National Science Foundation
WHERE DISCOVERIES BEGIN

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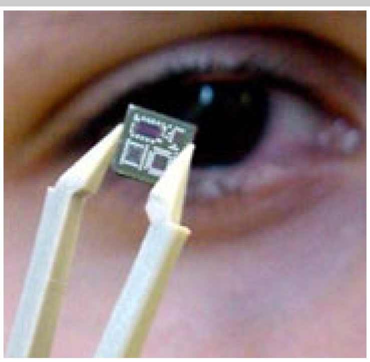
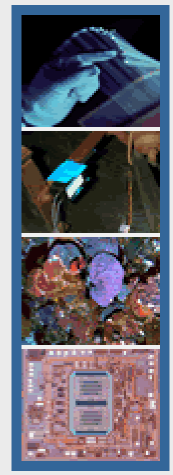


This prototype of a fingernail-sized position sensor integrates three gyroscopes on a single silicon chip.

Credit: Andrei M. Shkel, Micro-Systems Laboratory, University of California, Irvine

Credit: Design by Sara Raimo, National Science Foundation. Microcantilever image by Kenneth Hsu, Arun Majumdar, Department of Mechanical Engineering, University of California, Berkeley. Walrus network image © 2002 The Regents of the University of California, all rights reserved; for commercial use contact: invent@ucsd.edu

Overview



In the 1980s, the PC revolution put computing at our fingertips.

In the 1990s, the Internet revolution connected us to an information web that spans the planet.

And now the *next* revolution is connecting the Internet back to the physical world we live in-in effect, giving that world its first electronic nervous system.

Call it the Sensor Revolution: an outpouring of devices that monitor our surroundings in ways we could barely imagine a few years ago. Some of it is already here. The rest is coming soon.

Environment & Civil Infrastructure:

Networks of wireless humidity sensors monitor fire danger in remote forests. Nitrate sensors detect agricultural runoff in rivers, streams and wells, while distributed seismic monitors provide an early warning system for earthquakes. Meanwhile built-in stress sensors report on the structural integrity of bridges, buildings and roadways, and other man-made structures.

Industry & Commerce:

On the factory floor, networked vibration sensors warn that a bearing is beginning to fail. Mechanics schedule overnight maintenance, preventing an expensive unplanned shutdown. Inside a refrigerated grocery truck, temperature and humidity sensors monitor individual containers, reducing spoilage in fragile fish or produce.

Health:

Sensors embedded in clothing, networked with additional in-body sensors, continuously monitor our vital signs. The first indication of an impending heart attack or dangerously high blood pressure leads to early medical intervention. Surges in a diabetic's blood sugar levels, monitored continuously by minuscule sensors, trigger insulin delivery from an infusion pump, perfectly mimicking a healthy pancreas.

Safety & Security:

Firefighters scatter wireless sensors throughout a burning building to map hot spots and flare-ups. Simultaneously, the sensors provide an emergency communications network. Miniature chemical and biological sensors in hospitals, post offices, and transportation centers raise an alarm at the first sign of anthrax, smallpox, ricin, or other terror agents.

The National Science Foundation (NSF) has supported basic research on sensors for decades and now has a foundation-wide Sensors and Sensor Networks Program.

Still, with all this activity in sensor technology, it's fair to ask, "Why all the excitement now? Haven't sensors been around forever?"

By M. Mitchell Waldrop and Philip Lippel

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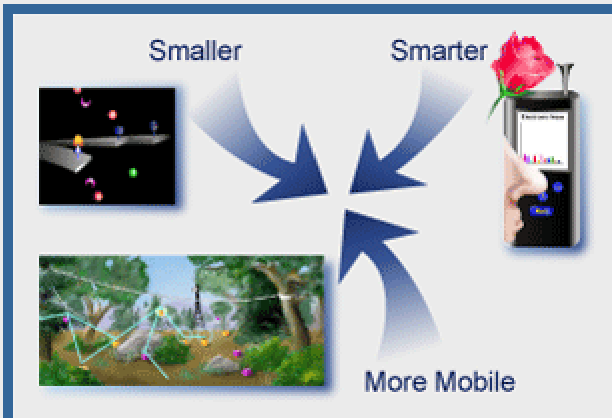
Sensor Technology: A Convergence of Forces



Credit: Nicolle Rager, Zina Deretsky, National Science Foundation

A sensor is any device that can take a stimulus, such as heat, light, magnetism, or exposure to a particular chemical, and convert it to a signal. Sensors have certainly been around for a very long time. Scales–weight sensors–were used by the Sumerians at least 9000 years ago. Thermometers–temperature sensors-were developed in the late 16th century by Galileo and others. Barometers–pressure sensors–were invented a few decades later by Galileo's assistant, Torricelli. More recently, scientists and engineers have come up with devices to sense light (photocells), sound (microphones), ground vibrations (seismometers), and force (accelerometers), as well as sensors for magnetic and electric fields, radiation, strain, acidity, and many other phenomena. From the metal detectors we pass through at airports to the smoke detectors that protect our homes, our modern civilization is utterly dependent on sensors.

While the *concept* of sensors is nothing new, the *technology* of sensors is undergoing a rapid transformation. Indeed, the forces that have already revolutionized the computer, electronics, and biotech industries are converging on the world of sensors from at least three different directions:

1. **Smaller:** Rapid advances in fields such as nanotechnology and (micro electro-mechanical systems (MEMS)) have not only led to ultra-compact versions of traditional sensors, but have inspired the creation of sensors based on entirely new principles. One example is the electronic nose developed by chemist Nathan S. Lewis and his colleagues at the California Institute of Technology. Another is the cantilever molecular sensor. And still others are to be found among the many projects that NSF has funded through its nanotechnology priority area, and through initiatives such as its recent XYZ on a Chip program.

2. **Smarter:** The exponentially increasing power of microelectronics has made it possible to create sensors with built-in "intelligence." In principle, at least, sensors today can store and process data on the spot, selecting only the most relevant and critical items to report.

3. **More Mobile:** The rapid proliferation of wireless networking technologies has cut the tether. Today, many sensors send back their data from remote locations, or even while they're in motion.

As these forces converge, however, they pose daunting new challenges for researchers and society alike.

An ordinary penny shows the scale of a “Golem Dust” mote: a sensor that detects ambient light and acceleration, and incorporates a tiny radio antenna for communication.

Credit: Brett Warneke, Kris S.J. Pister, Berkeley Sensor & Actuator Center, University of California, Berkeley

Researchers prepare for an experiment in modeling and controlling animal behavior. The cattle in the background are wearing "smart collars" consisting of handheld computers, global positioning system receivers, and sound amplifiers that squawk unpleasantly when a cow wanders too far in the wrong direction.

Credit: Ron Peterson, Computer Science Department, Dartmouth College

Sensor Technology: Surviving Out in the Field

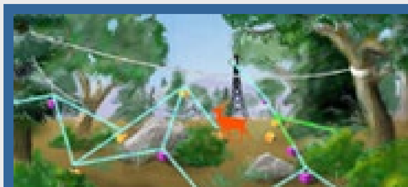
This "Golem Dust" mote is a sensor that detects ambient light and acceleration, and incorporates a tiny radio antenna (the cross) for communication.

Credit: Brett Warneke, Kris S.J. Pister, Berkeley Sensor & Actuator Center, University of California, Berkeley

The coming generation of sensors will have to be made of stern stuff. After all, many of the potential applications call for lots of sensors, scattered so widely through the target area that there's no hope of tending to each one individually. Instead, the devices will have to operate on their own for days, weeks, or months at a time—in places where there are no power sockets, no broadband cable connections, no tech support, and no protection from being soaked, baked, frozen, buried, stepped on, or even eaten.

This makes for some daunting engineering challenges. Among the toughest is power: a sensor that's made to be tiny, inexpensive, and mass-produced is a sensor with very little room for a battery. That's why designers often arrange to have the devices spend most of their existence in sleep mode, where they can survive on just the barest trickle of power. From there, they have to wake up only for a tiny fraction of a second every now and then, so that they can take a quick instrument reading and, if need be, beam back a few bits of data.

Another challenge is getting those bits back to headquarters. Out in the field, where there is no Internet, the latest sensors can do that by passing the data from one to the next via wireless networking technology—in effect, making their own network. But this is a lot trickier than it sounds. For one thing, the connections are typically restricted to very low power, very short distances, and very low data rates. Worse, the transmissions can be very noisy and erratic; furthermore, if the sensors are connected to a vehicle—or an animal—they will frequently be moving around.

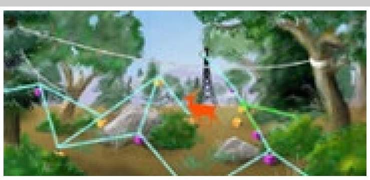


Credit: Nicolle Rager, Zina Deretsky, National Science Foundation

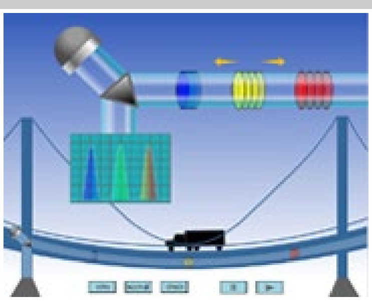
That's why many engineers are emphasizing *ad hoc* networks, in which the sensors are programmed to reach out, find their nearest neighbors, and form network links on their own—without anyone to show them how. If any of those links are blocked or broken; moreover, the sensors will automatically reach out and find new links to replace them.

And then there is the whole realm of societal challenges. What is the best way to build in privacy safeguards, for example, so that the new-generation sensors don't become a tool of Big Brother? And how do you build in equally strong security safeguards, so that hackers can't just eavesdrop on the wireless data stream?

NSF-funded researchers are pursuing solutions to all these challenges and more—as are researchers supported by other agencies, and by industry. Still, enough sensor technology is already in hand to support a host of applications. Read on for more examples from Environment & Civil Infrastructure, Industry & Commerce, Health and Safety & Security.



Credit: Nicolle Rager, Zina Deretsky, National Science Foundation



Credit: Zina Deretsky, National Science Foundation

Sensor Applications: Environment & Civil Infrastructure

To track changing conditions in deserts, forests, oceans, or the atmosphere, environmental sensors must (just like the postman) deliver their messages through snow, rain, heat, and gloom of night. Sensors attached to bridges, roadways and other structures face similarly extreme conditions—or worse, if they need to function through hurricanes and earthquakes.

NSF-sponsored researchers are developing new sensors that can operate reliably in those environments. They're also hard at work on sensor systems, designing and deploying networks of sensors that will bring unprecedented detail to civil and environmental monitoring.

Planting Sensors in the Forest

A robotic sensor package is suspended between two treetops at the Wind River Canopy Crane Research Facility in Washington State. The instrument can move along the cable as well as up and down, providing images and precise local climate data.

Credit: Center for Embedded Networked Sensing, UCLA; Wind River Canopy Crane Research Facility, University of Washington

At UCLA's Center for Embedded Network Sensing (CENS), William Kaiser monitors delicate ecosystems in California's San Jacinto Mountains. By networking fixed data-taking stations and mobile "infomechanical systems," Kaiser's research group is keeping tabs on the James Reserve, home to 50 endangered species. The group's mobile devices travel along wires strung from tree to tree, lowering sensors to take temperature, humidity and light-level measurements at varying heights above the forest floor. Powered by solar cell-battery combinations, the devices pass along data from node to node in a network that will eventually include one hundred stations.

Center director Debra Estrin and her colleagues developed the protocols and data management techniques that let this *ad hoc* wireless sensor network operate where power restrictions, unstable transmission environments, and ever-changing numbers of nodes would frustrate traditional networks. These same strategies are utilized in other CENS projects, such as monitoring the nesting habitats of birds, and tracking the flow of fertilizer from farms through a sediment zone and into the Merced River.

A Healthy Home for Health Science

When UCLA researchers set up an embedded sensor network at the Factor Health Sciences Building on campus, they had to adapt their technologies to face a new set of challenges. The building's 17-story steel frame wreaks havoc with wireless transmissions. (Think of using a cell phone inside an elevator.) The communications protocols they developed for reliable operation inside this structure will help them collect data from strain and vibration sensors attached to buildings and bridges, an application known as structural health monitoring.

Sense-able Bridges and Highways

Civil engineers like the New Mexico State University's Rola Idriss envision the day when sensors embedded in bridges and roadways routinely report the first signs of unusual wear long before they're visible to human inspectors. As with human healthcare, early detection of structural health problems allows early intervention, ultimately saving money, improving longevity, and increasing safety. Idriss and her colleagues installed 120 fiber optic sensors on a 1970s-era bridge on Interstate 10 in Las Cruces, with support from NSF and the Federal Highway Administration.

The fiber optic sensors supply the university researchers with a continual stream of data documenting the bridge's reaction to traffic, weather, and the ravages of time. But the New Mexico team has even higher hopes for the new Rio Puerco bridge near Alberquerque, an innovative high-performance concrete design with sensors built right into its beams.

The Rio Puerco bridge outside of Albuquerque, New Mexico, was built with embedded fiber optic sensors to monitor vibration and wear.

Credit: © Smartec

Comparing the data acquired from their internal sensors throughout the bridge's lifetime to information from standard inspection techniques will help them develop more efficient monitoring and maintenance procedures.

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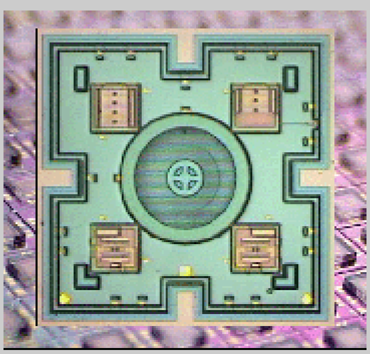

This tiny barometer (foreground) can be manufactured by the dozens on a single wafer of silicon (background).

Credit: NSF Engineering Research Center for Wireless Integrated MiicroSystems, University of Michigan

Sensor Applications: Industry & Commerce

From disk brakes to disk drives, American industry relies on sensors in its products and in its factories. By incorporating new sensor technologies, manufacturers can bring new capabilities to their products while improving performance and efficiency. Meanwhile, factory sensors help keep American industry competitive by improving product quality and reducing downtime.

Sensors on the Road

Air bag deployment is controlled by precise but inexpensive accelerometers–sensors that detect sudden impacts. The devices are among the most widely used Micro-Electro-Mechanical Systems (MEMS).

Credit: The Insurance Institute for Highway Safety

In today's automobiles, rotation sensors feed data from all four wheels to antilock brake and traction control systems. Combustion and antiknock sensors help engine computers adjust the fuel mixture for efficient, clean burning even as loads and conditions change. Impact-sensing accelerometers can subtly grade the severity of a collision, allowing the car's airbags to deploy with minimal appropriate force.

The number of sensing devices per car has doubled in the past few years, and continues to rise as sophisticated but inexpensive sensors become more available. Engineers like Wayne State University's Le Yi Wang help automobile designers make optimal use of sensor data. Yang is studying methods for combining information from multiple sensors to effectively control engines and powertrains, even when individual sensors supply imperfect data.

Inventory From Afar

Radio Frequency Identification (RFID) stands among the fastest-proliferating sensor technologies. RFID systems combine electromagnetic sensing with radio communications. RFID tags and interrogators can be used to track inventory in a warehouse or collect tolls from moving cars. Texas Instruments equips new semiconductor fabrication lines with RF interrogators, and places ID tags on each wafer carrier. Every processing step a wafer goes through can now be recorded in a central database while minimizing human handling and associated contamination.

Radio Frequency Identification tags (inset) tied to runners' shoelaces accurately record the time each contestant crosses the start and finish lines, even in a crowd.

Credit: ChampionChip World ®

Researchers like Vivek Subramanian, at UC-Berkeley, are working on methods to reduce the cost and increase the capabilities of RFID tags. They foresee the day when electronic tags replace barcodes in everyday commerce.

Sensors at School

At the Massachusetts Institute of Technology, Hari Balakrishnan, Seth Teller, Erik Demaine and Michael Stonebraker have big plans. They're combining global positioning (GPS), RF tagging and ultrasound beacons in a major effort to "activate" the MIT campus. They envision using the system for everything from monitoring and maintaining the physical plant, to inventorying library assets, to helping visitors find their way around the campus.

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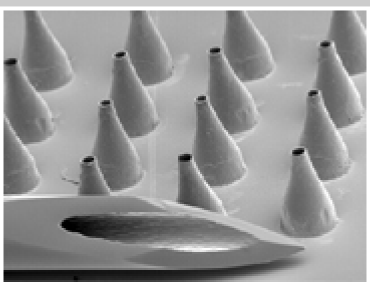
Sensor Applications: Health

In the iRevive system, tiny wireless sensors monitor an emergency patient's heart rate, blood oxygen level, and other vital signs. The sensor data is captured in a record that can be accessed via a secure wireless network, aiding medical decision-makers at every stage, from first responders to ambulance technicians to emergency room physicians.

Credit: Matt Welsh, Harvard University

Sensors have applications in every phase of health care and diagnostics. Doctors now perform tests in their offices that were sent out to laboratories just a few years ago. The results are available immediately, and at lower cost. Wireless, wearable sensors can provide continuous monitoring of the elderly or chronically ill in their own homes. And in an emergency situation, networks of wireless patient monitors can ensure the quick and accurate transfer of information between first responders and hospital emergency rooms, even when there are multiple casualties.



An array of tiny metal needles can draw blood for glucose monitoring or other diagnostic tests with less pain than a conventional needle (shown in foreground for comparison.)

Credit: S.P. Davis, M.R. Prausnitz, M.G. Allen, George Institute of Technology

Imaging Below the Surface

At the NSF's Center for Subsurface Sensing and Imaging Systems (CenSSIS) at Northeastern University in Boston, researchers are using a "physics-based imaging" approach to extract the maximum available information from subsurface sensing technologies. Scientists and engineers from Northeastern University, Boston University, and Rensselaer Polytechnic Institute combine state-of-the-art fabrication techniques with sophisticated physical modeling to create instruments that "see" through skin, water, or other tissues and fluids. They are using this approach to improve mammography and to raise the success rate of *in vitro* fertilization through internal examination of embryos. It works equally well for non-medical problems like land mine detection and monitoring of coral reefs—an application being pursued with partners at the University of Puerto Rico-Mayaguez.

Restoring Failing Vision

At Wayne State University, Loren Schwiebert and his colleagues at the Networking Wireless Sensors laboratory are using their technology to help the visually impaired. Their designs for artificial retinas and cortical implants transmit signals from external cameras to stimulators within the eye. The NEWS team uses retinal prosthetics to aid patients suffering from retinitis pigmentosa, macular degeneration, or other diseases in which the eyes' own sensors—the rods and cones—are destroyed, but the underlying retinal structure is sound. When the retina itself is damaged and will not respond to electrical stimulation, they use a cortical implant instead. Schwiebert is researching network protocols and power management for the systems, which can't rely on an internal power source—power for the implanted electronics must be supplied over the radio link together with high bandwidth video data.

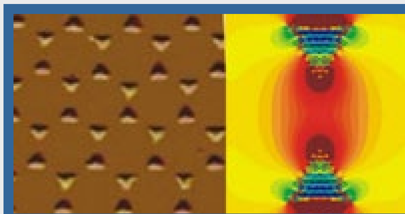
Catching Heart Attacks Early

University of Louisville researcher Kyung Kang and his colleague Chang Ahn, at the University of Cincinnati, use MEMS machining methods to make microfluidic devices that can simultaneously perform four separate biochemical assays. By measuring four cardiac markers rapidly and simultaneously, they hope to improve care for suspected heart attack patients.

Case Western Reserve University electrical engineer Darrin Young has another approach to bettering cardiac health. Young's team is working on pill-sized implantable sensors for heart rate, blood pressure and temperature. Initially, the devices will report the vital signs of a lab mouse to an external computer. Working with geneticist Joseph Nadeau at the Case School of Medicine, Young eventually hopes to identify at-risk patients and detect the onset of heart attacks or epileptic seizures before they reach a critical stage.

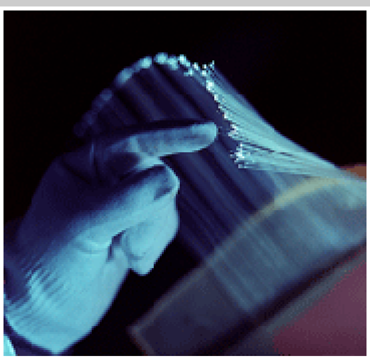
Comprehending Alzheimer's Disease

Alzheimer's patients may benefit from sensor research by Northwestern University chemist Richard van Duyne and neurobiologist William Klein. Van Duyne's group uses surface plasmon resonances to detect small shifts in the electronic properties of their sensors as molecules attach. By fine-tuning the surface chemistry of the sensor, the attachment properties of different molecules can be studied. Klein has a theory that small proteins called amyloid β-derived diffusible ligands (ADDLs) are key agents in Alzheimer's pathology, so he worked with researchers in van Duyne's lab to develop SPR sensors that monitor the binding of ADDLs with their antibodies.



(Left) This biosensor is made from an array of silver nanoparticles deposited on glass. The nanoparticles are surrounded by strong electric and magnetic fields (right) that change when molecules from the environment bind to the sensor.

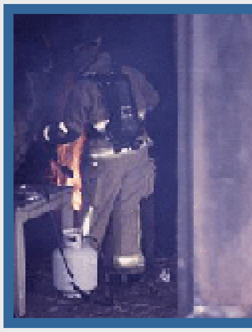
Credit: Amanda J. Haes, Richard P. Van Duyne, Department of Chemistry, Northwestern University (left). K. Lance Kelly, George C. Schatz, Nanoscale Science and Engineering Center, Northwestern University (right)



These glass fibers are flexible and rugged sensors for neutrons and gamma radiation with applications in national security, medicine, and materials research.

Credit: Pacific Northwest National Laboratory

Sensor Applications: Safety & Security

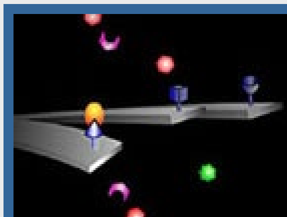


A network of sensors is deployed in a burning building. They create temperature maps that allow fire fighters to move through the space safely.

Credit: Ron Peterson, Computer Science Department, Dartmouth College

Household smoke and carbon monoxide detectors are commonplace. Motion-triggered floodlights illuminate driveways and parking lots. Metal detectors and biohazard monitors guard ports and transportation hubs. Spill sensors protect factory workers from hazardous chemicals. The safety and security of our homes, public spaces, and workplaces rests on sensing danger and issuing timely warnings. New sensing technologies developed with NSF funding, and new methods for gathering and processing data from distributed sensor systems, support a national effort to enhance capabilities for reliably and accurately evaluating situations that threaten our wellbeing.

Nanotech Sensors



Credit: Nicolle Rager, National Science Foundation

At Northwestern University's Nanoscale Science & Engineering Center (NSEC) for Integrated Nanopatterning and Detection Technologies, chemist and Center director Chad Mirkin uses dip-pen lithography to deposit "lock" biomolecules on silicon substrates. Mirkin and his coworkers write molecular patterns only a few nanometers wide, and then expose the decorated substrates to solutions containing "key" molecules. They are able to observe binding between pairs of complementary molecules with both exquisite sensitivity and high specificity. Sensors based on technologies like this will be able to detect hazardous substances in minute quantities, but false alarms will be a rarity. And the same sensor framework could be adapted to detect different substances just by changing the molecular "ink" with which the patterns are written.

Another chemist who applies the nanotechnologist's perspective to sensor development is Robert Hamers at the University of Wisconsin-Madison. Hamers also uses a molecular lock and key approach—for example, he's worked with the binding of biotin (vitamin B-7) to the small protein avidin. Hamers has developed methods for attaching biotin to diamond films and electrically probing for the partner protein. He has used similar techniques to detect specific DNA fragments. The rugged diamond-film devices can be reliably and repeatedly cycled, and the radio frequency measurements that signal the presence or absence of the complementary molecules lend themselves to integration in a sensor chip.

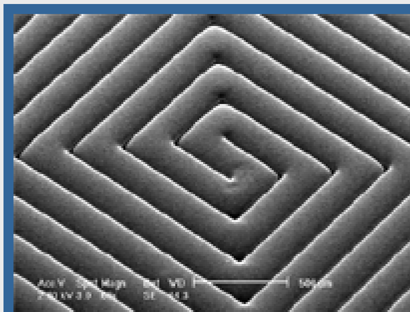
Artificial Nose

Credit: Nicolle Rager, National Science Foundation

Nate Lewis's work exemplifies a different approach to sensing chemical or biological agents. Lewis's technique uses an array of sensors, each of which senses not one highly specific molecule, but a group of related compounds. Using computational techniques to combine the signals from several different sensors and compare the results to known responses, he's created an artificial nose that can sniff out trace quantities of a variety of chemicals.

Lab on a Wrist

The Center for Wireless Integrated Microsystems (WIMS), an NSF Engineering Research Center directed by microelectromechanical systems pioneer Kensall Wise, is putting together all the pieces needed to make networkable, wristwatch-sized chemical analyzers. Scientists and engineers from the University of Michigan, Michigan Technical University, and Michigan State University participate in the ERC, designing sensors, pumps, low-power microprocessors, and radio-frequency componentry for the miniature instruments.



This electron micrograph shows the center of a meter-long capillary tube etched into a silicon wafer. In gas chromatography, different gasses separate as they traverse long, narrow capillary columns.

Credit: NSF Engineering Research Center for Wireless Integrated MiicroSystems, University of Michigan

While the WIMS's work will ultimately become part of many different types of sensor and monitoring systems, they're concentrating current efforts on two testbeds: a cochlear implant and an environmental monitoring system. Ted Zellers from the University of Michigan's School of Public Health heads the team designing the monitoring testbed, a microscale chromatograph that could detect hazardous gases equally well in homeland security applications or industrial process control. To shrink this chemical analysis workhorse down to 1 cubic centimeter, Zellers, Wise, and their students wrap meter-long, 100 micron-wide chromatography columns into tight spirals. They design and fabricate microscopic pumps, valves, and injectors to capture sample gasses and transport them through the instrument. They build electronic circuitry that generates all necessary voltages from batteries, and transmits data via integrated micromachined antennas and radiofrequency circuitry. Size and power consumption must be minimized without compromising performance.

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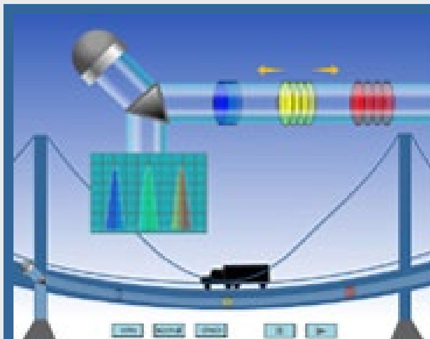
Fiber Bragg Grating



Credit: Zina Deretsky, National Science Foundation

Fiber Bragg Grating sensors can accurately measure movement of large structures like bridges, roadways or skyscrapers, with a single sensor providing data from many different points along the structure.

To make a Fiber Bragg Grating sensor, engineers start with optical communication fibers – those threadlike strands of glass that usually carry phone conversations or Internet traffic on beams of laser light. They modify these fibers by introducing small periodic variations in the glass, called Bragg gratings. This makes the fibers act like very special mirrors, reflecting light of particular colors while remaining transparent to others. The precise color reflected depends on the spacing between the disturbances, called the *period* of the grating. Gratings with large periods reflect redder, or longer wavelength, light while gratings with small periods reflect bluer, or shorter wavelength, light.

A single sensing fiber can be several kilometers long, and can contain as many as 100 gratings, each designed to reflect a slightly different color of light. A real sensor uses light from the infrared region of the spectrum, with wavelengths in a narrow band around 1500 nanometers. But the human eye can't see infrared light, so our animation uses 400-700 nanometer wavelengths to show you the sensor in operation.

When a laser shines down the sensing fiber and the color of the laser light is gradually varied, each grating in turn reflects its characteristic color back towards the light source. Recording the sequence of reflected colors gives a baseline position for every grating along the fiber. Now when a truck deflects a bridge, or some other disturbance applies stress to part of a sensor, some of the gratings are strained. Strain in the sensor corresponds to a change in the gratings period, so the next time the laser sweeps through its color range, the reflected colors are slightly different. Comparing the shifted colors to the baseline readout gives the deflection at each part of the sensor.

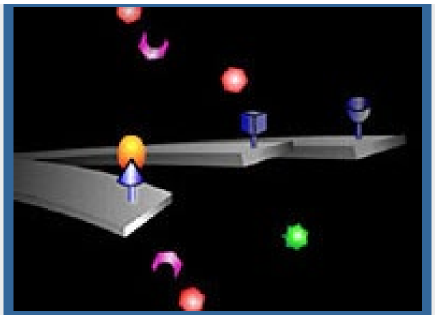
Fiber Bragg Gratings and tunable infrared lasers were first developed for the telecommunications industry, where they are used to combine multiple signals on a single fiber and later to re-separate them. The gratings' sensitivity to vibration, displacement, and temperature led to the development of FBG sensors—a productive cross-fertilization between telecom engineers, optical scientists, and structural engineers.

Micro-Cantilever

The working elements of the micro-cantilever sensor—those projections that look like diving boards—are essentially microscopic tuning forks.

Like any tuning fork, each of the cantilevers vibrates at a natural frequency that depends on its mass. Add more mass, and the vibrations will slow down; take away mass, and the vibrations will speed up.

The micro-cantilever sensor array exploits that fact to detect minute quantities of chemical substances. Each of the vibrating levers has a different chemical coating, so when the array is exposed to a test sample, molecules will stick to certain levers and not to others. This increases the mass of those particular levers, and lowers their frequency of vibration. By monitoring which levers are affected, the sensor can identify the molecules in the sample. By monitoring the magnitude of the frequency change, it can estimate their concentration.



Credit: Nicolle Rager, National Science Foundation

Electronic Nose

Credit: *Nicolle Rager, National Science Foundation*

The Electronic Nose sensor developed by Caltech chemist Nathan Lewis and his colleagues produces “smell spectrum” that’s unique to each kind of airborne chemical.

To achieve this, the scientists wire their sensor with a series of minuscule circuit breakers, each made from a tiny blob of polymer that’s wrapped around a chain of electrically conducting carbon granules. The trick is to choose a polymer that swells up when it’s exposed to certain types of airborne molecules. Any swelling will then pull the carbon grains apart and greatly increase the resistance in the circuit, which will produce a detectable signal.

By making the various circuit breakers out of different polymers with different responses, the scientists can then get a unique spectrum for each type of airborne chemical.

Ad Hoc Networking in the Forest

Credit: Nicolle Rager, Zina Deretsky, National Science Foundation

Out in the field, where there is no Internet, sensors have to get their data back to headquarters via wireless networking technology. Each one passes bits on to the next, creating their own network on the fly—an *ad-hoc* network.

We can see how this works in the environmental monitoring application shown here. Once the sensors are in place, they automatically reach out to find their nearest neighbors, and then form the network links that can transmit the data.

Of course, these connections can be pretty chancy. Not only are they generally restricted to very low power, very short distances, and very low data rates, but the sensors themselves are miles from any tech support. They are out there with no protection from being soaked, baked, frozen, buried, stolen, stepped on, or even eaten.

But then, as shown here, the ad-hoc network as a whole is far more robust than any one device. If any of the links is blocked or broken, the sensors will automatically reach out and find new links to replace them.

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Resources

News, Overviews and Industry Information

Institute for Electrical and Electronic Engineers (IEEE) Sensors Council Tutorials

MEMSnet

MotionNet.com Engineering Directory (Sensors and Measurement)

Radio Frequency Identification at the Association for Automatic Identification and Mobility

RFID in Wikipedia: The Free Encyclopedia

RFID Handbook

Sensors Expo & Conference (2004 Exhibitor's List)

Sensor History from Allsensors.com

Industry Links from Sensors Online Magazine

Small Times Magazine, featuring MEMS and nanotechnology news

WIRELESS INTEGRATED MICROSYSTEMS: Coming Revolution in the Gathering of Information an overview of MEMS by Dr. Kensall Wise

NSF Sensor Research

Programs

- Sensors and Sensor Networks (2004 Solicitation)
- Research Highlights
- Engineering Microsystems: "XYZ on a Chip" (1999)

Workshops and Reports

- The New Challenges of Chemical and Biological Sensing (NSF Workshop, January 9-10, 2002)
- Future Sensing Systems: Living, Nonliving, and Energy Systems (Multi-Agency Workshop, August 26-8, 2002)

Federal Sensor Research Beyond NSF

Defense Advanced Research Projects Agency (DARPA) Sensor Research

Defense Threat Reduction Agency Chemical and Biological Defense Program

The Center for Bio/Molecular Science and Engineering at the Naval Research Laboratory

Chemical Sensor Technology and Chemical Sensing Research at the National Institute of Standards and Technology (NIST)

National Nanotechnology Initiative

Academic and Industrial Research

Berkeley Sensor and Actuator Center at the University of California- Berkeley

Biomimetic Microelectronic Systems Engineering Research Center at the University of Southern California)

Center for Embedded Networked Systems at the University of California-Los Angeles

Center for Subsurface Sensing and Imaging Systems at Northeastern University

Center for Wireless Integrated Microsystems at the University of Michigan

MEMS Technologies at the Charles Stark Draper Laboratory

Habitat Monitoring on Great Duck Island from Intel Research Laboratories

Biological and Chemical Sensor Research at the Northwestern University Institue for Nanotechnology

Sensor-Related Public Policy

Center for Information Technology Research in the Interest of Society