The Incredible Shrinking Sensor

By J.R. Wilson

Devices that monitor a wide variety of phenomena such as light, motion, RF energy, and sound are becoming physically smaller as they follow advances in microelectronics, yet companion technologies and design issues such as power management, optics, and heat dissipation may temper progress in attempts to shrink sensors even further for applications in reconnaissance, surveillance, and counter-terrorism.

The world of sensors is getting smaller. In fact, it is moving, in some cases, into what had been the realm of science fiction.

Some sensors already in prototype measure only 1 cubic millimeter, and still-smaller sensors are in development. Generally, however, a "miniature" sensor is any design with a mass of less than about 3.5 ounces (100 grams), although many are lighter than an ounce. The increased application of high-production-volume micro electro-mechanical systems (MEMS) in the future also is likely to mean decreased size and increased numbers in sensors.

But this shrinkage is largely due to major advances in microcircuitry; limiting the continued shrinkage of electronic sensors are technological problems where advances have not been as rapid as they have been in microelectronics — principally power sources, optics, and heat dissipation.

The NeoStack from Irvine Sensors is a microsensor based on chip-stacking technology and integrates support electronics with the sensors, rather than packaging support electronics in separate boxes.

"Certainly things will get smaller as all the electronic technology gets smaller," says Ron Cybulski, senior vice president for business development at the DRS Technologies Electro-Optical Systems Group in Melbourne, Fla. "The final limitation on the size you can take an IR [infrared] sensor to is dependent on how far you want to see and the optics you put in front of it. The electronics will continue to shrink and get cheaper, but at some point you reach a limit on physical size because of the optics you're looking through."

Electronic power supplies, in addition to optics, also provide barriers to new generations of micro-miniature sensors, Cybulski says. "Today the biggest area that has not changed much is the power source needed to drive these devices in a man-application. Batteries haven't advanced much. Fuel cells may be the solution, but that's still a ways off," he says. "There just haven't been a lot of dollars spent on developing those. The last thing anybody has ever worried about in any system we've ever designed or developed is the power supply. It's not a very exciting technology, I guess, for engineers and those evolving and developing programs."

The other side of the energy equation is output — the heat that a sensor generates as it does its work. And in that area, small size may mean bigger heat problems, explains James Pierson, vice president for applications engineering for Entran Devices Inc. in Fairfield, N.J.

Power dissipation 'through the roof'
"Many sensors, especially anything that senses a static phenomenon, have to shed heat to function," Pierson says. "That might be a micro-quantity, but the output of any sensor is energy. When you make something geometrically smaller, what happens to the power density? If you shed a micro-calorie of heat through a nanometer for space, that's pretty hot. If these tiny sensors are to communicate with each other, they have to have a power source and they have to emit energy. The problem becomes geometric. As you make things smaller and smaller, power dissipation densities go through the roof."

At the same time, one approach that may help shrink the size of some future devices is the use of uncooled sensors, especially infrared (IR) sensors.

"The direction all sensors will be moving is toward uncooled, probably in the next 10 years," Cybulski predicts. "A lot of the reason is the uncooled focal plane technology is improving to the point where it will provide 70 to 80 percent of the performance of a cooled sensor for maybe half or less the price."

Scientists at the Microsystems Technology Office at the Defense Advanced Research Projects Agency (DARPA) in Arlington, Va., are especially interested in uncooled sensors, which they say would significantly reduce the cost and accelerate the widespread use of sensors for applications such as targeting, surveillance, and threat warning, as well as enable imaging sensors for new platforms, such as robotics and micro-air vehicles (MAVs). Uncooled IR sensors also could reduce the weight, size, and power requirements for night-vision goggles and thermal weapons sights.

As sensors shrink in size and cost, they tend to increase in numbers used for any given application. But using lots of tiny sensors to make systems more capable also increases the number of sensor errors.

Using many sensors
Pierson contrasts that with what faced engineers nearly half a century ago in building the first manned space launch systems, when "we could count on everything making a contribution to overall error. We broke those all up into black boxes, where we could compartmentalize the errors, for example saying the accelerometer could have no more than 1 percent error."

But that kind of "black box" approach falls apart when dealing with dozens, perhaps hundreds, of individual miniature sensors.

"If you have 70 sensors, each with errors going in different directions, how do you get the bullet to hit the target? You wind up with a bullet that is smarter than hell, but can't hit anything," Pierson warns. "When you get the sensor count up that high, the finite probability of failure per channel, the uncertainties per channel, could concatenate in the end until you can't trust the output."

Such an approach requires a new system architecture. "You have to calibrate it from a systems point of view, where any combination of sensors can fail and the system will still function accurately, Pierson says. "You have to teach the system the net error, rather than compartmentalizing the uncertainty, and how to accommodate it with correction algorithms, which may require other inputs, as well. It is smart sensors combined with smart systems design."

Sri Kumar, DARPA program manager for Sensor Information Technology (SenseIT), says developing new algorithms and software for to process information from large arrays of distributed microsensors is the focal point of his project.

Networked microsensors have potential applications in a broad spectrum of military and homeland security applications, a fact that is helping to drive research in microsensors for reconnaissance, surveillance, and other tactical applications, Kumar says.

"Smart disposable microsensors can be deployed across the board, on the ground and in the air, on bodies and buildings, on vehicles, and under water, all networked to detect and track threats, winged and wheeled vehicles, personnel and chem-bio agents, and for weapons targeting and area denial," Kumar says.

He suggests applications in Military Operations in Urban Terrain — better known as MOUNT. In these applications, "you want them to go into buildings, look for people, for guns. So the rapidity with which the network must be set up is important. There will be no infrastructure in place, so it has to be rapid, ad-hoc networking. The kind of networking methods we have today, such as the Internet or even the commercial wireless network, are not suitable. They aren't concerned about power, prolonging the life of the nodes or having them sleep when not doing anything."

Experts in the SenseIT program also are looking at software for performing two kinds of sensor-processing tasks:

- collaborative information processing in the network; and
- querying, tasking, and automatically communicating information to a remote station.

Making sensors work together
"Each node could have multiple sensors — acoustic, seismic, IR, magnetometers, imagers, micro-radars, etc. The question is how can clusters of them collaborate to do various kinds of efforts, such as detection, classification, and tracking," Kumar says. "Querying means a soldier would be able to remotely query a sensor network, such as asking how many vehicles of a particular type passed by at a particular time. Related to that is tasking; you tell the network to look for these kinds of vehicles in specific areas. And if they are detected, take a picture and send it back. We're trying to push for as autonomous an operation as possible."

SenseIT is experimental platforms that Kumar says might be called "smart pebbles" — devices based on commercial off-the-shelf (COTS) technology and measuring from as small as 1 cubic inch to as large as 6 by 8 by 8 inches, although production units could be much smaller.

Take an application-specific integrated circuit (ASIC), for example, Kumar says. "If you go to an ASIC, it will be a single chip containing the radio, processor, and all the sensors, perhaps 2 by 2 centimeters. Even if the chips are small, depending on the application, if you are going to airdrop them, you might want them a bit bulkier so they don't float away from the target or get blown away by the wind."

Officially, sensors of this size are called motes. "Motes are here now. We have done a lot of lab experimentation and field demonstrations and they will be ready for deployment in the immediate future, depending on the functionalities required," Kumar says. What is at stake, he explains, is making sure the software is mature enough for deployment, and packaging the motes for air drops from unmanned aerial vehicles (UAVs).

"Each mote will have its own processor in addition to sensors and a radio link," Kumar says. "The software will be installed in every mote. We have different versions, some smaller than others. We have clock speeds ranging from 50 MHz to 150 MHz, memory from tens of kilobytes to tens of megabytes, and radio speed ranging from 2 to 3 kilobits to one running at 66 kilobits per second. We can make them faster."

While these "motes" are small and getting smaller, they are still tied down to an antiquated power supply — regular commercial batteries, from AAA to 9-volt. Kumar says future designs may include some kind of solar panel, but a lot more research is necessary in power sources and power-efficient electronic design.

The first generation

"We should think of the sensor network the same way we do about telephones and wireless devices," Kumar says. "You have first, second, third generations, and so on. As we get more processing capability, we can move to a new generation. There also are power requirements and new algorithms. Right now, we are working on the first generation. The second generation should recognize complex patterns of activities, which will require a lot more work on the algorithms."

Applications will also influence power and size requirements. For example, sensors intended for use by the individual foot soldier — perhaps as part of the Army's Land Warrior (LW) or Objective Force Warrior (OFW) programs — do not need optics as powerful as those intended for a UAV or even a large ground vehicle. The typical soldier needs to see no more than a kilometer, compared to several kilometers range for the other applications. At the same time, those fighters must be able to access and use inputs from external sensors, including "smart pebbles" and even more miniaturized follow-ons.

"It is important that users — the soldiers, the Marines — have a simple interface to interactively task and query the sensor network through a simple human-network interface," Kumar says. "For example, through a simple handheld unit, which may accept speech input, the users should be able to access — and command access to — information (priority, type of target, etc.), and necessarily hide all details about individual sensors. We are developing a language for querying and tasking to do just that."

The miniature piezoresistive semiconductor pressure transducer is targeted for applications such as unsteady flow measurement in wind tunnel model testing of the Joint Strike Fighter.

The goal of these advanced programs is to make every individual warrior a self-sufficient system, electronically interlaced with the entire battlefield, he says.

"With LW/OFW, one of the big things is trying to put a suit on the soldier that makes him immune to biological and chemical weapons, plus body armor, which is a few more pounds," Cybulski says. "Then you start adding sensors and wires that have to interconnect everything, a display to show what the sensors are reporting, and communications and power to run everything for eight or 10 hours. Then add in the canteen, food, rifle, and munitions. The goal is to get something on a man that weighs around 40 to 45 pounds, which is quite a challenge considering all the functionality they want to have."

Some of the research in that arena is being conducted under the SenseIT umbrella at the Massachusetts Institute of Technology in Cambridge, Mass. MIT's objective is to develop and field-test a variety of networked embedded sensor packs (ESPs) for critical applications, including monitoring human vital signs, advanced environment sensing, and object tracking.

According to MIT researchers, the central issues they are pursuing include developing versatile, nimble, and embeddable sensor/processor/communications elements and integrating new generations of capillary networks to connect ESPs to larger global nets. To accomplish that, they are working toward ultra-miniature sensor networks that can be embedded in a wide variety of applications, initially for military use in the field, but ultimately for commercial applications as well.

Software issues

Another SenseIT research effort is in progress at the Rockwell Science Center in Thousand Oaks, Calif. This effort seeks to develop software for distributed microsensor networks. The objective, Rockwell officials say, is to create a super-lightweight runtime environment with distributed services specifically for microsensor networks. This software should help reduce memory and computation requirements by at least 100 times over existing systems as well as meet performance constraints that different sensor-specific applications impose, such as latency and scalability.

The resulting distributed middleware layer and real-time runtime environment would apply to densely distributed sensor nodes with communications and processing capabilities for military applications such as battlefield surveillance, machinery diagnostics, and environmental monitoring.

Engineers at Sensoria Corp. in San Diego are working on another element of SenseIT called the Wireless Integrated Network Sensors — or WINS — that seeks to develop a low-cost, scalable, self-installing architecture for battlefield, perimeter, and base-security applications, as well as condition-based maintenance environments.

In 2001, Sensoria experts developed a next-generation WINS architecture that combines high-performance sensing, actuator control, frequency-hopped spread-spectrum communications, and global positioning system (GPS) location capability. Company officials say the WINS NG 2.0 multiprocessor computing platform provides a micropower, constantly vigilant real-world interface and a 32-bit platform for power computation, along with the first dual RF modem architecture for distributed systems. Software APIs provide access to sensing, signal processing, communication, networking and platform management for each processor.

Irvine Sensors Corp. in Costa Mesa, Calif. — one of numerous contractors working to provide this new generation of microsensors to the military — is working with DARPA to develop new technologies. Much of Irvine's effort is based on chip-stacking technology that company engineers developed for space applications under DARPA sponsorship in the 1980s, says John Carson, Irvine's chief operating officer. In that application, Irvine experts made tiny devices by integrating support electronics with the sensors, rather than packaging support electronics in separate boxes. Today they offer several different types of miniaturized sensors based on dense packaging of electronics and very low power CMOS readout electronics.

Irvine makes MEMS microgyros and accelerometers, as well as unattended ground sensors primarily for the U.S. Department of Defense (DOD), Carson says. "Our primary effort with DOD is miniaturizing IR cameras — uncooled IR imaging devices for night-vision goggles and a line of products we call covert cameras for special operations, where they want to leave the camera behind to take pictures and then radio the results." Irvine won two contracts — one from U.S. Special Operations Command (SOCOM) at MacDill Air Force Base, Fla., and another with the U.S. Army Night Vision Laboratory at Fort Belvoir, Va. — to make weapon-mounted versions of this sensor for a rifle or handgun to enhance night vision.

"The minicams we've been making are roughly 1 by 1 by 3 inches, including the lens and battery. These are 320 by 240 QVGA (quarter VGA). The technologies we're using in that are high-density chip stacking to get all the electronics in a very small cube. Another trick is power management, so the camera is instant on," Carson says. Because of our chip-stacking, we put a ton of memory inside the camera, fully calibrated for all temperature conditions."

Typically, such a camera will have a lot of memory, some special logic units, and assorted other elements (voltage levels, clocks, etc.), all contained within a solid epoxy cube measuring about 1 by 1 by 0.5 inches. The chips are individually thinned and encapsulated, then stacked and interconnected inside the cube, which is then effectively hermetically sealed, which Carson says makes the cube rugged enough on its own to withstand most application environments.

Power management also is an important consideration. The company's uncooled IR camera — called the Cam-Noir — goes to sleep when not in use, but has an instant-on feature that can bring it back online in about one-half second, compared to as long as 60 seconds for other cameras. Some are turned on by vibration or voice activation, others by preprogramming to take a picture at fixed intervals. The key, Carson says, is having all the programs and commands in nonvolatile flash memory, which consumes no energy when not in use.

"We usually get involved in an RF link in situations where the camera is left behind and needs to be interrogated from a distance," Carson says. "We've used two approaches. One is RF, using spread spectrum for security." In commercial applications, Irvine engineers have used the IEEE 802.11b wireless networking standard, as well as Bluetooth; the military versions are classified. Carson says infrared data links are not so desirable because enemy forces can see them with IR equipment and they require line-of-sight. "When it is body- or weapon-mounted and only needs to transmit a few feet at the most, the issue is not radiating very far. For longer range transmissions, it is the platform providers' problem," he says.

Technology spinoffs
In one major sense, microsensors hearken back to the heyday of NASA technology spinoffs. The military leads initial development, primarily DARPA, but commercial companies handle volume production and cost optimization. In the case of microsensors, the leading applications are automotive, cell phones, PCs, home and business security, and firefighting.

"Usually, miniaturization is a forerunner to humongous cost implosion," Carson points out. "Once they get cheap, they fall into the consumer market and the high-volume military market — the infantry. Automotive is generally the last adopter, because it is the worst combination of low cost/high reliability, but it also is the big market, with 60 million or so new cars produced every year."

Carson predicts the total mini-sensor market to be in the billions of dollars in the future, especially in automotive. "As that huge market becomes available, the costs will come down. They also are interested in ranging sensors, inertial sensors, and more. Situational awareness in the automotive market will involve all kinds of sensors. Sensors with integrated lasers for 3-D imaging or ranging will be significant."

Entran's Pierson says the automotive experience also can serve as a benchmark for what can be expected in military applications of miniaturized sensors in the future.

"The average number of car sensors has gone from about seven to more than 70 to meet fuel consumption, crash worthiness, durability, performance, and emissions requirements," he says. "If you took the probability of failure for all those different sensors and treated them separately, a normal car shouldn't work at all. You have to take a systems approach, where large numbers of sensors work in adverse conditions over long periods of time. All these systems have to be integratable and functional out into the future. That also means reduced maintenance, but the backyard mechanic can't do a lot except swap out black boxes. And that also is true for the military."

Commercial applications for miniaturized sensors include determining such factors as wind velocities, barometric pressure, and location — all inputs that also can locate a weapons system or soldier, or target a munition. The potential information content from sensors is enormous — but so may be the number of sensors required to provide that information.

Sensor-laden era
All of which indicates the world — military and civilian — is fast moving into a new sensor-laden era, but Pierson, who teaches courses on sensor design, warns it is a far more complex environment than most may believe.

"Sensors are imperfect mechanisms and our understanding of them is imperfect," he says. "My whole philosophy is to look at sensors as systems through which various forms of energy flow and where we have expected interactions — positive and negative — and unexpected interactions, some of which may actually be positive, but usually are negative. It is those kinds of interactions we need to understand better than we do now, a true intrinsic understanding of the imperfect materials from which we construct sensors.

"We're building some extremely complex systems," Pierson continues. "There are energy interactions between the sensors and the environment we weren't smart enough to see. We can't foresee all permutations of all environments and all combinations of inputs, but it's always some unique set of input conditions that causes an abnormal sensor performance. It could even be one sensor impacting the others."

The potential sources of such problems are as large as the applications for sensors themselves. It could be something as simple as tiny amounts of acid from the fingertips of the person installing the sensor, which leads to a failure 15 years down the road. Or it could be as complex as materials thermodynamics.

"Materials that don't thermally expand very much can actually tend to produce a much larger thermal delta, meaning they expand more than higher expansion materials when forced to conduct heat," Pierson says. "That's an unexpected negative interaction. We have to design around the fact materials expand and contract when heated and cooled, and design smart sensors with built-in microprocessors that can correct output errors."

A battlefield situation is extremely challenging for new technologies, Pierson points out. "You get reflected pressure pulses from the ground or even the fact a weapon has been lying with one side up to the sun instead of another — there can be dramatically negative impact on sensors from being out in the sun. A very small change in temperature can have a monstrous negative effect."

Given that military operating conditions tend to be harsh, uncertain, and dynamic — with often-unreliable communications links — the real future of microsensors on the battlefield will depend on the development of networks that can respond to and survive equally dynamic changes in energy, bandwidth, and processing power, while remaining free from detection or compromise. As Kumar points out, other challenges include finding efficient distributed mechanisms for query and task compilation, placement, data organization, and caching.

DARPA officials are field-testing each of the developments coming from their microsensor programs with the Army, Navy, Air Force, and Marines on a continual basis.

"Our approach is to develop algorithms and software, on experimental platforms, test them in field and laboratory experiments, understand the limitations, and iteratively refine design," Kumar says. "We are planning on at least one field experiment and one or more laboratory experiments in each fiscal year to provide real-time proof of functionality of current baseline and collection of data to support laboratory experiments and ongoing algorithm development.

The SenseIT program "is enabling radical and revolutionary advances to the military," Kumar says. "Revolutionary advances in low cost, high-capability military sensing for open field and MOUNT operations; for users such as dismounted soldiers, command post, force level and for applications such as fast tracking of moving targets, area control, weapons targeting, air campaign, and land mine replacement."

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