TECH EXPEDITIONS

BIRD-WATCHER: Thanks to an experimental wireless sensor network, ornithologist John Anderson [right] is getting a bird's-eye view, literally, of the nesting habits of the Leach's storm petrel [chick shown below], a tiny and reclusive seabird that digs burrows in sandy soil and emerges only at night.

The Secret Life of Birds

How do you study a thing that doesn't want to be studied?

BY JEAN KUMAGAI

PHOTOS: JOE DEVENNEY

Sometime next month, not long after winter has called it quits, Alan Mainwaring will board an old 12-meter-long work boat and take it across the icy waters of Bar Harbor, Maine, to a small, rocky patch of land that the locals know as Great Duck Island. There, he and a few colleagues will get to work, setting out a series of small plastic cylinders across a meadow and some woods at the island's southern edge.

Each cylinder holds a bit of circuitry capable of simple computation and communication, plus a few environmental sensors, a battery, and an antenna. Taken alone, it's nothing special. But scatter around a dozen or a hundred or a thousand of these film-canister-sized cylinders—called motes—and switch them on, and something amazing happens: within seconds, they will organize themselves into a powerful yet stealthy data-gathering machine. Their quarry? A small and secretive seabird known as the Leach's storm petrel, whose comings and goings bird-watchers have long puzzled over but have never fully understood.

It seems an unlikely spot for such a setup, out here on the shore of nowhere, but in certain circles, the goings-on at Great Duck are being closely watched. Mainwaring is a computer scientist at the Intel Research Laboratory in Berkeley, Calif., and together with a longtime friend, John Anderson, an ornithologist at the College of the Atlantic, Bar Harbor, he's spent the last three years conducting one of the most sophisticated tests of wireless sensor networks yet devised.

The petrel-watching apparatus consists of a distributed system of motes, each having the dual functions of data collection and communication. For the former role, the mote contains application-specific sensors and signal-processing hardware; for the latter, the mote has a low-power radio transceiver. When the motes are networked together, each simultaneously collects data from its immediate surroundings and passes its own and other motes' data through the network.

Though wireless sensor networks have been widely heralded for tracking everything from traffic to crops to people, their potential is still largely unrealized. While industry types figure out how sensor networks can boost their bottom line, and privacy advocates debate their social costs, researchers like Mainwaring are actually moving the technology out into the real world. Those efforts have transformed this tiny island and its petrels into a test bed for the future of sensing technology.

"PEOPLE THINK I MUST LOVE BIRDS," Mainwaring tells me, as we stand on the deck of Great Duck's small, 114-year-old lighthouse, "but I don't." We've walked here along a narrow plank way from the old lightkeeper's cottage, now used to house the

JOE DEVENNEY

DESERT ISLAND: Sitting 15 kilometers from Bar Harbor, Maine, 90-hectare Great Duck Island has no year-round human occupants but boasts the largest colony of Leach's storm petrels in the lower 48 states.

petrel project's computer base station, and also its researchers. It's nearly noon in early August, but the air is cool and damp. Looking out to sea, the horizon is a flat gray expanse. If I were to draw a line due south from here, it would continue unbroken until it hit the edge of Venezuela.

As if to prove his lack of interest in birds, Mainwaring struggles to identify a few that have perched on the rocks below. "That's a black-backed gull. I think that one's a herring gull." "Do they live here year-round?" I ask. He shrugs: "I have no idea."

But ask Anderson about birds, and you'll get a very different answer. "Petrels are really cool," he says. "And they're a mystery." This much is known: Leach's storm petrels, so named for their habit of showing up during bad weather, spend much of their lives out on the waters of the South Atlantic, heading north and to shore in the springtime to mate. Once on dry land, the male digs a shallow, narrow burrow, 2 to 6 centimeters below ground, 3 to 6 cm across, and anywhere from 30 cm to 2 meters long. Here the female will lay just one egg. Both parents will occasionally leave the nest to fly back out to deep waters to feed.

The desire to gain intimate knowledge about the petrel raises, if only indirectly, another concern. In our world, birds and other creatures don't have any real claim to privacy, so monitoring their reproductive rituals is perfectly okay. But when wireless sensor nets are turned on people, which they inevitably will be, it will be another matter.

The current capabilities of sensor networks are still primitive, but their social implications are already obvious. As the technology shrinks in size and grows in sophistication, ultimately reaching the state of microscopic "smart dust," one can easily imagine how sensor nets could be used to monitor and spy on the unsuspecting.

"Like any technology, sensor networks can be used for good or ill," Mainwaring says. "For now, I think it's better that we stay away from people."

As it happens, the 90-hectare island has no year-round human occupants, and it boasts the largest petrel population in the lower 48 states: 9000 nesting pairs, plus or minus 4000. (That estimate comes courtesy of one of Anderson's grad students, who spent a couple of summers crawling over every rock and crevice of the island taking a census.) But apart from the burrows, which to the unschooled eye look a lot like gopher holes, you'd never know. Petrels do the bulk of their flying late at night, spending their days either far offshore or squirreled away underground.

Among bird-watchers, Anderson says, the last great innovation was binoculars. "They make the science very anthropocentric." And they're not much help for studying birds like the petrel. There's no good way of looking inside a burrow without causing the creature some distress, and thus no way of knowing what conditions are like down there, how much time the parents sit on their eggs, or any of the other things bird scientists want to know. That's where the motes, which are small and unobtrusive enough to place inside the burrow, are proving invaluable. "Now, we can study the bird from the bird's perspective," Anderson says.

GREAT DUCK ISLAND sits about 15 kilometers from Bar Harbor. You can get there only by boat, helicopter, or hydroplane, and even then, getting to shore usually requires some tricky negotiation in a rowboat. Much of the year, it's a cold and lonely place, but from May to late September, the College of the Atlantic, which shares the island with the Nature Conservancy, sends a boat there a few times a week, weather permitting, to drop off researchers, supplies, and the occasional visitor. My two-hour ride out on a mercifully calm though foggy August morning is punctuated by sightings of harbor porpoises, puffins, and seals.

As we make our way up from the boathouse, Anderson sniffs the air. "Smell that?" he asks. I do smell something, but to my city nose, it's like a bus has just pulled away from the curb. That diesely odor comes from a greasy, protein-rich goop that the petrel distills in its gut from plankton and then regurgitates for its young, Anderson explains. The scent hangs in the air above the petrels' burrows. (Since returning from Great Duck last August, I've kept a petrel feather sealed in a Ziploc bag on my desk. The scent is still strong, even through the plastic.)

Walking further down a muddy trail, we start to see trees and shrubs festooned with pink and red tags; these mark the whereabouts of the motes. The sensor guys tend to be zealous with their tags, Anderson notes, much to the dismay of aesthetics-conscious Nature Conservancy officials.

At one point he kneels down on a mossy lump of earth, maneuvers his arm into a small opening, and slowly draws forth a bird. I get my first and only glimpse of a petrel. The size of a skinny robin, it fits easily in Anderson's hands, its soft gray head and black knobby beak poking out one end, its two webbed black feet and long forked tail sticking out the other. It's a funny little thing.

If I stick around until midnight, Anderson tells me, I'll get to see them in action. Petrels are basically day birds that have taken to flying at night, and so they tend to fly by rote. If you happen to wander into a petrel's usual flight path, it'll smack

PETREL PATROL: When Intel computer scientist Alan Mainwaring [back right] first suggested to his boss, David Culler [front right], that they deploy a wireless sensor network on a remote New England island, there was skepticism all around. But Culler okayed the project, and Berkeley grad students Joseph Polastre and Robert Szewczyk [front and back left] soon signed on.

ANGELA WYANT

NOTHING BUT NET: John Anderson [1] buries a mote [2, two variants shown] in the dirt wall of a petrel burrow. Other motes nearby on thin wire stalks [3] monitor the weather.

right into you. The mosquitoes are starting to swarm, though, so we move on.

FOR MAINWARING'S PART, the project's draw has been the chance to test all the ideas about sensor networks out in the real world. Few places get more real than this. When the experiment first got under way three years ago, the island had no infrastructure to support a computer-driven experiment—no power, no phone lines, not even a well. Mainwaring and Anderson didn't intend to spend the whole summer on the island, so the network had to be able to run largely unattended, enduring all the weather extremes that coastal Maine would throw at it. And would a mote's radio signal propagate underground? No one really knew. There's no Official Rule Book of Experiment Design, but if there were, Mainwaring's would have incurred numerous infractions. It just had too many ways to fail. "Alan picked the most difficult thing to do first," says Joe Hellerstein, director of the Intel Research Laboratory at Berkeley.

Hellerstein's predecessor, David Culler, now back at his job as professor in computer science at the University of California, Berkeley, and an expert on embedded wireless networks, was responsible for approving the project. To date, Intel has provided most of the money for the petrel project, and researchers there worked side by side with Culler's students to develop and deploy the motes. Culler, in turn, had been brought in to start up Intel's quasi-academic "lablet" in Berkeley by the company's director of research, David L. Tennenhouse, who has a keen business interest in sensor networks. Beyond just monitoring seabirds, motes could be used for agriculture, hospitals, nursing homes, and factories—anyplace where real-time data collection would be useful.

Even so, when Mainwaring first pitched the idea in 2001, he says, "there was skepticism—it was Tennenhouse's impression that there was no way this could work." At the time, though, no one shared those doubts with Mainwaring. "David's philosophy is that people should be comfortable taking risks," he says.

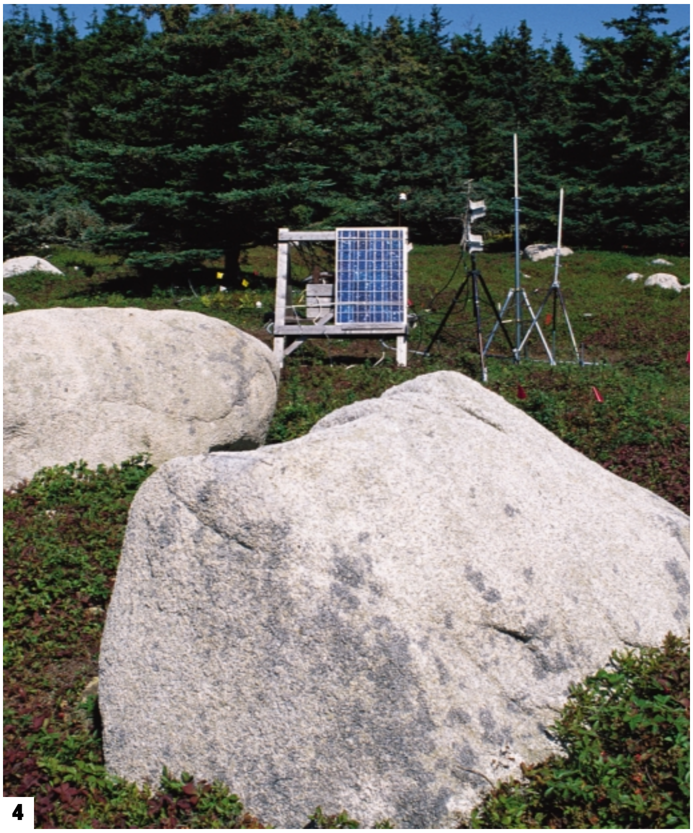
That first summer in 2002, Mainwaring and a couple of Berkeley students, Joseph Polastre and Robert Szewczyk, spent most of their time hammering out logistical problems with the motes and attendant equipment and seeing if the network would work at all.

Compared with Intel's penthouse digs overlooking the San Francisco Bay, Great Duck was short on creature comforts. The old lightkeeper's cottage, which doubles as computer lab and dormitory, has a thrift-store aesthetic: mismatched furniture, wood paneling, linoleum in the kitchen. An old Coast Guard tipsheet advises that in the event of a nuclear, biological, or chemical attack, occupants should "muster in the basement, provide coveralls, 4 rolls duct tape." Food, water, and fuel are all carted in from the mainland; you bathe in seawater or not at all. And when the wind kicks up, there's no way on or off the island.

For all that, the only real hardship, if you can call it that, may be having to tolerate other's foibles. "Why, oh, why is retro rock so popular with today's youth?" complains Anderson. "I retreat to the tower when I've heard too much of the worst of my childhood music." Still, he concedes, "life on the island isn't that bad—at least compared to my grad school days when I lived out of the back of a very small Toyota pickup in the Nevada desert."

Back in 2002, Mainwaring and company deployed 32 motes running an open-source operating system called TinyOS, both developed by Culler's group. The motes were built by Crossbow Technology Inc., in San Jose, Calif. In their first incarnation, each rectangular mote had a microcontroller, a low-power radio operating in the unlicensed ISM band, flash and RAM memory, and two AA batteries, plus sensors for temperature, humidity, baro-

PHOTOS: JOE DEVENNEY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Signals from both types of mote travel to a gateway mote's antenna [4] and then to the computer base station [5], located in the old lightkeeper's cottage[6]. From there, data travels by satellite over the Internet to the Intel Research Laboratory in Berkeley, Calif.

metric pressure, and ambient light. Some of the motes were buried in the walls of burrows; other motes for measuring the weather were placed just outside.

Every 70 seconds, each mote sampled its sensors, and when it had accumulated a 36-byte chunk of data, it sent the whole packet to a gateway mote, which relayed the data to a solar-powered computer base station, housed in the lightkeeper's cottage. Those readings in turn fed into a two-way satellite link that allowed researchers back in California to access the mote data over the Internet in real time. When the last mote shut down in October 2002, over a million readings had been logged.

The sensor network, in a word, worked.

THERE WERE BUMPS along the way, to be sure. "You try to anticipate all the contingencies. Then you head out to the field, and some of them never happen, and others happen you hadn't even thought of," Mainwaring says. Considerable thought went into how to keep the mote's electronics dry, for instance. It rains a lot on Duck Island, and then there's dew and flooding and dense fog with pH levels of less than 3 (the acidity of vinegar). Initially, the hardware designers thought the standard polymer coating sprayed on the mote's circuit boards would be sufficient. "But things started to rust, the sealant scratched off, and we started to get corrosion on the connectors," Mainwaring says.

They then tried encasing the mote in a waterproof acrylic housing, only to watch as the temperature sensor heated up from lack of ventilation. The acrylic also had a strong smell, which wouldn't have troubled most birds, but petrels have unusually good noses. The eventual solution was to take a cheap plastic rod and then have it milled and threaded, so it screwed together, with an O ring and marine adhesive to fill in the gaps. The occasional mote still got kicked out of the burrow or pecked apart by its occupants. Yet, given the alternative—"you stick your arm down until you feel feathers," says Anderson—the motes are clearly better.

Another surprise was the radio signals sent by the motes. Contrary to some predictions, the motes could reliably transmit from under the ground. What's more, in the open field, the signals traveled up to 10 times farther than they did back in the lab, a phenomenon Mainwaring attributes to the absence of interference out on the island.

Last summer, the sensor team rolled out a larger, second-generation network, consisting of 190 burrow and weather-station motes. The new cylindrical motes were a noticeable improvement over their predecessors; during the winter, Crossbow shrank the size by two-thirds simply by rearranging the components. In addition to the microprocessor and radio, these new motes had 4 kilobytes of RAM, 128 KB of internal flash memory, and 512 KB of external flash.

The network software was also enhanced to do multihop routing, so that each mote could not only send messages but also listen for and forward messages from its neighbors. [For a description of how wireless networks are being used for Internet access, see "Broadband A Go-Go," June 2003.] No longer constrained by the radio range of a single mote, the network could now extend more than 300 meters, allowing the researchers to deploy motes in three distinct microclimates where petrels tend to nest: near rocks, in open fields, and under trees.

Even now, power remains the motes' limiting factor. Their current operating mode is to spend 99 percent of their time asleep, waking up only to send messages and to listen for signals from other motes. TinyOS, which controls the radio, formats data from the sensors, and handles the routing, is also optimized for low-power operation. While the mote will draw 50 to 100 milliwatts to operate the CPU, radio, and sensors, its average power consumption is a mere 50 microwatts.

Apart from the motes, almost all the equipment is off-the-shelf. A pair of IBM ThinkPads sits in the lightkeeper's cottage, serving as the computer base stations. They communicate with each gateway mote via a directional antenna mounted to the side of the house. The equipment inside the house is plugged into a Web-controlled power strip so that each device can be turned on and off remotely.

It's worth mentioning that the entire project operates off the grid. The ThinkPads and other base station equipment are powered by photovoltaics; the motes and sensor networks run on small batteries. "Reliability, remote administration, and power management become issues at each layer of the system—for a mote, for the laptops, for the Internet gateways," says Mainwaring. "Although the computer science research focuses on the sensor networks, these classic engineering issues also arise when you deploy them in the real world."

THE PETREL PROJECT has generated an enormous database; how much of that will ultimately prove useful is yet to be determined. "The motes give us this fine-grained information, which we wouldn't be able to get in any other way," Anderson says. "Right now, I'm keen on oversampling, because I don't know yet what I want to look at." Though the birds would no doubt prefer to live unmonitored, it doesn't seem to be harming them. During the second summer, petrels returned to burrows that had been monitored the previous year.

Anderson has spent this past winter crunching numbers. "Some fun things are showing up, which are not totally unexpected, but it's still nice to get quantitative measurements. We can see, for instance, the enormous buffering effect of the burrow." Comparing readings from a pair of motes, one inside the burrow and one outside, reveals that even when the external temperature changes by 25 °C, the difference inside is less than 2 °C; likewise, the humidity outside can vary by 80 percent, but in the burrow's interior the change is just half a percent.

Bird-watchers know that petrels leave their egg unattended while they fly out to sea to forage. But for how long? And what happens to the egg while they're gone? By looking at spikes in the temperature data, Anderson can infer whether an adult is present or not, and he's also getting a clearer picture of the kind of environment the egg can withstand. Eventually he'd like to establish the specific sensor readings that correspond to specific states: "petrel in burrow," "egg unattended," "adult with chick," and so on. Ultimately, he hopes to answer questions like why the petrels prefer Great Duck to seemingly similar islands and why they nest in only a few select areas on the island.

CANDID CAMERA: To verify that the mote sensors are working correctly, researchers installed infrared video cameras above several burrows. The cameras yielded the first-ever images of nesting petrels, despite the near absence of ordinary light.

From Mainwaring's perspective, the experiment has really helped push both the hardware and the software of motes. From their lab in Berkeley, 5000 kilometers away, he and his colleagues could watch in real time as the network's communication layer adapted. "At any given time, there are a bunch of motes working, and some not working, and some resetting. It's in a state of flux," Mainwaring explains. When a mote crashed, they could see the signal get routed around to the closest healthy mote. And when a mote had a choice of two healthy neighbors, it shifted

"You try to anticipate all the contingencies. Then you head out to the field, and some of them never happen, and others happen you hadn't even thought of."

PHOTOS: JOE DEVENNEY


A TWO-HOUR CRUISE: Great Duck Island's rocky edge makes boat landings impossible. Instead, passengers are ferried to shore by rowboat, which then gets tugged uphill, roller coaster style, to the boathouse. When the wind kicks up, though, there's no good way on or off the island, and researchers can get stranded for days.

its signal to the more reliable one. They were also able to show that the sensor readings indicated the health of the mote. When the motes are wet, for example, their voltage tends to drop. So readings from the mote's humidity sensor can tell the mote whether to turn on.

With more motes deployed, the researchers were also able to verify the network's performance. In some burrows, they installed two motes and then compared the data to see if they matched (they did). In a few other burrows, they installed infrared video cameras, which yielded the first-ever footage of nesting petrels. When a mote showed that a bird was present, they could double-check that reading against the image coming from the infrared camera and then triple-check by playing a tape recording of a petrel's distinctive chuckle call at the burrow's entrance. If a petrel is present, it will invariably answer back, as if to say, "I'm home!"

The Intel team's goal is to develop a generic sensor-network-in-a-box, complete with motes and software, that any field researcher can easily deploy for virtually any type of habitat or environmental monitoring. To that end, this summer they're adding a new querying program called TinyDB to complement TinyOS; it will allow the network to be easily interrogated, much as you'd query a database.

"We'd like to get to the point where you can set out your motes, turn the switch on, and the network will organize itself and start collecting data," Mainwaring says. "It'll be a while before we're at the point where you can just drop it and it's 100 percent automated." It still takes about 5 minutes to position each mote inside a burrow—if you had a network of thousands, the time would become prohibitive. The price will also have to come down. The Crossbow motes used last summer go for US $250 a pop, plus the time needed to customize them. "Can you build a $15 mote?" Mainwaring asks. "We think the answer is yes. But we're not there yet."

Anderson, for his part, envisions all kinds of new sensor-based research he could do. "This technology will be incredibly interesting to the ecological community," he says.

He can't wait until the motes are small and lightweight enough to strap onto a petrel's back, complete with a Global Positioning System transceiver. That information would help complete the petrel picture, both on and off the island. For now, though, the Great Duck network will do. When the birds return from their winter homes in the South Atlantic, the motes will be waiting. ■

TO PROBE FURTHER

During the summer months, when the Great Duck Island motes are live, their sensor readings are continuously uploaded to the project's public Web site. For a more technical description of the first-generation network, see "Lessons from a Sensor Network Expedition," by Robert Szewczyk, Joseph Polastre, Alan Mainwaring, and David Culler. Both the sensor readings and the paper are available at http://www.greatduckisland.net.

For a general description of storm petrels, see Louis J. Halle's *The Storm Petrel and the Owl of Athena* (Princeton University Press, 1970).