Army Requirements for Micro and Nanotechnology-Based Sensors in Weapons Health and Battlefield Environmental Monitoring Applications

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ABSTRACT

The Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) and the Army Research Laboratory (ARL) have initiated a joint advanced technology demonstration program entitled "Prognostics/Diagnostics for the Future Force (PDFF)" with a key objective of developing low or no power embedded sensor suites for harsh environmental monitoring. The most critical challenge of the program is to specify requirements for the embedded sensor suites which will perform on-board diagnostics, maintain a history of sensor data, and forecast weapon health. The authors are currently collaborating with the PDFF program managers and potential customers to quantify the requirements for remotely operated, micro/nano-technology-based sensors for a host of candidate weapon systems. After requirements are finalized, current micro/nanotechnology-based temperature, humidity, g-shock, vibration and chemical sensors for monitoring the out-gassing of weapons propellant, as well as hazardous gaseous species on the battlefield and in urban environments will be improved to meet the full requirements of the PDFF program. In this paper, performance requirements such as power consumption, reliability, maintainability, survivability, size, and cost, along with the associated technical challenges for micro/nanotechnology-based sensor systems operating in military environments, are discussed. In addition, laboratory results from the design and testing of a wireless sensor array, which was developed using a thin film of functionalized carbon nanotube materials, are presented. Conclusions from the research indicate that the detection of bio-hazardous materials is possible using passive and active wireless sensors based on monitoring the reflected phase from the sensor.

KEYWORDS: MEMS-based sensors, nanotechnology-based sensors, harsh environmental monitoring, embedded sensor suites, miniature sensor systems

1. INTRODUCTION

The U. S. Army has a growing interest in the investment of funds to develop advanced technologies to enhance the Army's ability to identify out-of-specification weapons, predict remaining useful shelf-life, improve the reliability and readiness of the weaponry stockpile, and support weapon shelf-life extension via innovations in conditioned based maintenance (CBM). Likewise, there is interest in sensing chemical/biological agents that are currently or can be potentially used in warfare by a diverse fleet of adversaries. Remote miniature sensor systems are needed that notify soldiers of harmful chemical species and biological agents on the battlefield and/or in urban environments; additionally, instrumented weapon systems are needed that warn the user of their exposure to conditions beyond manufacturer's specification.

The CBM or proactive maintenance, which is defined by Mitchell[1] as "maintenance actions based on actual condition obtained from in-situ, non-invasive tests, operating and condition measurements," is one of the highest priorities at the Army Aviation and Missile Command (AMCOM). In comparison to preventive/ time-based maintenance and

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corrective/emergency maintenance, CBM has advantages that include reduced life cycle costs and improved reliability/maintainability. Research efforts are underway at the Army AMRDEC to develop miniature sensors for weapons environmental monitoring. The initial outcome of this research effort indicates that Micro Electro Mechanical Systems (MEMS)-based temperature, humidity, g-shock, and vibration sensors have reached the level of laboratory demonstrations in limited environments.

Although, plans are in place to improve these MEMS-based sensors to meet the full requirements of the PDFF program, efforts are needed to address the issues associated with chemical sensors for monitoring the out-gassing of weapons propellant. In addition, other issues must be addressed relative to chemical sensors for monitoring hazardous gaseous species on the battlefield and in urban environments. The authors are currently collaborating with Professor V. K. Varadan to develop passive wireless sensors[2] utilizing chemical-resistive sensor technology to address issues associated with the detection and identification of bio-terrorism agents and hazardous gases. In order to prolong the life of miniature power sources, this effort considers the use of MEMS/nanotechnology energy scavengers and storage devices.

An overview of the joint advanced technology demonstration program entitled "Prognostics/Diagnostics for the Future Force (PDFF)" between AMRDEC and ARL is presented in the next section. The critical requirements for embedded sensor suites, to be used in various weapon systems, are discussed in Section 3. The status of research efforts, that are underway to develop micro and nanotechnology-based sensor systems for weapons health and battlefield condition, is presented in Section 4. The initial results of joint efforts with Professor V. K. Varadan are presented in Section 5. The final section is the "Summary" of essential results.

2. PROGNOSTICS/DIAGNOSTICS FOR THE FUTURE FORCE

Before the turn of the Century, the Chief of Staff of the Army initiated the Army Transformation program, which drives the development of advanced weapons systems with embedded prognostics/diagnostics.[3] Since its inception, the Army Transformation program has brought about fundamental changes in the Army's structure, equipment, and doctrine that will provide the end user, the warfighter, with real-time situational awareness and rapid reaction capabilities. This enhancement to the Army's spectrum of operations improves the sustainability, deployability, readiness, and reliability of military systems. In order to support the Transformation, current and future weapon systems must be low cost, readiness-driven, and capable of detecting and correcting maintenance problems. To accomplish this mission, the Army is currently conducting an advanced technology demonstration program entitled, "Prognostics/Diagnostics for the Future Force." The key mission of this program is to develop low power, low cost, embedded sensor suites for harsh environmental monitoring to provide:

- Virtual logistics situational awareness at all levels
- Proactive vs. reactive combat logistics
- Improved readiness for weapons platforms and support equipment
- Reduced logistics footprint on the battlefield
- More effective fleet management and reduced life cycle costs.

In order to perform the aforementioned tasks, the Army must develop advanced sensor systems to collect the prognostic/diagnostic data on various weapon systems. The sensors should be capable of performing stress/strain measurements, checking vibration levels, monitoring chemicals/gases, identifying structural faults in the missile casings via statistical analysis, and detecting overheating of component level electronics. Additionally, the sensor system should keep a running history of vibrations/shock (to the missile) and access the chemical integrity of the motor and propellant. Autonomous real-time health monitoring is required to predict the faults on the weapon system, correct the diagnosed maintenance issue, and expeditiously deliver a mission readiness level report to the end user. Tactical commanders use the readiness data to make informed decisions about what systems can be deployed in combative situations.

The concept of embedded diagnostics frees the end user from having to perform routine maintenance checks, reducing soldier involvement in costly, routine tasks. The ability to obtain readiness data from each missile will drastically improve the missile's reliability, which in turn will reduce the load of the soldier (less "just-in-case weapons" to transport) and lower the life cycle cost of each missile (less maintainability cost, to include operating on "good" weapons). All of the advantages of prognostic/diagnostic equipment embedded in the missile will increase the sustainability, deployability, reliability, and readiness of the warfighter, therefore, ensuring the execution of campaigns that protect our freedoms, deter our adversaries, and if required, defeat our enemies.

The Army is currently pursuing the concept of incorporating embedded diagnostic systems into all new Army weapon systems by researching and developing existing and emerging technologies that will enable the Army to expeditiously field the automated diagnostics and prognostics in its legacy systems as well as future equipment and weapon systems. Four key areas, Condition Based Maintenance (CBM), damage assessment tools, forward reconnaissance/surveillance, and smart munitions are being considered in current Army programs. CBM is the center of the Army's transformation to more proactive maintenance programs that provide commanders with accurate, relevant readiness information. CBM includes not only prognostic/diagnostic data, but interactive technical manuals, automatic identification tags for the equipment, automated logbooks, and seamless transitions of the sensor data to the base control system. Prognostic/diagnostic data can be used to assess the shock or impact the missile has encountered and to provide battlefield conditions (situational awareness). More details are provided in Section 4.2.

3. CRITICAL REQUIREMENTS FOR EMBEDDED SENSOR SUITES

There is a range of requirements for embedded sensor suites. The natural environmental parameters (temperature, humidity, pressure, etc.) are very similar for the various weapon systems, except for the salient environments inherent to ground, air, and underwater operations. This also holds true for bio-terrorism/hostile (chemical, biological, etc.) environments. However, the environments (vibration, shock, etc.) due to weapon platform/system maneuvers are platform/systems-dependent.

Research is currently underway to develop a method to effectively address the network array of sensors for the Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS) program,[4] predecessor to PDFF, that is discussed in the next section. Intelligent, distributed, networked, embedded micro-sensors significantly contribute to mission readiness, safety, extended life-cycle, and maintenance-cost reduction of future and retrofitted legacy military systems. Given the high-mobility nature of military assets, it is desirable to make these sensor networks wireless. The sensor nodes will also be low-power battery operated or passive transponder systems with interrogation systems that can query addressable individual sensors from a distance in an un-tethered wireless environment. The interrogation system consists of a computer controlled electronically steerable phased array antenna system, onboard data acquisition, and real-time processing and/or data-storage capabilities. The interrogator queries each platform sensor by focusing the radiated electromagnetic energy in the direction of a particular sensor node's physical location. Thus the sensors are spatially separated to reduce mutual interference between sensor data and electromagnetic multi-path. The other reason is to reduce the power requirements for individual on-board sensors. The interrogator is also equipped with an electronically steered phased array system for focusing the electromagnetic energy and establishing robust communication links with individual on-board sensors in an automatic sequential manner. This research will provide electro-statically actuated digitally-controlled MEMS-based phase shifters for electronically steered phased array applications in embedded prognostic/diagnostic systems.

Unattended sensors on the battlefield must be operational for up to 30-days. These sensor suites, which are remotely monitored from greater than 20-meter range, must operate in an idle mode for low power dissipation. The sensors are activated when a notable change is observed in the ambient energy level from seismic/acoustic, thermal/infrared, and magnetic sources.[5, 6]

4. MICRO AND NANOTECHNOLOGY-BASED SENSOR SYSTEMS

AMRDEC has initiated several science and technology projects aimed at developing micro and nanotechnology-based sensor systems for monitoring harsh environmental conditions in military and commercial locales. The status of research efforts that are underway to develop micro and nanotechnology-based sensor systems for weapons health and battlefield condition is provided in this section.

4.1 Weapons Health Monitoring

MEMS and Nanotechnology accomplish the merger of sensors, actuators, and microprocessors to build closed feedback components that can gather and process information, decide on a course of action, and control the outcomes. DoD is utilizing these embedded sensor devices in military equipment to predict failure with increased confidence for real-time weapons health monitoring. To provide an integrated system transparent to the warfighter that monitors health/condition and delivers advanced diagnostics/prognostics while an asset is tactically deployed, in storage, and/or being transported, the Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS) is continuously being innovated by AMRDEC. As illustrated in Fig. 1, the RRAPDS[4] concept consists of an assembly of low-power sensors or sensor suites to collect environmental data, a processor termed the Asset Electronics Package to autonomously control the RRAPDS operation, a power source capable of extended years of continuous system life, a capability to transmit real-time data, and the necessary tools to provide seamless users interface.

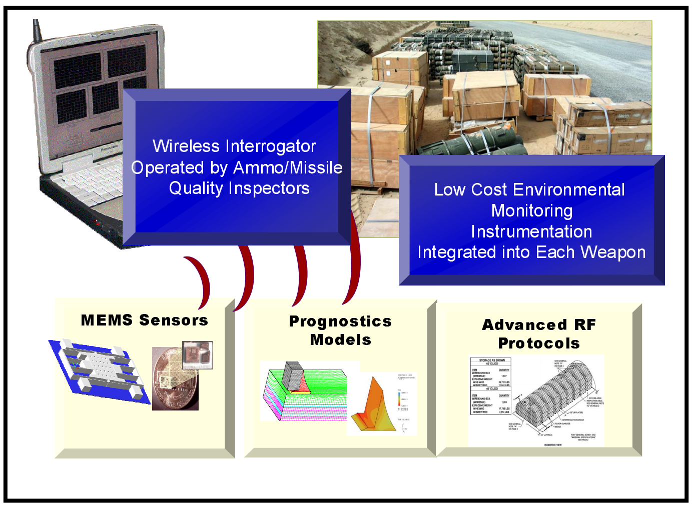


Fig. 1. Concept Model of RRAPDS.

RRAPDS devices have the potential to monitor hazardous environmental conditions and collect temperature, humidity, and vibration/shock data. The system allows for real-time access of source data and can provide critical information needed to monitor and control the structural response. The time dependent outcome of the data mining algorithms and predictive trending analysis has the potential to enhance the diagnostic and prognostic capability of missile failure, extend missile shelf life, save maintenance costs and improve reliability, resulting in an improved overall life cycle.

Future innovations for RRAPDS include chemical/gas sensors capable of detecting the chemical composition of gases inside the missile motor casing that has shown a direct correlation to missile decomposition and erosion on the casings, to include Nitrous Oxide/Dioxide, Carbon Oxide/Dioxide and Hydrogen (NO, NO_2, CO, CO_2, and H_2). By utilizing expertise in physics and fiber optics, various types of chemical sensing mechanisms are being developed by universities[7] to include: surface acoustic wave gas sensors, which consist of an inter-digital transducer (IDT) on a piezoelectric substrate coated with sensing film to absorb gas; fiber-optic evanescent wave sensors consisting of a coated thin film of material whose absorption fluorescence properties change with absorption of vapors of interest; and semiconductor thick-film electrical sensors that measure the change in conductivity of semiconductor oxide as gas vapors are absorbed in the porous thick films.

Various methods of detection are being compared by two key factors, sensitivity to the oxides (NO, NO_2, CO, CO_2, and H_2) and the cost of the sensor. Flexible and wireless self-assembled multi-walled carbon nanotube-based mechanical and chemical sensors are being used to detect damage to the structure of missiles. Nanotubes with diameters of a few nanometers and lengths up to 100 micrometers [8,9] are being used as nanowires between two electrodes as shown in Fig. 2.

The conductance between the electrodes changes as a function of the amount of gas or chemical in the surrounding environment bond to the nanotube. The change in conductance is easily detected by electron current signals, making CNTs extremely small sensors sensitive to their chemical and mechanical environments.

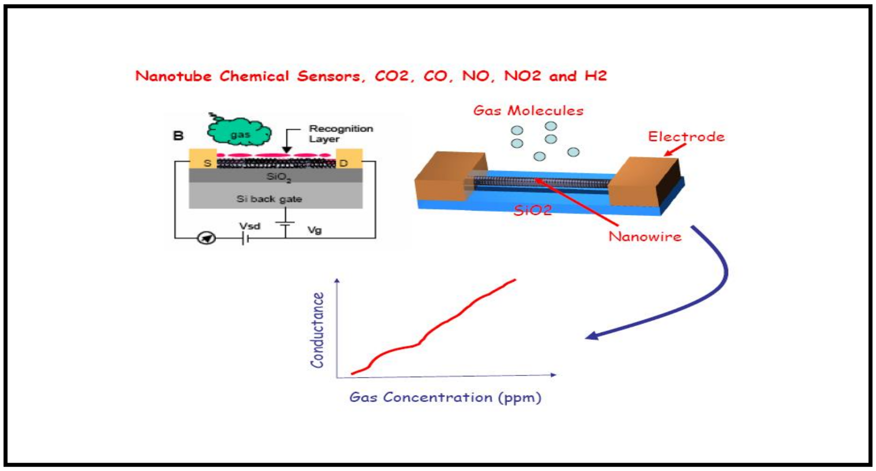


Fig. 2. Demonstration of CNT detection of Gases.

Another method being investigated for detecting chemicals and eruptive gases in rocket motor casings is Fiber-Optic Evanescent-Wave Spectroscopy. The technique utilizes characteristic absorption and fluorescence signatures of molecules of interest. A plastic optical fiber without the cladding is submersed into the gas contaminated specimen. Light in the tested wavelength region is input to the system. Optical absorbance of the chemical/gas changes the optical transmission properties. Spectral analysis of light exiting the plastic fiber shows an optically active specimen (showing intrinsic fluorescence) in the wavelength range of the light in the optical fiber as shown in Fig. 3.[10]

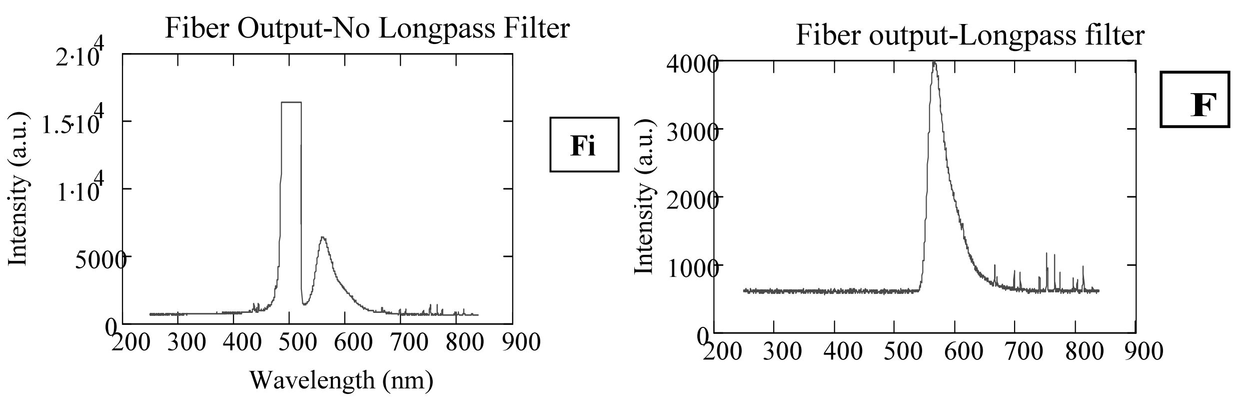


Fig. 3. Results of non-filtered vs. filtered fluorescence of exiting light.

4.2 Battlefield Condition Monitoring

There is a very high interest in sensing and monitoring chemical/biological agents and toxic gases that can be potentially encountered in both military and civilian environments. Remote miniature sensor systems that notify soldiers of harmful chemical species and biological agents on the battlefield and/or in urban environments and instrumented weapon systems have been developed and are being upgraded as the technologies evolve. With the potential likelihood that chemical-biological agents and or toxic gases will be encountered, the evolving technologies to sense chemical/biological agents and toxic substances are in a rapid state of development.

Micro-sensors and devices using the latest MEMS and nanotechnology developments, and coupled with advanced micro-electronics, are providing better performance for both stand-off and point sensor devices. These devices have enhanced sensitivity along with a reduction in size to better meet the form, fit, and function needs of the modern Army soldier. In order to help keep cost of these devices to a minimum, both civilian and military joint applications are being considered. Civilian sensing applications would consider potential hazardous situations such as transportation accidents and chemical plant fires where the situation awareness needs to be established rapidly and communicated to the appropriate command/operation center for decision making necessary to warn personnel, residents, fire fighters and emergencies personnel, etc. such that appropriate safety who, what, when, and where actions need to be performed. These situation awareness factors will also consider the influence of meteorological conditions that might influence the contamination direction and distribution.

MEMS and Nanotechnology are applied to battlefield awareness by the use of unmanned vehicles and self-guided munitions with embedded sensor suites in tactical operations to support the soldier in advanced intelligence, surveillance, and reconnaissance (ISR). Intelligence, the product gained by analyzing combat information for its relevance to the unit's mission, has always been critical to successfully accomplishing the mission. Reconnaissance is a combined-arms maneuver operation that employs the soldier's unit reconnaissance assets to observe named areas of interest and target areas of interest, by visual or other detection methods, in order to collect combat information. Surveillance involves the systematic observation of a particular named area of interest by visual, electronic, photographic, or other means. ISR requirements feed into the development of precision-guided munitions with embedded diagnostic equipment (smart munitions or smart bombs). These smart munitions are self-guiding weapons intended to maximize damage to the target while minimizing collateral damage and enabling a target to be effectively attacked with fewer and/or smaller bombs, reducing the cost of the missile and friend-to-friend fire.

Both DoD and DoE are working together to transition the technologies from the laboratory environment to the military and civilian environments in a timely manner and within budget restrictions. Along with the micro-technology and device developments, modeling and simulation efforts are being pursued to help ensure that broad-based scenarios are understood and anticipated for encountering and managing the battlefield and civilian actions when chemical/biological and toxic substances are encountered.

5. A WIRELESS SENSOR ARRAY

Noteworthy efforts relative to the design of a wireless sensor array[2] for the detection and identification of bio-terrorism agents and hazardous gases are presented in this section. The technology can be used in sensing current or future chemical/biological agents that can be potentially used in warfare by a diverse fleet of adversaries. The application of these nanotechnology-based sensor systems allows for the alerting of soldiers relative to the presence of harmful chemical species and biological agents. In addition, this technology can be of great benefit in warning the users when instrumented weapon systems are being exposed to conditions beyond manufacturer's specifications.

5.1 Array Sensor Design

Since previous developments in gas sensors, such as the resistive metal oxide designs, produced systems that typically operate at an elevated temperature for maximum performance and can result in higher power consumption, the resulting operating conditions are not considered suitable for wireless applications. The application of carbon nanotubes polymethylmethacrylate (CNT/PMMA) is considered in this design in order to take advantage of the nanotube's unique electronic and mechanical properties that are appropriate for emission devices and gas sensors.

The general chemistry configuration of PMMA is shown in Fig. 4 below. Industry commonly considers PMMA as a vinyl polymer that is made by free radical vinyl polymerization from monomer (light, simple, capable of being joined in long chain more complex polymers) methyl methacrylate.

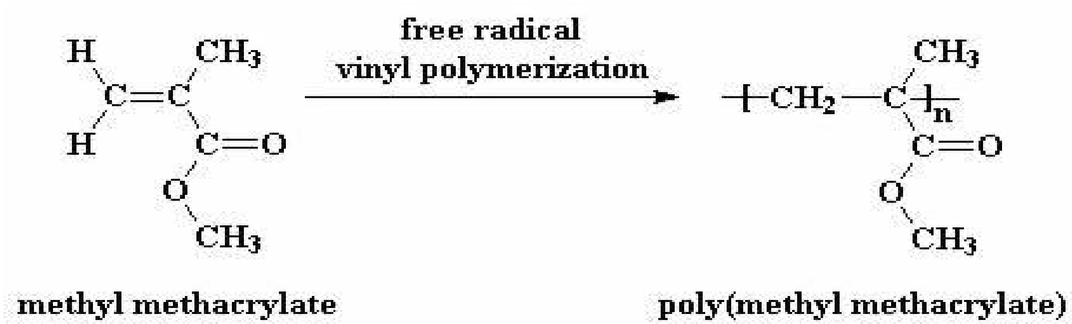


Fig. 4. This diagram depicts the general chemistry configuration of PMMA.

Using surface modified CNTs (*f*-CNT), chemiresistor thin films are fabricated on a printed circuit board, as well as on coplanar waveguides, and were integrated to a wireless system using signal conditioning circuits. The gas detection principle is based on the change in electrical resistance of the thin films due to the presence of organic vapors. The change in electrical resistance due to the presence of various organic vapors is evaluated. The *f*-CNT composite shows better response and reversibility to organic vapors like dichloromethane, chloroform and acetone.

Fig. 5 shows the schematic diagram of the wireless gas sensor setup. Carbon nanotubes are synthesized using the microwave Chemical Vapor Deposition (CVD) setup. Resulting component is oxidized and purified to make the composite film of gas sensing element. These CNTs are used to make the chemiresistor as well as coplanar waveguide sensing element. It could be possible to connect the chemiresistor gas sensor or the coplanar waveguide gas sensor to the wireless system and the results can me monitored using a small personal computer. Various gases are tested using the wireless system and the next section explains the gas sensing mechanisms of the carbon nano-tube polymethylmethacrylate (CNT/PMMA) composite film.

The CNT/PMMA sensing film consists of composites fabricated with different thickness and surface areas. It is known that the conducting paths are formed inside the CNT/polymer composites due to quantum mechanical tunneling effects, where the distance between the conducting sticks is such that electron hopping can occur. The contact resistance between carbon nanotubes increases owing to an increase in distance between adjacent nanotubes. The CNT surface contains polar functional groups which can adsorb solvent molecules (dipole-dipole interaction, including hydrogen bonding). Swelling of polymer matrix due to absorption of organic vapors may also increase the volume and thus increasing the distance between nanotubes thereby increasing the contact resistance. The extent of swelling and hence the electrical response depends on the solubility of the polymer in the solvent.

The response of the composite films to solvents like dichloromethane, chloroform and acetone, which are good solvents for PMMA, was high. The response was found to be irrespective of the polar nature of the solvent molecule. This shows that the predominant mechanism for the response of vapors of good solvent of PMMA is matrix swelling. Solvents in which PMMA is insoluble or less soluble (like methanol, ethyl acetate and toluene) also showed sensor response. In such cases, alternation of electronic properties of the semiconductor CNT surface by charge transfer (induced by adsorption of polar organic molecules) becomes predominant. Here the polar nature of the solvent and the extent of interaction determine the sensor response. The methanol vapors, which can form hydrogen bonding with the polar groups on the CNT surface, showed a maximum response among the three. However, this mechanism can induce only a small response. Hexane is not a good solvent (as well as non-polar) and hence did not show any response. Hence surface modified carbon nanotube (*f-CNT*) is used for the sensor development.

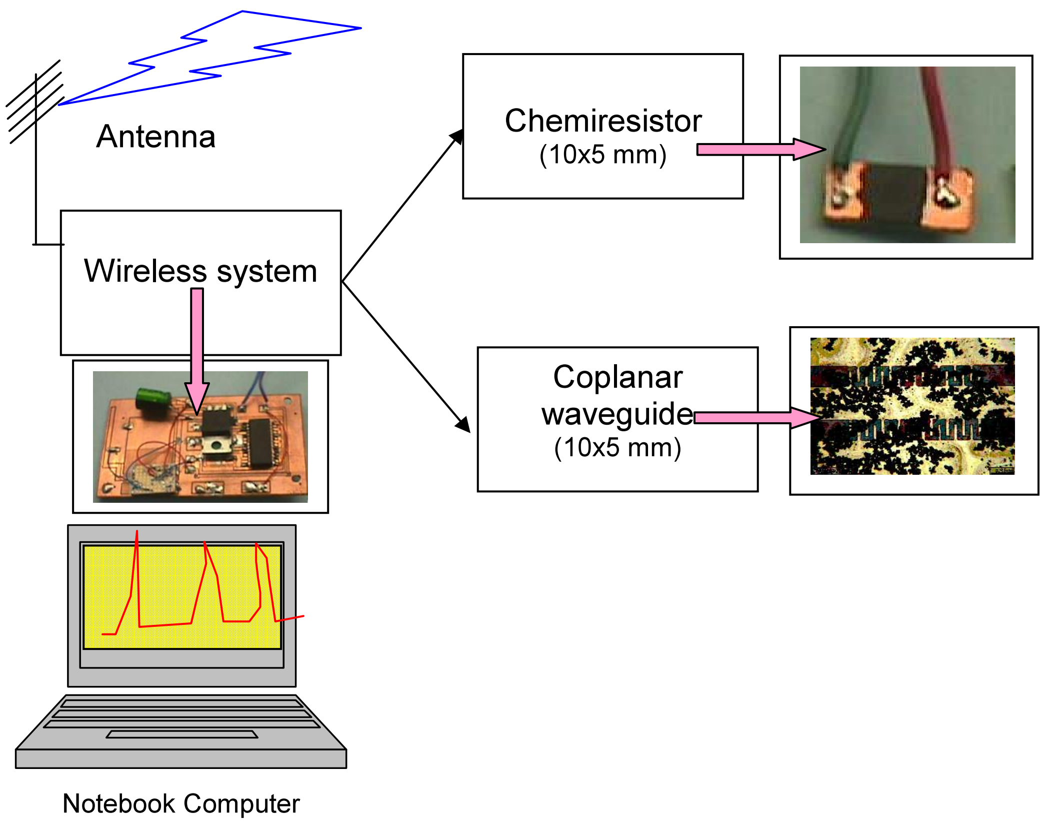


Fig. 5. Schematic diagram of the wireless gas sensor setup showing two types of sensors developed using CNTs.

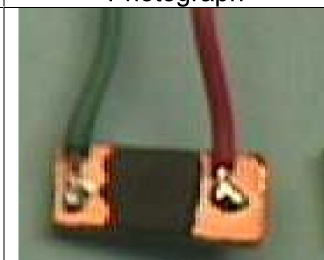
5.2 Laboratory Procedure and Test Results

Different gas sensors were fabricated and tested using *f*-CNT/PMMA as the sensing element. This section presents the fabrication details and the experimental results of these gas sensors. Table 1 shows the resulting sensor, sensing medium used, photo of sensing element, and the gases tested for each sensor.

Carbon nanotubes were synthesized by the decomposition of acetylene gas by microwave chemical vapor deposition (CVD) at 600^{o}C with fine Iron (III) nitrate as a catalyst. This method is based on the pyrolysis of acetylene by microwave heating on nano-sized catalyst particles embedded in magnesium carbonate, which serves as a catalytic support. This method is capable of producing raw nanotubes about 60-80% in purity. The average diameter of these multi-walled carbon nanotubes (MWNTs) cylinders ranges from 10 to 15 nm.

The nanotubes are oxidized using potassium permanganate (KMnO4) with the help of phase transfer catalyst. The higher yield of this functionalization process is the major advantage. Purified nanotubes (0.12 g) and dichloromethane (25 ml) are added to a 100 ml flask and the suspension is vibrated ultrasonically for 30 minutes. Phase transfer agent (1.0 g, Aliquat 336, from Aldrich) is added, followed by powdered potassium permanganate (5 g) in small portions over a period of 2 hrs. Acetic acid (5 ml) is also added. The mixture is then stirred vigorously overnight at room temperature. It is then filtered, washed with concentrated HCl and water and then dried.

Table 1. Resulting sensors and gases tested for detection

Gas Sensor	Sensing medium	Sensing element Photograph	Gases Tested
Chemiresistor Gas sensor	*CNT/PMMA* *f*-CNT/PMMA		Dichloromethane Chloroform Acetone Methanol Ethyl acetate Toluene
Coplanar Waveguide gas sensor	*f*-CNT/PMMA		Dichloromethane

The *f*-CNT/PMMA composite films are prepared by ultra-sonication of 20 mg of carbon nanotubes or functionalized CNT and 80 mg of PMMA for 2 hours in dichloromethane. The chemiresistors are fabricated by coating the film between two conducting electrodes on a printed circuit board by dip coating. The sensors are dried in air at 50^{o}C.

The changes in the electrical parameters are measured by exposing the unit to different solvent vapors inside a gas chamber. The vapor pressure of all solvents is controlled at 25^{o}C. In order to evaluate the electrical responses of the chemiresistors (prior to being integrated to the wireless system), the resistance variation of the sensor film is measured relative to exposures to various gas vapors. The measurements are repeated for different gases and when electrical resistance reached a maximum value, the measurements continued by exposing the units to air.

These chemiresistors are integrated to a wireless system, exposed to the vapor for 5 seconds duration, and then exposed to air to attain the initial value. The change in resistance of the chemiresistor is converted to change in voltage using OP-AMP signal conditioning circuits and is connected to the microcontroller unit. The complete wireless system consists of a sensing unit and a monitoring unit, which is a Windows application running on any computer as shown in Fig.6. The microcontroller-based sensing unit interfaces to up to 5 different sensors and is capable of acquisition, digitization and wireless transmission of the signals using the Bluetooth standard. The Bluetooth protocol stack has been built for the sensing unit with a microcontroller and Ericsson ROK101 007/21E point-to-point Bluetooth module as well as the monitoring unit using a notebook computer.

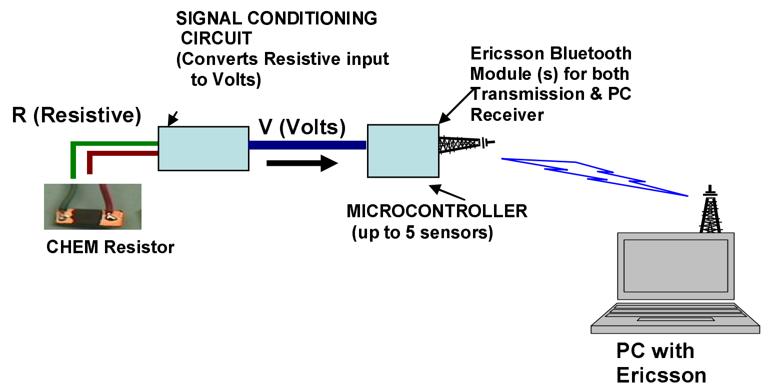


Fig. 6. Diagram of Complete System for wireless Chemiresistor system

The responsiveness, S, of the composites to various solvents can be determined from the equation

$$S = \frac{R - R_o}{R_o} \qquad \{1\}$$

where, R_o is the initial resistance value, and R is the maximum steady state response value. The responsiveness of the sensor is calculated for different vapors and is presented in Fig. 7.

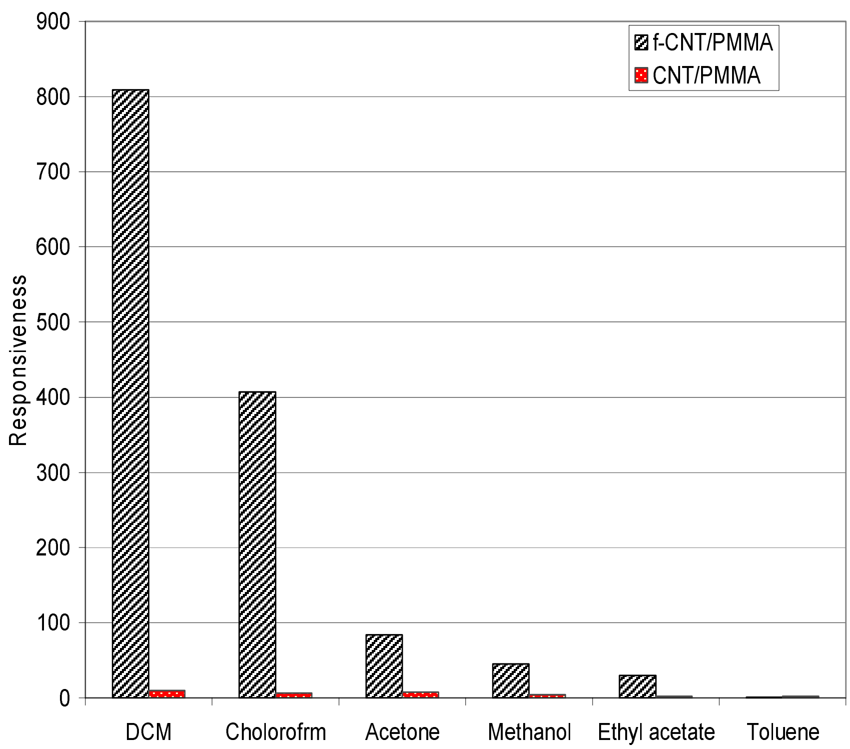


Fig. 7. Comparison of the response of *f*-CNT/PMMA composite film and CNT/PMMA composite film for different gases.

Although only one example is discussed in details, the results (as shown in Fig. 8) demonstrate wireless active and passive sensors for detection of bio-hazards gases (of various concentrations) based on the chemi-resisitve and coplanar wave guide reflected-wave phase monitoring techniques. Conductivity variation with the adsorption of different gas into composite thin film is clearly observed by resistance measurement. Feasibility of a passive wireless sensor is demonstrated in this research as a measurement of the phase of the reflected wave from the resistive load (using a network analyzer). Based on the radio frequency characteristics, a wireless gas sensor integrated with circulator and two antennas are developed and tested.

In other AMRDEC efforts, the detection of bio-hazard materials using passive and active wireless sensors based on monitoring the reflected phase from the sensor is achieved using a thin film of functionalized carbon nanotube/PMMA composite. Resistance increase with absorption of dichloromethane gas into composite thin film is clearly observed by resistance measurement. Based on the preliminary observations, wireless gas sensors with integrated wireless modules are being designed and characterized. Measurement results of sensors and reference loads indicate that response is sufficient enough to allow the sensors to monitor bio-hazardous material in real-time with high sensitivity. In order to allow for practical use of these sensor techniques, sensor components and antenna elements have to be miniaturized for packaging.

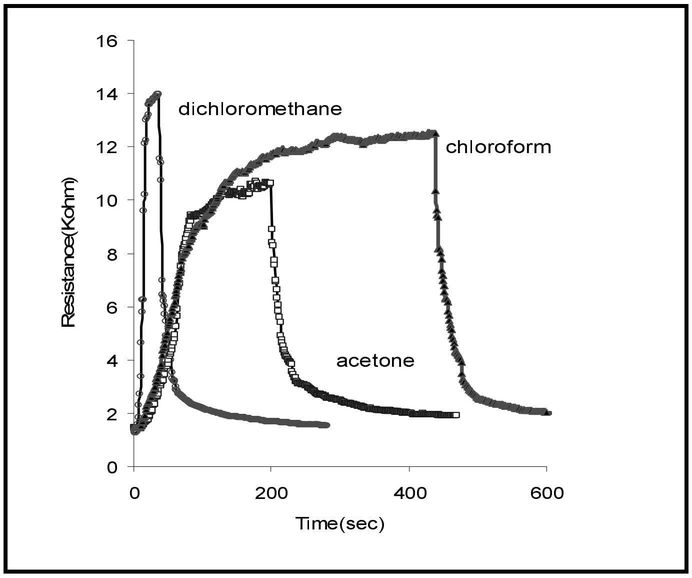


Fig. 8. Response of CNT/PMMA composite to dichloromethane, chloroform and acetone vapors

6. SUMMARY

Performance requirements, along with the associated technical challenges for MEMS and nanotechnology-based sensor systems operating in military environments, are discussed in this paper. In addition, laboratory results from the design and testing of a wireless sensor array, which was developed using a thin film of functionalized carbon nanotube materials, are presented. Conclusions from the research indicate that the detection of bio-hazardous materials is possible using passive and active wireless sensors based on monitoring the reflected phase from the sensor.

The application of MEMS and Nanotechnology research to the rapid development of prognostic/diagnostic systems for missile health monitoring has significant potential to bring about the vision of the Army Transformation to a leaner, quicker, more advanced workforce and technological community striving to enable the warfighter with the most up-to-date equipment in an expedited time frame. Developing smart munitions, unmanned vehicles, and other future weaponry platforms for the application of prognostic/diagnostic embedded sensor suites is possible; however, the technology is still a few years away from fielding. The technology needed to implement this task has three areas of key improvements that have to be accomplished:

- Developing advanced, miniaturized, low power, low cost sensors to collect data on the weapon system's performance,
- Improve the analysis and data storage capabilities of digital hardware,
- Perfect secure communications technologies that will enable the transfer of vast amounts of data in real-time with extreme reliability.

ACKNOWLEDGEMENTS

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