March of the motes

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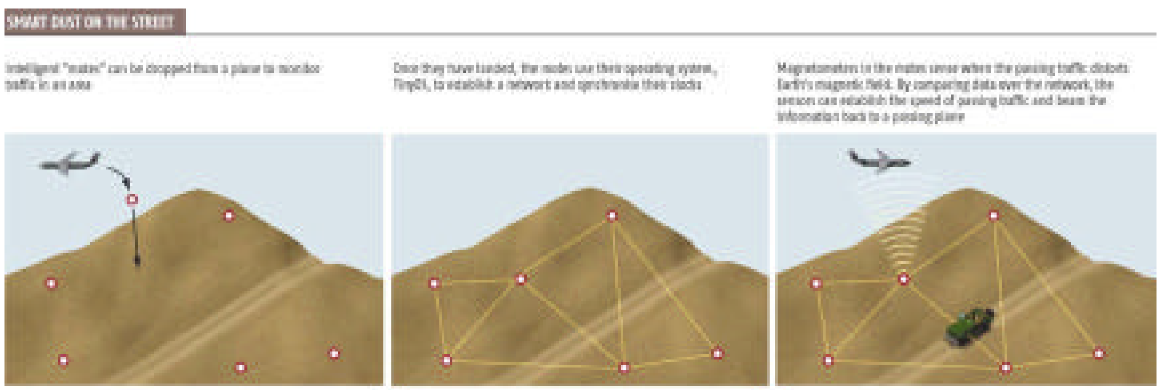
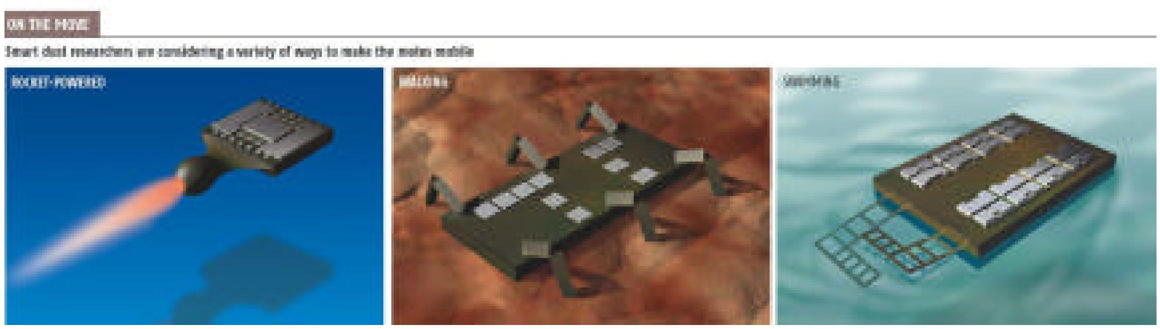
An unseen silicon army is gathering information on Earth and its inhabitants. It's not an alien reconnaissance mission: smart dust is finally hitting the streets, says Anil Ananthaswamy

KRIS PISTER wants to cover the world with dust. His company, Dust, certainly seems to be shifting the stuff pretty fast. Stacked outside Pister's glass-walled office in the industrial west side of Berkeley, California, are empty cardboard boxes ready to be packed with dust and shipped across the globe. As Pister talks animatedly about his vision, an employee picks one up and Pister whoops with delight: "Ah, great! Another box comes off the stack."





The box is not, of course, going to be filled with any ordinary dust. This is "smart dust", a moniker for tiny, cheap, intelligent wireless sensors that can communicate with each other, form autonomous networks and monitor almost anything: local temperatures, the presence of people, the volume of passing traffic, even the extent of earthquake damage or the health of seabird colonies. You may have heard of it: the technology is already being touted as something that will change the way our world works.

While that remains to be seen, smart dust at last looks ready to make its mark. The "motes" rolling out of the research labs at the University of California, Berkeley, are now as small as a grain of rice. Future versions will soon be able to do away with batteries, scavenging power from their surroundings. Scatter them across the globe and they could establish a network of silent, unseen sentinels that record and transmit information about their environment.

Some say that smart dust could bring about a surveillance nightmare, but others insist it could help save the planet. Pister has a broader vision. He believes that smart dust technology could literally network Earth, forming another layer of infrastructure between the internet and the physical world. "I really do believe that this is going to have the same kind of profound impact on society that the internet did," he says.

Pister is an engineering professor at UC Berkeley, but he is currently on industrial leave to get Dust off the ground. He first thought of building wireless sensors in the mid-1990s. His vision was of networks of sensors that could be sprinkled anywhere to collect information that would otherwise be difficult to gather. Pister believed that such sensors could be shrunk to just a cubic millimetre and put this proposal to DARPA, the research wing of the Pentagon. "I coined the phrase 'smart dust' as a joke, because everyone was talking about smart houses and smart bombs and smart freeways," says Pister. "'Smart dust' was meant to be tongue-in-cheek."

Nonetheless, DARPA funded the project and the name stuck. Along with UC Berkeley colleague David Culler and a handful of dedicated graduate students, Pister built the first smart dust units - he also coined the term "mote" to describe them, which has since passed into computer-speak to mean a wireless sensor. These prototypes had a microprocessor, bi- directional radio, and a light sensor on board.

The next generation of motes was significantly more advanced. They included an interface to which different sensors, such as magnetometers or barometers, could be clipped. These eventually led to smaller and more powerful motes, nicknamed Mica, which have been manufactured commercially since October 2001. Slightly larger than a matchbox, each Mica mote is powered by two AA batteries and can support up to eight sensors.

Although their size may not yet do justice to the name "dust", these Mica motes have already demonstrated the potential of the concept. For example, Steve Glaser, professor of civil engineering at UC Berkeley, has shown that mote networks can quickly check whether buildings that have survived earthquakes are safe to re-enter.

Large buildings and skyscrapers are normally closed to their everyday users after a quake until safety checks are completed. The process is hugely expensive and can take months. But cover every key structural element in the building with motes containing accelerometers that sense vibrations and you can compute how much the structure shook during the quake. And the sensors can calculate the stiffness of a structure by measuring how much they are moving relative to each other, immediately revealing the degree of damage at each location. In a laboratory test of a three-storey wood-frame structure constructed atop a shaking platform that simulates earthquakes, two UC Berkeley graduate students installed nearly 100 wireless motes equipped with accelerometers in an afternoon. These motes beamed back information on how the building moved when shaken, allowing an immediate damage assessment. "The civil engineers were ecstatic," says Pister.

If all this was merely a matter of building tiny sensors and sticking them everywhere, it would be easy. But the task is considerably more complicated than simply beaming readings to some number-crunching computer. For one thing, the computer would quickly be overwhelmed with data as the number of sensors increased. For another, the motes would soon run out of battery power if they were continually radioing data back. The solution is to create intelligent networks of motes that pre-process the data and only beam back information of interest, such as the stiffness of a structure, rather than sending back raw data such as real-time sensor readings about how much each mote has moved.

And this is where smart dust really gets smart. At the heart of the network is a revolutionary piece of software. Each mote has its own operating system (OS), similar to the Windows software that runs most PCs, or Unix, which runs most internet servers. But thanks to some skilful design work, the smart dust OS runs on microprocessors that need very little memory. Where the latest version of Windows uses over 100 megabytes of memory, smart dust's OS runs on as little as 8 kilobytes. "We thought about calling it 'Wee-nix' or 'Wee-ndows', but cooler heads prevailed and we called it TinyOS," says Pister.

TinyOS, which now has a large open-source community continuing its development, is what turns the smart-dust dream into reality. Part of an operating system's job is to efficiently manage its hardware resources. In a mote, that includes the various sensors attached to it, the radio link to other motes, and the power supply. TinyOS has to do this while consuming as little power as possible - after all, a mote with dead batteries is no better than, well, dust.

The software achieves this by "sleeping" for most of time. While asleep, all the hardware except the sensors is on standby. TinyOS wakes up, say, once a second and spends about 50 microseconds collecting data from the sensors, and another 10 milliseconds exchanging data with neighbouring motes. "From a human perspective, you get an essentially real-time response, and yet the motes are asleep 99 per cent of the time," says Pister.

To further increase battery life, TinyOS uses "multi-hop networking". Imagine hundreds of motes spread over acres of land, all monitoring soil moisture. Instead of having each mote communicate with a base station (a laptop, for instance), only those nearest the base station do so. These "first-level" motes then talk to other motes within range, forming a second level, and so on, until a multi-tiered network is established. All the motes know the best path through the network for communicating with the first-level motes, which allows any mote to send a message to the base station using a minimum number of hops.

The structure of the multi-hop network established by the motes can change if the strength of radio links between motes changes, with stronger links given preference over the weaker ones. If a mote stops functioning, the others reconfigure the network to bypass it, and a new mote can easily enter the network, with all the others reconfiguring around it.

Hopping also means the radio transmitters in motes can be extremely short-range - just powerful enough to reach the nearest motes tens of metres away. Contrast this with cellphones, which sometimes have to send signals several kilometres to reach a base station. "If you cut the transmission range in half, you can cut the power requirement by a quarter," says Jason Hill, who developed TinyOS as a master's thesis project with Culler and Pister. "We are saying, don't cut [the range] in half, cut it by a factor of 100."

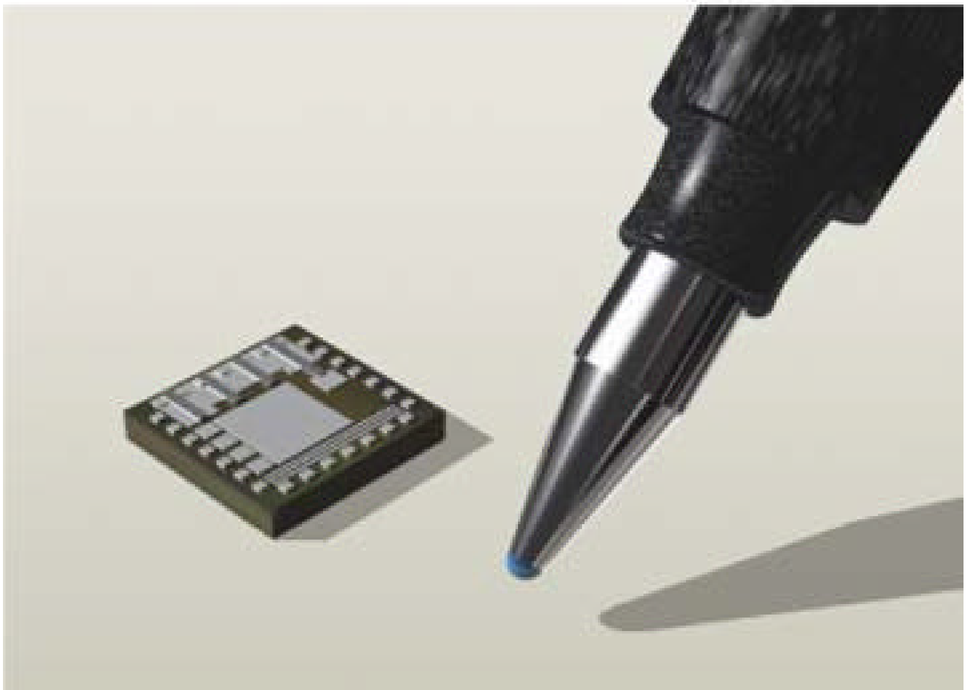
All this obsessive attention to power saving has paid off: motes consume just one-thousandth as much power as standard wireless devices, such as cellphones. "You get battery life in the 1 to 10-year range, depending on the application," says Pister.

But TinyOS can do much more than prolong battery life. The complexity of tasks that it can support, despite its small size, is exemplified by an intriguing experiment carried out by Pister and his colleagues for DARPA officials at a military base outside Twentynine Palms, California. In March 2001 they fitted six motes with magnetometers, wrapped them in styrofoam, and sent them up in a drone plane. The plane, flying alongside a road at a height of just 50 metres and at 50 kilometres per hour, dropped the motes one at a time, 20 metres away from the road. Their task: to monitor the movement of tanks, Humvees, and other military vehicles on the road.

Once the motes hit the ground, they contacted each other, established a wireless network and synchronised their clocks. Any time a vehicle went by it distorted the Earth's magnetic field and the motes duly recorded it. The motes then compared their data with each other, computing the direction and speed of the vehicle, stored the results in memory, and went back to watching their magnetometers. An hour later, the drone plane flew by again, and the motes transmitted their data to an onboard laptop. Their mission was a success.

Last month in Berkeley, the researchers showed off a more sophisticated version of the same application to the military, who intend to use smart dust to monitor enemy troop movements. A hundred motes were distributed inside a square grid, 18 metres to a side. Only the motes at the corners knew their absolute position. Using ultrasound signalling to determine the distance between immediate neighbours, and employing a sophisticated distributed algorithm, the other motes then figured out their coordinates - even though the majority of them were not in direct communication with those at the corners. Members of the audience then steered a small radio-controlled vehicle around inside the square. The motes monitored the vehicle with their magnetometers, calculated its position, and beamed the information to another, autonomous vehicle, which was then able to follow the remote-controlled vehicle - all in real time. It was an extraordinary feat because the motes had to constantly reconfigure their multi-hop network to maintain contact with the autonomous vehicle - essentially a mobile base station - as it tracked the other vehicle.

The latest smart dust particles are just 2.5 mm across



All of this is possible because of TinyOS. The same motes could easily be reprogrammed for a completely different task. And the reprogramming can be done wirelessly. Simply design your program on a PC and transmit it to the nearest mote. The mote reprograms itself, and then sends the new instructions to the other motes. The program spreads, virus-like, throughout the network, taking a mere 30 seconds to reprogram each mote, until eventually the whole population is ready to perform the new task.

Despite the military's interest in smart dust, it is the technology's non-military potential that gets Glaser most excited. His latest challenge for the motes is to help firefighters tame the raging wildfires that are common in California. "The fire makes its own local weather, especially winds," says Glaser. "Sometimes the fire will come back behind the firefighters, and they get surrounded."

To show how smart dust could help, Glaser plans to drop motes from a helicopter into the path of a wildfire. The motes will have a slew of sensors to measure temperature, barometric pressure, humidity, light and wind speed. Each of these motes will also have a GPS module to fix its exact location on the ground. Just as in the Twentynine Palms experiment, the motes will beam up information about the effects of the advancing fire to a helicopter overhead. From there the data will bounce to a central lab that can forecast the fire's path by combining the sensor information with other data such as vegetation cover and topography. Glaser's team will start testing the idea this summer by participating in the controlled burns that are routinely carried out in California's state parks. If it works, smart dust could make fighting forest fires a lot less hazardous in future.

Pister's motes are also being signed up to monitor the unusual conditions inside Yucca Mountain in Nevada, the US government's proposed storage site for nuclear waste.

Joseph Wang of the Lawrence Berkeley National Laboratory in Berkeley, California, is planning to evaluate how well motes could monitor the relative humidity and temperature inside Yucca Mountain's tunnels. It is feared that heat from the waste could push the temperature inside the tunnels above the boiling point of water, and plumes of steam could carry radiation out of the tunnels, so this kind of monitoring will be essential for the early activation of cooling systems. If the motes are successful, Wang sees a great future for them at Yucca Mountain; they could also monitor radiation levels directly, for instance.

Smart dust motes are already appearing in tunnels elsewhere - inside the nests of Leach's storm petrels on Great Duck Island, off the coast of Maine. These birds' habits are far from easy to study: they only come to the island to breed, arrive only at night, and they nest underground in shallow burrows that can be up to two metres long. "Most of what we know about their breeding biology is the result of people literally sticking their arms down the burrow and feeling for feathers or an egg," says biologist John Anderson of the College of the Atlantic in Bar Harbor, Maine. He is excited about motes that he and his colleagues have placed inside many of the burrows. Apart from monitoring temperature, humidity and pressure, the motes also have infrared sensors to tell if there is a bird in the nest. Not only will such close-quarters monitoring shed light on the petrel's breeding biology, it will provide a more accurate count of its populations, which will help researchers decide whether the birds are endangered.

Anderson says that smart dust is already changing the study of nature. In the past, field ecologists have had to either extrapolate from a few "coarse-grained" environmental measurements - fixed meteorological detectors at research stations, for example - or else work in the field, which can disturb whatever species is under study. Either way, results are likely to be skewed. But with smart dust, it is a different story. "Motes give us high-resolution micro-environmental data and we don't have to be there to get it," Anderson says.

And the influence of smart dust is spreading across the globe. Glaser, together with Chik Tanimoto of Osaka University in Japan, has started installing motes inside caves in Dunhuang in China, 1800 kilometres west of Beijing. Here, 1600-year-old Buddhist cave paintings are being damaged by salty groundwater, and the motes are there to monitor humidity and light intensity. The data will help art conservators from the Los Angeles-based Getty Museum restore and preserve the paintings - enabling them to decide how best to ventilate the caves, for example. "Once a week, somebody can walk by with a laptop and collect the data," says Glaser. "It's a very helpful application, making use of what we can do now."

These motes are still the relatively large matchbox-size Mica motes, but for many applications, such as monitoring the caves or tagging earthquake-prone buildings, the size of these commercially available motes is just fine. "Size is a relative thing," Glaser says. "If it's too small, and you put it on a building, you'll never find it again." But many more applications are bound to emerge now that the latest generation of motes is proving more worthy of the "dust" tag.

For his doctoral dissertation, Hill designed a flat, rectangular mote nicknamed Spec that is only 2 by 2.5 millimetres across. A prototype of Spec was built by chip manufacturer National Semiconductor of Santa Clara, California, in March. "We have demonstrated that it's definitely feasible, and the next step is commercialisation," says Hill. Although these motes still require external antennas and batteries, Panasonic is making millimetre-scale batteries that could do the job.

Batteries will eventually be redundant, however: the miniaturised motes will scavenge energy from light (both natural and artificial), magnetic fields emanating from power lines and even almost-imperceptible vibrations. Paul Wright of UC Berkeley and his doctoral student Shad Roundy have developed tiny devices that can generate up to 200 microwatts from low-level vibrations that are commonplace in buildings, pumps, air-conditioning ducts, and even microwave ovens. The vibrations from such sources are used to change the capacitance of devices etched in silicon or bend strips of a piezoelectric material, in both cases generating a useful voltage. "We can certainly power our motes off Paul's vibrational energy source," says Pister.

The ever-shrinking smart dust also raises issues about privacy. Could this be a Big Brother technology? The Mica motes already come with microphones, and researchers are developing cameras for them - although size limitations may mean that Spec motes can never carry a camera. People should be concerned about privacy issues, says Deborah Estrin of the University of California in Los Angeles, who develops software systems for smart dust. "It's something that's going to require attention both at the legal and regulatory level," says Estrin.

Pister accepts that smart dust raises privacy issues that need to be addressed. But he doesn't agree with those who worry that the environment will be polluted with motes. In one of the most dramatic applications yet proposed, for instance, a meteorologist has asked Pister about releasing 10 billion motes into the atmosphere to monitor changing weather conditions. Even with such huge numbers, Pister thinks the density of motes would never threaten anyone's health. "That works out to one mote per cubic kilometre. You would have to walk around for a long, long time before you ever had to worry about breathing in that one mote," says Pister. "If you did inhale, it would be no more unpleasant than inhaling a gnat. You'd just cough it right out immediately."

While the arguments about smart dust's risks continue, it is clear that the technology is now ready to hit the streets. "The possibilities seem tremendous," says Estrin. "If you look at really critical problems of our day, from pollution and contaminants to understanding global change indicators and their impact on fragmentation of the rain forest, there's just a tremendous opportunity." Smart dust could gather data at the appropriate spatial resolution and enable us to properly understand those complex processes for the first time, Estrin says. "From a scientific perspective, everyone's so excited about it."

And no one's more excited than Pister. He believes that smart dust technology could eventually link us to the physical world, forming a technology as formidable as the internet. It is a grand but perhaps slightly disturbing vision: sprinkled around the globe, the smart dust web could supply unceasing streams of data about the Earth and its inhabitants, covering everything from traffic flows to ozone holes. "The internet connected people and ideas," Pister says. "This is going to do the same thing for the physical world."