



# SIZING UP SMART DUST

By Pam Frost Gorder

**T**HE NAME STARTED OUT AS SOMETHING OF A JOKE. “EVERYONE WAS TALKING ABOUT SMART HOUSES, SMART BUILDINGS, SMART BOMBS, AND I THOUGHT THAT IT WAS funny to talk about smart dust,” remembers Kris Pister.

Though he might have named his invention partly in jest, “smart dust” is now part of the technical lexicon. The tiny, wireless sensors that started out in his University of California, Berkeley, office can now be found in laboratories around the country, where scientists and engineers across many disciplines are eagerly devising applications for them.

With possible uses in the military, the home, and the environment—and a new commercial company (Dust, Inc.) devoted solely to its development—today more than ever, smart dust is no joke. How Pister’s company came to be, and the means through which smart dust is entering American industry, make for an interesting case study in modern technology commercialization.

## Thinking Big About Small Things

Appropriately, Pister first envisioned smart dust while attending a workshop at the RAND Corporation, the first organization ever to wear the label “think tank.” The Santa Monica-headquartered nonprofit was created after World War II to promote science education and help guide national policies in science and technology.

“We were supposed to dream about where technology would be in 30 to 40 years, and we came up with these crazy ideas about miniature wireless sensors with onboard power and computation,” he says of the 1992 workshop. “Two years later, I realized that I could probably make it happen much sooner, so I started giving presentations and writing papers on the concept.”

The concept was sensors the size of dust motes scattered unobtrusively over a wide area to form an autonomous computer network. Functioning as a unified, intelligent system, the sensor net could detect light, sound, temperature, vi-

brations, moisture, or even chemicals, and transmit that information back to a control unit far away.

The most obvious applications for smart dust are in the military. The sensors could, for instance, stay quiet and undetectable in the desert sands until some stimulus—the rumblings of a passing tank or the metal in a gun carried by an enemy soldier, for example—would cause them to wake up and sound an alarm. Once linked together, they could track the intruder’s movements the way radar does today.

In 1998, the US Defense Advanced Research Projects Agency (DARPA) stepped up to fund Pister’s research, letting him craft the first smart-dust hardware. In keeping with the dust theme, his team called their creations “motes.”

## It’s All About Energy

By 2001, Pister’s lab was refining its third-generation hardware, the matchbox-size Rene mote. Running on a battery pack many times larger than the mote, Rene’s performance was tied directly to battery voltage—Rene motes could operate, but not very reliably.

Around that time, there was a push at Berkeley to “move beyond the desktop computer into this new style of device [wireless devices on a distributed network],” says Jason Hill, a smart-dust technology software consultant who was then a graduate student. He saw a way for Pister’s team to harness the power of their invention. “They had these great hardware prototypes, but they needed a partnership with people on the software side,” Hill said.

He worked with David Culler, a Berkeley software engineer who was developing a bare-bones operating system versatile enough to embed in a wide variety of electronics. Hill brought the two research projects together by redesigning the mote circuitry and incorporating the operating system, known as TinyOS. The resulting mote, named Mica, required only two AA batteries to operate, making the entire device roughly equal in size to a modern pager.

TinyOS requires little power to run because it has a very small digital footprint—the core system requires only 400 bytes of memory. Depending on the desired application, functions are added as modules and typically raise the memory cost to 4 Kbytes. Even the most complicated TinyOS ap-

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plication (one with a database engine attached) uses only 64 Kbytes—much smaller than the megabyte required to run the average system embedded in a cell phone. The OS conserves power because it makes the mote's hardware perform only critical functions, which in turn extends the mote's lifetime.

In sum, Pister says, "It's all about energy."

## DARPA Builds a NEST

The defense agency selected Mica for its Network Embedded Systems Technology (NEST) project, causing first a dozen laboratories to adopt the mote, then a hundred more.

Sensor maker Crossbow Technology fostered a connection with Berkeley by making the motes commercially available at cost. "They were instrumental in putting the Mica platform in the hands of the companies that are developing applications," Hill says.

For people interested in sensors or wireless networking, Mica is now the fun new toy they most want to play with. And thanks to Crossbow's pricing of US\$150 and up for a starter kit, it's a luxury most labs can afford.

The feedback Hill and Pister received from Mica fans during the early months of NEST excited them about smart dust's commercial potential. Soon, Pister says, he "couldn't think about anything else except bringing this technology to market." The two cofounded Dust, Inc. in 2002.

Although NEST's goal isn't to commercialize any particular brand of sensor, it supports efforts to develop this technology in both academia and industry. Among its partners are Boeing, Lockheed Martin, Honeywell, and a host of universities. As a result, graduate students across the country are now earning their PhDs in sensor networking thanks to DARPA.

The funding enabled Pister, Hill, and the rest of the Berkeley team—including students Ben Cook, Mike Scott, Brett Warneke, and Al Molnar—to build the smallest and most capable smart-dust mote to date.

## A Speck Named Spec

Spec is the first mote to integrate radio frequency communication with custom-designed circuits running on TinyOS. Measuring only 5 square millimeters, the single-chip sensor is about the size of a piece of glitter, and is easily lost on the surface of a Mica circuit board. Prototypes are available in limited quantities and are circulating among NEST participants.

In tests, the first Spec chip to go online transmitted radio signals to a receiver 40 feet away. That distance, plus the fact that it transmitted through walls, would seem to indicate that the mote has what it takes to form a reliable network in the outdoors, where rocks, tall grass, and trees could otherwise block signals between sensors.

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Because Spec is so much smaller than Mica, it also bodes well for smart dust one day approaching the size suggested by its name. More than ever, mote size will depend on new developments in battery technology. In the meantime, researchers are devising ways for the sensors to conserve the battery power they have now.

## Applications Galore

One strategy that could suit military purposes involves having deployed sensors store data in flash memory until an aerial drone flies over to pick up the information. The motes wouldn't have to expend the energy necessary to transmit a signal to a far-away receiver.

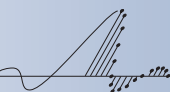
Theoretically, the sensors could stay passive on the desert floor for years, waiting for something to happen, Hill says. When a drone passes over on reconnaissance, "it would be as if a soldier had been sitting there the whole time and could say, 'a bunch of tanks went north five hours ago.'"

Outside the military, the shipping industry could also benefit from using smart dust. Trailers often carry products from more than one company, and mote-labeled packages could help eliminate mix-ups by literally telling workers whether they needed to be loaded or unloaded. For the manufacturing industry, motes could supply data for process control at a low cost, because they are easier to install than wired sensors. Yet another application is environmental monitoring; one project in California is currently scrutinizing the health of redwood trees. Since only 4 percent of California's old-growth redwoods are still standing, scientists are keen to preserve and study them. Tiny sensors planted along the trunks of five young redwoods at the University of California Botanical Garden at Berkeley are currently measuring the trees' temperature, moisture, and light level. The sensors have already confirmed what scientists only suspected before—that redwood branches trap cool air and life-sustaining moisture near the ground.

The August 2003 power outage that darkened much of the American Northeast also has experts wondering whether smart dust can help maintain the nation's electric power Grid. Keeping close tabs on the temperature of individual transformers and transmission lines could give power companies advance notice of impending failures, for example.

Motes could also help boost power transmission, Hill says. "When you push current through power lines, they start to heat up, so the maximum temperature tolerated by the lines determines the amount of power you can transmit," he explains.

Pister elaborates: "In general, transmission lines are run well below their peak capability because their actual temperature is unknown. As a result, as demand increases, new lines are built at a huge cost long before they are actually needed."



Before sensors can be installed on every power line or transformer in the country, a different power-related application might take hold. A recent test at Berkeley showed that temperature-sensing motes installed in offices could control air conditioning and make a building more energy efficient.

At Xerox Palo Alto Research Center, networking specialist Feng Zhao is looking ahead to the time when researchers will have to figure out how to process the potentially huge amounts of data obtained via smart-dust networks. "This is going to be a lot harder than traditional data mining because the data the sensors collect are about physical conditions of phenomena, rather than clean relational attributes," he says.

### Tiny Future

So far, smart dust and TinyOS have both benefited from open-source development, but anyone could take the publicly available technology and build proprietary enhancements.

"It is really nice to see the open-source development surrounding TinyOS," Zhao says. "The research community has been able to leverage each other's effort, and the TinyOS team is able to get valuable feedback and improvements. Other components or layers of sensor networks may see more proprietary technologies—for example, ultralow radio or sensor hardware design."

Dust, Inc. also will be commercializing some of that proprietary technology.

"Everything that I did in the university environment is public domain—every board design, chip design, line of code, algorithm. Things are different at the company," Pister says. He has taken a leave of absence from Berkeley to make room for his new role.

Hill has since left to form yet another company—JLH Labs—that will "build the higher-level software capabilities" of smart dust. He continues to work closely with Dust, Inc.

TinyOS continues to evolve, but exactly how it will evolve is an open issue. "Many companies would like to see TinyOS remain open source, but they also want to see the quality maintained. They wonder when we're going to come out with our own Red Hat," Culler says, referring to the commercial company that supports a version of the Linux code.

Since the OS has already been ported to other platforms besides the Berkeley motes, many companies could conceivably step in as providers. "They are waiting to see how things shake out," Culler says. "It will be interesting to see what happens." His group continues to refine nesC, the C-based computer language that codes TinyOS.

At Old Dominion University, computer science professor Stephen Olariu and his team are working on sensor networks that could build on TinyOS or do away with it en-

tirely. ("Why do we need an operating systems," he asks philosophically, "if simpler protocols could do the job and consume even less battery power?")

According to Hill, the next hurdle for the company will be to take the original design for the Spec circuitry and rearrange it for efficient mass production. National Semiconductor built the Spec prototypes for Berkeley, but only for research purposes, so the task of scaling up production will fall to Dust, Inc. Hill is confident that the company will meet its goal of manufacturing an aspirin-size Spec mote within a year, with production costs of less than a dollar per mote.

Pister acknowledges that not everyone shares Hill's optimism. "A lot of people have a hard time believing that we'll be able to do what I say we're going to do," he says. "Historically, I have performed best when people doubt what I'm saying, so hopefully I'll be able to prove them wrong again." **SE**

Pam Frost Gorder is a freelance science writer living in Columbus, Ohio.



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