

Sensor Review for Trace Detection of Explosives

Lama Mokalled, Mohammed Al-Husseini, Karim Y. Kabalan, Ali El-Hajj

Abstract— The detection of explosives covers a very important hazardous problem for people, due to the advancement of dangerous terroristic activities as well as of breakdowns in the production of these explosives. Border conflicts and terrorist attacks increased and hence detection of hidden bombs and explosives in lands, luggage, vehicles, aircrafts, and suspects became a must. The detection approach must take into consideration several factors including safety, sensitivity, accuracy, speed of recovery, and ease of implementation. This paper deals with a review of electronic/chemical sensors, optical sensors, and biosensors and their usage in tracing explosive devices and detecting landmines. Available techniques are covered which are characterized by a high degree of technological development. In addition, means of detection for vapor trace explosives is also presented in this review paper. Commercially available electronic/chemical trace explosive detection approaches are also presented with their characteristics.

Index Terms— Detection, Explosives, Vapor, Trace, Detection, Electronic/Chemical, Optical, Sensors, Biosensors.

1 INTRODUCTION

Explosives existing around the world pose serious problems. Numerous solutions are explored and performed.

The purpose behind such researches is to acquaint safe and fast methods for mines detection to preserve precious human life, whether they were innocent civilians or part of the demining teams. Explosives are indiscriminate weapons, in other words, they do not distinguish between soldiers and civilians, or between adults and children. Hence the need for efficient, reliable, and fast methods for explosive detection has been an active area of research during the last few years to diminish the threat of terroristic activities [1]. Explosives have already injured or killed thousands of people all over the world hence inspiring researchers to dig for solutions. There exists a major concern about people security and environment protection which urged researchers for the development of sensors for explosive detection of compounds. Development of methods and instrumentations for explosive detection derived lots of attention. Several techniques have been explored and performed with the aim of implementing methods to preserve human lives [2].

Trace detectors are security tools that are able to detect explosives of small magnitude by means of sensors. Detection is performed by sniffing vapors in a vapor explosive detector or by sampling traces of a particulate or even joining both methodologies based upon the need. Long time ago, and even nowadays, dogs are solely used to detect explosives through vapors [3], [4]. This technique is considered the most effective and efficient among other detection methods that are currently in use. Dogs undergo rigorous training in various operational fields with several types of explosives to be prepared for explosive detection. However, a dog's performance declines with age and overtime especially after extensive fieldwork [5].

Detection methodologies are divided into two major categories: Trace detection and bulk detection of explosives. Trace detection involves the chemical detection of explosives by gathering and analyzing small amounts of explosive vapor. Bulk detection requires the detection of a macroscopic mass of explosive material which is outside the scope of our review paper. The term trace detection refers to both vapor and particulate forms. Vapor sampling requires no contact whilst particulate sampling requires direct contact to remove explosive material particles from a contaminated surface [6], [7].

This paper presents a review of electronic/chemical sensors [8], optical sensors [9], biosensors [10], and their usages in tracing explosive devices and detecting landmines. Available techniques are covered which are characterized by a high degree of technological development. In addition, means of detection for vapor trace explosives is also thoroughly presented in this review paper. Commercially available electronic/chemical trace explosive detection approaches are also deployed with their characteristics. Explosives detected by each sensor type are also tabulated. The review ends with a comparison between various detection types reaching conclusion and future work.

2 VAPOR DETECTION METHODS

Solids and liquids emit vapor at certain temperature and pressure conditions. The amount of vapor emitted by each substance characterizes its volatility. Sampling and analysis of saturated vapor is collected near the surface of explosive material without the need for contacting it. Sensitivity of vapor trace detection methods depends on several factors such as: vapor pressure, efficiency in collecting vapor, temperature, and wind strength. Vapors and traces are currently detected by means of electronic/chemical sensors, optical sensors, and biosensors. References [11], [12] present a survey and an overview of commercially available explosive detection techniques. Fig. 1 represents a tree listing various types of vapor trace detection of explosives. Each type shall be covered in the coming three sections of the paper.

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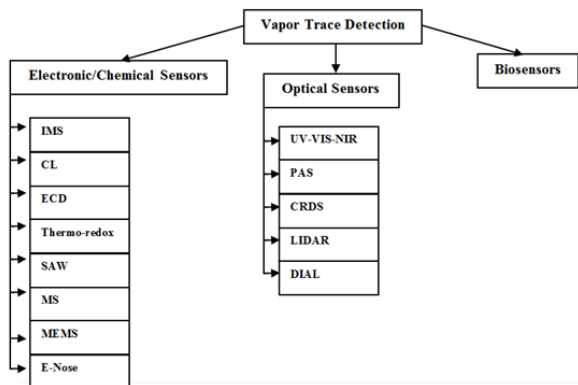


Fig. 1: Overview of vapor trace detection types [12]

2.1 Electronic/Chemical Trace Detection Method

2.1.1 Ion Mobility Spectrometry (IMS)

IMS is one of the most commonly used techniques for trace detection of explosives. It consists of an ion source region, an ion gate, a drift region, and an ion detector as shown in Fig. 2.

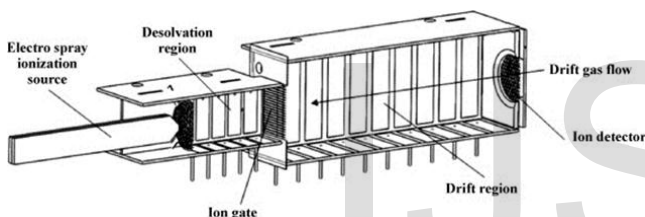


Fig. 2: High Resolution Ion Mobility Spectrometer (HRIMS) fitted with an electro spray ionization (ESI) source [13]

IMS detection is based on how fast ions move through the drift region reaching the detector. An applied electric field through the gas sample allows mobility of ions. Hence vapors are ionized at atmospheric pressure before reaching drift region. Reaching drift region within a certain time interval is determined according to the mass/charge ratio of the ions and hence characterizes each component of the explosive material as shown in Fig. 3. An advantage of this method is its speed where measurements take only few seconds, but a disadvantage is its low selectivity. A review of IMS for detection of explosives is presented in [13].

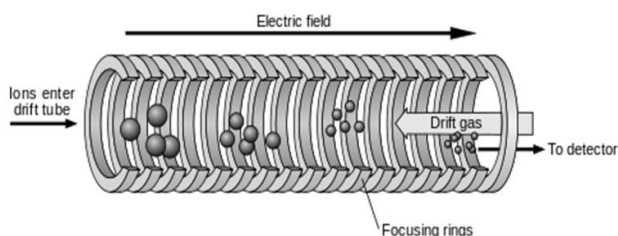


Fig. 3: Schematic of IMS operation [14]

Martin et al [15] presented a micro fabricated hotplate coated with a sorbent polymer as away to trap analytes of interest

prior to analysis with IMS; this technique enhanced sensitivity acquainted by at least one order of magnitude. Waltman et al [16] showed a distributed plasma atmospheric pressure ionization source that included the application of a high voltage alternating current through dielectric to produce plasma within which the sample was ionized. Tabrizchi and Ilbeigi [17] described a positive corona discharge technique using a curtain plate blocking the diffusion of NO_x into the ionization region and accordingly allowing analysis in air as opposed to nitrogen. Fig. 4 shows some commercially available IMS detection technologies.



Fig. 4: Pictures of commercial IMS technologies [11]

2.1.2 ChemiLuminescence (CL)

CL is the production and emission of light as the output of a chemical reaction. The produced light is proportional to the amount of NO present, which is related to the amount of the original nitrogen containing explosive material. CL can identify the characteristic emission of radiation from a molecule, atom or effective fluorophore, in an excited state, produced in an exothermic chemical reaction. It can take place in gas, liquid, and solid state. The analyzed vapors of explosives (NO₂ groups) are mixed with ozone, exciting NO₂ molecules. Characteristic light emitted by these molecules is then detected [19]. A significant drawback of CL technique is its inability to detect explosives that are not nitro-based. Another disadvantage of this method is lack of selectivity but this can be enhanced by coupling CL by means of different separation Ground Separation (GS) methods [20]. GS method uses fluorescent dyes by which a luminescent signal can be enhanced, depending on the distance separating the energy donor (emitting molecule) from the energy acceptor (dye molecule). Excited state donor exchanges a high energy electron for one of lower energy, thus returning to the ground state. The ground state acceptor molecule loses the low energy electron and gains one of higher energy, thus entering an excited state. The rate of energy transfer depends on the concentration of acceptor molecules. Fig. 5 represents mode of operation of a CL. In the market, products handheld and portable are shown in Fig. 6.

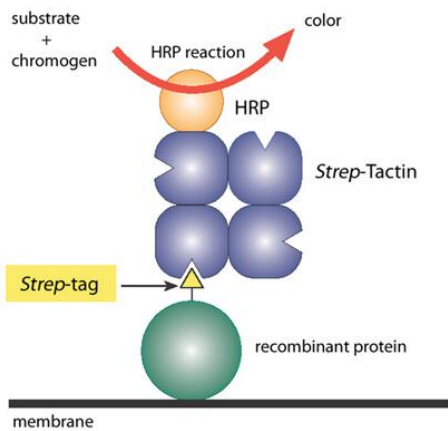


Fig. 5: Image of CL operation [14]



Fig. 6: Commercially available CLs in the market: left-handheld, right-portable [11]

2.1.3 Electron Capture Detector (ECD)

ECD sensors can detect vapor or invisible particulates in the air that strongly capture thermal electrons. ECD is usually combined to a gas chromatograph for identification of explosives since an ECD sensor by itself can't recognize individual explosive types when other interferences exist. The detector is characterized by its moderate sensitivity and small size in which it can fit in the palm of the hand [21, 22]. Theory of operation of an ECD is detailed in [23].

A prototype of ECD was built in the first place by James E. Lovelock during late 1950s [24]. Lovelock was trying to determine the damage that takes place to living cells when they are frozen. His instrument had low sensitivity so he tried to

implement a device to detect substances in the 10-15 grams range and hence ECD came to light. Fig. 7 shows Lovelock's ECD during 1958. In 1962, Rachel Carson drew the public's attention to the detrimental effects of chlorinated hydrocarbons and pesticides employed as economic poisons in agriculture on organisms [25]. A picture of a commercially available ECD is presented in Fig. 8.



Fig. 7: ECD image invented in 1958 [24]

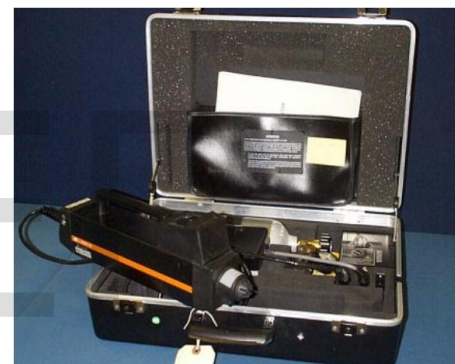


Fig.8: Commercially available ECD [18]

2.1.4 Thermo-Redox

Thermo-redox technology is an electrochemical method based on the thermal decomposition of explosive molecules and the subsequent reduction of NO₂ groups. A sample is drawn into the system and is passed through a tube, which traps explosive materials. The sample is heated to release NO₂ molecules, and these molecules are detected using appropriate technology. The method is used to detect the presence of NO₂ molecules in explosive materials. A critical pitfall in this method is that sensors can neither detect non nitrogen explosives; nor distinguish explosives in other substances containing NO₂ groups [26]. A handheld device of this methodology is shown in Fig. 9.



Fig. 9: Handheld thermo-redox explosive detection system [18]



Fig. 11: Portable commercial SAW system [11]

2.1.5 SURFACE ACOUSTIC WAVE/GAS CHROMATOGRAPHY (SAW/GC)

SAW/GC is technological method that allows excel for hundreds of individual SAW sensors. SAW sensors are oscillator circuits whose resonance frequencies are controlled by SAW delay line or resonator devices in the feedback path [27]. SAW devices are functionalized for chemical vapor sorption by depositing broadly selective polymer thin films in the acoustic wave propagation region. Exposure to vapor produces shift in oscillator frequency, and is considered to be the chemical signal. The measurement of changes in the surface wave characteristics such as amplitude, phase, frequency, etc is a sensitive indicator of the properties of the vapor. Fig. 10 illustrates the performance of the SAW approach.

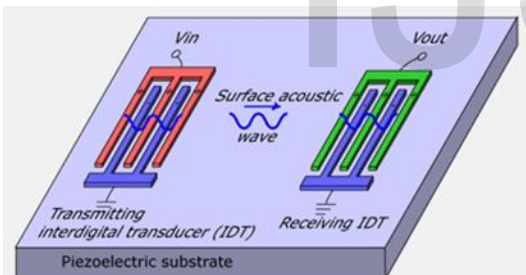


Fig. 10: Schematic of a simple SAW device [14]

[28] and [29] employ the principle of zNose approach where a gas mixture is separated using a chromatographic column where the outlet from each column is detected by a SAW sensor. A SAW/GC is developed for detecting explosives using a resonator crystal functioning at 500MHz. The crystal is subject to the gas exit of a capillary column. When condensable analyte vapors influence the active area of the SAW crystal, a frequency shift exists that is proportional to the mass of the analyte, the temperature of the crystal, and the chemical nature of the crystal surface [30, 31]. The main advantage of using SAW/GC is its ability to detect chemicals in addition to explosives. Fig. 11 shows a commercially available SAW system.

2.1.6 MASS SPECTROMETRY (MS)

MS divides and analyses the chemical composition of a specimen by ionizing molecules and passing them through a filter. Ions are thus identified according to the molecule mass to charge ratio. Desorption Electro Spray Ionization (DESI) allows detection of the substance of interest in its ambient environment by bombarding it with a mist of electrically charged droplets hence creating ions which are drawn into the MS with a vacuum [32]. In an another technique to DESI, named Direct Analysis in Real Time (DART), a voltage is applied to a carrier gas and the resulting excited state species release molecules from the sample which are introduced into the MS [32, 33]. Mode of operation of an MS is viewed in Fig. 12 while Fig. 13 shows portable MS portable detection systems.

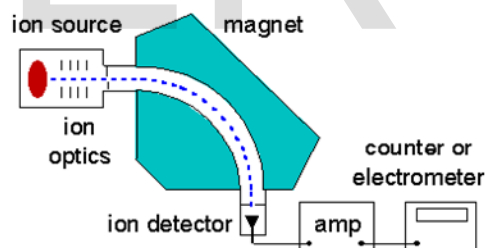


Fig. 12: MS working principle [14]



Fig. 13: Portable commercial MS explosive detection systems [11]

2.1.7 MICRO ELECTRO MECHANICAL SYSTEMS (MEMS)

MEMS technique uses an integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate by micro fabrication. Fig. 14 displays the contents of a MEMS sensor. MEMS sensors called microcantilevers, which are hair like silicon based devices that can detect and measure relative humidity, temperature, pressure, flow, viscosity, sound, ultraviolet and infrared radiation, chemicals, and bio-molecules.

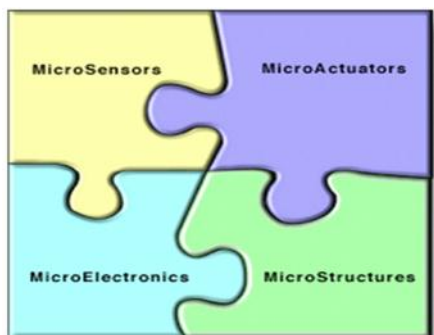


Fig. 14: Components of a MEMS sensor [14]

An operational mode for MEMS that includes change in the vibration frequency of a heated polymer coated silicon based cantilever is discussed in [34, 35]. These changes are a result of nano explosions of the detected explosive vapors. Detecting the temperature of the cantilever allows pointing various explosive types according to their temperature changes. MEMS based microcantilever sensors are rugged, reusable, and extremely sensitive, yet they can be low-cost, and consume little power. Another advantage in using the sensors is that they work in air, vacuum, or under liquid environments. A proposal for a handheld MEMS system is viewed in Fig. 15.



Fig. 15: A future handheld MEMS explosive detector [36]

2.1.8 ELECTRONIC NOSE (E-NOSE)

An electronic nose sensor, as its name indicates, is a device used to detect odors and flavors. The aim of this electronic sensor or e-sensor is to imitate human nose sensing capability. With the addition of nano-enhanced sensors and improvements in pattern recognition systems, such as neural network

technologies, e-sensors have undergone important shifts from a technical and commercial perspective. An electronic nose has the capability of detection and identification of miniature amounts of explosive chemicals. A detailed description of electronic noses and their application to explosive detection is reviewed in [37]. Fig. 16 shows an e-nose sensor.



Fig. 16: An e-nose sensor [14]

2.1.8.1 COMPONENTS OF AN ELECTRONICS NOSE

An electronic nose is basically composed of a chemical sensing system and a pattern recognition system. Each vapor introduced to the system produces a signature or fingerprint. Presenting many different chemicals to the sensor forms a database of fingerprints, which the pattern recognition system uses to identify each chemical. Sensor arrays offer several advantages over single sensors mentioning; better selectivity, multicomponent analysis, and analyte recognition. Some electronic noses use fluorescent polymers, fiber optic cables [38], arrays of different polymeric thin film sensors [39], gold nanoclusters deposited on interdigital micro electrode arrays [40], surface acoustic wave [41], [42], quartz crystal microbalance gas sensors, and micro electromechanical systems [43]. In future, these systems will replace some of the larger and more expensive detection devices. E-Nose can detect an electronic change of about 1 part per million [44]. Some of the e-nose techniques used will be presented in the coming sections of the review. [45] gives insight investigation of e-nose techniques used in explosive detection that can be of great value to readers. The components of an e-nose are shown in Fig. 17.

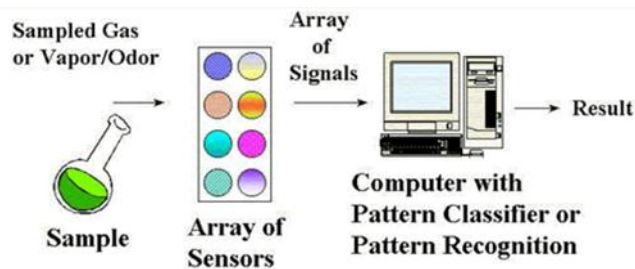


Fig. 17: Components of an e-nose [14]

2.1.8.2 AMPLIFYING CHROMOPHORE QUENCHING

Some electronic noses use fluorescent polymers as chemical detectors for explosives that react to volatile chemicals such as nitrogen based components. Commonly used fluorescence detection techniques usually measure a variation in fluorescence intensity or a wavelength shift that occurs when a single molecule of the analyte interacts with an isolated chromophore. In that case, only the chromophore that interacts directly with the analyte molecule is suppressed, whilst the remaining chromophores continue to fluoresce. Fig. 18 is a schematic of the basic sensor design used in explosive detection by electronic nose.

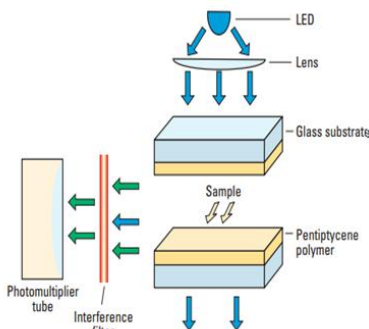


Fig. 18: Schematic of basic sensor design [45]

Swager et al [46], [47], [48], developed a polymer which reacts with nitrocompounds and thin films to reveal high fluorescence of TNT and DNT vapors emanating from landmines. The backbone of the polymer acts as a molecular wire enabling propagation of a quantum of electronic energy through the polymer chain. The sensory elements of the detection system are made up of thin films coated into a substrate.

2.1.8.3 FIBER OPTICS AND BEADS

For the sake of imitating a biological nose, a detector with millions of sensors is required. Walt et al [49], [50], [51], [52], presented an explosive sniffer that uses a sensor array of fiber optic cables. The sniffer is used to sample the air and watch for a color change of the sensor. Each sensor produces a different reaction for the same chemical. Hence, each odor creates a different pattern that can be stored on a computer database.

Fig. 19 shows three test tubes A, B, and C each containing a different type of polymer sensor suspended in a solution. A combination of them is formed by mixing the three constituents and a new compound is formed. A drop of the mixture is placed onto the distal tip of an etched imaging fiber. Consequently, beads rest in random localizations through the well array. They are identified by their characteristic response to a test vapor pulse. The beads are self-encoded and the signal of each bead is used to identify it and map its position in the array

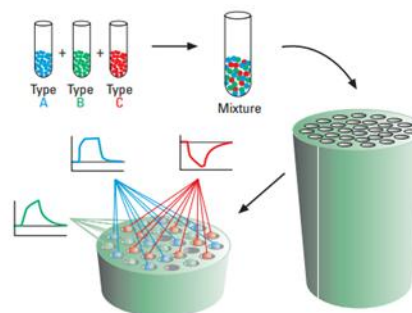


Fig. 19: Self encoded bead array concept [45]

2.1.8.4 POLYMERIC THIN FILMS

Lewis et al [53], [54], [55], developed a new type of electronic nose based upon an array of different polymeric thin film. It is based upon multisensing principle, where individual sensors are not specific to any one compound. Each detector of the sensor array consists of a conductive carbon black mixed with a non-conducting polymer.

The detector materials are deposited as thin films on an alumina substrate across each of two electrical leads to create conducting chemiresistors. Detector is exposed to an analyte vapor which allows polymer to act as a sponge and absorb the analyte. When the analyte is removed, the polymer sponge returns to its original configuration, the film shrinks, and the conductive pathways are reestablished. The baseline resistance (R baseline) of the device is measured while a representative background vapor flows over the array. The response from the chemiresistor during exposure to an analyte is measured as a relative resistance change ($\Delta R/R$ baseline). Fig. 20 reveals the response of a collection of incrementally different sensors used to generate a complex pattern or fingerprint, characteristic of a given analyte.

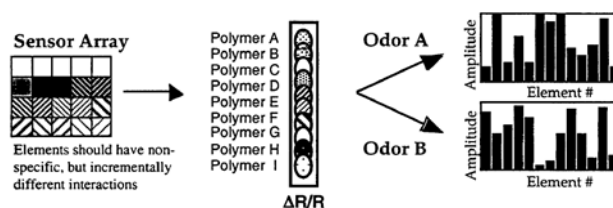


Fig.20: Patterns produced by an array of broadly responsive vapor detectors [56]

2.1.8.5 GOLD NANOCCLUSERS

A new nanometer scale, low power and solid state device is being utilized for the detection of explosives. This chemical vapor sensor is composed of nanometer sized gold particles encapsulated by monomolecular layers of alkanethiol surfactant deposited as thin films on interdigitated microelectrodes as shown in Fig. 21.

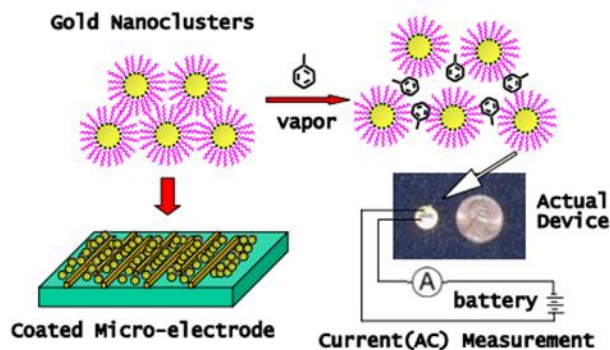


Fig. 21: A picture showing a gold nanocluster [60]

Jiang *et al* [57], described a simple colorimetric visualization of TNT. It is based on the interaction between TNT and primary amines named cysteamines. The cysteamine acts as a stabilizer to the gold nanoparticles (Au NP). Depositing TNT into the aqueous solution caused aggregation of the amine covered Au NPs which resulted in a color change from red to violet. Dasary *et al* [58] described a Surface Enhanced Raman Scattering (SERS) probe coated with gold nanoparticle cysteine conjugates; this system was able to form aggregating Meisenheimer complexes within water in the presence of TNT. A similar approach was taken by Yang *et al* in [59] using functionalized silver nanoparticles coated on silver molybdate nanowires.

2.9 OPTICAL TRACE DETECTION METHOD

2.9.1 ULTRA VIOLET-VISIBLE_NEAR_INFRARED (UV-VIS-NIR) SPECTROSCOPY

UV-VIS-NIR, also called Differential Reflectometry (DR), measures the differential reflection from materials at multiple wavelengths. In [61], Ultra Violet (UV) light sweeps two adjacent zones with reflectivities R_1 and R_2 on a piece of luggage placed on a moving conveyor belt as shown in Fig. 22. Reflected light is collected using spectrograph and CCD (Charge Couple Device) camera. A computer processes the resulting data and produces in turn a differential reflection spectrum. This technique is fast, can potentially scan large quantities of parcels or luggage for surface explosives threads with a fairly sensitive level.

Hatab *et al* [62], developed a project using Raman Spectroscopy (SERS) as the interaction process of inelastic scattering of photons by molecules of a substance. The Raman spectrum consists of bands shifted with respect to the line of exciting radiation. This shift and shape of spectral bands are the fingerprints of detected material.

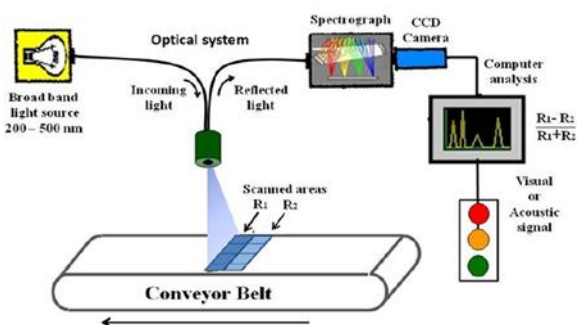


Fig. 22: Schematic representation of a DR system [61]

2.9.2 PHOTO ACOUSTIC SPECTROSCOPY (PAS)

PAS is a form of spectroscopy that uses sound to identify sample components. It is a part of a class of photothermal techniques, in which an incoming light beam is absorbed and affects the thermal state of the sample. However, if the incoming light is modulated, the sample warms and cools in a cycle. If the cycle is so fast, that the sample does not have time to expand and contract in response to the modulated light, a change in pressure develops. This pressure wave can lead to the production of a sound wave [63].

Fig. 23 shows a general setup for the photoacoustic spectroscopy of a gas sample. When a species absorbs some of the incoming light, it increases translation energy of the gas particles and allows their heating [64]. Varying the wavelength of the incoming light will change the amount of light absorbed. The amount of pressure changes also and accordingly the amount of sound produced. One advantage of PAS is that it can be performed on all phases of matter. A disadvantage can be noted as a result of narrow laser light bandwidth, where the analyte molecule must absorb some light from the source for the sake of detection.

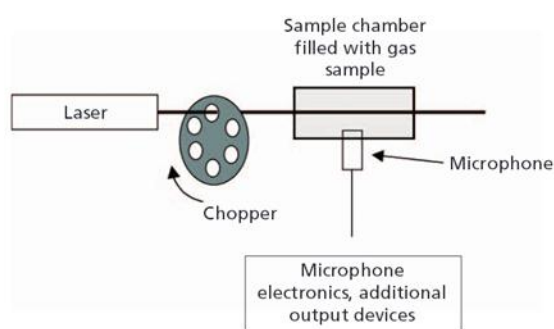


Fig. 23: Experimental setup that shows PAS performance on a gas [64]

2.9.3 CAVITY RING DOWN SPECTROSCOPY

This technique is based upon measurement of absorption rate rather than magnitude of absorption of a light pulse. A short pulse of light is inserted into a resonant cavity which is surrounded by highly reflective mirrors. When sufficient radiation is build up within the cavity, laser is turned off and exponential decay for light intensity is measured as a function of time. The decay time for an empty cavity is then compared with one containing the sample. The molecular absorbance and hence concentration can be derived from the rate of decay [65 -66].

Ramos and Dagdigan [67], described a study into the use of ultra-violet CRDS as a means to improve on the low sensitivities related to infra-red CDRS. The issue, however, is that this technique is unable to decisively identify specific samples due to its poor selectivity in the 240-260 nm spectral range [67].

A typical experimental setup for CRDS is shown in Fig. 24. The ring down cavity is formed by two planoconcave mirrors placed at a distance slightly less than twice their radius of curvature. The mirrors are coated for an optimum reflectivity in the desired wavelength range. The mirrors often act at the same time as windows for the closed cell, which contains the specimen to be studied. Photo Multiplier Tube (PMT) is used to ensure that all transverse modes are detected [68]. The output signal is then amplified and recorded using a fast and high resolution digitizer through General Purpose Interface Bus (GPIB).

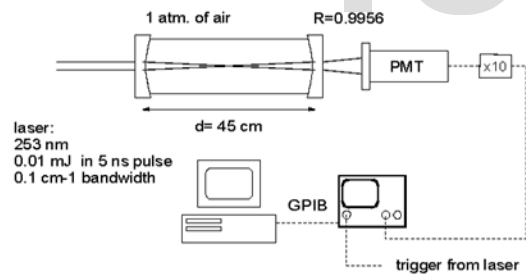


Fig. 24: Scheme for the experimental setup of CRDS [68]

2.9.4 LIGHT DETECTION AND RANGING (LIDAR)

LIDAR is the acronym of Light Detection and Ranging and started with the innovation of laser. It is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. A narrow laser beam is used to map physical features with very high resolution. The structure of LIDAR system consists of transmitting beam, receiving optics and signal processing.

One of the adequate applications of the inline type LIDAR is a Raman LIDAR [69]. It is developed for the detection of hydrogen leak gas. The hydrogen concentration is estimated by calculating the ratio between the nitrogen echo and hydrogen echo intensities. The receiving characteristics coincided well with the results estimated on the optical designs and in

the observation range. The compact Raman LIDAR estimates low hydrogen concentration in the order less than 1%. Fig. 25 shows Raman LIDAR setup.

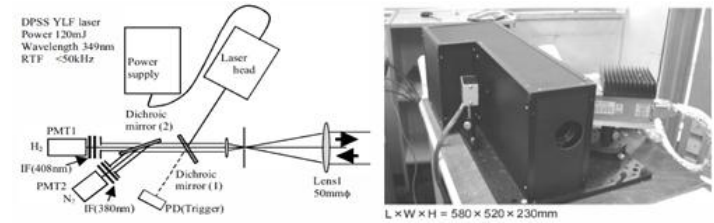


Fig. 25: Compact Raman LIDAR for hydrogen gas detection [69]

2.9.4 DIFFERENTIAL ABSORPTION LIDAR (DIAL)

DIAL is a technique for the remote sensing of atmospheric gases. DIAL lasers transmit into the atmosphere pulses of radiation at two wavelengths: one of which is absorbed by the gas to be measured and the other is not. The difference between the return signals from atmospheric backscattering of the absorbed and non-absorbed wavelengths is used as a direct measure of the concentration of the absorbing species.

A DIAL system that is capable of measuring natural gas pipeline leaks as an aircraft flies over the surveyed pipeline location is introduced in [70]. The DIAL is deployed in an aircraft so that long segments of pipeline can be rapidly surveyed. Fig. 26 shows an example of pipeline leak detection. DIAL sensor has greatly advanced the capability for remote detection of trace concentrations of gases.

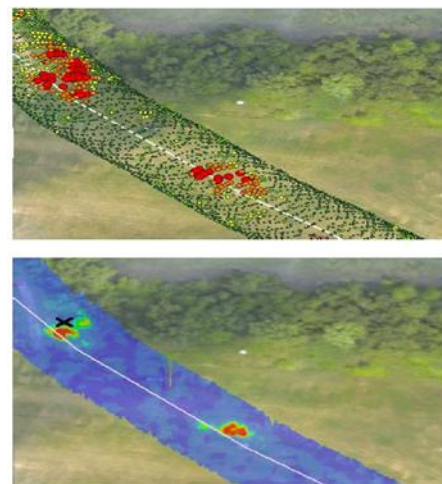


Fig. 26: Leakage detected in a pipe line using a DIAL [70]

2.10 BIOSENSORS

2.10.1 BIOSENSOR DEFINITION

The most commonly used definition of a biosensor is: a self-contained analytical device that incorporates a biologically active material in intimate contact with an appropriate transduction element for the purpose of detecting (reversibly and selectively) the concentration or activity of chemical species in any type of sample [71]. The first biosensor, an enzyme-based glucose sensor, was developed by Clark and Lyons [72]. Since then, hundreds of biosensors have been developed in many research laboratories around the world [73], [74], [75], [76]. Several research papers and books about biosensors are published reviewing the principles of operation and fabrication in addition to potential applications in food and agricultural industries in particular [77]. Fig. 27 shows a biosensor in operation mode on an analyte.

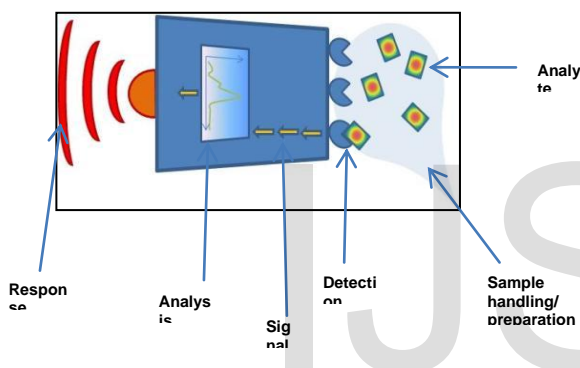


Fig. 27: Biosensor acting on an analyte [14]

2.10.2. COMPONENTS OF BIOSENSOR

A biosensor consists of two components: a bioreceptor and a transducer. The bioreceptor is a biomolecule that recognizes the target analyte whereas the transducer converts the recognition event into a measurable signal. The uniqueness of a biosensor is that the two components are integrated into one single sensor. The simplicity and the speed of measurement are the main advantages of a biosensor.

2.10.3. CONSIDERATIONS IN BIOSENSOR DEVELOPMENT

Once a target analyte is identified, the major tasks in developing a biosensor involve [78]:

- Selecting a bioreceptor molecule
- Selecting a transducer
- Designing a biosensor considering measurement range, linearity, and minimization of interference, and
- Packaging of biosensor

2.10.4 REQUIREMENTS FOR BIOSENSORS

To be commercially successful, a biosensor has to meet the general requirements of commercial sensors [78]. These are:

- Accuracy and repeatability
- Sensitivity and resolution
- Testing and calibration
- Reliability and self checking
- Physical robustness and service requirements
- Safety and speed of response
- Dynamic range and user acceptability, and
- Insensitivity to temperature, electrical or environmental variations

2.10.5 HISTORY OF BIOSENSORS

Table 1, shown below, includes the history of biosensors from year 1956 reaching current year [79].

Table 1: History of biosensors

Year	Historical Accomplishment
1956	Clark published his definitive paper on the oxygen electrode
1962	First description of a biosensor: an amperometric enzyme electrode for glucose (Clark)
1969	Guilbault and Montalvo – First potentiometric biosensor: urease immobilized on an ammonia electrode to detect urea
1970	Bergveld – ion selective Field Effect Transistor (ISFET)
1975	Lubbers and Opitz described a fiber-optic sensor with immobilized indicator to measure carbon dioxide or oxygen
1976	First bedside artificial pancreas (Miles)
1980	First fiber optic pH sensor for in vivo blood gases (Peterson)
1983	First surface plasmon resonance (SPR) immunosensor
1984	First mediated amperometric biosensor: ferrocene used with glucose oxidase for glucose detection
1990	SPR based biosensor by Pharmacia BIAcore
1996	Launching of Glucocard
1998	Blood glucose biosensor launch by LifeScanFastTake
Current	Quantum dots, nanoparticles, nanowire, nanotube, etc

3. COMMERCIALLY AVAILABLE SELECTION METHODOLOGIES

Table 2, shown below, summarizes the specs for electronic/chemical trace detection methods [11]. The cost is as reported in [11] which is subject to changes with years and innovation of new technologies

Table 2: Commercially available electronic/chemical trace detection equipment

	Portability	Ease of Use	Throughput Rate	Sample Collection	Cost
IMS	handheld, bench top, and portals	operated by a person with only a few hours of training	two to three samples per minute	vapor and particle	handheld: \$19,000 to \$30,000 benchtop: \$40,000 to \$50,000 portals: \$130,000 to \$750,000
CL	handheld and portable systems	operated by a person with only a few hours of training	three samples per minute	vapor and/or particle	handheld: \$18,000 to \$20,000 portable: \$50,000 to \$60,000
Thermo-Redox	handheld systems	operated by a person with only a few hours of training	two to three samples per minute	vapor and/or particle	handheld: \$8,000 to \$20,000
SAW	portable systems	vendor offers a training course	one or more samples per minute	vapor sampling	portable: \$21,000 to \$25,000
MS	portable systems	technical ability or experience is necessary	3 samples per hour	NA	portable: \$135,000 to \$215,000

Other in the market products can be also listed mentioning Vreeland Direct Reading Spectroscope, where the specimen is illuminated by continuous spectra of light and the recordings are saved on transparent films that are embedded inside the instrument. Comparison of the obtained film takes place with a master film and allows identification of the explosive substance [80]. On the other hand, EX-Detect XD-2 is a color indicator for explosives it uses colorimetric screening for detection of explosives. A swipe is rubbed over the surface to be tested and then it is placed into a clamp at the center of the detector and power is turned on. Two solutions are present; dispensing solutions in a certain manner and then heating allows color change as explained thoroughly in the reference [81] and hence detection.

Seeker XDU is an easy to use, light weight colorimetric device. It is made up of seven button keypad that allows navigation on the LCD screen of the XDU. Moving to the operation, a swipe card is to be selected in the first place and the sample should be rubbed against it. After that, bar code scanning takes place prior to inserting the card into the device. Finally, result analyses can be witnessed on graph [82]. Fido On Board [83] is based upon amplifying chromophore quenching where the sensing element or fluorescent material is placed inside the detector. Air sample is passed into the sys-

tem and hence affecting fluorescence intensity. The Fido system is matched to a communication box and mounted on the surface of a robot to keep the operator at far away distance. Results are displayed on the robot control unit for the sake of analyses and detection.

3 COMMON EXPLOSIVE TYPES

Explosives are chemical or nuclear materials which can undergo pretty fast self-propagating decomposition which result in the production of heat or development of abrupt pressure effect. Explosives require a stimulus to liberate energy and hence produce explosion. The various stimuli to which every explosive material responds separately allow classification of explosives into several types. Fig. 28 shows a tree representing explosive types. Explosives are mainly classified as low and high explosives. Low explosives burn at relatively low rates of the chemical reaction in the range of cms, whereas high explosives detonate at velocities of kms [84], [85].

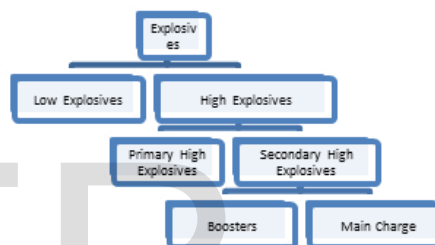


Fig. 28: Explosive Types [84]

Low explosives or propellants contain oxygen for combustion which in turn produce a gas that forms an explosion. Explosives belonging to this category vary widely in the rate at which they deliver energy mentioning black powder, smokeless powder, and flash powder [86].

High explosives are subdivided into two groups: primary explosives and secondary explosives. Primary explosives are highly susceptible to initiation and are often referred as initiating explosives because they can be used to ignite secondary explosives. They explode when heated or exposed to shock. Materials differ in the amount of heat and brisance they produce during explosion. Examples of primary explosives include lead azide, lead styphnate, mercury fulminate, Diazodinitrophenol (DDNP), tetrazenelead salts of picric acid and trinitroresorcinol, m-nitrophenyldiazonium perchlorate, tetracene, nitrogen sulfide, copper acetylide, fulminating gold, nitrosoguanidine, mixtures of potassium chlorate with red phosphorus or with various other substances, the tartrates and oxalates of mercury and silver [87].

Secondary explosives are insensitive to heat, friction, and shock. They are often called base explosives or bolstering explosives and are formulated to detonate only under specific circumstances. Secondary explosives can be categorized into melt-pour explosives which are based on nitroaromatics, such as trinitrotoluene (TNT), dinitrotoluene (DNT) and plastic bonded explosives which are based on a binder and crystalline

explosive, such as hexahydro-1,3,5 trinitroazine (RDX). One can also state tetryl, picric acid, nitrocellulose, nitroglycerin, liquid oxygen mixed with wood pulp, fuming nitric acid mixed with nitrobenzene, compressed acetylene and cyanogen, nitroguanidine, ammonium nitrate and perchlorate as secondary explosives [88].

4 EXPLOSIVES DETECTED BY EACH SENSOR TYPE

Comparative assessment of sensor performance for detection of explosives is represented in Table 3. Useful information can also be found in review paper [89] and in references [90], [91], [92].

Table 3: Sensor types and the corresponding detected explosives

Method	Sensor Type	Explosives detected	
Electronic/ Chemical Sensors	IMS	TNT, RDX	
	CL	Capable of detecting all types of Nitro based explosives, such as TNT, Dynamite, PETN, Semtex, RDX, C-4, Nitroglycerine, EGDN, DMNB, Plastic Explosives, and ICAO Taggants, TATP, HMDX and various peroxide explosives	
	ECD	Capable of detecting all types of Nitro based explosives, such as TNT, Dynamite, PETN, Semtex, RDX, C-4, Nitroglycerine, EGDN, DMNB, Plastic Explosives, and ICAO Taggants, TATP, HMDX and various peroxide explosives	
	Thermo-redox	explosives containing NO ₂ molecules only	
	SAW	TNT, 2,4-DNT	
	MS	TNT, DNT	
	MEMS	TNT, DNT, RDX	
	E-Nose	TNT, 2,4-DNT	
	Optical Sensors	UV-VIS-NIR	TNT, RDX, PETN
		PAS	TNT, RDX
CRDS		TNT, triacetone triperoxide [TATP], RDX, PETN, and Tetryl	
LIDAR		RDX, TNT, and PETN, as well as nitrate- and chlorate-containing materials	
DIAL		RDX, TNT, and PETN, as well as nitrate- and chlorate-containing materials	
Biosensors	Biosensors	TNT, RDX, PETN	

An important characteristic of each explosive type is sensitivity. Table 4 below shows Electronic/ Chemical, Optical, and Biosensor sensitivities depending upon field of application and explosive material detected [87].

Table 4: Sensitivity of trace detection of explosives

Method	Application field	Detected Explosive	Sensitivity
Electronic/Chemical	Soil samples	RDX	0.12ppm
Electronic/Chemical	Marine water	TNT	25ppb
Electronic/Chemical	Laboratory samples	DNB and TNT	60ppb for both
Electronic/Chemical	Soil extract and ground water	RDX, TNT, 2,4-DNT, 2,3-DNT, 2,4-DNT	RDX 0.2ppm, TNT 0.11ppm, 2,4-DNT 0.15ppm, 2,3-DNT 0.16ppm, 2,3-DNT 0.15ppm
Optical	Soil Samples	DNT	120ppb
Optical	Marine water	TNT	250ppb
Optical	Laboratory samples	TNT and RDX	450fmol for TNT, 1ppb for RDX
Optical	Soil extract and ground water	TNT and RDX	0.1ppm

5 COMPARISON OF VARIOUS TRACE DETECTION TYPES

Each technology of the above mentioned trace explosive detection techniques has its own advantages and disadvantages. The electronic/chemical sensors are sensitive and rapid in addition to being inexpensive, but they suffer from low selectivity meaning that different electronic/chemical sensors might be required for different materials. For instance, IMS systems have attractive features due to their moderate cost, ease of use, and portability. IMS instruments in contrast contain radioactive material as ionizing source and have low selectivity [93]. CL method contains no radioactive source whilst inability to detect explosives that are not nitro-based. ECD detector has a fast response time, moderate sensitivity, small size, low cost, and light weight. Two problems arise with ECD which are the need for radioactive ionization source and the presence of the carrier gas which can put limits on field applications [94]. Thermo-redox contains no radioactive source yet detects NO₂ groups only [93]. No radioactive source exists in SAW/GC either but its major disadvantage is being non-specific, hence the presence of other chemicals will make detection of explosives more complex [93]. MS detectors do not utilize radioactive source and are specific with the drawback of long sample analysis time [93]. MEMS have the pros of high reproducibility with cheap manufacture cost and cons of small test masses and inertial forces as the case of accelerometers [95]. The biggest benefit of E-Nose relies in calibration simplicity on the other hand; they are severely affected by environmental conditions mentioning temperature and humidity [96].

Optical trace detection methods generally have high sensitivity and fast response but they could falsely detect the composition of the material in question. UV-VIS-NIR or DR Spectroscopy is characterized by fast sample analysis whilst confusing optical constants [97]. PAS can be applied to all phases of matter but limitation exists in narrow laser bandwidth [98]. CRDS measurements are dependent upon rate of signal decay and are insensitive to laser power fluctuations. Its main disadvantage is being unspecific to a certain point in the plasma [99]. LIDAR reduces costs for field measurements over wide areas and helps locate useful field data positions though it requires specialized skills and software for operation [100]. DIAL has the ability of attaining direct measurements of certain gases irrespective of day, time, or season. A potential drawback is the amount of energy needed to illuminate the desired target [101].

Biosensors, on the other hand, have a complicated design in terms of their integration of a biological material on top of an appropriate transduction element. However, the design of the biological material (e.g. antibody) itself is easier with the possibility of replacing it on the same transduction element to detect a different material composition.

6 CONCLUSION AND FUTURE WORK

The presented work focuses on a very important problem of hazard for people, due to the danger of terroristic activities as well as of breakdowns in the production of explosives or dangerous materials. It is evident that almost all presented techniques in this review have undergone significant changes to improve one or more aspects of their working practices including, for example: sensitivity, specificity, cost, and ease of use. Further advancement will be necessary to provide a system that incorporates all aspects of an ideal explosive identification technique due to the inherent issues that are associated with low volatility of explosive vapors, concealment, interferences and the actual damage caused by a false response.

A system for the remote detection and localization of landmines will be designed in the near future. This system will be based on the use of wireless biosensors. Several (usually a large number of) biosensors shall randomly be deployed in a field with suspected existence of landmines. The biosensors will be equipped with wireless functionality, including an antenna. The biosensors will form a sensor network, and using some routing algorithm, they will relay their location information to a Data Processing Unit (DPU), e.g. a computer, located outside the field, which will determine the location of each biosensor using localization algorithms. The sensors will later register and route their readings of the explosive particles concentrations to the DPU. After that, remote explosion for the materials will take place to remove the threat of mines without human interaction.

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REFERENCES

- [1] M. Nambayah and T. Quickenden, "A Quantitative Assessment of Chemical Techniques for Detecting Traces of Explosives at Counter-Terrorist Portals", *Talanta*, vol. 63, pp. 461-467, 2004.
- [2] S. Singh and M. Singh, "Explosives Detection Systems (EDS) for Aviation Security: A Review", *Signal Processing*, vol. 83(1), pp. 31-55, 2003.
- [3] D. S. Moore, "Recent Advances in Trace Explosives Detection Instrumentation", *Sensing and Imaging: An International Journal*, vol. 8(1), pp. 9-38, 2007.
- [4] U. Tomsic, "Detection of Explosives: Dogs vs. CMOS Capacitive Sensors", *Department of Physics, University of Ljubljana*, March 2013.
- [5] J.W. Ternee, "Integration of the Human, Canine, Machine Interface for Explosives Detection", *Proceedings of the 1st International Symposium on Explosive Detection Technology*, pp. 891-902, Atlantic City, NJ, 1991.
- [6] M. Krausa and A.A. Reznev, "Vapour and Trace Detection of Explosives for Anti-Terrorism Purposes", *Kluwer Academic Publishers*, Moscow, Russia, March 2003.
- [7] J. Yinon and S. Zitrin, "Modern Methods and Applications in Analysis of Explosives", *John Wiley & Sons Ltd*, West Sussex, England, April 1996.
- [8] J.S. Caygill, F. Davis, and S.P.J. Higson, "Current Trends in Explosive Detection Techniques", *Talanta*, Vol. 88, pp. 14-29, January 2012.
- [9] C.A. Munson, J. L. Gottfried, F.C. De Lucia, K.L. McNesby, and A.W. Miziolek, "Laser-Based Detection Methods for Explosives", September 2007.
- [10] R.G. Smith, N. D'Souza, and S. Nicklin, "A Review of Biosensors and Biologically-Inspired Systems for Explosives Detection", *Analyt*, vol. 133(5), pp. 571-584, 2008.
- [11] L. Thiesan, D. Hannum, D.W. Murray, and J.E. Parmeter, "Survey of Commercially Available Explosives Detection Technologies and Equipment", Report written for the National Law Enforcement and Correction Technology Center, a Program of the National Institute of Justice, U.S. Department of Justice, November 2004.
- [12] Z. Bielecki, J. Janucki, A. Kawalec, J. Mikołajczyk, N. Pałka, M. Pasternak, T. Pustelny, T. Stacewicz, and J. Wojtas, "Sensors and Systems for the Detection of Explosive Devices-An Overview", *Metrolgy and Measurement Systems*, Vol. XIX (1), pp. 3-28, 2012.
- [13] R.G. Ewing, D.A. Atkinson, G.A. Eiceman, and G.J. Ewing, "A critical Review of Ion Mobility Spectrometry for the Detection of Explosives and Explosive Related Compounds", *Talanta*, Vol. 53 (3), pp. 515-529, May 2001.
- [14] <http://www.sepscience.com/Information/Archive/MS-Solutions/1473-/MS-Solutions-25-Ion-Mobility-Spectrometry-A-Primer>
- [15] M. Martin, M. Crain, K. Walsh, R.A. McGill, E. Houser, J. Stepnowski, S. Stepnowski, H. Wu, and S. Ross, "Microfabricated Vapor Preconcentrator for Portable Ion Mobility Spectroscopy", *Sensors and Actuators B: Chemical*, Vol. 126 (2), pp. 447-454, October 2007.
- [16] M.J. Waltman, P. Dwivedi, H.H. Hill Jr., W.C. Blanchard, and R.G. Ewing, "Characterization of a Distributed Plasma Ionization Source (DPIS) for Ion Mobility Spectrometry and mass Spectrometry", *Talanta*, Vol. 77 (1), pp. 249-255, June 2008.
- [17] M. Tabrizchi and V. Ilbeigi, "Detection of Explosives by Positive Corona Discharge Ion Mobility Spectrometry", *Journal of Hazardous Materials*, Vol. 176 (1-3), pp. 692-696, April 2010.
- [18] <https://www.ncjrs.gov/pdffiles1/nij/178913.pdf>
- [19] <http://www.hindawi.com/journals/isrn/2013/230858/>
- [20] <http://repositorio.ucp.pt/bitstream/10400.14/3373/3/An%20overview%20on%20flow%20methods%20for%20the%20chemiluminescence.PDF>.
- [21] www.scribd.com/doc/56952947/38/The-Electron-Capture-Detector (2011).

- [22] K. Gut, A. Zakrzewski, and T. Pustelny, "Sensitivity of Polarimetric Waveguide Interferometer for Different Waveguides", *ActaPhysicaPolonica A*, vol. 118, pp.1140-1142, 2010.
- [23] <http://www.ecs.umass.edu/eve/facilities/equipment/Agilent6890ser/0340%20ECD%20detector.pdf>.
- [24] <http://sensingchange.chemheritage.org/sensing-change/instruments/electron-capture-detector>
- [25] A.S. Travis, "Detecting Chlorinated Hydrocarbon Residues: Rachel Carson's Villains", *Ambix*, vol. 59 (2), pp. 109-130, July 2012.
- [26] Z. Bielecki, J. Janucki, A. Kawalec, J. Mikolajczyk, N. Palka, M. Pasternak, T. Pustelny, T. Stacewicz, and J. Wojta, "Sensors and Systems for the Detection of Explosive Devices-An Overview", *Metrology and Measurement Systems*, vol. 19 (1), pp. 3-28, January 2012.
- [27] H. Wohltjen and R. Dessy, "Surface Acoustic Wave Probe for Chemical Analysis. I. Introduction and Instrument Description", *Analytical Chemistry*, vol. 51 (9), pp. 1458-1464, August 1979.
- [28] S.J. Toal and W.C. Trogler, "Polymer Sensors for Nitroaromatic Explosives Detection", *Journal of Materials Chemistry*, vol. 16, pp. 2871-2883, 2006.
- [29] E.J. Staples, "Detecting Chemical Vapours from Explosives Using the zNose®, an Ultra-High Speed Gas Chromatograph", *NATO Science Series II: Mathematics, Physics, and Chemistry*, vol. 159, pp. 235-248, 2004.
- [30] G.W. Watson, W. Horton, and E.J. Staples, "Vapor Detection Using SAW Sensors", *Proceedings of the 1st International Symposium on Explosive Detection Technology*, pp. 589-603, Atlantic City, NJ, 1991.
- [31] E.J. Staples and G.W. Watson, "A GAS Chromatograph Incorporating an Innovative New Surface Acoustic Wave (SAW) Detector", *Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy*, Paper 1583CP, New Orleans, LA, 1998.
- [32] R.G. Cooks, Z. Ouyang, Z. Takats, and J.M. Wiseman, "Ambient Mass Spectrometry", *Science Magazine*, vol. 311 (5767), pp. 1566-1570, March 2006.
- [33] Z. Takats, J.M. Wiseman, B. Gologan, and R.G. Cooks, "Mass Spectrometry Sampling Under Ambient Conditions with Desorption Electrospray Ionization", *Science Magazine*, vol. 306 (5695), pp. 471-473, October 2004.
- [34] L.A. Pinnaduwege, A. Wig, D.L. Hedden, A. Ghel, D. Yi, T. Thundat, and R.T. Lareau, "Detection of Trinitrotoluene via Deflagration on a Microcantilever", *Journal of Applied Physics*, vol. 95 (10), pp. 5871-5875, May 2004.
- [35] <http://www.azonano.com/article.aspx?ArticleID=1927>.
- [36] Hand-Held MEMS Explosive Detector. Document available at: www.virtualacquisitionshowcase.com/document/805/briefing.pdf
- [37] L.C. Pacheco-Londoño, W. Ortiz-Rivera, O.M. Primera-Pedrozo, and S.P. Hernández-Rivera, "Vibrational Spectroscopy Standoff Detection of Explosives", *Analytical and Bioanalytical Chemistry*, vol. 395, pp. 323-335, July 2009.
- [38] S.E. Stitzel, L.J. Cowen, K.J. Albert, and D.R. Walt, "Array-to-Array Transfer of an Artificial Nose Classifier", *Analytical Chemistry*, vol. 73 (21), pp. 5266-5271, November 2001.
- [39] M.E. Koscho, R.H. Grubbs, and N.S. Lewis, "Properties of Vapor Detector Arrays Formed Through Plasticization of Carbon Black-Organic Polymer Composites", *Analytical Chemistry*, vol. 74 (6), pp. 1307-1315, March 2002.
- [40] H. Wohltjen and A.W. Snow, "Colloidal Metal-Insulator-Metal Ensemble Chemiresistor Sensor", *Analytical Chemistry*, vol. 70 (14), pp. 2856-2859, May 1998.
- [41] T.C. Pearce, S.S. Schiffman, H.T. Nagle, and J.W. Gardner, "Handbook of Machine Olfaction- Electronic Nose Technology", Wiley-VCH, Weinheim, Germany, November 2003.
- [42] W.P. Jakubik, M. Urbanczyk, E. Maciak, and T. Pustelny, "Bilayer Structures of NiOx and Pd in Surface Acoustic Wave an Electrical Gas Sensor Systems", *ActaPhysicaPolonica A*, vol. 116 (3), pp. 315-320, 2008.
- [43] A. Murugarajan and G. L. Samuel, "Measurement, Modeling and Evaluation of Surface Parameter Using Capacitive-Sensor-Based Measurement System", *Metrology and Measurement Systems*, vol. 18 (3), pp. 403-418, October 2011.
- [44] http://science1.nasa.gov/science-news/science-at-nasa/2004/06oct_enose/
- [45] J. Yinon, "Detection of Explosives by Electronic Noses", *Analytical Chemistry*, Vol. 75 (5), pp. 98-105, March 2003.
- [46] J.-S. Yang and T.M. Swager, "Porous Shape Persistent Fluorescent Polymer Films: An Approach to TNT Sensory Materials", *Journal of the American Chemical Society*, vol. 120, pp.5321-5322, 1998.
- [47] C.J. Cumming, C. Aker, M. Fisher, M. Fok, M.J. la Grone, D. Reust, M.G. Rockley, T.M. Swager, E. Towers, and V. Williams, "Using Novel Fluorescent Polymers as Sensory Materials for Above-Ground Sensing of Chemical Signature Compounds emanating from Buried Landmines," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39 (6), pp. 1119-1128, June 2001.
- [48] A. Rose, C.G. Lugmair, and T.M. Swager, "Excited-State Lifetime Modulation in Triphenylene-Based Conjugated Polymers", *Journal of the American Chemical Society*, vol. 123, pp. 11298-11299, 2001.
- [49] K.L. Michael, L.C. Taylor, S.L. Schultz, and D.R. Walt, "Randomly Ordered Addressable High-Density Optical Sensor Arrays", *Analytical Chemistry*, vol. 70 (7), pp.1242-1248, April 1998.
- [50] T.A. Dickinson, K.L. Michael, J.S. Kauer, and D.R. Walt, "Convergent, Self-Encoding Bead Sensor Arrays in the Design of an Artificial Nose", *Analytical Chemistry*, vol. 71(11), pp. 2192-2198, June 1999.
- [51] K.J. Albert, M.L. Myrick, S.B. Brown, D.L. James, F.P. Milanovich, and D.R. Walt, "Field-Deployable Sniffer for 2, 4-Dinitrotoluene", *Environmental Science & Technology*, vol. 35 (15), pp. 3193-3200, August 2001.
- [52] S.E. Stitzel, L.J. Cowen, K.J. Albert, and D.R. Walt, "Array-to-Array Transfer of an Artificial Nose Classifier", *Analytical Chemistry*, vol. 73 (21), pp. 5266-5271, November 2001.
- [53] M.S. Freund and N.S. Lewis, "A Chemically Diverse Conducting Polymer-Based Electronic Nose", *Proceedings of the National Academy of Sciences of the United States of America*, vol. 92 (7), pp. 2652-2656, 1995.
- [54] B.J. Doleman, E.J. Severin, and N.S. Lewis, "Trends in Odor Intensity for Human and Electronic Noses: Relative Roles of Odorant Vapor Pressure vs. Molecularly Specific Odorant Binding", *Proceedings of the National Academy of Sciences of the United States of America*, vol. 95 (10), pp. 5442-5447, May 1998.
- [55] G.A. Sotzing, S.M. Briglin, R.H. Grubbs, and N.S. Lewis, "Preparation and Properties of Vapor Detector Arrays Formed Form Poly (3,4-Ethylenedioxy) Thiophene-Poly (Styrenesulfonate)/Insulating Polymer Composites, *Analytical Chemistry*, vol. 72 (14), pp. 3181-3190, July 2000.
- [56] N.S. Lewis, R.M. Goodman, and R.H. Grubbs, "A Conducting Polymer-Based Electronic Nose for Landmine Detection", *Final report submitted to the Defense Advanced Research Projects Agency (DARPA), Advanced Technology Office (Regina Dugan), Arlington, VA, October 2001.*
- [57] Y. Jiang, H. Zhao, N. Zhu, Y. Lin, P. Yu, and L. Mao, "A Simple Assay for Direct Colorimetric Visualization of Trinitrotoluene at Picomolar Levels Using Gold Nanoparticles", *Angewandte Chemie*, vol. 120 (47), pp. 8729-8732, October 2008.
- [58] S.S.R. Dasary, A.K. Singh, D. Senapati, H. Yu, and P.C. Ray, "Gold Nanoparticle Based Label-Free SERS Probe for Ultrasensitive and Selective Detection of Trinitrotoluene", *Journal of the American Chemical Society*, vol. 131 (38), pp. 13806-13812, September 2009.
- [59] L. Yang, L. Ma, G. Chen, J. Liu, and ZQ. Tian, "Ultrasensitive SERS Detection of TNT by Imprinting Molecular Recognition Using a New Type of Stable Substrate", *Chemistry A European Journal*, Vol. 15 (42), pp. 12683-12693, November 2010.
- [60] R.R. Smardzewski, N.L. Jarvis, A.W. Snow, H. Wohltjen, and R.A. Mackay, "Metal-Insulator-Metal Ensemble (MIME) Chemical Detectors", *Proceedings of the 2004 NSTI Nanotechnology Conference and Trade Show*, vol. 3, pp. 163-164, Boston, MA, March 2004.

- [61] T. Dubroca, K. Vishwanathan, and R.E. Hummel, "The Limit of Detection for Explosives in Spectroscopic Differential Reflectometry", *Proceedings of the SPIE 8018, Chemical, Biological, Radiological, Nuclear, and Explosives (CBRNE) Sensing XII*, vol. 8018, Orlando, FL, April 2011.
- [62] N.A. Hatab, G. Eres, P.B. Hatzinger, and B. Gu, "Detection and Analysis of Yclotrimethylenetrinitramine (RDX) in Environmental Samples by Surface-Enhanced Raman Spectroscopy", *Journal of Raman Spectroscopy*, vol. 41 (10), pp. 1131–1136, October 2010.
- [63] <http://www.mtecpas.com/Docs/Photoacoustic%20Technology%20Overview.pdf>
- [64] D.W. Ball, "Photoacoustic Spectroscopy", *Spectroscopy Global Edition*, pp. 8-13, September 2006.
- [65] B.A. Paldus and A.A. Kachanov, "An Historical Overview of Cavity-Enhanced Methods", *Canadian Journal of Physics*, vol. 83 (10), pp. 975–999, October 2005.
- [66] G., R. Peeters, and G. Meijer, "Cavity Ring-Down Spectroscopy: Experimental Schemes and Applications", *International Review in Physical Chemistry*, vol. 19 (4), pp. 565–607, November 2000.
- [67] C. Ramos and P.J. Dagdigian, "Detection of Vapors of Explosives and Explosive-Related Compounds by Ultraviolet Cavity Ring-down Spectroscopy", *Applied Optics*, vol. 46 (4), pp. 620–627, 2007.
- [68] <http://onlinelibrary.wiley.com/doi/10.1002/9780470027318.a5602m/abstract>.
- [69] T. Shiina, "Optical Design and development of Near Range Compact Lidar", *SPIE Asia Communications and Photonics 2011*, November 2011.
- [70] C.R. Philbrick, D.M. Brown, A.H. Willitsford, P.S. Edwards, A.M. Wyant, Z.Z. Liu, C.T. Chadwick, and H. Hallen, "Remote Sensing of Chemical Species in the Atmosphere", *Proceedings of Fourth Symposium on Lidar Atmospheric Applications, as part of the 89th AMS Annual Meeting in Phoenix, Arizona*, January 2009.
- [71] M.A. Arnold and M.E. Meyerhoff, "Recent Advances in the Development and Analytical Applications of Biosensing Probes", *CRC Critical Review in Analytical Chemistry*, Vol. 20 (3), pp.149–196, 1988.
- [72] L.C. Clark Jr. and C. Lyons, "Electrode Systems for Continuous Monitoring Cardiovascular Surgery", *Annals of the New York Academy of Sciences*, vol. 102, pp. 29–45, October 1962.
- [73] E. Kress-Rogers, "Handbook of Biosensors and Electronic Noses", *CRC Press Inc.*, New York, 1997.
- [74] E. Kress-Rogers, "Instrumentation and Sensors for the Food Industry"; *Wood head Publishing Ltd*, Cambridge, England, 1998.
- [75] A.P.F. Turner, I. Karube, and G.S. Wilson, "Biosensors Fundamentals and Applications", *Oxford University Press*, Oxford, England, 1987.
- [76] R.D. Schmid and F. Scheller, "Biosensors, Applications in Medicine, Environmental and Process Control", *GBF Monographs, VCH Publishers*, New York, New York, 1989.
- [77] A. D. Dias, D. M. Kingsley, and D. T. Corr, "Recent Advances in Bioprinting and Applications for Biosensing", *Department of Biomedical Engineering*, NY 12180, USA, April 2014.
- [78] www.gatewaycoalition.org/files/Hidden/sensr/ch1/1_1f.htm
- [79] www.authorstream.com/Presentation/vipul_lukhi_sctet-505271-biosensor/
- [80] www.spectrex.com/html_files2/vreeland-spec.php
- [81] www.spectrex.com/html_files2/exp-detector.php
- [82] www.detectachem.com/seeker_xdu
- [83] <http://gs.flir.com/detection/explosives/fido-onboard>
- [84] http://lem.ch.unito.it/didattica/infochimica/2008_Esplosivi/Classificazione.html
- [85] <http://onlinelibrary.wiley.com/doi/10.1002/anie.199708001/abstract>
- [86] <http://webserver.dmt.upm.es/~isidoro/bk3/c15/Pyrotechnics.pdf>
- [87] S. Singh, "Sensors-An effective approach for the detection of explosives", *Journal of Hazardous Materials*, Vol. 144, pp. 15-28, February 2007.
- [88] D. Kalderis, A.L. Juhasz, R. Boopathy, and S. Comfort, "Soils Contaminated with Explosives: Environmental Fate and Evaluation of State-of-the-Art Remediation Processes", *Pure and Applied Chemistry*, vol. 83 (7), pp. 1407–1484, May 2011.
- [89] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, Y. Sun, "Sensitive Optical Biosensors for Unlabeled Targets: A review", *Analytica Chimica Acta*, vol. 620, issues 1-2, pp. 8–26, July 2008.
- [90] <http://www.nanowerk.com/spotlight/spotid=28691.php>
- [91] <http://www.dtic.mil/dtic/tr/fulltext/u2/a474060.pdf>
- [92] <http://www.dpl-surveillance-equipment.com/19021792200.html>
- [93] A.A. Fatah, R. D.Arcilesi, J. A. McClintock, C.H. Lattin, M. Helinski, and M. Hutchings, "Guide for the Selection of Explosives Detection and Blast Mitigation Equipment for Emergency First Responders", *U.S. Department of Homeland Security, Washington, DC*, February 2008.
- [94] J. Reno, R.C. Fisher, L. Robinson, N. Brennan, and J. Travis, "Guide for the Selection of Commercial Explosives Detection Systems for Law Enforcement Applications", *National Institute of Justice, U.S. Department of Justice*, Washington, DC, September 1999.
- [95] www.owl.net.rice.edu/~phys534/notes/week07_lectures.pdf
- [96] G. Sujatha, N. Dhivya, K. Ayyadurai, and D. Thyagarajan, "Advances in Electronic-Nose Technologies", *International Journal of Engineering Research and Applications (IJERA)*, vol. 2, pp.1541–1546, July-August 2012.
- [97] C.W. Shanley, "Use of the Differential Reflectometer in the Study of Thin Film Corrosion Products on Copper", *PhD Dissertation, University Of Florida*, 1977.
- [98] F.J.M. Harren, G. Cotti, J. Oomens, and S. te Lintel Hekkert, "Photo-acoustic Spectroscopy in Trace Gas Monitoring", *Encyclopedia of Analytical Chemistry*, pp. 2203–2226, 2000.
- [99] A.J. Orr-Ewing, "Pulsed and Continuous Wave Cavity Ring-Down Spectroscopy Probes of Chemical Vapour Deposition Plasmas", *School of Chemistry, University of Bristol*, England, September 2006.
- [100] <http://www.fs.fed.us/eng/rsac/documents/pdfs/0073-TIP1.pdf>
- [101] www.epa.gov/gasstar/documents/workshops/2005-annual-conf/brake.pdf