards land mine detection, aims at being able to detect 10 pg shifts in mass.
[12] 1pg of methane in a 1-liter sample volume at standard temperature and pressure produces a methane concentration of 1.4ppb.

IX. Issues with Creating a Sensor Array

Several issues need to be considered when integrating a large number of vapor sensors into a single sensing system. Some of these considerations are discussed here. Including a reference sensor for each of the vapor sensors in the array can be valuable since some of the environmental and manufacturing variances can be compensated for in this manner. All sensors will have to be encased in partially sealed chambers with airflow to and from the sensor chamber controlled via a valve capillary system.[13] The reference sensors will remain sealed within vacuum chambers and will not be connected to the capillary system. Each sensing unit will require some form of container filled with "clean air" (for example, pressurized nitrogen) to allow cleansing of the sensors between samples. Since one of the possible drawbacks of the system would be the time required for cleaning the sensors, efficiency can be introduced by having different sets of sensors operating in parallel – i.e. when one set of sensors is being cleaned, another set is detecting. Using different types of polymers or polymer layers of different thickness can allow variation in the sensor response for different sensors in the array. Finally, the output of the sensing array can be fed into a neural net system (or some other pattern recognition mechanism) for identifying the sensor response signature for the detected chemical compound.

X. Discussion

Each of the two sensor types presented in this report has its limitations. The varistor can only achieve the necessary sensitivity if the carbon-polymer composite is prepared in such a manner that the percolation threshold is passed when the film is exposed to vapor. In contrast, the QCM sensors can achieve the necessary sensitivity levels quite easily. However, fabricating these devices with MEMS techniques proves to be challenging.

Reaction times and cleaning times required for these sensors have not been accurately studied thus far. For most experiments presented, the sensors are allowed to react with the vapor for times ranging from tens of seconds to a minute, while cleaning times seem to be a few minutes. However, a statement indicating that the reaction and cleansing times could be much shorter usually follows these times. Hence, more experimentation is required to pin down these times with greater accuracy.

A final issue for concern is that the smallest version built of each of the two types of sensors presented in this report have been on the order of 200μm x 200μm. If we incorporate a billion of these sensors (in order to match the number of sensors in a dog's nose) onto a single planar array, the array would be on the order of 6.5m x 6.5m! If we are to localize the array to a plane of 15cm x 15cm, the sensors will have to be shrunk down to 5μm x 5μm. Another possibility is to construct dimensional arrays where several planar arrays of sensors are stacked in some manner. This could complicate the building of a capillary system to some extent.

[13] Current MEMS techniques for building valve capillary systems do exist.

XI. Conclusions

In summary, this report has presented two possibilities for vapor sensor designs that could be used for land mine detection. Initial calculations and design considerations based on existing experimental data indicate that detecting land mines using vapor sensing technology is indeed viable. However, some design considerations for assembling billions of these sensors on single arrays need to be sorted out. Furthermore, most of the calculations are based on approximations that need to be refined further. This can only be accomplished with further experimentation. The favorable indications of initial calculations warrant further research in areas such as the response of polymers to TNT and DNT vapor, and also the migratory behavior of TNT and DNT that leak into the surrounding environment from buried land mines. Research in these areas can provide valuable information for better localization of buried land mines.

XII. Future Research Directions

It appears that humanitarian demining cannot be successful using a single type of sensor. Hence, all indications are that sensor fusion is a must if we are to succeed in this task. To achieve economic feasibility and lowest possible danger in demining, technology has to advance to the point where autonomous mobile bases that can traverse a variety of terrain (ant-like robots) can be mass produced. Once this is achieved, each of these robots can be equipped with some form of subsumption architecture[14] that will allow programming a basic set of behaviors such as coverage of an area and obstacle avoidance. If each of these robots is then integrated with a sensing array, where different groups will carry different types of sensors (for example vapor sensors and metal detectors), points at which these different types of sensors converge will indicate high probability sites for buried mines. Another important extension of mine detection work is the safe disposal of land mines. Finally, perhaps the most important aspect of the humanitarian demining effort is to ban future use of land mines.

XIII. Acknowledgements

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