Sizing Up the Mighty Mote

Jonathan W. Lowe

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Try this wild idea: What if every person on Earth simultaneously stopped whatever they were doing to step outside and see if it was raining? Then suppose they sent their observations and locations to a central GIS. Their collective input would light up the globe with a spatiotemporal map of rain or shine. If only people would cooperate this way, scientists could harvest a bumper crop of world environmental data.

People, however, are notoriously uncooperative, so scientists have kept this wild idea and replaced the humans with tiny sensors called motes. Carefully deployed at known locations, the motes become a networked observatory capable of detecting temperature, humidity, barometric pressure, vibrations, even bat calls. Details of such observatories' inner workings, their current uses, and their connection to our geospatial industry are the topics of this month's Net Results.

Unobtrusive Observatories

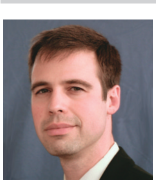
Most of us probably picture an observatory as a domed building perched on a mountaintop with a giant telescope peeking out at the starry night sky. To Paul Morin, a developer at University of Minnesota's department of Geology and Geophysics (www.geo.umn.edu) and the National Center for Earth-Surface Dynamics (NCED, www.nced.umn.edu), today's observatories are both larger — and smaller — than that. Morin defines an observatory as a stable set of sensors pulling in a large array of data. The sensors could be anywhere, not just on a mountaintop. The Neptune Project (www.neptune.washington.edu), for instance, uses a fiber-optic linked string of submersible sensors along a strip of ocean floor on the Juan de Fuca plate in the Northeast Pacific Ocean. The sensors track real-time geologic plate-scale movements, ocean currents, chemistry, and many other variables over the long term. Other modern-day observatories monitor dry land (such as the wireless sensor networks at Great Duck Island, Maine) or single structures (such as San Francisco's Golden Gate Bridge or Redwood trees in California's Sonoma County).

These unobtrusive observatories may cover large regions with widely distributed nodes, or they may be quite local and densely deployed. This latter approach characterizes the Golden Gate Bridge's experimental sensor network of approximately 200 devices, each containing an accelerometer that measures movement (such as the vibrations caused by wind, traffic, and earthquakes). By comparing readings from all the sensors, engineers can detect irregularities that signal structural weaknesses in need of repair.

One instance of a sparse regional wireless sensor network is the 32 devices on Great Duck Island, Maine that monitor temperature, humidity, barometric pressure, and mid-range infrared radiation both in and near Leach's Storm Petrel nesting burrows (www.greatduckisland.net). Because the devices are small and require no maintenance once deployed, scientists can monitor the birds' habitats without upsetting the sensitive inhabitants. Storm Petrels are an endangered species and tend to abandon their nests when disturbed, making motes one of the only possible non-disruptive Petrel monitoring strategies.

Whether a mote has a circular circuit board or a rectangular construction, it fits easily in the palm of your hand.

Different projects demand different observatory designs. The Neptune Project's sensors are submersible and wired whereas Great Duck Island's are wireless and either above ground or in burrows. Though the sensors may change to match project needs, development on wireless motes makes them a good commercial off-the-shelf choice for many outdoor projects. For instance, to the dismay of researchers, wired sensor networks are popular with rodents, such as squirrels that like to chew plastic wires. Wireless networks, on the other hand, have nothing narrow enough to chew through. Also, deploying the many wires of a large sensor network is not a scalable



Net Results columnist Jonathan W. Lowe covers the role of emerging technologies in the exchange of spatial information. Lowe is the owner of Local Knowledge Consulting (Berkeley, California), where he designs and implements spatial Web sites. He can be contacted at info@giswebsite.com.

endeavor: Imagine pushing through dense undergrowth to place a single sensor while trailing a tangle of wires through the brambles, then multiply that effort by the total number of sensors, potentially in the thousands. Deploying motes still requires the bushwhacking, but once you're through the brush, just place the mote and move on to the next drop point without dragging any wire in your wake. Adding to the inconvenience of deployment, the power and networking costs of large wired sensor networks may even exceed the cost of the sensors themselves. Because of these advantages, researchers can more easily expand wireless sensor networks than wired networks. Motes scale well.

Mighty Mote

Before explaining what motes are, it's worth knowing what they are not. Motes may be confused with "smart dust," a term coined by the U.S. Department of Defense to describe a much smaller sensor technology approximately the size of a ballpoint pen tip. Smart dust is intended to be randomly scattered from a plane or helicopter, maybe over enemy territory, and to report back enemy movements or environmental data. Each grain of smart dust provides the same single function dictated by its initial design over its entire working life.

Motes, on the other hand, are approximately the size of a silver dollar, or, with water-resistant casing included, somewhere between a golf ball and tennis ball in volume. Researchers typically place motes at known locations rather than scattering them randomly.

The core of a mote handles communications, data storage, and power management. Motes' sensors are modular — mote circuit boards have a set of basic environmental sensors plus open interfaces for additional sensors. So if a project demands accelerometers, or bat-detectors, for example, you can add them. Motes also have their own operating system that can be programmed to fit the task at hand, making them adaptable even after they've been deployed.

A mote's core capabilities are to store sensor data and to transmit them to a base station. Each mote has a microcontroller, memory, batteries, and a low-power radio which relays periodic sensor readings to neighboring motes. These neighbors pass the data to a base station's database via hops from neighbor to neighbor. Over time, even small networks of motes generate plenty of data — the 32 motes on Great Duck Island generated approximately 1.8 million readings in one seven-month period.

The greatest limiting factor for motes is power. Consequently, they are power misers by design. Motes "sleep" most of their lives, staying powered-off with only a clock and a few timers running. As their timers expire, motes spring into service, capture and store sensor data, then shut down again. Another timer controls a receiver, which periodically and briefly checks for incoming packets, powering down if there's nothing to send or receive. Motes handle several types of packets, including bundles of new program code that a user sends to change the behavior of the mote from afar. They have just enough power to communicate across 20-meter ranges, and can run from one week in continuous operation to 2 years with 1 percent duty cycling.

Operationally, motes take direction from a microcontroller that periodically polls the sensors for readings (such as temperature, ambient light, vibration, acceleration, air pressure) then processes the data and stores it in memory. At regular intervals, the microcontroller turns on the mote's receiver to see if any other devices are trying to communicate with it. Often in a sensor network, incoming communication includes messages from other motes being relayed to the base station. Or the messages may be entirely new programs sent by the base station. In response to these messages or in an attempt to relay its own data, the microcontroller activates its radio transmission hardware and contacts a neighboring mote in the network.

To merit the distinction of "self-configuring network," a group of motes must, upon activation, be able to find and remember their neighbors then develop routing tables to pass messages between themselves and the base station. If an existing route fails, impacted motes must wake up and reestablish a new route.

TinyOS, Big Challenge

The motes' microcontrollers are administered by TinyOS (webs.cs.berkeley.edu/tos), collaboratively designed by Intel (www.intel.com) and University of California, Berkeley (UCB, www.berkeley.edu). TinyOS is an open-source, stripped-down operating system built to run on 128 KB of memory. TinyOS developers face their greatest challenges in perfecting the capability of self-configuring networks and the subsequent bandwidth- and energy-efficient use of the network.

Like all of us, motes eventually break down or get confused. Malfunctioning motes may repeatedly try to send the same data to their neighbors without recognizing the successful completion of the message relay. Such bad motes quickly exhaust their power supply by trying too hard, and also run down unfortunate neighbors' batteries. TinyOS developers are trying to anticipate this sort of possibility and guard against it, writing procedures that recognize and disregard malfunctioning motes, for instance.

Mote hardware and software are still in development, so one can't just walk down to the store and order a wireless sensor network. And in practice, it still takes a seasoned TinyOS programmer to use motes effectively. To improve usability, Intel's Wei Hong is working on a TinyOS Application Sensor Kit (TASK), a turnkey application that allows scientists and non-programmers to install TinyOS on a desktop computer, configure the network, and view the output data in a table format (berkeley.intel-research.net/task).

For some researchers trying to interpret the data that their sensor networks capture, TASK's tabular view may be adequate. But what about projects that include both geographic and temporal components — motes are spatially aware, aren't they? There must be visualization tools capable of ingesting and displaying four-dimensional spatio–temporal data.

Four-Dimensional Sensor Maps

As shocking as this may sound to the geospatial community, even with motes' variety of sensors, they don't know their own locations. Because GPS receivers need enough strength to detect signals from distant satellites orbiting Earth, they use far too much power to survive the projected two years on a mote's meager battery supply. So researchers interested in tying sensor data to geographic locations must know in advance the coordinates of each sensor. This usually means capturing GPS coordinates with a location-aware device at each mote deployment point.

Since each mote in a network normally doesn't move once it's deployed, the resulting dataset is a fixed set of geographic points linked to numerous temporal sensor readings. Though mainstream GIS and CAD tools are quite sophisticated two- and three-dimensional (3D) respectively, there are few commercial software packages built specifically to ingest and display four-dimensional data (x, y, and z coordinates, as well as a timestamp).

At least that's what Morin encountered when initially researching his modern sensor network observatory ideas. Working in collaboration with Incorporated Research Institutions for Seismology (www.iris.edu), the Electronic Visualization Lab (www.evl.uic.edu), and the GeoWall Consortium (www.geowall.org), Morin's team has since produced a visualization system called the "GeoWall," which includes both software and display hardware such as dual projectors coupled with 3D viewing glasses. The GeoWall is a "system" rather than a product because it can be assembled from off-the-shelf components that include, minimally, a PC or Mac with a dual-head graphics card, two DLP projectors, polarizing filters with matching glasses, and a screen that preserves polarization. GeoWall's software components are open-source and freely available. The software visualizes the data and sends it to the dual projectors, but adds slight offsets to each projector's view, superimposing the offset images on one screen (see Figure 1). Viewed through 3D glasses used in theme parks or an IMAX theater, the projected image appears to have volume, depth, and motion. (As for compatibility with commercial GIS tools, ESRI users will be pleased to hear that ArcGIS 9 supports the GeoWall.)

Morin's group continues to expand GeoWall's base capabilities. The newest version, GeoWall II, "consists of 15 LCD panels tiled in a 5 × 3 array comprising a total resolution of 8,000 × 3,600 pixels. Each LCD panel is driven by a single PC with a high-end graphics card such as Nvidia's Quadro FX3000, at least 250 GB of disk space, 2.5-3GHz CPU, and Gigabit Ethernet networking" (see Figure 2). The GeoWall team is also exploring virtual reality environments by leveraging CAVE Technology (www.evl.uic.edu/pape/CAVE/prog/CAVEGuide.html), which Morin reports was the prototype for Star Trek's holodeck. CAVE projects stereoscopic computer graphics to virtual, collaborative, 3D visualization studios at 300 different sites around the world (see Figure 2). Participants at these sites don virtual reality gear, stand surrounded by screens, and navigate (virtually) a 3D rendering of a single time slice, or an animated view of data changing as time passes.

Though it's difficult to interpret as a static snapshot, Figure 3 illustrates a partial global view of North American earthquake hypocenter data as visualized by GeoWall. Atul Nayak, formerly a student at the Electronic Visualization Laboratory at the University of Illinois (www.evl.uic.edu), now a researcher at Scripps Institution of Oceanography (http://sio.ucsd.edu), wrote the program Wiggleview www.evl.uic.edu/cavern/agave/wiggleview/), which tackles the challenge of visualizing four-dimensional seismic data. Clearly, this is a specialized application in a single field. Other researchers, however, are also at work to map sensor network data, such as Great Duck Island's, in the GeoWall environment.

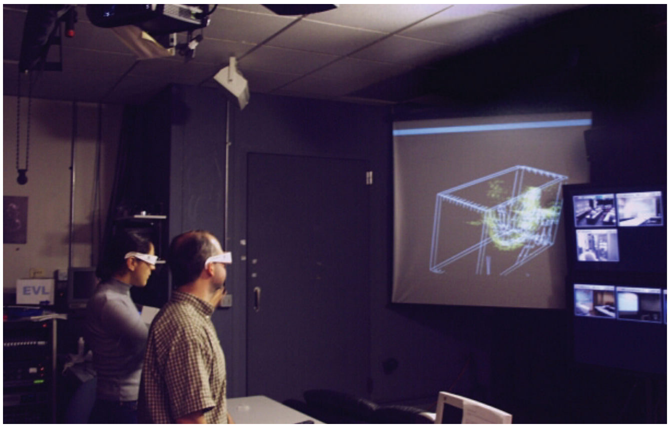


FIGURE 1 Wearing 3D glasses, two researchers view a GeoWall display in the Electronic Visualization Lab at the University of Illinois at Chicago, the dual projectors directly overhead.

FIGURE 2 GeoWall II's 15-panel display contains 25 million pixels and, like the original GeoWall, supports stereoscopic visualization.

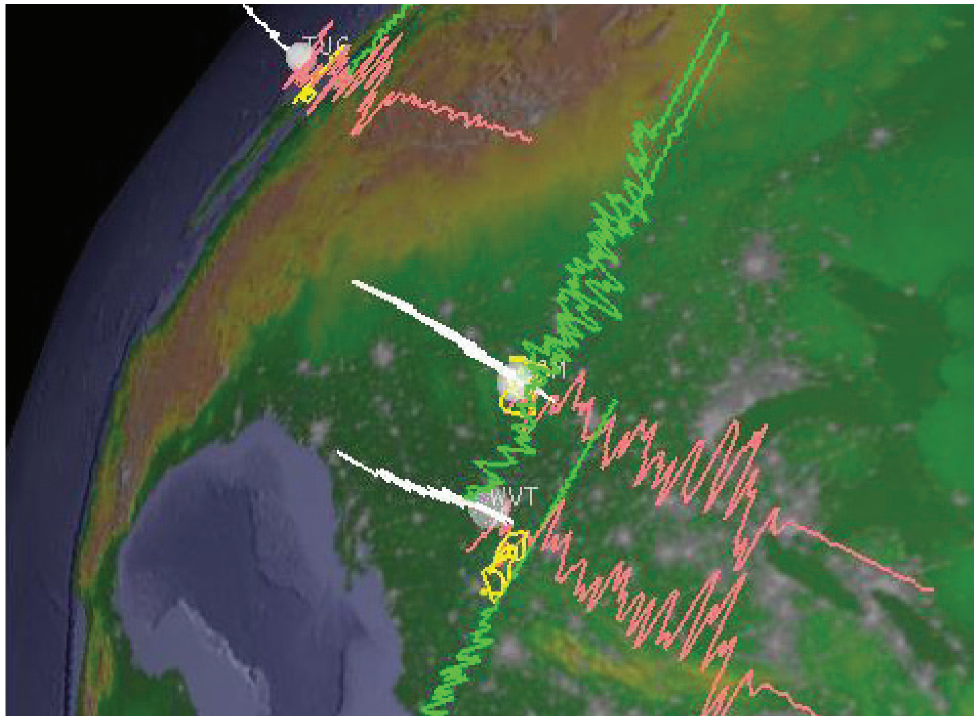


FIGURE 3 A static snapshot of seismic data displayed in WiggleView illustrates the need for dynamic multi-dimensional visualization tools — without them it's hard to tell the behind from the beyond from the between.

Sensor Friends

Bringing together specialized hardware, software, and people is no small challenge, as illustrated by the lethargic progress of the GPS-enabled cell phones and the location-based services industry. Motes have matured fairly rapidly in comparison. What's their secret?

The combination of hardware, software, and customized data-collection processes is the result of an unusually successful partnership between a private corporation (Intel) and four public universities, including UCB. Intel builds the hardware, UCB develops the operating system (called TinyOS), and any interested third parties use both to deploy customized wireless sensor networks — the observatories.

Berkeley's Intel Lab mission statement conveys Intel's eagerness to push the technical envelope: "The focus of the Intel Research laboratory at Berkeley is to invent, develop, explore, and analyze highly interconnected systems at the extremes of the computing and networking spectrum — the very large, the very small, and the very numerous. Extreme systems are likely to spur wholly new kinds of applications, demand new technology, require novel design approaches, and present previously unseen phenomena. Opportunities arise not only from size and number, but because these systems are increasingly interconnected."

Working closely with academic researchers, the Intel Research laboratory at Berkeley performs leading-edge computer science on problems of scale, cutting across traditional areas of architecture, operating systems, networks, and languages to enable a wide range of explorations in ubiquitous computing, both embedded in the environment or carried easily on moving objects and people.

According to UCB GIS Informatics Researcher Collin Bode, Intel Lab's description of the partnership — "working closely" — is an accurate characterization. More often than not, such private-public partnerships are problematic because the different members have fundamentally conflicting goals. The private entities are involved to bring innovative products to market as rapidly as possible and to protect any intellectual capital the partnerships generate. University researchers want funding and the ability to advance their careers by publishing their findings. Third-party customizers just want easily modifiable tools or nimble technical support. Intel seems to have recognized that corporate protection of intellectual property and academic desire to publish widely would mix about as well as oil and water. To walk away from the academic community, however, would mean slower or more expensive software development. So, to their credit, unlike some of their predecessors in the biotech industry, Intel solved the private–public partnership problem with a smart business plan.

Before ever engaging with the academic community, Intel decided that their source of profit from motes would be the hardware alone. The operating system would be the responsibility of the academic community and would be completely open-source. This way, academics could freely publish their work on the TinyOS without challenging a corporate stricture against release of intellectual property. Likewise, customization vendors could make direct (even extreme) modifications to motes without having to badger a proprietary software vendor. And the typical widespread adoption of open-source software would carry Intel's hardware along with it. Hardware sales, high-quality operating system, published research, and plenty of custom offerings — everybody wins.

Today Ecology, Tomorrow the World

According to Bode, the discipline of ecology has struggled to capture local microclimatic data from multiple sample points simultaneously, especially for regional-scale study areas. "Motes don't just improve an existing capability, they introduce an entirely new one," he explains. In one day, a researcher can deploy a mote field observatory that will generate two years' worth of exactly the sort of consistent and synchronized data ecologists need, but without an army of field workers. In Bode's opinion, "Wireless sensor networks could do for ecology what automatic gene sequencers did for biology." So, if there's an observatory in your future, or just an interest in advancing the science of ecology, the time may be ripe for a closer look at motes. ⊕