AUTONOMOUS MONITORING METHOD AND SYSTEM USING SENSORS OF DIFFERENT SENSITIVITIES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority under 35 U.S.C. §119(e) to provisional application number 60/564,233 filed on April 22, 2004, the disclosure of which is incorporated herein in its entirety.

FIELD OF THE INVENTION

[0002] The present invention relates generally to a method and system for monitoring an area for chemical or other toxic agents using autonomous sensors having different sensitivities.

BACKGROUND OF THE INVENTION

[0003] A growing risk of asymmetric attacks has increased the need for distributed chemical detectors or detectors for other agents with vastly superior false positive rates relative to current solutions. Using two tiered sensors for detecting biological or other hazards are known. However, these known arrangement of two tiered sensors typically consist of two types of sensors that are co-located at a sensor location such that the more sensitive or more reliable sensor is only operated or triggered when the less sensitive or less reliable sensor initially detects a presence of an agent that is being monitored.

[0004] However, in view of the risks posed by terrorism, some of the chemical warfare and other toxic agents need to be monitored over a vast area. Use of such known co-located dual sensors may be prohibitively expensive if used to cover such a vast area that needs to be monitored.

SUMMARY OF THE INVENTION

[0005] In certain embodiments, the present invention provides a method of monitoring for chemical or other toxic agents, including: operating a plurality of first type sensors having a first level of sensitivity to an agent in a monitored area; concurrently operating a second type sensor having a second level of sensitivity to the agent in the monitored area, wherein the second level of sensitivity is at least ten times more sensitive than the first level of sensitivity; and receiving and analyzing, at a central location, input from the plurality of first type sensors

and the second type sensor in order to determine the presence of the agent in the monitored area.

[0006] In certain embodiments, both the plurality of first type sensors and the second type sensor are operated continuously.

[0007] In certain embodiments, both the first type sensors and the second type sensors are chemiresistor based sensor arrays.

[0008] In certain embodiments, the chemiresistor based sensor arrays are conductive polymer composite vapor sensors.

[0009] In certain embodiments, a preconcentrator is provided with the second type sensor.

[0010] In certain embodiments, the present invention provides a system for monitoring for chemical or other toxic agents, including: a plurality of first type sensors, having a first level of sensitivity to an agent, arranged in a monitored area; a second type sensor, having a second level of sensitivity to the agent, arranged in the monitored area, and a central analysis unit connected to the plurality of first type sensors and the second type sensor, wherein the central analysis unit analyzes data from the plurality of first type sensors and the second type sensor in order to determine the presence of the agent in the monitored area.

[0011] In certain embodiments, the present invention provides a method for monitoring for chemical or other toxic agents, including: operating a first type sensor having a first level of sensitivity to an agent in a monitored area, operating a second type sensor having a second level of sensitivity to the agent in the monitored area, and receiving and analyzing, at a central location, input from the first type sensor and the second type sensor in order to determine the presence of the agent in the monitored area, wherein the first type sensor and the second type sensor each comprise a plurality of orthogonal sensing technologies on a single sensor array, wherein a transduction mechanism in each of the sensing technologies detects a change in electrical resistance.

[0012] In certain embodiments, the present invention provides a system for monitoring for chemical or other toxic agents, including: a first type sensor, having a first level of sensitivity to an agent, arranged in a monitored area; a second type sensor, having a second level of sensitivity to the agent, arranged in the monitored area, and a central analysis unit connected to the first type sensor and the second type sensor, wherein the central analysis unit analyzes data from the first type sensor and the second type sensor in order to determine the presence of the agent in the monitored area, wherein at least one of the first type sensor or the second type sensor comprises a plurality of orthogonal sensing technologies in a single sensor array,

wherein a transduction mechanism in each of the sensing technologies detects a change in electrical resistance.

[0013] In certain other embodiments, the present invention provides a method of monitoring for chemical or other toxic agents, comprising: operating a plurality of first type sensors having a first level of specificity to a group of agents in a monitored area; concurrently operating a second type sensor having a second level of specificity to the group of agents in the monitored area, wherein the second level of specificity is more specific than the first level of specificity; and receiving and analyzing, at a central location, input from the plurality of first type sensors and the second type sensor in order to determine the presence of the agent in the monitored area.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate a presently preferred embodiment(s) of the invention, and, together with the general description given above and the detailed description given below, serve to explain the principles of the invention.

[0015] Figure 1 is a block diagram illustrating the arrangement of sensors in certain embodiments of the present invention.

[0016] Figure 2 illustrates the change in property of a polymer in the presence of a vapor.

[0017] Figures 3 and 4 provide examples of the data obtained for testing of sensors with HD and GA.

[0018] Figure 5 is a diagram illustrating a tested sensor's response over a range of blister (0-5 mg/m^3) and nerve agent (0-1 mg/m^3) concentrations.

[0019] Figure 6 is a discrimination plot for chemical warfare agents over wide ranges in concentration.

[0020] Figure 7 is a diagram that illustrates the detection limit of sensors to a wide range of analytes.

[0021] Figure 8 is a graphical display of the time to detect versus concentration for specific toxic industrial chemicals.

[0022] Figure 9 is graph illustrating sensor response times versus film thickness for polymer composite sensors.

[0023] Figure 10 is diagram illustrating the use of a SWCNT network chemiresistor as a sensor.

[0024] Figure 11 is a diagram that illustrates performance of a sensor array consisting of different types of chemiresistors to different analyte vapors.

[0025] Figure 12 is a diagram illustrating a graphical user interface that may be displayed at a control station.

[0026] Figure 13 shows a micromachined preconcentrator.

[0027] Figure 14 is graph that illustrates the variation in response of the CASPAR preconcentrator with temperature.

DETAILED DESCRIPTION OF THE INVENTION

[0028] , The applicants have developed low cost, array based, nanocomposite based sensor technology based on earlier work at Caltech as described for example, in U.S. Patent No. 5,571,401 and its related patents . These patents are incorporated herein for all purposes. This technology has been demonstrated to be sensitive to a wide range of chemicals, environmentally robust, accurate (e.g. not susceptible to false positives), low cost, reliable, and easily upgradeable.

[0029] In certain embodiments, the present invention provides a distributed monitoring system based on this technology. This system incorporates highly distributed low cost, less sensitive nodes (or sensors) able to detect at the Immediately Dangerous to Life or Health (IDLH) level and below (as one example of a first level of sensitivity). The system also incorporate "truth nodes" that integrate this detection technology with more sensitive nodes, for example, nodes that include miniaturized pre-concentrators. These "truth nodes" (or more sensitive nodes) detect at a 10 or 100 times lower level of concentration, for example, than the low cost, less sensitive nodes but are often more expensive and take longer to make measurements. The combination of these two detection approaches result in the lowest cost and most highly capable system. This system utilizes the information from the two different node types either individually or collectively at a central location or at a distributed network of locations that are each centrally located for a set of sensors. In certain embodiments, the system also includes a central command monitor that allows all of the nodes in the system to be monitored from one central location. Therefore, for example, each of the distributed network of locations, or a subset thereof, may communicate with the one central location so that the entire system may be monitored from the one central location.

[0030] Figure 1 is block diagram that illustrates the arrangement of sensors in certain embodiments of the invention. Figure 1 is exemplary only and one skilled in the art would

recognize various modifications and alternatives all of which are considered a part of the present invention. A plurality of first type sensors 10 are arranged to monitor an area and the monitored area also includes one or more second type sensors 20 (only one shown in figure 1). Data from the less sensitive or less specific (and therefore typically lower cost and lower power) first type sensors 10 and from the more sensitive (or more specific) second type sensor 20 are sent to a central analysis unit 30. It should be noted that the central analysis unit 30 may be located where it directly receives data from the first type and second type sensor. Alternatively, the central analysis unit may be located at a central location 50 where data from the one or more monitored areas may be transmitted over a public or private wide area network 40 (which may be the Internet which is a public wide area network) to the central location. In yet another alternative, all the sensors in a monitored area may transmit their data to an "intermediate" central analysis unit 30 with a multitude of such intermediate central analysis units transmitting the received data to a remote central analysis unit located at the central location 50. It should be noted that each of the first type sensors 10, the second type sensors 20, the central analysis unit 30, and the central location 50 (with its analysis units) include processors, memory, and program code that are configured to perform the collection, transmission, and analysis of sensor data that is discussed further herein.

[0031] The communication from the first type sensor 10 and the second type sensor 20 to the central analysis unit 30 may be by a direct point-to-point communication link as shown by the solid lines in figure 1. Alternatively, the first type sensors 10 and the second type sensors 20 may communicate with each other in a mesh type communication network so that the communication originating at one of the sensors reaches the destination central analysis unit 30 through one or more intermediate nodes or sensors. The dotted lines in figure 1 are indicative of the communication between the sensors or nodes in such a mesh communication network which enables an originating sensor or node 10 or 20 to communicate with the central analysis unit 30.

[0032] The first and second type sensors provide a low cost, low power and highly sensitive chemical detector capable of continuous distributed monitoring of both chemical warfare agents (CWAs) and toxic industrial chemicals (TICs) and provides for improved monitoring of buildings and facilities.

[0033] As discussed earlier, applicant has developed low cost, array based, nanocomposite based sensor technology based on earlier work at Caltech. This technology has been demonstrated to be sensitive (IDLH and PEL detection) to a wide range of chemicals,

environmentally robust, accurate (e.g. not susceptible to false positives), low cost, reliable, and easily upgradeable. This core technology is reviewed below and results supporting the performance standards are detailed.

[0034] One embodiment of the present invention proposes a distributed monitoring system based on this technology. This system incorporates highly distributed low cost nodes (or first type sensors) able to detect at the Immediate Danger to Life or Health (IDLH) level of concentration and below. The system will also incorporate "truth nodes" (or second type sensors) that are more sensitive and detect much lower concentrations of the agents of interest. For example, these truth nodes may integrate this detection technology with miniaturized preconcentrators. These "truth nodes" may detect at 10 to 100 times lower level than the low cost nodes but are typically more expensive and take longer to make measurements. The combination of these two detection approaches result in the lowest cost and most highly capable system possible.

[0035] Most simple, low cost chemical sensors produced today are directed at the detection of a single compound or class of compounds. Typical examples include electrochemical cells, metal oxide semiconductors (so called Taguchi sensors), pilasters, and photionization detectors. More sophisticated systems designed to identify multiple chemicals are complicated but vacuum systems, complex sampling systems, or expensive detection schemes. Recently, array based sensors have been demonstrated that combine the ability to identify a wide range of analytes with the low cost and simplicity of single compound detectors.

[0036] Arrays of conductive polymer composite vapor sensors were developed at Caltech and have been optimized by applicant. In this approach, the presence of a chemical is detected through a change in the electrical resistance of a chemically sensitive resistor. These sensor films are derived from composites that contain regions of a conducting phase with regions of an insulating organic material. This approach allows use of a wide range of polymeric materials with a range of chemical binding properties, so that an enormous diversity in array composition can be achieved using readily available conventional polymeric materials. When a vapor is present, sorption-induced swelling of the polymer produces a change in the electrical resistance of the material due to the swelling of the film. As shown in figure 2, when the vapor is removed, the swelling reverses (see 101 and 101')and the resistance returns to its original value. These responses of these sensors have been proven to be are reversible over tens of thousands of vapor exposures as well as reproducible over a large number of

trials under a variety of ambient conditions. With the emergence of newer nanomaterials that can serve as the conducting phase, even greater chemical diversity and sensitivity is achievable.

[0037] To verify the sensitivity of these sensors, live agent testing at Battelle Memorial Institute (BMI) has been completed. Test results for HD, GB, GA, DMMP and phosgene (CG) in air confirm detection of low parts per billion level of agents for a hand held chemical point detector. In addition, a high degree of response repeatability and sensor stability was demonstrated even at the lowest limit of detection. An example of the data obtained for HD and GA is shown in Figures 3 and 4. For these sensors, discrimination between HD and GA is seen clearly between sensors 9 and 11 and sensors 10 and 12 at all concentrations tested. As shown in Figure 3, the results 301 for the sensors for blister agent detection is much superior to the results 305 for the nerve agent sensors in the presence of HD (a blister agent). Likewise, as shown in Figure 4, the results 405 of the nerve agent sensors is much superior to the results of the blister agent sensors in the presence of GA (a nerve agent). In general, as shown in figure 5, these tested sensor's display a linear response (see 501 and 510 in figure 5) over a wide range of blister (0-5 mg/m^3) and nerve agent (0-1 mg/m^3) concentrations.

[0038] In addition to H and G-series agents, these composite sensors also show remarkable sensitivity to higher vapor pressure (> 1 atm) blood and choking agents, phosgene (CG) and hydrogen cyanide (AC). An example of the response measured for 100 ppm phosgene is shown in the discrimination plots 601 in figure 6 where even at this low concentration, the new sensor array can clearly distinguish between all the agents tested, as well as common chemical interferents (toluene, diesel fuel). It is estimated that the detection levels for detection of blood or choking agents are in the low ppm range.

[0039] In certain embodiments, the sensitivities described above can be further enhanced by incorporation of a miniaturized preconcentrator. Prior work has clearly indicated that sensitivities of 100 fold are achievable with miniaturized preconcentrators. This allows for Permissible Exposire Limit (PEL) level detection even in instances where the fundamental sensing technology cannot achieve this level. Therefore, certain embodiments of the present invention provide for combining simple sensing nodes for IDLH (or less sensitive) detection with more sophisticated nodes that incorporate preconcentrators for PEL (or more sensitive) level detection.

[0040] As shown in the diagram 701 of figure 7, the detection limit of these sensors to a wide range of analytes has been measured and is commonly in the low ppb for CWAs and TICs.

While the absolute detection levels of gases such as hydrogen cyanide and phosgene are higher than those for CWAs, the detection capability is still significantly below immediately dangerous to life and health (IDLH) levels.

[0041] Results for specific TICs (NO_2 801 and acrylonitrile 810) are presented in Figure 8 in the form of time to detect versus concentration curve. Applicant has already developed sensor materials that can detect TICs of interest at or below IDLH (803, 812) and PEL (805, 814) levels in well less than two minutes and further improvements are achievable.

[0042] Any sensing system must be able to perform under a wide range of external conditions including wide variation in humidity, temperature, and confounding environments. The live agent testing has included testing sensors over a varying temperature and humidity.

[0043] Detection on fully autonomous devices was determined as part of a validation study on five hand held devices with temperature varied between 10 and 40°C, humidity between 1-80% relative humidity, and interfering elements including 1% each of AIFF, diesel fuel, bleach, antifreeze, ammonia, vinegar, floor wax, Windex, and Spray 9 cleaner. These results are summarized below. The results indicated that the devices were able to detect G series nerve agents at or below the Joint Services Operational Requirement (JSOR) requirements (0.1-1.0 mg/m^3) and was able to detect blister agents below JSOR requirements (2 mg/m^3).

[0044] With respect to temperature, the following results were observed:

At 0°C, all 5 tested units were operational (function test only, no agent challenge).
At 10°C, all 5 tested units correctly alarmed to GB and HD in all tests (10/10).
At 40°C, all 5 tested units correctly alarmed to GB and HD in all tests (10/10).

[0045] Based on the above results, temperature and humidity are not significant risks to reliable operation of the sensors used in certain embodiments of the present invention.

[0046] In total, over 300 validation experiments were conducted on 5 different hand held devices. Overall prediction success for one of these units has been analyzed using receiver operator characteristic (ROC) curves. The results of these experiments clearly demonstrated very favorable specificity (false positive ratio) and sensitivity (false negative ratio).

[0047] One of the advantages of sensors provided by the present invention is that it uses technology characterized by the low cost nature of the sensing materials as well as the read out electronics and the use of such sensors in the two or more tier arrangement discussed herein wherein a plurality of low cost sensors (of lower sensitivity and/or specificity) are arranged concurrently with a higher cost sensors (of higher sensitivity and/or specificity) so that a large area can be continuously and effectively monitored for chemical and other toxic

agents. This arrangement of low cost sensors is ideally suited for a widely distributed, low cost monitoring system.

[0048] This sensing technology has been tested in the industrial market and this product has demonstrated excellent reliability in the field. In addition to this field experience, extensive laboratory testing of the sensor technology itself has been conducted. These tests indicated little sensor degradation, even when challenged with higher than expected agent concentrations.

[0049] Another element of a successful sensor is that the manufacturing process be robust with high manufacturing yields. Applicant has developed a robust manufacturing process for polymer composite sensors. The sensor uniformity was recently investigated for the arrays sent for live agent testing. A comparison of the training data for six units under test demonstrated a high degree of uniformity across these units.

[0050] Another feature of certain embodiments of the present invention is the expandability of the system. Because the detectors use an array based approach and these sensors are broadly sensitive to a wide range of chemistry, the system can easily be upgraded to detect new threats by updating the identification algorithms, either on board the device, or through a centralized data analysis system. In fact, the commercial hand held device that is sold by applicant is designed to be "user trained" so that the same product is used in a vast array of different applications by simple changes to the on-board algorithms. The instrument is designed so that these changes can be made by the end user. In one embodiment, these upgrades are provided to the user via downloadable software upgrades (if local data analysis is implemented) or in a seamless manner if remote data analysis is implemented.

[0051] As discussed earlier herein, certain embodiments of the present invention use polymer composite sensors for CWA and TIC detection. The performance of these existing materials can be improved through improved deposition methods and control of film thickness. As shown in the graph 901 in figure 9, while the response of these sensors is rapid (typically less than 30 seconds), the response time is proportional to t^2, where t is the film thickness. Thus, a reduction of film thickness from 1 micron (for example, the film thickness in certain embodiments) to 500 nm improves response time by 4 fold and result in response times significantly less than ten seconds. Thus, certain embodiments of the present invention provides for an improved sensor with a film thicknesses less than or equal to 500 nm and ideally with a film thicknesses less than 100 nm.

[0052] Additional improvements in the composite sensors can be accomplished through modifying both the non-conducting and conducting phases as a part of investigating materials and optimizing their performance. There are indications that some of these materials may have sensitivities that are 4-10 times better than previously demonstrated.

[0053] In certain embodiments, the present invention uses novel filler materials that improve sensor sensitivity. Recent work with single wall carbon nanotubes (SWNTs) has demonstrated a potential for enhanced sensitivity to a wide range of chemicals including nitrogen dioxide and other strong oxidizing or reducing agents. It has also been recently demonstrated that certain metal nanoparticle conductors also produce sensors with enhanced chemical sensitivity and these sensors are also used with certain embodiments of the present invention. Use of SWNTs and SWNT networks is described, for example, in J. P. Novak et al., APPL. PHYS. LETT., vol. 18, 4026 (2003), which is incorporated herein for all purposes.

[0054] In addition to enhanced sensitivity, it is imperative that any new materials are also robust to changing environmental conditions. For each sensor material described above, comprehensive testing of sensitivity, response to humidity, temperature stability, and sensitivity to interference compounds is performed to test the robustness of the sensor materials to environmental conditions .

[0055] Initial results focused on CW simulant detection clearly indicate that these sensors are sensitive to DMMP, a standard nerve agent stimulant, as shown in the graph 1001 in figure 10. Figure 10 also shows an optical image 1005 and an AFM image 1010 of a SWNT network chemiresistor and the measured change in resistance upon exposure to 100 ppb if a chemical simulant for nerve agents. The SWNT networks can be patterned with high yield using conventional photolithographic techniques. The use of SWNT networks eliminates the need to position individual SWNTs and produces a more easily manufacturable device with a more reproducible response.

[0056] To monitor sensor performance, extensive laboratory testing is conducted on the sensor materials. Detection versus response time curves are generated and an initial determination of P_{fp} (probability of false positives) and P_{fn} (probability of false negatives) are conducted. Some of these arrays are then sent out for live agent testing (at a mutually determined surety laboratory) and others are incorporated into the initial prototypes for system testing. In certain embodiments, the system parameters including the analytical models are adjusted so that a target $P_{fa} < 0.1\%$ and a target $P_{fn} < 5\%$ is achieved for all compounds tested at the IDLH level of concentration without preconcentration.

[0057] The optimal sensor array uses orthogonal sensing technologies on a single, simple, platform. Thus, the optimal sensor array includes several different chemiresistor approaches, possibly including sensors in a single sensor array made from regions of conducting and non-conducting materials, sensors based on intrinsically conducting polymers (ICPs) and composites made from ICPs, sensors made from single wall carbon nanotubes (SWNTs) and composites made from SWNTs, metal oxide semiconductor sensors, sensors based on porphyrin materials, and sensors based on metallic nanotubes made from metals and metal oxides. In general, in certain embodiments which use orthogonal sensing technologies, each sensor array includes different types of sensors in which the transduction mechanism in all sensors measure a change in electrical properties. Furthermore, in certain embodiments, the at least one of the sensors has regions of conducting and non conducting material.

[0058] Figure 11 is a diagram that illustrates performance of a single sensor array consisting of different types of chemiresistors. As illustrated in figure 11, such an array made from multiple types of thin film chemiresistors sensors exhibits a highly differentiated pattern of response to different classes of analyte vapors. Graph 1110 displays the response of the PCS polymer composite sensors in the single sensor array to DMMP in the air at IDLH concentration level, graph 1120 displays the response of SWCNT and ICP conducting polymer sensors in the single sensor array to presence of ammonia in the air at IDLH concentration level and graph 1130 displays the response of the SWCNT sensors in the single sensor array to the presence of HCN in the air at IDLH concentration level. The use of orthogonal sensing technologies in a single sensor array provides for greater reliability and range of detection by the sensor array.

[0059] One of the features of certain embodiments of the present invention is provision of an electronic platform that provides low noise measurements, and appropriate power and communications interfaces. While the detailed design of these components may be refined, a current design is described in more detail in the following paragraphs.

[0060] Applicants have determined that current performance is limited by electronic noise rather than sensor noise. Therefore, there is a focus on improving the electronics design to improve overall signal to noise, and therefore sensitivity, by decreasing the electronic noise. An electronic noise reduction of 10x could lead to a 10 fold sensitivity enhancement.

[0061] One of the issues in certain embodiments of present invention concerns how to communicate alarms back to a centralized location. There are two competing techniques that may make sense depending on installation issues (time, installation cost, etc). One approach

is using a power line carrier. This approach provides a reliability benefit since a wire is used to communicate key information and a cost benefit as it uses pre-existing infrastructure to carry this information. The restriction to this technique is that the sensor must be connected to a power line which can add installation cost and/or restrict available deployment locations.

[0062] The second approach would be a wireless communication protocol. With improved mesh networks this approach offers the advantage of being able to locate a device anywhere (assuming adequate battery power) and reduced installation costs. However, this approach may result in a less reliable connection in an application where data flow is critical.

[0063] The system of this invention is designed to use, among others, wireless or power line carrier communications and to include a modular approach so that the communications module is a separate part of the sensor node. This allows for a common sensing platform that could be utilized with different communications methods.

[0064] With respect to power, the sensor devices can be either battery or line powered with battery back-up. The advantage of line power is a lower cost of ownership, ability to move away from ultra low power designs, and greater design flexibility of power hungry elements such as the preconcentrator. The advantage of using battery power is the freedom of placement and lower cost of installation (if new power connections are required).

[0065] In certain embodiments, the system may be designed for distributed monitoring throughout a building or other location. Therefore, the information collected at each sensor can be best utilized if it is brought back to a central location. Once centralized, this data can be fused and further interpretation can be conducted. In addition, the resulting information can be interfaced to control systems and/or displayed. This data aggregation and interpretation provides for fewer false alarms and centralized information display.

[0066] Software is provided that allows each node (for example, the nodes 10 or 20 in figure 1) to communicate appropriate information back to a central location (for example, the nodes 30 or 50 in figure 1). This data can include alarm information and raw data for use in further computations in the central location. The full data transmission can be event driven (e.g. only sent when an event is detected) to minimize band width and reduce complexity. The aggregated data is utilized by the system level data interpretation software as described below. Furthermore, as would be recognized by those skilled in the art, the data aggregation could be performed at several tiers. For example, in one tier, all the data from all the sensors in one building or location could be aggregated (for example at node 30) while sensor data

from multiple buildings could be aggregated at a second tier (for example, in a central location 50 as shown in figure 1).

[0067] In certain embodiment, the present invention proposes extensive software control for both low level and high-level control of node function, code to aggregate and interpret sensor data at a single node, and software to provide for calibration of devices at the point of manufacture and in the field. The array based sensing technology discussed herein uses a pattern matching approach to detect and identify compounds from a library. This library can reside either on the device or at a remote location. Applicant's U.S. Patent No. 6,422,061 provides additional details of detecting and transmitting sensory data and identification libraries over a network, the disclosure of which is incorporated by reference herein for all purposes. This approach allows for rapid upgrading of instruments as new threats become important. Analysis of live agent test data has indicated a 5-10 (or greater) fold improvement in sensitivity and accuracy is achievable through software optimization at the node.

[0068] A network of autonomous sensors reporting to a central location offers the potential to further reduce false alarms and improve alarm prediction through software deployed at the network level. In certain embodiments, the present invention provides an extensive software capability for sensor data fusion. In one embodiment, one module of this system is a symbolic data model that reads discrete data (e.g. alarms, settings) and applies two different mathematical or analytical approaches to identify anomalies. In the first case, a set of rules is applied to this data to generate derived states and anomalies. While the mathematical analysis software is generic, the set of rules must be determined for a given application so the it may best be described as a "knowledge-based" component. In other words, this portion operates on rules such as: if alarm A sounds do nothing unless alarm B sounds. In addition to this rules based module, a second module uses more advanced mathematical tools to identify anomalies. This module utilizes Hidden Markov Models (HMM) to identify anomalies based on probabilities of passing from one state to a second state. The HMM use different algorithms to define these probabilities such as a Viterbi algorithm, a forward-backward algorithm, or a Baum-Welsh algorithm, as would be known to those skilled in the art. All of these methods are designed to find hidden patterns in data. The output is a prediction of an anomaly based on a number of discrete state variables.

[0069] An element of the system provides how information is presented. In one embodiment, the system of the present invention is an autonomous system that interfaces with existing control functions by providing a data feed to these existing control systems. In

certain other embodiments. the present invention includes other visualization capability such an indication of overall system health with drill down capabilities. In this approach, a central display will present a red light/green light indication (or other similar indicator) of system health/alarm status. On alarm (or system error), further information will be available in graphical form to indicate the fault/alarm location. This capability may prove extremely helpful to first responders or other emergency personnel. An example of such a GUI 1201 that may be used is shown in figure 12.

[0070] An element of the system is an understanding of node density and distribution throughout the facility both from the perspective of deploying the nodes and interpreting the results received from the nodes. From the perspective of deploying the nodes in a cost and result effective manner, the main principle is that analysis of data from diverse networked sensors generates a system whose performance is significantly better than the sum of its parts. One of the main results of applying this principle is the suppression of false alarms from inexpensive generic sensors. This is achieved by using cutting edge data analysis with a clustered array of networked sensors (whether of the first type sensors and/or second type sensors). At both the array and cluster levels, diverse sensors and optional supplementary sensors such as meteorological ("met"), GPS, may be used. This allows modeling to design clustered array configurations to answer a variety of questions, including: whether supplementary sensor are needed with each sensor, or only with each cluster; what is the optimal distance between sensors and clusters; and what is the effect of weather on specific sensors. The modeling is also used to answer system-level cross-correlation questions such as: what is the best number of sensors per cluster; what is the best mix of sensor types in a cluster; or is there a combination of generic sensors that can cover for each other's failings, with at least one type that works in most relevant weather conditions. The data fusion and analysis approach also provides software that can learn patterns of system behavior and optimize its performance at each particular site. It learns from its mistakes and evolves to become better using techniques such as neural networks which are within the abilities of one skilled in the art.

[0071] From the perspective of interpreting results received from particular nodes, certain embodiments of the present invention model different deployment options and node placements and factor that information in the analysis of the data received from the nodes. Therefore, in certain embodiments, the analysis models may give different weightage to different nodes (or sensor arrays) based on the location, type, and or density of nodes in a

monitored area. For example, if an area has a large number of first type sensor nodes, a single node indicating the presence of a particular agent when the other nodes do not indicate the presence of such an agent is given less weightage than if the node indicating the agent was in an area with relatively sparse coverage of nodes.

[0072] In certain embodiments, the second type sensors (or more sensitive sensors) may be provided with preconcentrators. Such preconcentrators are used for improved performance with analytical equipment such as gas chromatographs and mass spectrometers. More recently, miniaturized versions of these devices have been developed for use with hand held devices. While such a device does offer the possibility of sensitivity and perhaps even specificity enhancements, it does come with a price of additional power needs, reduced system robustness, increased operational costs, and more complex manufacturing. Therefore, this capability may not be used on all nodes and a tradeoff of incorporation of the preconcentrator is made before deciding how many of the nodes would include a preconcentrator.

[0073] Figure 13 shows a micromachined preconcentrator CASPAR 1301 (Cascade Avalanche Sorbent Plate ARray), which can be used to selectively trap analyte(s) of interest and thermally desorb a narrow time width pulse of concentrated analyte into a narrow orifice intake. The design of CASPAR provides a high surface area "collection plate" with an extremely low-pressure drop, to allow a high flow to be passed through the device and intimately contact the majority of the collection surface, with the minimum power expended. Collection flow is directed normal and directly through the surface of CASPAR, which is machined with a dense array of holes or perforations. Approximately 50 % of the surface corresponds to air openings. One or more collection plates can be used as necessary. Multiple plates can also be stacked to provide increased collection efficiency, however a single collection plate has been demonstrated as an efficient analyte collector design for explosives and a nerve agent simulant (DMMP).

[0074] Alternative micromachined preconcentrator technologies have been developed in which air collection flows are directed parallel to the collection surface. This approach does not allow high airflows, with intimate air to collector surface contact.

[0075] The surface of CASPAR is coated with one or more areas of sorbent polymer(s), which act to selectively collect and concentrate analyte at ambient temperatures. The sorbent polymers for a number of analytes including chemical agents have been designed for trapping chemical agents. These materials have also been specifically designed with high temperature

stabilities, necessary for thermal cycling. Naval Research Laboratories (NRL) "HC" polymer coated CASPAR devices have been demonstrated to provide very high collection efficiencies for the nerve agent, dimethylmethylphosphonate (DMMP). Even with an "early" non-optimized prototype device, sensitivity gains observed were in the region of multiple orders of magnitude. After thousands of thermal desorption cycles, no degradation in device performance has been observed. Multiple areas of CASPAR coated with different sorbent materials, targeting different agents and TICS, can be thermally desorbed in sequence and from initially different operating temperatures to different desorbing temperatures to provide additional measures of analyte selectivity.

[0076] The low thermal mass of CASPAR allows the device to be heated from ambient to analyte desorption temperatures in the milliseconds time domain. This allows the injection of a high concentration analyte sample into the sensor module. CASPAR can be thermally ramped to intermediary temperatures to allow desorption of analytes that correspond to different vapor pressures as shown in the diagram 1401 in Figure 14. This process offers separation between more volatile analytes such as hydrocarbon fuels, other solvents and analytes of interest such as the chemical agents. In addition, multiple areas of CASPAR coated with different sorbent polymers, targeting different analytes, can be thermally desorbed in sequence to provide additional measures of analyte selectivity. Flow through CASPAR will be provided by a miniature fan during collection and a miniature pump during desorption.

[0077] Some of the technology discussed herein are described in greater detail in the following U.S. patents, whose entire disclosures are incorporated herein in their entireties:

6,234,006 Hand held sensing apparatus

6,085,576 Hand held sensing apparatus

6,418,783 Hand held sensing apparatus

6,537,498 Colloidal particles used in sensing arrays

[0078] The invention is described herein with reference to accompanying drawings. These drawings illustrate certain details of specific embodiments that implement the systems and methods and programs of the present invention. However, describing the invention with drawings should not be construed as imposing on the invention any limitations that may be present in the drawings. The present invention contemplates methods, systems and program products on any computer readable media for accomplishing its operations. The embodiments of the present invention may be implemented using an existing computer

processor, or by a special purpose computer processor incorporated for this or another purpose.

[0079] As noted above, embodiments within the scope of the present invention include program products on computer-readable media and carriers for carrying or having computer-executable instructions or data structures stored thereon. Such computer-readable media can be any available media which can be accessed by a general purpose or special purpose computer. By way of example, such computer-readable media can comprise RAM, ROM, EPROM, EEPROM, CD-ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of computer-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer. When information is transferred or provided over a network or another communications connection (either hardwired, wireless, or a combination of hardwired or wireless) to a computer, the computer properly views the connection as a computer-readable medium. Thus, any such a connection is properly termed a computer-readable medium. Combinations of the above should also be included within the scope of computer-readable media. Computer-executable instructions comprise, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing device to perform a certain function or group of functions.

[0080] The invention has been described in the general context of method steps or system components which may be implemented in one embodiment by a program product including computer-executable instructions, such as program modules, executed by computers in networked environments. Generally, program modules include routines, programs, objects, components, data structures, etc. that perform particular tasks or implement particular abstract data types. Computer-executable instructions, associated data structures, and program modules represent examples of program code for executing steps of the methods disclosed herein. The particular sequence of such executable instructions or associated data structures represent examples of corresponding acts for implementing the functions described in such steps.

[0081] The present invention is suitable for being operated in a networked environment using logical connections to one or more remote computers having processors. Logical connections may include a local area network (LAN) and a wide area network (WAN) that are presented here by way of example and not limitation. Such networking environments are commonplace

in office-wide or enterprise-wide computer networks, intranets and the Internet. Those skilled in the art will appreciate that such network computing environments will typically encompass many types of computer system configurations, including personal computers, hand-held devices, multi-processor systems, microprocessor-based or programmable consumer electronics, network PCs, minicomputers, mainframe computers, and the like. The invention may also be practiced in distributed computing environments where tasks are performed by local and remote processing devices that are linked (either by hardwired links, wireless links, or by a combination of hardwired or wireless links) through a communications network. In a distributed computing environment, program modules may be located in both local and remote memory storage devices.

[0082] Other embodiments of the invention will be apparent to those skilled in the art from a consideration of the specification and the practice of the invention disclosed herein. It is intended that the specification be considered as exemplary only, with the true scope and spirit of the invention also being indicated by the following claims and equivalents thereof.

What is claimed is:

1. A method of monitoring for chemical or other toxic agents, comprising:

operating a plurality of first type sensors having a first level of sensitivity to an agent in a monitored area;

concurrently operating a second type sensor having a second level of sensitivity to the agent in the monitored area, wherein the second level of sensitivity is at least ten times more sensitive than the first level of sensitivity; and

receiving and analyzing, at a central location, input from the plurality of first type sensors and the second type sensor in order to determine the presence of the agent in the monitored area.

2. The method according to claim 1, wherein the second level of sensitivity is at least one hundred times more sensitive than the first level of sensitivity.

3. The method according to claim 1, wherein both the plurality of first type sensors and the second type sensor are operated continuously.

4. The method according to claim 1, wherein both the first type sensors and the second type sensors comprise chemiresistor based sensor arrays.

5. The method according to claim 4, wherein the chemiresistor based sensor arrays comprise conductive polymer composite vapor sensors.

6. The method according to claim 1, further comprising providing a preconcentrator with the second type sensor.

7. The method according to claim 1, wherein the agents comprise one or more from the group consisting of chemical warfare agents and toxic industrial chemicals.

8. The method according to claim 1, wherein the first level of sensitivity is the IDLH (Immediately Dangerous to Life or Health) level and the second level of sensitivity is the PEL (Permissible Exposure Level) level.

9. The method according to claim 4, wherein the chemiresistor sensor arrays comprise orthogonal sensing technologies on a single sensor array.

10. The method according to claim 1, further comprising activating an alarm only when data analyzed from both a first type sensor and the second type sensor indicate presence of a particular agent.

11. The method according to claim 1, further comprising activating an alarm only when two separate analytical models applied to data from either a first type sensor or a second type sensor indicate the presence of a particular agent.

12. The method according to claim 11, wherein the analytical model includes assigning different weights to different sensors based on the type or location of the sensor or the density of sensors at a location.

13. The method according to claim 11, wherein activating the alarm is determined based on a model configured such that the results from the two separate analytical models indicate a false alarm percentage of less than 0.01% and the false positive percentage of less than 5% for all agents tested at the IDLH level of concentration.

14. A system for monitoring for chemical or other toxic agents, comprising:

a plurality of first type sensors, having a first level of sensitivity to an agent, arranged in a monitored area;

a second type sensor, having a second level of sensitivity to the agent, arranged in the monitored area, and

a central analysis unit connected to the plurality of first type sensors and the second type sensor, wherein the central analysis unit analyzes data from the plurality of first type sensors and the second type sensor in order to determine the presence of the agent in the monitored area.

15. The system according to claim 14, wherein the first type sensors and the second type sensors comprise chemiresistor based sensor arrays.

16. The system according to claim 15, wherein the chemiresistor based sensor arrays comprise conductive polymer based vapor sensors.

17. The system according to claim 14, wherein the second type sensor further comprises a preconcentrator.

18. The system according to claim 14, wherein the central analysis unit is configured to activate an alarm only when input from both a first type sensor and the second type sensor indicate the presence of a particular agent.

19. The system according to claim 14, wherein the central analysis unit is configured to activate an alarm only when two separate analytical models each indicate the presence of a particular agent when provided with input from either a first type sensor or a second type sensor.

20. A method for monitoring for chemical or other toxic agents, comprising:

operating a first type sensor having a first level of sensitivity to an agent in a monitored area,

operating a second type sensor having a second level of sensitivity to the agent in the monitored area, and

receiving and analyzing, at a central location, input from the first type sensor and the second type sensor in order to determine the presence of the agent in the monitored area,

wherein the first type sensor and the second type sensor each comprise a plurality of orthogonal sensing technologies on a single sensor array, wherein a transduction mechanism in each of the sensing technologies detects a change in electrical resistance.

21. The method according to claim 20, wherein at least one of the sensors in the first type sensor and the second type sensor has regions of conducting and non-conducting material.

22. A system for monitoring for chemical or other toxic agents, comprising:

a first type sensor, having a first level of sensitivity to an agent, arranged in a monitored area;

a second type sensor, having a second level of sensitivity to the agent, arranged in the monitored area, and

a central analysis unit connected to the first type sensor and the second type sensor, wherein the central analysis unit analyzes data from the first type sensor and the second type sensor in order to determine the presence of the agent in the monitored area,

wherein at least one of the first type sensor or the second type sensor comprises a plurality of orthogonal sensing technologies in a single sensor array, wherein a transduction mechanism in each of the sensing technologies detects a change in electrical resistance.

23. The system according to claim 22, wherein the orthogonal sensing technologies in the single sensor array comprise respective two or more sensors made from respective two or more from a group consisting of intrinsically conducting polymers (ICPs), composites made from ICPs, sensors made from single wall carbon nanotubes (SWCNTs), composites made from SWCNTs, metal oxide semiconductor sensors, and sensors made from porphyrin materials.

24. The system according to claim 22, wherein the at least one of the first type sensor or the second type sensor comprises a plurality has regions of conducting and non-conducting material.

25. The system according to claim 22, wherein the orthogonal sensing technologies in the single sensor array comprise respective two or more sensors made from respective two or more from a group consisting of intrinsically conducting polymers (ICPs), composites made from ICPs, sensors made from single wall carbon nanotubes (SWCNTs), composites made from SWCNTs, metal oxide semiconductor sensors, sensors made from porphyrin materials, and sensors made from metallic nanotubes made from metal or metal oxides.

26. A method of monitoring for chemical or other toxic agents, comprising:

operating a plurality of first type sensors having a first level of specificity to a group of agents in a monitored area;

concurrently operating a second type sensor having a second level of specificity to the group of agents in the monitored area, wherein the second level of specificity is more specific than the first level of specificity; and

receiving and analyzing, at a central location, input from the plurality of first type sensors and the second type sensor in order to determine the presence of an agent in the monitored area.

27. The method according to claim 26, further comprising:
determining an optimum layout and number of first type and second type sensors in the monitored area by modeling to meet specified performance standards and minimizing costs.

28. The method according to claim 1, further comprising:
determining an optimum layout and number of first and second type sensors in the monitored area by modeling to meet specified performance standards and minimizing costs.