Summary of the Sensing and Positioning Technology Workshop of the Committee on Nanotechnology for the Intelligence Community: Interim Report

Greg Eyring, Rapporteur, National Research Council

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Summary of the Sensing and Positioning Technology Workshop of the Committee on Nanotechnology for the Intelligence Community

Interim Report
October 27–28, 2003
Washington, D.C.
Greg Eyring,
Rapporteur

NATIONAL MATERIALS ADVISORY BOARD
DIVISION ON ENGINEERING AND PHYSICAL SCIENCES
NATIONAL RESEARCH COUNCIL *OF THE NATIONAL ACADEMIES*

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INTRODUCTION

The Sensing and Positioning Technology Workshop of the Committee on Nanotechnology for the Intelligence Community was organized by the staff at the National Materials Advisory Board (NMAB) of the National Research Council (NRC) and was conducted under the intelligence community's Nano-Enabled Technology Initiative (NETI), administered by the staff of the Intelligence Technology Innovation Center (ITIC). The committee was formed to assist the intelligence community in illustrating the potential for nanotechnology to address key intelligence community needs.[1] Nanotechnology offers the potential to produce power, sensing, and locating devices that are small, robust, and cost-effective.

This report summarizes the second of two workshops called for in the statement of task, including the presentations made to the committee and the subsequent discussion. As such, it follows the interests and knowledge of the presenters and does not necessarily provide a comprehensive analysis of the topics discussed. While some speakers did have expertise in nanotechnology, they were chosen primarily for their knowledge of tagging, sensing, and tracking applications of interest to the intelligence community. Like the report of the first workshop,[2] it is being issued as an interim report written by an appointed rapporteur who attended the workshop; it was reviewed for accuracy according to standard NRC procedures prior to release.

The third and final report will be a full consensus study by the committee and will contain the committee's findings and recommendations. In its final report, the committee will elaborate on the specific role nanotechnology can play in enhancing these applications.

For the purposes of this workshop, the committee chose not to draw a bright line between micro-and nanoscale devices, believing that a promising new opportunity should not be excluded from discussion just because strictly speaking it might be microscale instead of nanoscale. This summary report, together with the summary of the earlier workshop on power systems, will provide useful input to the final report.

The external data-gathering portion of the workshop was organized in six topic areas, with several speakers addressing each topic:

1. Security technologies overview
2. Systems
3. Natural chem/bio tags
4. Passive chem/bio tags
5. Radio/radar/optical tags

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[1] See Appendix A for details on the workshop, Appendix B for biographies of committee members, Appendix C for definitions of acronyms, and Appendix D for the statement of task.

[2] National Research Council, Summary of the Power Systems Workshop on Nanotechnology for the Intelligence Community, The National Academies Press, Washington, D.C., 2004.

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Following the presentations for each topic, there was a brief discussion involving all of the speakers on that topic. The workshop summary follows this same organizational scheme: For each topic area, the main points of each speaker's presentation are highlighted, followed by a recapitulation of the general discussion.

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TOPIC 1:

SECURITY TECHNOLOGIES OVERVIEW

Two papers on this topic were presented, one by Richard Jotcham, Axess Technologies Ltd., and the other by Michael Kolodny, U.S. Army Research Laboratory.

SECURITY TECHNOLOGIES OVERVIEW AND APPLICATIONS

Richard Jotcham outlined the various kinds of security tags that are currently used in the commercial world and commented on each. Tags may be added directly to products or be associated with their packaging. The areas discussed were these:

- Biometric tags
- Covert tags
- Forensic level tags
- Product characteristic tags
- Coding tags
- Electronic tags

Biometric Tags

Biometric identification systems include DNA and fingerprint analysis, iris, hand, and facial recognition, retinal scanning, signature authentication, and speech recognition. All are widely used, although facial recognition technology currently has a high rate of false positives.

Covert Tags

Examples of covert tags are color-coded plastic particles 20–30 μm on a side distributed throughout a product and gem stones with 10 μm colored spheres inserted between the crystal grains. Another example given was tagging a car by spraying tiny particles containing the vehicle identification number (VIN) all over the underside, to help identify parts that might be later removed and sold by thieves. Many covert tags are read spectroscopically using visible, ultraviolet, or infrared light. For example, documents can be tagged with ultraviolet fluorescent compounds and identified by analyzing the time-resolved fluorescence decay.

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Forensic Level Tags

Forensic level tags involve a complex authentication process and are often undetectable by normal methods. One example is DNA analysis, in which a strand binds with its complement and gives a machine-readable signal or a machine-readable hologram. When asked whether a person's environment affects his body in an identifiable way, Jotcham noted that there is ongoing work on analyzing the bacteria that colonize the body and relating them to unique strains that may inhabit specific local environments.

Product Characteristic Tags

In-product analysis or authentication can be used to identify a specific product and determine if it has been diluted or subjected to other forms of tampering. The product itself can be characterized (by, for example, colorimetric testing, isotopic identification, spectroscopic fingerprinting, elemental analysis, and so on) or it can be identified by adding taggants such as molecules with hydrogen/deuterium isotope ratios (or ratios of other stable isotopes) that do not occur in nature. Commercial companies tend to be more interested in tracking the intermodal transportation of the aggregates through the supply chain rather than in tracking individual products per se.

Coding Tags

Coding (e.g., bar coding) provides a way for manufacturers to attach unique data or variable information to a product that creates a data stream as it moves through the supply chain. Bar coding had many skeptics when it was first proposed, but it is now inexpensive and ubiquitous and supported by a well-developed infrastructure. Unique identification data can be coded with an inkjet, and laser coding of identification data onto a product creates a tag that cannot easily be removed. Two-dimensional bar codes can be made very small (invisible to the eye) and may contain many times the information contained in one-dimensional bar codes.

Electronic Tags

Electronic tags can be used to identify a product's current position to track its history of environmental changes and additions, and help to predict its future location and composition. Commercial industry primarily uses these tags to better control their supply chain dynamics and inventory. The best example is Dell Computer, which transformed the computer industry's use of supply chain management to cut its operating costs and excess parts inventories. Jotcham discussed four levels of ID tags that can be used: the individual package (level 1); the display carton (level 2); the shipping case (level 3); and the pallet (level 4). With electronic tags, it is possible to read a level 1 code without opening the level 4 packaging. The best systems can alert the manufacturer when tampering has taken place. He pointed out that individuals can also be tracked by data generated in their everyday lives: drivers' licenses, bill paying, insurance information, and payment of tolls and parking fees, as well as health care, schools, and work products.

Electronic tracking can be divided into chipless tags—for example, magnetic, electromagnetic, and antitheft electronic article surveillance (EAS) devices—and chip-containing tags, which may be passive, active, or smart active. In addition, there are electronic product codes (EPCs), which are tiny

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microchips (“nanoblocks”) that can carry many bits of product identification data unique to a particular item in a way that is similar to a car's license plate.

Advantages of chipless tags are their small size and low cost (1–5 cents per tag). Disadvantages are the short read range and low data capacity. Chip tags, on the other hand, have high data capacity with read, write, and erase capability and a high reading range but are expensive (50 cents to $5 per tag). The tags themselves are generally small, but the associated antennas are large.

Finally, Jotcham offered some thoughts on the problem of finding, in an urban setting, an individual who doesn't want to be found. He proposed three steps for finding such an individual: the elimination of cover; use of unique characteristics of the individual; and looking for an environmental fingerprint—the effects of the individual on his environment.

NETWORKED SENSORS FOR THE BATTLEFIELD

Michael Kolodny noted that the Army is moving toward fast, lightweight, smart forces that will trade armor for information. The Army is attempting to develop a family of high-fidelity, affordable, multimission, integrated sensors that will provide near-real-time, high-resolution, “in-the-mud” close-up information and a common operational picture to forces at all levels. The sensors will be deployed in clusters or networks that will require sensor fusion at the node and network levels, robust communication links, self-configuring and self-healing ad-hoc networks, and decision support tools. Five technology areas are key:

- Acoustic/seismic sensors that could detect and identify vehicles, helicopters, and the like and provide cueing for imagers (there are serious issues with triggering by spurious noises);
- Magnetic sensors that could detect vehicles and small arms (tanks can be detected at 50 to 500 meters, rifles at 2 to 17 meters);
- Infrared imagers for target identification;
- Radars as moving target indicators; and
- Radio frequency (RF) energy sensors to detect unintentional RF emissions (e.g., engine noise) as well as intentional emissions (e.g., detection and classification of radio signals).

Fusion of all of the signals from these sensors will create a network that is more than the sum of its parts. The sensor network should degrade gracefully when individual units fail.

Current programs are aimed at higher-cost (>$100 each), more capable sensor nodes but there is a desperate need for disposable sensors that could provide human detection capabilities in confined urban settings such as buildings, tunnels, and alleys. Urban warfare is the most difficult problem; most people in the world live in cities.

The Army's vision is for acoustic, magnetic, or seismic nodes (or very low-cost imagers) costing approximately $5 to $10 each that will require minimum communication bandwidth and power, because the more traditional form of RF devices probably will not be effective in these confined terrains. There are pacing issues regarding the timing of the sensor network communications, and the system must be resistant to jamming. Kolodny believes nanotechnology can contribute here by reducing size, thereby improving covertness. So far, the Army is focuing on commercial, off-the-shelf technology, because the design must be mass-producible. Low-power algorithms will have to be packaged into a modest-performance processor. The Army is evaluating a form of smart dust funded by the Defense Advanced Research Projects Agency (DARPA) that consists of a solar-powered chip (4.8 mm^3 displaced volume) combined with acceleration and ambient light sensors and bidirectional communications. GPS-based systems are probably not viable.

Major challenges include cost/size reduction of integrated microelectronics (wireless networks and filters for communications; large number of sensor arrays; high-frequency components; and

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packaging), communications (energy-efficient miniature radios; energy-aware, ad-hoc networking), processing (power conservation; sensor and data fusion), and node location and orientation. Kolodny believes that many of the enabling technologies already exist, but the systems will have to be made smaller and less expensive, and all the elements of nodes will need to be integrated up front for a successful network.

PANEL 1 DISCUSSION

In response to a question about whether the enabling technologies already exist for unattended ground sensor networks described by Kolodny, he stated that the basic performance capabilities of individual pieces (e.g., sensors) are good enough if we can fuse the data and make them smaller and cheaper. One comment, however, was that as we go to smaller and smaller length scales, we may have to take an entirely different technological approach. The Army has specified a cost of no more than $10 per node, including communications, and is focusing on the commercial sector because it is interested in production runs on the order of 10 million units. On a small scale, there are commercial drivers for multiplexed sensors, such as sensors for tracking the location of products (e.g., laptops) within a building.

Asked whether any self-assembled networks are currently available, Kolodny mentioned Millennia Net in Boston, as well as Smart Dust, Inc.'s Motes. He emphasized that the nodes must be emplaceable and mobile (e.g., wearable). Emplaceable does not necessarily mean stationary (they could be on wheels or wings); as forces engage, it might be desirable to move them. They should have a 75-km range and when used in caves may be deployed on microrobots. Mobile sensors today are not networked. If we wanted to tag an entire regiment rather than an individual soldier, how would the data be processed? High-capability nodes today have 32-bit floating point arithmetic processors, while less capable nodes have 8-bit processors.

Companies are currently using radio frequency identification (RFID) tags to sense environmental conditions and track shipped material. (Temperature and humidity changes during shipping can cause a product to degrade, which can reflect poorly on the manufacturer.) Asked about the lifetime of sensors, Jotcham noted that passive sensors have essentially an infinite life, while the life of active sensors can be extended if one programs them to send out intermittent transmissions of information. For many military missions, a lifetime of at least 72 hours is desired, and all kinds of power conservation techniques are used. Where lifetimes of one month or so are required, one could spread the tags over a large group and activate them individually (e.g., with a laser) from a distance. This approach is being evaluated with RF tags.

Organic electronics is one way to create cheap tags. Plastic chips are now available, and there is a great deal of research going on. The Army is looking 6 years out for deployment and hopes that advances in nanotechnology will provide a low-cost system on a chip. On the cost issue, it was noted that all of the examples given thus far appeared to describe a heterogeneous group of tags with unique characteristics. For an integrated national system of tags with standard capabilities, the panelists believed that commercial companies would likely favor any approach that reduced costs, as occurred with the existing bar coding system.

Kolodny was asked whether there had been any real progress in unattended ground sensors recently. He responded the track record was poor. Essentially, there has been no progress since the 1970s. There are fieldable systems, but they are not used because they are too expensive (>$8,000 per node) and not easily deployable. With the Army shifting its focus to warfare in urban environments, deployable, cheap nodes are needed that can be fielded in the next 6 years.

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TOPIC 2:

SYSTEMS

Three papers were presented in this session, one by Kwan Kwok, DARPA, one by Rich Fletcher, the Massachusetts Institute of Technology (MIT) and TagSense, Inc., and one by Chris Murphy, NRC Board on Chemical Sciences and Technology.

APPLICATIONS OF MOLECULAR ELECTRONICS TECHNOLOGY (MOLEAPPS) PROGRAM

Kwan Kwok reviewed the goals and achievements to date of the new 5-year DARPA MoleApps program, which aims to apply molecular-scale electronics technology to the development of ultradense molecular electronic computer processors (this thrust is called MoleComputing) and molecular electronic sensor systems (MoleSensing). For the purposes of the MoleApps program, molecular-scale electronics technology refers to using single molecules, small numbers of molecules, nanoparticles, nanoscale metallic and/or semiconductor wires, nanotubes, and so on as electronic components.

The goal of the MoleComputing thrust is to develop a prototype molecular (no-silicon) electronic computer processor having local molecular device densities of $10^{11}/\text{cm}^2$ and a clock rate of at least 10 kHz and consuming no more than 10 W/cm^2 of power. Such a processor would be equivalent in complexity to a 1971-vintage microprocessor such as the Intel 4004 but have an area 100,000 times smaller.

It would have to be compatible with molecular memory devices such as those being developed in the concurrent DARPA programs, Moltronics, for example, a team of researchers from Rice and Yale Universities, is developing a 10 μm×10 μm 16-kbit memory consisting of an ultra-high-density network of molecular wires and switches that will fit on a human cell. The manufacturing processes to produce such components in bulk do not exist yet, and such molecular memories are affected by, among other things, cosmic rays and incomplete reactions, but they will be self-repairable and fault-tolerant (able to operate with up to 10 percent defects). In 2001, researchers from Hewlett-Packard and the University of California at Los Angeles produced crossed-wire memory devices by sandwiching perpendicular layers of nanoscale wires (reminiscent of the ferrite core memory structures used in the early days of computers). The pitch (spacing between parallel wires) was 33 nm in those devices, and more recent efforts have reduced the pitch to 20 nm.

The goal of the MoleSensing thrust is to develop a prototype molecular electronic sensor system having at least 1,000 nanosensors per square micrometer (10^{11} per square meter) and sensitivity and discrimination equivalent to a dog's nose. DARPA has funded research on artificial dog's noses for a number of years, but progress has been slow. The sensor should be able to uniquely identify any of 255 different chemical and biological agents in concentrations as small as 500 parts per trillion. It should have a chemical response time of no more than 10 seconds after exposure to the sample and an electrical

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response time (after receptor attachment) of no more than 1 second. The active detection area should be no more than 25 nm^2. The research is being conducted at the Army Research Laboratory (ARL), Naval Research Laboratory (NRL), MITRE, and Northwestern, Harvard, and Yale Universities. Kwok speculated that with the new sensing capabilities of molecular-scale sensors, one would be able to differentiate dirty radiological bombs from nuclear weapons and locate hard-to-identify terrorists, though he did not explore how this would be done operationally. Kwok noted two concept targets that might result from this effort: a personal computer with the thickness of a piece of paper with a chem/bio detector attached; and a black box detector mounted on a watch battery.

RFID TECHNOLOGY: OPPORTUNITIES AND CHALLENGES

Rich Fletcher reviewed the basics of RFID tags, which were invented in 1975, noting that WalMart is requiring all vendors to tag their products by 2007, with DoD and the FDA also issuing requirements for vendor RFID tags to help in management of product inventories. Credit cards are also converting to RFID technology (e.g., ExxonMobil's smart tag system). The simplest type of RFID tags are chipless tags, which are stamped metal foils that can code on the order of 10 bits of information. At short range, where the tag and reader are in close proximity, the RFID tag looks like a resonant LC circuit, and information is encoded in the resonant frequency or the loss profile, or by modulation. At longer ranges, a chip (which may be powered by a battery) is used in the circuit to create an active tag, and information is coded in the modulated backscatter. Radio frequency is not the only available power source for these kinds of tags; tags can also be powered by light, sound, or by changes in the electric field (capacitively coupled).

Chipless RFID sensors are tags that convey information not only about the object's ID but also about its state or history—for example, has it been broken or tampered with, or is it being squeezed? Commercial examples include simple pressure and temperature sensors.

A major challenge with RFID tags is providing the power to turn them on; they must be held close to the reader to be activated, although the sensing function itself does not require much power. Fletcher favors capacitively coupled tags because they do not require large activation currents—small gradients in the electric field are sufficient. Examples include (1) touch-based tags, where touch can be used to transfer information (e.g., an instrumented doorknob) and (2) tags that use the human body, both as a power source and as an antenna. An option for electronically displaying information from RFID tags is to use microencapsulated black and white ink particles that respond differently to dipole fields and can be read optically.

Fletcher cited some key challenges for the future. One is reducing the cost of manufacturing and handling tiny chips, which may be 0.1 μm on a side. Fluidic self-assembly based on shaking the chips and allowing them to settle in precision-machined channels is now used. Another challenge is ensuring compatibility of different RFID systems. Options include making readers with multiple front-ends to read different tags or making more agile tags that can be read by multiple readers such as those using multifrequency power and readout. In the future, analog information from sensors may also be encoded in smart antennas. Polymer electronics with printed logic and batteries and solar cells and displays on flexible substrates are enabling a whole new range of smart tags for products. Also in the future, DNA could be tagged with gold nanoparticles attached to specific sites that could be read by irradiating with a specific frequency that would be absorbed, producing local heating that would change the local molecular conformation.

In conclusion, Fletcher noted that RFID applications are already a large business that is growing very rapidly. Materials and manufacturing technologies are enabling an increasing market for wireless and cheap tags. Nanotechnology and new power sources can enable greater performance.

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REVIEW OF EXISTING AND POTENTIAL STANDOFF EXPLOSIVE DETECTION TECHNIQUES

Chris Murphy described an ongoing NRC study aimed at standoff detection of explosives (e.g., those contained in a belt worn by a suicide bomber). In this case, standoff is defined as detection from at least 20 meters with a response time of 5–10 seconds. Promising technologies include x-ray backscatter, IR imaging, and terahertz imaging, but there does not appear to be a clear winner for all scenarios. A systems-level approach is needed, with fusion of data from multiple sensors, discrimination, and identification to yield a high probability of detection with a low false alarm rate.

PANEL 2 DISCUSSION

Discussion in this segment began with concerns being expressed about the feasibility of molecular-scale sensing devices. For example, would bacteria in the background environment interfere with the detection of biological agents? Kwok's answer was that one is not dealing with a single 1 µm x 1 µm CMOS chip; rather, if the sensor is structured in a crossed-wire configuration with target-specific antibody sites at the nodes, one has the equivalent of an array of 1,000 such chips, and only one triggered cross point is needed for detection. Diffusion is fast across this area and one can design 255 different signatures to detect an equivalent number of agents.

Another issue was raised: the significant problem with detecting small things in large volumes—for example, screening 5 liters of liquid to find one organism. Selectivity is yet another key issue, indeed a bottleneck: The transduction element must only respond to the target ligand. Kwok's response was that DARPA's goal is not to develop new chem/bio sensor systems per se but to push nanotechnology forward using the performance of a dog's nose as a metric. He wants to “build a different way to look at the problem.” It was also asked whether having more nodes in sensors is necessarily better. With a large number of nodes, there could be a data processing problem that would degrade the overall signal. An important question for sensor integration is, How many nodes are enough?

Rich Fletcher was asked about the limitations imposed on the covertness of RF tags by the need for antennas, and whether negative refractive index materials (and photonic band gap materials in general) might be useful in addressing this problem. What power levels are required for these materials as a function of distance? Fletcher did not answer directly but noted that while good work on negative refractive index materials is being done in academia, the work has not yet been transitioned to the commercial world. With regard to antennas, while they may be long, they can be made so thin that they are invisible to the eye. One can also use higher-frequency systems to reduce antenna size, but the higher frequencies don't penetrate well in enclosed spaces. It was also asked why if capacitive RFID tags are so promising, Motorola had dropped its program in this area. Fletcher believes that this was a case of throwing out the baby with the bath water: Motorola determined it was losing money in the tagging area and terminated all of its programs in that area.

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TOPIC 3:

NATURAL CHEM/BIO TAGS

Two presentations were made in this session, one by Alan Gelperin, Monell Chemical Senses Center, and one by Steven Martin, Sandia National Laboratories.

DESIGNING CHEMICAL SENSOR SYSTEMS FOR ELECTRONIC OLFACTION

Alan Gelperin reviewed recent progress in electronic olfaction technology based on biological models. For example, moths are hypersensitive to a few specific compounds (e.g., pheromones), while a dog's nose has more general sensitivity. The general-purpose nose can be trained to detect new odors, such as TNT. The artificial nose requires an array of odor sensors, with diverse odor responses (there are some 1,000 different odor receptor classes in mice, 300 in humans), and a computational module for analyzing odor patterns. Hopfield published a paper[3] showing that a larger number of different sensor classes in an array (up to ~100) gives a different and richer response than an array with a smaller number of sensor classes. Gelperin felt that an algorithm developed by Hopfield is quietly revolutionizing this field. The algorithm allows a system to recognize a new odor pattern in terms of known odor patterns.

Gelperin focused on organic field effect transistors in which the odor vapor is flowed over a chemically active organic layer between the source and drain of a transistor, and the degree of interaction between the odorant molecules and the active layer is reflected by changes in the current flow. This system has the advantage that the odor can be driven out (to reset the sensor) by reversing the gate voltage rather than having to flow fresh air over the sensor. The organic surface layer should be as thin as possible to maximize the influence of the surface. Another configuration demonstrated for the detection of O_2 and CO gases uses changes in current flow through carbon nanotube wires (or nanowires made of other materials) as the sensor.

Special challenges of these systems include the following:

- Ensuring that the identification of the odor does not depend on concentration;
- Separating odor “objects” (multiple odors that arrive together);
- Identifying weak known odors against a background of strong unknown odors;
- Storing odor patterns for later pattern matches; and
- Subtracting constant background odors while remaining sensitive to new weak odor inputs.[4]

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[3] J.J.Hopfield 1999. Odor space and olfactory processing: Collective algorithms and neural implementation, Proceedings of the National Academy of Sciences 96 (22):12506–12511.

[4] For example, dogs have to be trained on local background odors for about 2 weeks before they are used to detect land mines in a given region.

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An optimal system in the future would have sensor arrays with 50–100 unique sensor types. The array would be small enough to allow one-sniff coverage and would be cheap and easy to replace. It would have low power consumption, interface easily with processing electronics, and have enough processing power to implement fast, new pattern analysis algorithms. Detector replacement is necessary because, like natural olfactory cells, sensor arrays will eventually become poisoned with use.

To use artificial nose technology for tracking, robots are being built that can follow a scent using search algorithms inspired by the pheromone-following strategy of a moth—i.e., moving back and forth perpendicular to the wind direction to pick up the scent, then moving upwind toward the source.

MICROSENSOR DEVELOPMENT

Steven Martin discussed the miniaturization of analytical devices, focusing on the MicroChemLab, a handheld gas chromatograph (GC) that can detect chemical warfare agents or other vapors of interest. Microfabricated components such as sample concentrators, analyte separators, and detectors offer small size, low power, low sample volumes, few (or no) reagents, and rapid analysis (e.g., 2 minutes for MicroChemLab). Disadvantages include high initial costs, less versatility than full-size instruments, less sensitivity, and lower resolution.

MicroChemLab uses three microfabricated analysis stages: a sample preconcentrator, a micro gas chromatography stage, and a surface acoustic wave (SAW) detector to provide sensitive detection. The preconcentrator and the SAW detector have nanostructured surfaces. The chromatograph stage uses a thin-film sol-gel coating on the column surface that has tailored porosity to provide separation of analyte chemicals. A system can be designed with multiple parallel GC columns to confirm the analysis and reduce the false alarm rate. Various kinds of detectors (other than the standard SAW detector) are possible.

In principle, it is possible to use the MicroChemLab as a reader for a signal encoded as a chemical mixture. The retention time window is used to form individual bits: An eluted peak within a given window is a 1; no peak is a 0. If detectors with different specificities are used, further information can be encoded.

PANEL 3 DISCUSSION

Initial discussion focused on the information requirements for electronic noses. These include training, pattern recognition algorithms, a database for matching patterns, and an algorithm to determine the statistics of matching. Gelperin mentioned an experiment in which an artificial nose was tested to see if it could identify grocery store produce by its odor. The rapidity of response is critical—the system must identify the odor within about 2 seconds. In addition to speed, reliability and effective background subtraction are key features. There are trade-offs to be made among these characteristics. Gelperin indicated that the prototype device had trouble distinguishing between some types of produce.

A question was raised as to whether these artificial systems really mimic natural systems. For example, the eye does not raster over a pattern—it processes certain recognition elements. Do we understand this preprocessing step for olfaction? Gelperin agreed, but felt that the Hopfield model is a good place to start. It was commented that one should focus not just on the size of the array but also on the manner in which the sensors are clustered and on the time derivative of their responses. Another question was raised about whether we understand the vomeronasal organ in mice, where neurons respond to specific pheromones. If we can design an artificial nose whose sensitivity is specific to a given compound, such as TNT, then our analysis is simplified.

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Can we distinguish one human from another on the basis of scent? There is ongoing research to determine what molecules are different from person to person and what level of difference can be identified. Laboratory tests have been able to distinguish differences in the scents of fraternal twins but not identical twins. Quantitative studies on sensitivity and recognition are very recent.

It was noted that natural systems (e.g., a dog's nose) use cascade amplification mechanisms to increase sensitivity; do we need similar amplification in artificial noses? Optically based sensor systems are already within a factor of 10 of the sensitivity of a dog's nose. We would like amplification, but we are getting close to the sensitivity of natural systems without it. Some researchers are looking at ion channel amplification as one mechanism for improving sensitivity.

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TOPIC 4:

PASSIVE CHEM/BIO TAGS

Two papers were presented on this topic, one by Todd Allen, Isotag, Inc., and the other by Jill Trewhella, Los Alamos National Laboratory.

ISOTOPIC AND FLUORESCENT TAGGANTS

Todd Allen noted that isotopic tags, which are based on isotopic ratios not found in nature, were first used in the oil and gas industry out of concern for product tampering, product dilution, and liability issues. They are now widely used in consumer products and government applications (e.g., tax compliance and explosives marking). Active markers involve the addition of a unique compound to the product/package, while passive markers exploit compounds that are already present. Markers may be overt (e.g., a hologram visible to the general public) or covert (requiring special instruments or readers to decode). Isotag, Inc. uses multiple taggants to provide added security. The concentration of active tags is usually in the low parts-per-billion range.

Isotag, Inc. uses stable isotope markers involving a non-naturally occurring distribution of mass-enhanced markers (e.g., deuterated benzene in place of natural benzene). Using isotope ratio mass spectrometry, one can track the isotope ratios of the compound of interest. Natural geographic variations in isotope ratios must be accounted for.

Fluorescence tags may exploit various regions of the spectrum, both visible and invisible. An example might be a fluorescent bar code on a product package that can only be read when the illuminated product is viewed through a special filter. These tags can be read at a distance using handheld optical devices.

Allen believes nanotechnology, including quantum dots, nanobarcodes, and manipulation of various nanoparticles, will have widespread application in the tagging industry. A key concern, however, is the chemical, structural, and thermal stability of nanomaterials.

BIOSCIENCE IN THE NANOTECHNOLOGY OF TRACKING AND LOCATING

Jill Trewhella discussed recent developments at the nano-bio interface, primarily for tagging and tracking biological entities, including viruses, bacteria, and toxins. One could use this tagging, for instance, to find out where people had been. The emerging nanotechnologies she discussed include new molecular recognition elements, called “fluorobodies,” that are more robust than DNA and antibody

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assays; patterned mesophases for compartmentalizing detection devices; and quantum dots for lasing, detecting, and signaling.

Current recognition systems in biology primarily involve DNA hybridization or antigen-antibody binding. These methods are effective but often require significant sample preparation time and may be messy, involving unstable secondary reagents. The chemistry is often complicated, and detection of each new target requires that a new chemical assay be developed. DNA assays take “more time, reagents, and sample preparation than are generally acknowledged.”

The recently developed fluorobodies, which are simple fluorescent tags that bind to a specific target and travel with it, offer a method for simpler and faster assays. Fluorobodies consist of antibody-binding loops fused with thermally stable green fluorescence protein (GFP). The recognition surface is generated and selected using phage display techniques to create large libraries, yielding high-affinity tags. These tags can bind, for instance, to unique glycolipids or glycoproteins on the cell surface of pathogens and thus identify them. (A comment at this point was that the GFP tags are monovalent, whereas most real antibodies are divalent, significantly increasing their affinity and specificity.) When mice eat the GFP, their skin fluoresces green. The latest development in this technology is split-GFP, whereby fluorescence occurs only after the binding to the target has occurred. By incorporating the fluorobodies into patterned mesophases (micrometer-level, not nanometer-level) on Si wafers, arrays of chemical and biological sensing elements can be established, making systematic, multiplexed analyses possible.

The second focus of Trewhella's presentation was quantum dots (Q-dots)—semiconductor nanocrystals whose fluorescence properties can be tuned by varying their size. When the Q-dots are stabilized by incorporating them in a sol-gel nanocomposite, they can be combined with optical microcavities to produce microlasing devices. This lasing property can be exploited in the interrogation of Q-dot arrays. One can also use the Q-dots as luminescent tags by crosslinking them with biological molecules that bind to specific sites.

Trewhella foresees revolutions exploiting the nano-bio interface involving molecular recognition elements held in predesigned scaffolds to generate a signal and amplify it (e.g., using Q-dots), as well as the use of active biomolecules, such as motor proteins, to assemble and actuate nanomaterials and structures (e.g., nanowires with programmable interconnects). Asked whether one can hook Q-dots on DNA, Trewhella said that this is probably feasible, although no one has done it, probably because of the highly hydrophobic environment of DNA.

PANEL 4 DISCUSSION

Discussion began with a question about the relative merits of natural antibodies and artificial structures such as fluorobodies. The advantage of antibodies is that they are raised in vivo and therefore naturally avoid binding to targets they are not supposed to bind to. Fluorobodies would not be expected to show this specificity. Most tests of fluorobodies are against intended targets, not against all of the other molecules that might bind nonspecifically to the binding loop. Nevertheless, fluorobodies were developed to detect successfully folded proteins in the human genome project and appear to show the same specificity as antibodies. The binding loops of fluorobodies may not be identical to the corresponding antibodies, but they must be similar.

The observation was made that Q-dots (at least those made from CdSe nanocrystals) are not covert, since the Cd signature is detectable, for example, with x-rays. Could an invisible, two-dimensional bar code—for example, one that uses upconverting phosphors that can be irradiated at 980 nm and emit in the green and blue—be transferred to the skin of an uncooperative target? This would depend on how long the bar code takes to transfer and how long it can be expected to last. There was also speculation about feeding GFP to targets, thus creating people with fluorescent skin.

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With regard to active markers added to products, what is the mass fraction of marker? Markers are typically small compounds, generally present at the parts-per-billon level, although with deuterium-substituted isotopes, one can operate on the parts-per-trillion level. Isotag uses only stable isotope markers, in deference to public perceptions of the risks of radioactivity.

Given variability in the natural abundance of isotopics—for example, deuterium is more abundant on the West Coast than on the East Coast—it was asked whether it would be possible to use geographical differences in isotope abundances to determine where a person had been. The answer is likely to be no, because people move around so much. Some work is being done to try to determine where people have been by analyzing the populations of bacteria that colonize their bodies, given that these populations reflect local environments. In a similar vein, it was asked how the anthrax spores mailed to various individuals 2 years ago could have been traced. One possibility was isotopic analysis not only of the spores themselves, but also of the admixed chemicals to determine where the spores had been grown. However, the biggest hope was DNA analysis of the strain. Unfortunately, DNA analysis revealed that the strain was garden variety anthrax used broadly to test vaccines.

Another question was whether it would be possible to irradiate individuals with neutrons and create tags inside their bodies by neutron activation. Such tags were seen as likely to be short-lived (a few hours), although it was noted that palladium activates down to stable isotopes, which might be detectable for much longer times.

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TOPIC 5:

RADIO/RADAR/OPTICAL TAGS

Four papers were presented on these topics, by Mark Shellans, Pathfinder Technology, Inc.; Bill Hurley, Inkode; Dennis Prather, University of Delaware; and Stephen Griggs, DARPA.

VESTA/PARD TECHNOLOGY

Mark Shellans discussed two related technologies for the acquisition or analysis of data on subjects at considerable distances: vibro-electronic signature target analysis (VESTA) and passive acoustic reflection devices (PARDs). These technologies could be used to identify vehicles on the battlefield as well as communicate covertly with forces on the ground.

The VESTA technology is based on the fact that physical motions of target objects will cause slight modulations of the reflected signals—for example, the sound vibrations of a moving vehicle modulate the return signal when the vehicle is illuminated by radar. Based on the modulated return, empirical, non-pattern-matching algorithms can be used to identify the class of vehicle and even to recognize a particular vehicle's unique vibrational pattern, provided the algorithm was previously “trained” on that vehicle's signal.

Shellans's approach is based on the principle that the number of features that describe the physical state of a system can be represented by a multidimensional polynomial, and any arbitrary multidimensional polynomial can be matched by expansion of a McLauren series. A typical recognition problem might involve analyzing a polynomial surface in 12 dimensions; the sheer number of possible patterns in a library of templates for pattern matching would make a pattern-matching approach unmanageable. Instead, one must limit the dynamic range of the variables or cluster around variable values for targets one expects to see. Shellan's algorithm uses a “Twenty-Questions” approach to narrow down the phase space. The VESTA approach enables fine-grain discrimination of signals requiring orders of magnitude less storage and processing than would otherwise be needed to analyze the signal, and Shellans believes this property will make the technology more useful for nanoscale devices with limited processing capabilities.

Shellans has used radar analysis techniques and recorded the acoustic characteristics of five different cars from a distance to train the system using a single 2- to 3-second scan of a Doppler radar. Later, the cars were driven past the detector many times in random order and could be identified with 100 percent accuracy. A similar technique was also used successfully with multiband, polarimetric synthetic aperture radar images of forested terrain to locate objects—for example, downed aircraft, tanks, or even cars—under the foliage. The technique can be applied to other kinds of sensor data, including biometric sensors.

Shellans also described a passive acoustic reflection device that superimposes information onto reflected radar signals. A radar receiver would be able to extract the superimposed information using the same analytical methods used to identify unique vehicle sounds. Because the PARD is not a transmitter,

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it could be used by ground-based friendly forces to communicate covertly with radar systems on aircraft. A simple message (e.g., 30 bits) could be coded into the PARD and read by a VESTA radar system passing overhead without the message being detectable to hostile forces.

COVERT RADAR TAGS AND APPLICATIONS

Bill Hurley discussed his company's technology, which involves incorporating a large number of radar reflectors in a substrate to form passive RFID tags. The radar reflectors used by Inkode are usually simple aluminum fibers that form half-wave resonators within the object to be tracked (e.g., a piece of paper). The radar-reflecting fibers are approximately the same diameter as paper fibers (typically 6.5 mm long and 1.5 μm in diameter). Randomly oriented radar-reflecting fibers provide a unique backscatter pattern that can be read and stored in a database for future identification. Ordered patterns can also be designed so that individual resonators are coupled or decoupled, whatever is likely to give the optimum backscatter pattern. Tagging an object with this technology costs about 1 cent.

When illuminated with radar, the backscattered fields interact to create a unique interference pattern that enables one tagged object to be identified and differentiated from other tagged objects. In the near field (that is, where there is an interaction between the tag and antenna), the backscatter depends on the position of the tag in the substrate, and information is represented in a scalar waveform. Beyond the near field, the backscatter is like a traditional radar, with no coupling between tag and antenna. For nonmilitary applications, the reader is less than 1 meter from the tag. For military applications, the reader and tag could theoretically be separated by a kilometer or more. The tags are the same in these two cases, but the reader is different. The normal operating point is 10 mW at 24 GHz.

The three most commonly used tags are free, individual resonators, continuous filaments, and photolithographically printed patterns of filaments. They consist of aluminum/glass fibers, either coaxial or side by side. These may be adapted for inclusion in a variety of objects, including paper, airline baggage tags, book bindings, clothing and other fabrics, and plastic sheet. The reflectance of the half-wave resonators is very efficient. In a typical 8½ by 11 inch piece of paper, there are over 8,000 radar reflecting fibers. This can theoretically be seen from a distance comparable to the distance from which a 1 m^2 target can be seen.

NANOSCALE DESIGN AND FABRICATION CONSIDERATIONS FOR PHOTONIC TAGS AND RADAR DEVICES

Dennis Prather discussed applications of nanoscale photonics technology and some of the tools being developed to fabricate these devices. Applications include (1) diffractive (as opposed to refractive) lenses that can reduce the size and weight of millimeter wave imaging systems; (2) polarization-dependent tags or reflectors that can be read with a CO_2 laser; (3) integrated sensors using components made from photonic crystal devices—that is, devices that guide light based on the scattering properties created by tailoring the material profile—such as beam splitters, optical switches, and couplers; and (4) motion microsensors, both rotational and linear.

The beam routing in photonic crystal devices is strongly wavelength-dependent; for instance, such devices exhibit a sharp spike in reflectivity over a narrow frequency bandgap. This property can be exploited in photonic tags.

Prather discussed the capabilities of various fabrication methods for creating nanoscale patterned structures, such as e-beam and interferometric lithography, methods for optical drilling of nanoscale cylindrical holes through silicon, and techniques for making tapered connectors to link microscale

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components to nanoscale components. He showed how silicon could be patterned on the nanoscale by E-beam lithography to create dramatically different images when viewed with horizontally (as opposed to vertically) polarized infrared laser light.

Prather showed how a micro-ring laser patterned in silicon (~10 μm in diameter, with coupled output-sampling waveguides) could measure rotation rate and an optical waveguide can be inserted into a microcantilever MEMS device to measure linear motion.

The small dimensions of nano-optical waveguides mean that relatively small electric fields (millivolts) can be used to modulate light transmission through the electro-optic effect, because these fields equate to kilovolts per meter. By coupling an RF antenna to a nano-optical waveguide fabricated from silicon and a few micrometers in width, for instance, one can impose millimeter-wave sidebands on the optical carrier using the electro-optic effect, separate the sidebands from the carrier with a dispersive element, and measure the sideband strength with a low-frequency detector, thus avoiding the need for any RF circuits.

Future challenges include further development of nanoscale integration techniques and refining the compatibility of manufacturing processes for both micro- and nanostructures.

DYNAMIC OPTICAL TAGS

Stephen Griggs described a DARPA-funded program starting to develop small, retro-reflecting optical tags that can be attached to targets, assets, and precision special reference points. These tags would provide non-RF location and tracking, with covert, two-way data exchange in friendly and denied areas. The specifications are as follows: size, 25×25×5 mm (a small thickness is critical for covertness); operating temperature •40° to 70°C; data rate, >100 kbps; optically readable from a distance of 10 km (line of sight) by an airborne or handheld interrogator; operating time >2 months; acceptance angle >+/•60°; cost, <$100 per tag; and non-visually alerting.

As the tagged object moves through a region, the Department of Transportation could record location information (via GPS) as well as other data (imagery, audio, etc.) that can provide vital information and decrease target ambiguity. The main technical challenges are to develop (1) thin, retro-reflecting optics that can be modulated and (2) tag-specific transceiver systems that are eye-safe at the tag (range of =1.3–2 μm) and that can search and interrogate quickly and automatically (both handheld and airborne versions).

The power requirements for the tag are estimated to be about 75 mA-hours total over 2 months. Commercial lithium coin batteries can be used. They are available in the appropriate thickness and can provide up to 120 mA-hours at approximately 3 volts. The range requirement also appears achievable based on the sensitivity of present photomultiplier tubes relative to the expected return signal intensity.

The program will be structured in three phases. The first, beginning in FY04, will develop various tag technologies and utilize a bench interrogator. The second, beginning in FY05 (assuming a positive go-no go decision), will focus on dynamic optical tag system design, including a handheld interrogator. If progress through FY05 is acceptable, prototype dynamic optical tag systems will be demonstrated using an airborne interrogator in FY 06 and 07.

PANEL 5 DISCUSSION

The discussion consisted largely of questions directed at individual presenters. Shellans was asked what materials are used in the PARD, given that one must modulate at rates greater than 100 kbps. He described the use of indium phosphide, which can be modulated at rates greater than 200 kbps (by

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moving just the electron cloud). In the future, it should theoretically be possible to transmit voice using PARD.

Hurley was asked how one can read a specific passive RF tag at a random angle if the tag is made up of randomly oriented fibers. The answer is that the computer processing the return signal can calculate what the return signal from each tag in its library should look like as it is rotated with respect to the interrogating radar and match the pattern to the observed pattern. Instead of inserting fibers into the material to be tagged, it is also possible to print metal lines on the surface. Currently, the main applications of these passive tags are in security documents (e.g., passports) and currency.

Prather was asked why, given the potential value of photonic band gap materials, the technology is not in use. For example, one can control the reflection spectra off various materials (though it is hard to make the reflection isotropic) and one can use the band gap to confine light effectively in waveguides and achieve a very high photonic “wiring density” and overlay capability with no crosstalk between waveguides. His answer was that satisfactory processes for integrating hybrid devices on silicon still need to be developed, and losses need to be reduced.

Griggs was asked how small the optical retroreflectors can be made. With UV interrogating light, it is possible to make them with micrometer-scale dimensions. All of the corner cube reflectors being evaluated can modulate light at frequencies of at least 200 kHz. To make retroreflectors more covert, one can make them reflective at only a single frequency using photonic band gap materials. The reflection wavelength can be tuned to suppress the visible wavelength signal. Gratings can also be used as retroreflectors if they are oriented at the right angle, but of course the angle is wavelength-dependent.

Griggs stressed that if one wants to make the tags very small and have reasonable data transmission rates, they must be optical. No RF device can match the size and data rate of optical devices. For example, using an optical device one can detect voice signals on the ground from a U2 aircraft using a 2-ft. by 2-ft. box. RF may be appropriate if lower data rate, power, and range are acceptable. The disadvantage of optical devices is that they must operate within the line of sight. Covert dynamic optical tags are expected to be manually placed on noncompliant targets.

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Appendix A

Workshop Presenters, Agenda, and Attendees

PRESENTERS

Topic 1: Securities Technologies Overview
Presenters:

Richard Jotcham, Axess Technologies Ltd.

Michael Kolodny, U.S. Army Research Laboratory

Topic 2: Systems
Presenters:

Kwan Kwok, Defense Advanced Research Projects Agency

Rich Fletcher, Massachusetts Institute of Technology and TagSense, Inc.

Chris Murphy, NRC Board on Chemical Sciences and Technology

Topic 3: Natural Chem/Bio Tags
Presenters:

Alan Gelperin, Monell Chemical Senses Center

Steven Martin, Sandia National Laboratories

Topic 4: Passive Chem/Bio Tags
Presenters:

Todd Allen, Isotag, Inc.

Jill Trewhella, Los Alamos National Laboratory

Topic 5: Radio/Radar/Optical Tags
Presenters:

Mark Shellans, Pathfinder Technology, Inc.

Bill Hurley, Inkode

Dennis Prather, University of Delaware

Stephen Griggs, Defense Advanced Research Projects Agency

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AGENDA

Monday October 27, 2003

7:30 a.m.	*Continental breakfast*	
8:00	Call to Order and Meeting Objectives	Robert Hermann, Chair

Topic 1: Security Technologies Overview

8:05	Overview of Private Sector Applications and Approaches	Richard Jotcham
8:40	Overview of Government/Military Applications and Approaches	Michael Kolodny
9:15	Discussion	

Topic 2: Systems

9:50	Nano Computing and Sensor Systems	Kwan Kwok
10:10	Commercial RFID Systems	Rich Fletcher
10:30	Sensing Systems Overview	Chris Murphy
10:50	Discussion	

Topic 3: Natural Chem/Bio Tags

11:15	Design Considerations for “Electronic Nose” Chemical Sensors Systems	Alan Gelperin
11:35	Nanoscale Chemical Sensors	Steven Martin
12:05 p.m.	Discussion	
12:30	*Lunch*	

Topic 4: Passive Chem/Bio Tags

1:30	Isotopic and Fluorescent Taggants	Todd Allen
1:50	Bio/Electronic Taggants	Jill Trewhella

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2:10	Discussion
2:40	*Break*

Topic 5: Radio/Radar/Optical Tags

2:50	Micro Doppler Radar Analysis and Passive Radar Tags	Mark Shellans
3:10	Covert Radar Tags and Applications	Bill Hurley
3:30	Nanoscale Design Considerations for Radio/Radar Systems and Tags	Dennis Prather
3:50	Dynamic Optical Tags	Stephen Griggs
4:10	Discussion	
4:40	Chair's Time	
5:30	Adjourn	

ATTENDEES

George Atkinson, NETI Technical Working Group
Martin Carr, ITIC
Kenneth Crelling, Department of Defense
Aladar Csontos, Nuclear Regulatory Commission
James Ellenbogen, MTTRE
David Forrest, Naval Surface Warfare Center
Pomrenke Gernot, NETI Technical Working Group
Hollis Helms, NETI Technical Working Group
Eric Landree, RAND
Ronald Lucas, Department of Defense
Richard Silberglitt, RAND
Diane Snyder, NETI Technical Working Group
Bill Vanderlinde, NETI Technical Working Group
Cung Vu, Department of Defense
Enoch Wang, NETI Technical Working Group

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Appendix B

Biographies of Committee Members

Robert J.Hermann, NAE, *Chair,* is currently a senior partner at Global Technology Partners, LLC, a Boston-based firm specializing in investments in technology, defense, aerospace, and related businesses worldwide. In 1998, Dr. Hermann retired from United Technologies Corporation, where he was senior vice president, science and technology. Prior to joining UTC in 1982, Dr. Hermann served 20 years with the National Security Agency, with assignments in research and development, operations, and the North Atlantic Treaty Organization (NATO). In 1977, he was appointed principal deputy assistant secretary of defense for communications, command, control, and intelligence. In 1979, he was named Assistant Secretary of the Air Force for research, development, and logistics and in parallel was director of the National Reconnaissance Office. He received B.S., M.S., and Ph.D. degrees in electrical engineering from Iowa State University. He was a member of the President's Foreign Intelligence Advisory Board from 1993 to 2001 and a chairman of the board of directors of the American National Standards Institute from 1998 to 2000. Dr. Hermann was also chair of the board of directors of Draper Laboratory. He is currently a member of the board of directors of Condor Systems, a member of NAE, and a member of the Defense Science Board.

Antonio A.Cantu is the chief research scientist of the Forensic Services Division of the United States Secret Service. His forensic interests include the chemical analysis of inks and paper on documents for determining their date and origin; the visualization of latent fingerprints using chemical, optical, and physical methods; and the optical and chemical tagging of targets for tracking and locating them. He has assisted in developing countermeasures against threats involving chemical, biological, radiological, nuclear, and explosive (CBRNE) materials. The latter includes technology for point detection and standoff detection of explosives. He co-chairs the Investigative Support and Forensic Subgroup of the Technical Support Working Group (the technical arm of the Interagency Working Group on Counter Terrorism). He has held positions at the U.S. Department of Justice, the Bureau of Alcohol, Tobacco and Firearms, and the FBI. Since 1986, he has been with the U.S. Secret Service. Dr. Cantu received a B.Sc. (1963) and a Ph.D. (1967) in chemical physics from the University of Texas, Austin. He was a postdoctoral fellow at the University of Alberta, Edmonton, and an OAS visiting fellow at the University of Mexico (1970).

James J.De Yoreo is currently acting director, Bio-Security and Nanosciences Laboratory of the Lawrence Livermore National Laboratory's Chemistry and Materials Science Directorate. His research interests include scanned probe nanolithography, nanoscale surface patterning, nucleation templates, physics of crystal surfaces in solutions, macromolecular crystallization, biomineralization, interaction of organic molecules with inorganic crystal surfaces, assembly of supramolecular motifs, high-resolution imaging, physics and chemistry of crystalline defects, and characterization of optical crystals. Dr. De Yoreo is a member of the Materials Research Society and vice president of the American Association for Crystal Growth. In 1994 he was presented the R&D 100 award—Development of rapid growth process for KDP, and in 2001 he received the Lawrence Livermore National Laboratory Science and Technology Award. Dr. De Yoreo earned a B.A in physics from Colby College and an M.S. and Ph.D. in experimental physics from Cornell University.

Daniel H.Doughty received his Ph.D. in inorganic chemistry from the University of Minnesota in 1979. His thesis work explored the synthesis, characterization, and mechanistic study of organometallic complexes used in homogeneous decarboxylation catalysis. He studied various compounds, primarily in the family of rhodium phosphine complexes. He also studied at the Catholic University of America and the University of New Mexico, where he obtained a B.S. in chemistry and an M.S. in inorganic chemistry. Dr. Doughty currently is the manager of the Lithium Battery Research and Development Department,

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Sandia National Laboratories. This group has responsibility for developing advanced power sources, typically batteries and electrochemical cells based on lithium. Areas of expertise include various lithium chemistries (e.g., lithium-ion rechargeable batteries and lithium thionyl chloride cells and batteries). The group works on cutting-edge electrochemistry as well as advanced batteries and battery materials for defense and commercial applications. Prior to taking this assignment in 1992, he led the Inorganic Materials Chemistry Division for 7 years. This group has responsibility for advanced ceramic and glass materials as well as general inorganic chemistry. Specifically, the preparation of preceramic materials was a major effort that used sol-gel chemistry and other solution routes to ceramic and glass materials. Previous projects at Sandia National Laboratories involved organometallic chemistry, inorganic chemistry, nanostructured gold colloids, and the kinetics of gas-solid reactions. Prior to joining Sandia, Dr. Doughty worked for 3 years at 3M Company as a research chemist developing advanced inorganic photoconductors. Other areas of interest are general materials chemistry and processing, including colloid chemistry, superconducting ceramics, intercalation compounds, and oxide surface chemistry. Dr. Doughty received the DOE Award of Excellence in 1989 and is a member of the American Chemical Society, the Materials Research Society, ECS, and Phi Kappa Phi honorary fraternity. He has over 80 publications, holds three patents, and has co-edited four technical proceedings volumes.

Lawrence H.Dubois received an S.B. degree in chemistry from the Massachusetts Institute of Technology in 1976 and a Ph.D. in physical chemistry from the University of California, Berkeley, in 1980. Dr. Dubois then joined AT&T Bell Laboratories to pursue studies of the chemistry and physics of metal, semiconductor, and insulator surfaces; chemisorption and catalysis by materials formed at the metal-semiconductor interface; and novel methods of materials growth and preparation. In 1987, he was promoted to distinguished member of the technical staff and technical manager. His efforts broadened to include projects on polymer-surface interactions; adhesion promotion; corrosion protection; chemical vapor deposition and thin-film growth; optical fiber coating; synthesis, structure, and reactivity of model organic surfaces; and time-resolved surface vibrational spectroscopy. In 1993, Dr. Dubois moved to MIT Lincoln Laboratory as a senior staff scientist and was assigned to the Defense Advanced Research Projects Agency (DARPA). In that capacity, he established the Advanced Energy and Environmental Technologies Program and managed projects on the development and manufacturing of rechargeable batteries; high-performance, direct-methanol, and logistic-fuel-powered fuel cells; and the development of new, more environmentally sound manufacturing processes, environmental sensors, and waste destruction/reclamation procedures. In 1995, Dr. Dubois was promoted to deputy director and in 1996 to director of the Defense Sciences Office at DARPA. This office is responsible for an annual investment of approximately $300 million for the development of technologies for biological warfare defense, biology, defense applications of advanced mathematics and materials, and devices for new military capabilities. In March 2000, Dr. Dubois joined SRI International as corporate vice president and head of the Physical Sciences Division, a group of over 150 scientists and engineers focusing on the development and commercialization of advanced materials, microfabrication technologies, power sources, biological warfare defense, medical diagnostics, molecular and optical physics, explosives and propellants, catalysts, coatings, and environmentally benign processing. Dr. Dubois is the author of over 130 publications and holds four U.S. patents and several foreign patents. His numerous honors include the prestigious IR100 and Alpha Chi Sigma awards as well as the Office of the Secretary of Defense Award for Outstanding Achievement and the Secretary of Defense Medal for Outstanding Public Service. He sits on the board of directors of two spin-off companies from SRI: Polyfuel and CYANCE.

Alan H.Epstein, NAE, is currently R.C.Maclaurin Professor at the Massachusetts Institute of Technology, Department of Aeronautics and Astronautics. He is also the head of the Division of Fluids, Propulsion and Energy Conversion. He is responsible for teaching gas turbine and rocket engine design at the undergraduate and graduate level; coordinating teaching, graduate admissions, and faculty staffing

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for fluid mechanics, propulsion, and energy conversion; directing the 80-person MIT Gas Turbine Laboratory; serving as principal investigator and director of the 50-person MIT MicroEngine Project; and conducting research on advanced propulsion and energy conversion technologies. His interests include teaching and research in the areas of compressor and turbine aerodynamics, compressor stability, turbine engine controls, turbine heat transfer, engine instrumentation and measurement, turbomachinery noise, and microengines and MEMS. Dr. Epstein's consulting activities include gas turbine engine design and design practice; engineering management and organization; and signature analysis of air-breathing vehicles. In addition to being a member of the National Academy of Engineering, Dr. Epstein also holds membership in the American Association for the Advancement of Science and the American Society of Mechanical Engineers, as well as being a fellow at the American Institute of Aeronautics and Astronautics. He has been a liaison, chair, and member of numerous National Research Council committees and boards, including committees for the Review of ONR's Aircraft Technology Program, Implications of Micro and Nanotechnology for the U.S. Air Force, and Review of Effectiveness of U.S. Air Force S&T Changes, and the Board on Army Science and Technology. Dr. Epstein received his B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology and has over 90 publications in the fields of gas turbine technology, air vehicle observables, instrumentation development, and MEMS.

Wilhelm B.Gauster is currently deputy director of the Physical and Chemical Sciences Center at Sandia National Laboratories, where he manages nanoscience activities for defense program applications. His own research has covered a wide range of topics in solid-state physics and nuclear technology, including thermomechanics, optical properties of semiconductors, neutron and electron irradiation effects, positron annihilation, muon spin rotation, plasma-materials interactions, and high-heat-flux components for fusion devices. He has managed a variety of programs in basic and applied research, fission and fusion technology, and energy policy. Dr. Gauster received an A.B. in applied physics from Harvard College and a Ph.D. in physics from the University of Tennessee. He has served as a member of numerous editorial boards and advisory panels, as an adjunct professor at the University of New Mexico, visiting scientist at the Jülich Research Center, and deputy head of site at the International Thermonuclear Experimental Reactor Joint Work Site in Garching (Germany). He was a member of the Department of Energy Magnetic Fusion Advisory Committee in 1988 and 1989 and received the Department of Energy Distinguished Associate Award in 1993.

Shirley A.Jackson, NAE, is currently the president of Rensselaer Polytechnic Institute. Her career prior to becoming Rensselaer's president encompassed senior positions in government, as chairman of the U.S. Nuclear Regulatory Commission; in industry and research, as a theoretical physicist at the former AT&T Bell Laboratories; and in academe, as a professor of theoretical physics at Rutgers University. Dr. Jackson holds a Ph.D. in theoretical elementary particle physics from MIT and an S.B. in physics from MIT. Her research specialty is in theoretical condensed-matter physics, especially layered systems, and the physics of opto-electronic materials. In 1995 President Clinton appointed Dr. Jackson to serve as chair of the U.S. Nuclear Regulatory Commission, which position she occupied from 1995 to 1999. As chair, she was the principal executive officer of and the official spokesman for the Nuclear Regulatory Commission. From 1991 to 1995, Dr. Jackson was professor of physics at Rutgers University, where she taught undergraduate and graduate students, conducted research on the electronic and optical properties of two-dimensional systems, and supervised Ph.D. candidates. She concurrently served as a consultant in semiconductor theory to AT&T Bell Laboratories. Dr. Jackson will become president of the American Association for the Advancement of Science (AAAS) in February 2004. She will chair the AAAS board in 2005. Dr. Jackson is a member of the National Academy of Engineering and a fellow of the American Academy of Arts and Sciences and the American Physical Society. Dr. Jackson holds 21 honorary doctoral degrees. She is a member of the National Advisory Council for Biomedical Imaging and Bioengineering of the National Institutes of Health (NIH), serves on the Advisory Committee for the

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Department of Energy National Nuclear Security Administration (NNSA), and is a member of the U.S. Comptroller-General's Advisory Committee for the Government Accounting Office (GAO). She also has served on a number of committees of the National Research Council of the National Academies.

Siegfried W.Janson is a senior scientist at the Aerospace Corporation. He obtained a Ph.D. in aerospace engineering from Cornell University in 1984. He was a postdoctoral associate at Cornell from 1984 to 1987, at which time he joined the Aerospace Corporation to pursue experimental research in electric thrusters and advanced laser-based propulsion diagnostics. Dr. Janson's current research interests are micropropulsion, micro/nanotechnology for space systems, formation flying, and distributed space systems. He has worked in the MEMS field for 13 years and authored or co-authored over 20 papers on microthrusters, micro/nanotechnology for space applications, and silicon satellites. He managed and co-managed two DARPA-sponsored MEMS programs (Digital Thrusters and Micro Power Generator) and participated in MEMS flight experiments on the shuttle and the International Space Station. Dr. Janson has given invited presentations on micro/nanotechnology for spacecraft to the National Academy of Engineering, the European Space Agency, and the International Space University. He was co-chair (2001) and chair (2003) of the SPIE conference MEMS Components and Applications for Industry, Automobiles, Aerospace, and Communications. Dr. Janson has served on several NRC panels for the review of Air Force Office of Scientific Research propulsion proposals and on the NRC Committee on Implications of Emerging Micro and Nano Technologies. He is a member of the IEEE and a senior member of the American Institute of Aeronautics and Astronautics (AIAA).

Anthony F.Laviano is a member of the Raytheon Space and Airborne Engineering staff in El Segundo, California. He is a member of the Patent Committee and is program manager for Advanced Technical Programs. His focus is advanced technologies and products, which include power electronics; sensor, processor and antenna technologies; and dual-use applications—that is, he identifies, organizes, and transitions technology into both military and commercial application. He established and is the leader of the Nano Engineering and Science Technology Interest Group. He led and facilitated the Power Electronics Technology Interest Group; represents engineering in industry endeavors such as the Open Systems Joint Task Force for Power Electronics through the U.S. Air Force; is the Power Sources Manufacturer's Association chairperson for the Industry Government Committee; and is co-leader of the Electronic Power Specification Standardization Industry Working Group, which writes power electronics standards under IEEE auspices. He is past chairman of the IEEE Power Electronics Society for Southern California, a member of the IEEE Standards Association, the IEEE Los Angeles Council, the IEEE Wescon, and the Academy of Management, and is on the editorial board of the *Journal of Public Administration*. He is a certified contracts manager and a National Contract Association fellow. He received a Ph.D. in business administration from Nova Southeastern University, Florida, an M.B.A. from Pepperdine University, and a B.A. from St. Charles College, Pennsylvania, and graduated from the U.S. Army Language School as a Chinese linguist. He is a former member of the National Faculty of Nova Southeastern University Graduate School of Business and Entrepreneurship, as well as the Hughes Aircraft Company technology staff. His technical involvement includes nanotechnology, antenna development, data and mission processors, power electronics, radar systems, software development, system architecture, terrestrial communication systems, and satellite communication systems.

Debra R.Rolison is currently the section head of Advanced Electrochemical Materials at the Naval Research Laboratory. Before this position, Dr. Rolison was a research chemist at the Naval Research Laboratory. She is also an adjunct professor of chemistry at the University of Utah. Her research interests include synthesis and characterization of nanostructured materials, including research into processes occurring at the electrified interfaces of nanostructured materials with emphasis on (1) aerogels; (2) supported electrocatalysts and nanoscale electrodes; (3) zeolites; (4) colloids; (5) dispersions of

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catalytically active solids; and (6) chemically modified and dimensionally structured electrode surfaces. A recent research focus has been nanoarchitectures for catalytic chemistries, energy storage and conversion, biomolecular composites, porous magnets, and sensors. Principal inventions include (1) electrified microheterogeneous catalysis; (2) using silica sol as a nanoglue to synthesize composite gels and aerogels; (3) electrodesulfurization of solid carbon; (4) creating a three-dimensional nanowired mesoporous architecture; and (5) infrared-emitting materials. Dr. Rolison also writes and lectures widely on issues affecting women in science. Her ideas with respect to using Title IX to evaluate academic science and engineering departments recently led to a hearing on Title IX and the sciences before the U.S. Senate Subcommittee on Science, Technology, and Space. Dr. Rolison is a member of the American Chemical Society, the Materials Research Society, and the Society for Electroanalytical Chemistry; she was elected a fellow of the AAAS in 2001. She coauthored *Ultramicroelectrodes,* the first text on this active area, with M.Fleischmann, S.Pons, and P.Schmidt. She guest edited an issue of *Langmuir* devoted to the electrochemistry of nanostructured materials and recently served as a guest editor of a *Journal of Physical Chemistry* Festschrift in honor of Royce Murray. Her past and present editorial advisory board service includes *Analytical Chemistry, Langmuir, Journal of Electroanalytical Chemistry, Nano Letters,* and the *Encyclopedia of Nanoscience and Nanotechnology*. She was a member of the board of directors of SEAC and served as editor of *SEAC Communications*. Dr. Rolison was named the 2003 Woman of Excellence by the University of Delaware. She chaired the 2001 Gordon Research Conference on Electrochemistry and the 2003 International Symposium on Aerogels. She received a Ph.D. from the University of North Carolina. She has published over 60 papers and holds 14 patents.

R.Paul Schaudies is a nationally recognized expert in the fields of biological and chemical warfare defense. He has served on numerous national-level advisory panels for the Defense Intelligence Agency, the Defense Advanced Research Projects Agency, and the Department of Energy. He has 14 years' bench research experience managing laboratories at Walter Reed Hospital and Walter Reed Army Institute of Research and was a visiting scientist at the National Cancer Institute. He served for 13 years on active duty with the Army Medical Service Corps, and separated from service at the rank of Lieutenant Colonel-select. Dr. Schaudies spent 4 years with the Defense Intelligence Agency as collections manager for biological and chemical defense technologies. As such, he initiated numerous intra-agency collaborations that resulted in accelerated product development in the area of biological warfare agent detection and identification. Dr. Schaudies is currently an assistant vice president and division manager of the Biological and Chemical Defense Division at SAIC. His division focuses on three major business areas: contract biomedical research, technology assessments, and scientific studies. Since joining SAIC, Dr. Schaudies has served on and chaired numerous technology review and advisory panels for U.S. government agencies. Dr. Schaudies received his bachelor's degree in chemistry from Wake Forest University and his doctoral degree from Temple University School of Medicine in the Department of Biochemistry. He has authored 27 scientific manuscripts in the peer-reviewed literature, as well as three book chapters. Dr. Schaudies is active in both government and academic circles.

Julia R.Weertman, NAE, has conducted research on the mechanical behavior of metals and alloys and the underlying phenomena that give rise to the observed behavior. Her research currently focuses on determining the mechanical properties of a variety of nanocrystalline materials, characterizing their structure, and studying deformation mechanisms in this small-grain-size regime. She also continues interest in the high-temperature behavior of metals. Her research has demonstrated the value of small-angle neutron scattering for detection and quantification of such features as voids and pores and for following the nucleation and growth kinetics of second-phase particles. Dr. Weertman is a member of the National Academy of Engineering and the American Academy of Arts and Sciences. She is past member of the Committee on Women in Science and Engineering and of the Committee on Human Rights of the

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National Academies and has served on several NRC panels. Currently she is a member of the NRC National Materials Advisory Board. She has served on advisory panels for DOE and NSF and for several national laboratories. She is on the board of review editors for *Science*. She is a fellow of the Materials Society and ASM International, received Special Creativity Awards for Research from NSF in 1981 and 1986, a Guggenheim Fellowship in 1986–1987, the Achievement Award from the Society of Women Engineers in 1991, and the Leadership Award from the Materials Society in 1997.

George M.Whitesides, NAS, received an A.B. degree from Harvard University in 1960 and a Ph.D. from the California Institute of Technology (with J.D.Roberts) in 1964. He was a member of the faculty of the Massachusetts Institute of Technology from 1963 to 1982. He joined the Department of Chemistry of Harvard University in 1982, and was department chairman from 1986 to 1989. He is now Mallinckrodt Professor of Chemistry at Harvard University. He received an Alfred P.Sloan Fellowship in 1968; the American Chemical Society (ACS) Award in Pure Chemistry in 1975; the Harrison Howe Award (Rochester Section of the ACS) in 1979; an Alumni Distinguished Service Award (California Institute of Technology) in 1980; the Remsen Award (ACS, Maryland Section) in 1983; an Arthur C.Cope Scholar Award (ACS) in 1989; the James Flack Norris Award (ACS, New England Section) in 1994; the Arthur C.Cope Award (ACS) in 1995; the Defense Advanced Research Projects Agency Award for Significant Technical Achievement in 1996; the Madison Marshall Award (ACS) in 1996; the National Medal of Science in 1998; the Sierra Nevada Distinguished Chemist Award (Sierra Nevada Section of the ACS); the Wallac Oy Innovation Award in High Throughput Screening (the Society for Biomolecular Screening) in 1999; the Award for Excellence in Surface Science (Surfaces in Biomaterials Foundation) in 1999; and the Von Hippel award (Materials Research Society) in 2000. He is a member of the American Academy of Arts and Sciences, the National Academy of Sciences, and the American Philosophical Society. He is also a fellow of the American Association for the Advancement of Science and the New York Academy of Science, a foreign fellow of the Indian National Science Academy, and an honorary fellow of the Chemical Research Society of India.

Ellen D.Williams is currently a professor in the Department of Physics and the Institute for Physical Science and Technology at the University of Maryland, as well as the director of the Materials Research Science and Engineering Center. Dr. Williams is a fellow of the American Academy of Arts and Sciences. In 2001 she was the recipient of the American Physical Society's David Adler Lectureship Award, and in 1998–1999, she was its centennial speaker. Dr. Williams serves on the National Security Panel of the University of California President's Council and is also on the editorial board of *Nano Letters* (ACS). Dr. Williams received a B.S. in chemistry from Michigan State University and a Ph.D. in chemistry from the California Institute of Technology, and she did postdoctoral research in physics at the University of Maryland.

Mary H.Young is the director of the Sensors and Materials Laboratory of Hughes Research Laboratories, a research company that is jointly owned by Boeing, General Motors, and Raytheon Company. Dr. Young manages an organization with research emphasis in microelectromechanical and nanofabrication technologies, energy technologies, electro-optical sensor materials and process technologies, materials engineering, and nanoelectronics. Dr. Young received her B.S. in physics at Wake Forest University, her M.S. in physics at the University of Maryland, and her Ph.D. at UCLA in electrical engineering. Since joining Hughes Research Laboratories in 1974, Dr. Young has conducted research on the development of ultrapure silicon, extrinsic semiconductors for use in IR detector programs, GaAs for a variety of electronic and optical device applications, superconductors for microelectronics, and superlattice materials for novel device concepts. Currently, she is engaged in directing the development of novel processes for materials, including semiconductors, active materials, materials for thermal management, and materials for energy and power, and in exploring innovative sensor types and designs,

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including MEMS devices, chemical and biological threat/environmental sensors, electromagnetic sensors, and multisensor control methodologies. Major application programs in energy storage and conversion, materials for automotive/aerospace sensors and power systems, semiconductor nanoelectronics, MEMS-based sensor and communications systems, and IR sensor-based systems are among the programs currently being conducted under the direction of Dr. Young. Dr. Young has contributed original work in electronic transport physics in semiconductors and in the physics of IR-sensitive materials and IR devices and managed a number of IR sensor development programs. From 1971 to 1974 she was manager of an analytic facility for the Materials Research Laboratory at the University of Maryland. Dr. Young is a member of Phi Beta Kappa and of the American Physical Society and the Materials Research Society. She has more than two dozen publications on semiconductor materials, infrared detectors, impurity hopping electronic transport, neutron transmutation in semiconductors, and superlattice materials and devices.

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Appendix C

Acronyms

ARL	Army Research Laboratory
CMOS	complementary metal oxide semiconductor
DARPA	Defense Advanced Research Projects Agency
EAS	electronic articles surveillance
EPC	electronic product code
GC	gas chromatograph
GFP	green fluorescence protein
GPS	Global Positioning System
ITIC	Intelligence Technology Innovation Center
MEMS	microelectromechanical systems
NETI	Nano-Enabled Technology Initiative
NMAB	National Materials Advisory Board
NRC	National Research Council
PARD	passive acoustic reflection device
Q-DOTS	quantum dots
RFID	radio frequency identification
SAW	surface acoustic wave
UV	ultraviolet
VESTA	vibro-electronic signature target analysis
VIN	vehicle identification number

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Appendix D

Statement of Task

1. Describe the technology challenges and opportunities for nanotechnology to enable new functions and systems for use by the intelligence community. Consider the implications of miniaturization, science at the nanoscale, and atomistic and molecular assembly in two separate workshops for the following:

a. Power technologies
b. Sensing and positioning technologies

2. Evaluate the potential for advances in these technologies to address needs as presented to the committee by the intelligence community.
3. For each technology, describe a path and associated risks to achieve near-term (immediate), mid-term (3–5 years), and long-term (10 years) goals. Consider the infrastructure, including equipment, human resources, and knowledge base, needed to carry out these activities.
4. In addition, discuss potential new and disruptive ways that nanotechnology can address these intelligence community needs.
5. Assess opportunities to counter these predicted technology capabilities.

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