How Motes Work

by Marshall Brain

Introduction to How Motes Work

Over the last year or so you may have heard about a new computing concept known as **motes**. This concept is also called **smart dust** and **wireless sensing networks**. It seems like just about every issue of *Popular Science*, *Discover* and *Wired* today contains a blurb about some new application of the mote idea. For example, the military plans to use them to gather information on battlefields, and engineers plan to mix them into concrete and use them to internally monitor the health of buildings and bridges.

Photo courtesy Crossbow Technology, Inc.
The MICA2 Mote uses 2 AA batteries to provide power to the CPU/radio for up to a year.

There are thousands of different ways that motes might be used, and as people get familiar with the concept they come up with even more. It is a completely new paradigm for distributed sensing and it is opening up a fascinating new way to look at computers.

In this article, you will have a chance to understand how motes work and see many of the possible applications of the technology. Then we will look at a **MICA mote** -- an existing technology that you can buy to experiment with this unique way of sensing the world.

The Basic Idea

The "mote" concept creates a new way of thinking about computers, but the basic idea is pretty simple:

- The core of a mote is a small, low-cost, low-power **computer**.
- The computer monitors one or more **sensors**. It is easy to imagine all sorts of sensors, including sensors for temperature, light, sound, position, acceleration, vibration, stress, weight, pressure, humidity, etc. Not all mote applications require sensors, but sensing applications are very common.
- The computer connects to the outside world with a **radio link**. The most common radio links allow a mote to transmit at a distance of something like 10 to 200 feet (3 to 61 meters). Power consumption, size and cost are the barriers to longer distances. Since a fundamental concept with motes is tiny size (and associated tiny cost), small and low-power radios are normal.

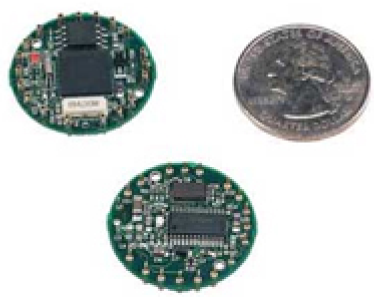


Photo courtesy Crossbow Technology, Inc.
The MICA2DOT mote, typically powered by a circular "button"

Motes can either run off of batteries, or they can tap into the power grid in certain applications. As motes shrink in size and power consumption, it is possible to imagine solar power or even something exotic like **vibration power** to keep them running.

battery, is not much bigger than a quarter.

All of these parts are packaged together in the smallest container possible. In the future, people imagine shrinking motes to fit into something just a few millimeters on a side. It is more common for motes today, including batteries and antenna, to be the size of a stack of five or six quarters, or the size of a pack of cigarettes. The battery is usually the biggest part of the package right now. Current motes, in bulk, might cost something on the order of $25, but prices are falling.

It is hard to imagine something as small and innocuous as a mote sparking a revolution, but that's exactly what they have done. We'll look at a number of possible applications in the next section.

Typical Applications

If you survey the literature for different ways that people have thought of to use motes, you find a huge assortment of ideas. Here's a collection culled from the links at the end of the article.

It is possible to think of motes as lone sensors. For example:

- You could embed motes in bridges when you pour the concrete. The mote could have a sensor on it that can detect the salt concentration within the concrete. Then once a month you could drive a truck over the bridge that sends a powerful magnetic field into the bridge. The magnetic field would allow the motes, which are burried within the concrete of the bridge, to power on and transmit the salt concentration. Salt (perhaps from deicing or ocean spray) weakens concrete and corrodes the steel rebar that strengthens the concrete. Salt sensors would let bridge maintenance personnel gauge how much damage salt is doing. Other possible sensors embedded into the concrete of a bridge might detect vibration, stress, temperature swings, cracking, etc., all of which would help maintenance personnel spot problems long before they become critical.
- You could connect sensors to a mote that can monitor the condition of machinery -- temperature, number of revolutions, oil level, etc. and log it in the mote's memory. Then, when a truck drives by, the mote could transmit all the logged data. This would allow detailed maintenance records to be kept on machinery (for example, in an oil field), without maintenance personnel having to go measure all of those parameters themselves.
- You could attach motes to the water meters or power meters in a neighborhood. The motes would log power and water consumption for a customer. When a truck drives by, the motes get a signal from the truck and they send their data. This would allow a person to read all the meters in a neighborhood very easily, simply by driving down the street.

All of these ideas are good; some allow sensors to move into places where they have not been before (such as embedded in concrete) and others reduce the time needed to read sensors individually.

However, much of the greatest excitement about motes comes from the idea of using large numbers of motes that communicate with **each other** and form **ad hoc networks**.

Ad hoc Networks

The Defense Advanced Research Projects Agency (DARPA) was among the original patrons of the mote idea. One of the initial mote ideas implemented for DARPA allows motes to sense battlefield conditions.

For example, imagine that a commander wants to be able to detect truck movement in a remote area. An airplane flies over the area and scatters thousands of motes, each one equipped with a magnetometer, a vibration sensor and a GPS receiver. The battery-operated motes are dropped at a density of one every 100 feet (30 meters) or so. Each mote wakes up, senses its position and then sends out a radio signal to find its neighbors.

All of the motes in the area create a giant, amorphous network that can collect data. Data funnels through the network and arrives at a collection node, which has a powerful radio able to transmit a signal many miles. When an enemy truck drives through the area, the motes that detect it transmit their location and their sensor readings. Neighboring motes pick up the transmissions and forward them to their neighbors and so on, until the signals arrive at the collection node and are transmitted to the commander. The commander can now display the data on a screen and see, in real time, the path that the truck is following through the field of motes. Then a **remotely-piloted vehicle** can fly over the truck, make sure it belongs to the enemy and drop a bomb to destroy it.

This might seem like an awful lot of trouble to go to, until you realize the system that these motes replace. In the past, the tool a commander used to prevent truck or troop movement through a remote area has been land mines. Soldiers would lace the area with thousands of anti-truck or anti-personnel mines. Anyone moving through the area -- friend or foe -- is blown up. Another problem, of course, is that long after the conflict is over the mines are still active and deadly -- laying in wait to claim the limbs and even lives of any passerby. According to this UNICEF report, over the last 30 years, landmines have killed or maimed more than 1 million people -- many of whom are children. With motes, what is left behind after a war are tiny, completely harmless sensors. Since motes consume so little power, the batteries would last a year or two. Then, the motes would simply go silent presenting no physical threat to civilians nearby.

This concept of ad hoc networks -- formed by hundreds or thousands of motes that communicate with each other and pass data along from one to another -- is extremely powerful. Here are several examples of the concept at work:

- Imagine a suburban neighborhood or an apartment complex with motes that monitor the water and power meters (as described in the previous section). Since all of the meters (and motes) in a typical neighborhood are within 100 feet (30 meters) of each other, the attached motes could form an ad hoc network amongst themselves. At one end of the neighborhood is a super-mote with a network connection or a cell-phone link. In this imagined neighborhood, someone doesn't have to drive a truck through the neighborhood each month to read the individual water or power meters -- the motes pass the data along from one to another, and the super-mote transmits it. Measurement can occur hourly or daily if desired.
- A farmer, vineyard owner, or ecologist could equip motes with sensors that detect temperature, humidity, etc., making each mote a mini weather station. Scattered throughout a field, vineyard or forest, these motes would allow the tracking of micro-climates.
- A building manager could attach motes to every electrical wire throughout an office building. These motes would have induction sensors to detect power consumption on that individual wire and let the building manager see power consumption down to the individual outlet. If power consumption in the building seems high, the building manager can track it to an individual tenant. Although this would be possible to do with wires, with motes it would be far less expensive.

- A biologist could equip an endangered animal with a collar containing a mote that senses position, temperature, etc. As the animal moves around, the mote collects and stores data from the sensors. In the animal's environment, the biologists could place zones or strips with data collection motes. When the animal wanders into one of these zones, the mote in the collar would dump its data to the ad hoc network in the zone, which would then transmit it to the biologist.
- Motes placed every 100 feet on a highway and equipped with sensors to detect traffic flow could help police recognize where an accident has stopped traffic. Because no wires are needed, the cost of installation would be relatively low.

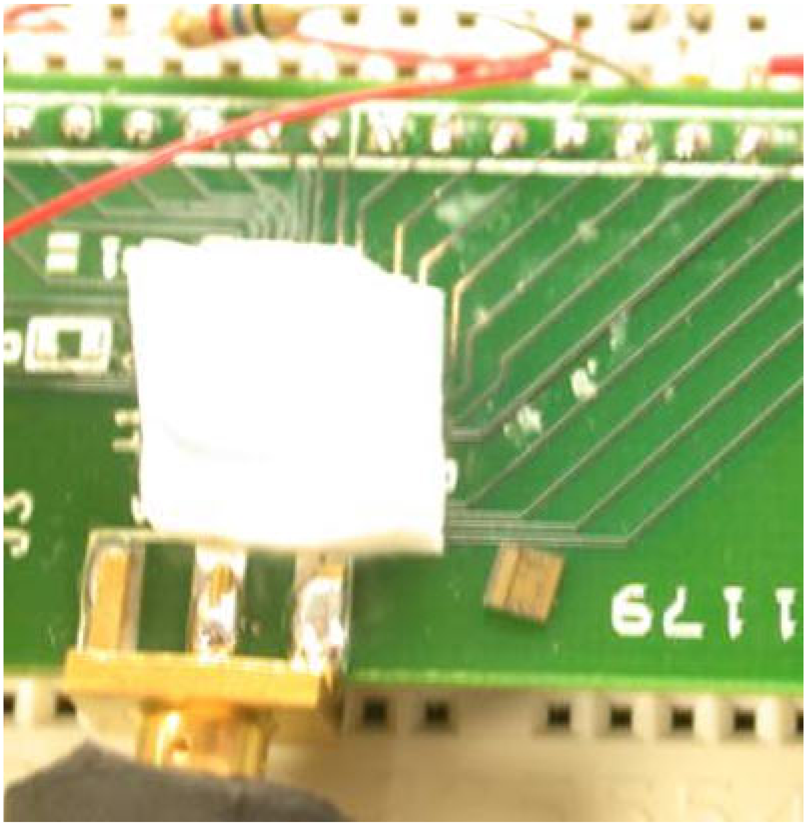


Photo courtesy JLH Labs

"Spec," a single-chip mote (hiding under the white wax square), measures approximately 2mm x 2.5mm, has an AVR-like RISC core, 3K of memory, an 8-bit, on-chip ADC, an FSK radio transmitter, a Paged memory system, communication protocol accelerators, register windows, and much, much more.

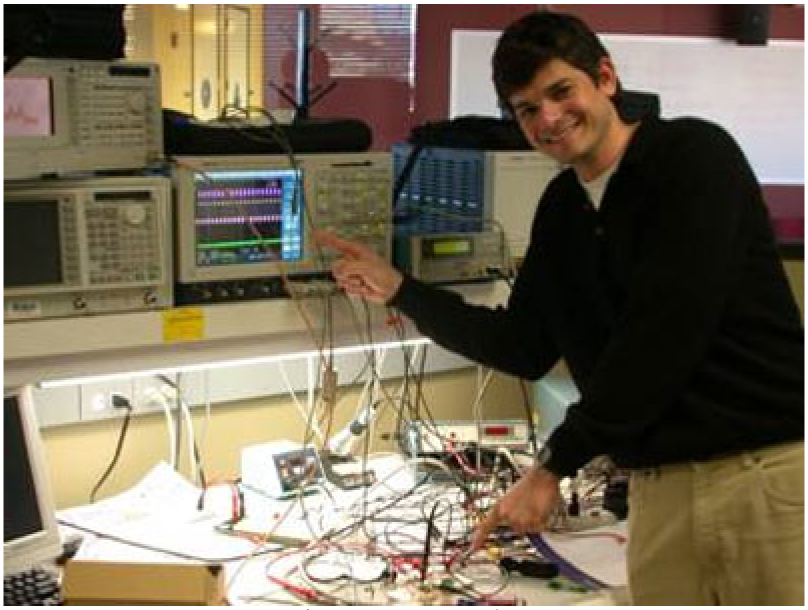


Photo courtesy JLH Labs
The work bench used to bring Spec (pictured above) alive.

A Typical Mote

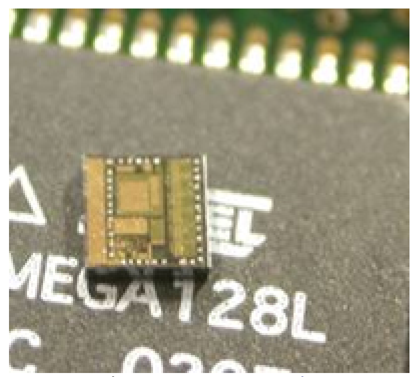


Photo courtesy JLH Labs
"Spec" sitting on top of the previous generation of UC Berkeley Motes, the Mica node. The size reduction is amazing.

MICA mote is a commercially available product that has been used widely by researchers and developers. It has all of the typical features of a mote and therefore can help you understand what this technology makes possible today. MICA motes are available to the general public through a company called Crossbow. These motes come in two form factors:

- Rectangular, measuring 2.25 x 1.25 by 0.25 inches (5.7 x 3.18 x.64 centimeters), it is sized to fit on top of two AA batteries that provide it with power.
- Circular, measuring 1.0 by 0.25 inches (2.5 x .64 centimeters), it is sized to fit on top of a 3 volt button cell battery.

The MICA mote uses an Atmel ATmega 128L processor running at 4 megahertz. The 128L is an 8-bit microcontroller that has 128 kilobytes of onboard flash memory to store the mote's program. This CPU is about as powerful as the 8088 CPU found in the original IBM PC (circa 1982). The big difference is that the ATmega consumes only 8 milliamps when it is running, and only 15 microamps in sleep mode.

This low power consumption allows a MICA mote to run for more than a year with two AA batteries. A typical AA battery can produce about 1,000 milliamp-hours. At 8 milliamps, the ATmega would operate for about 120 hours if it operated constantly. However, the programmer will typically write his/her code so that the CPU is asleep much of the time, allowing it to extend battery life considerably. For example, the mote might sleep for 10 seconds, wake up and check status for a few microseconds, and then go back to sleep.

Photo courtesy JLH Labs

Broad view of "Spec" sitting on top of the previous generation of UC Berkeley Motes, the Mica node. "Spec" is the tiny little square on top of the raised bit in the middle.

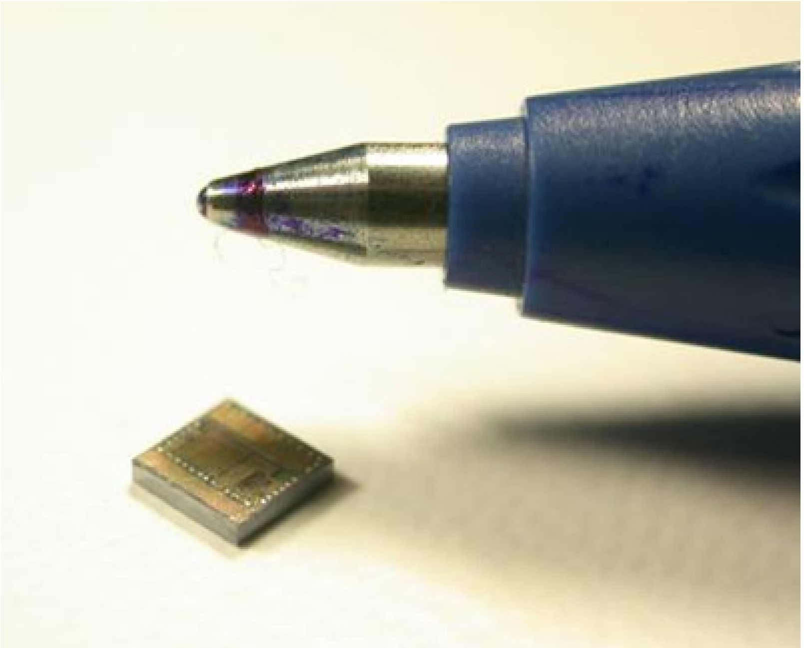
MICA motes come with 512 kilobytes of flash memory to hold data. They also have a 10-bit A/D converter so that sensor data can be digitized. Separate sensors on a daughter card can connect to the mote. Sensors available include temperature, acceleration, light, sound and magnetic. Advanced sensors for things like GPS signals are under development.

The final component of a MICA mote is the radio. It has a range of several hundred feet and can transmit approximately 40,000 bits per second. When it is off, the radio consumes less than one microamp. When receiving data, it consumes 10 milliamps. When transmitting, it consumes 25 milliamps. Conserving radio power is key to long battery life.

All of these hardware components together create a MICA mote. A programmer writes software to control the mote and make it perform a certain way. Software on MICA motes is built on an operating system called TinyOS. TinyOS is helpful because it deals with the radio and power management systems for you and makes it much easier to write software for the mote.

The Future

In March, 2003, researchers managed to cram all of the parts needed for a mote onto a single chip less than 3 millimeters on each side. The total size is about 5 square millimeters, meaning that you could fit more than a dozen of these chips onto a penny.



"Spec" pictured beside the tip of a ballpoint pen.

The chip contains all of the components found in a mote: a CPU, memory, an A/D converter for reading sensor data and a radio transmitter. To complete the package you attach the sensor(s), a battery and an antenna. The cost of the chip will be less than a dollar when it is mass produced. See this page for details.

For more information on motes, their applications and related topics, check out the links on the next page.

Lots More Information

Related HowStuffWorks Articles

- How Operating Systems Work
- How Computer Memory Works
- How Flash Memory Works
- How RAM Works
- How ROM Works
- How Virtual Memory Works
- How Bits and Bytes Work
- How Microprocessors Work
- How Microcontrollers Work
- How Radio Works

More Great Links

- Dust Keeping the Lights Off
- MICA, MICA2 Motes & Sensors
- NEST Projects at Berkely
- Getting up and running with TinyOS
- ATMega 128 data sheet
- Berkley Wireless Embedded Systems links

- Building Self-Organizing Sensor Networks with Reconfigurable Smart Components
- Wireless ad hoc networks
- Large-Scale Demonstration of Self-Organizing Wireless Sensor Networks
- Crossbow Technology, Inc.

Applications

- Making Wines Finer with Wireless
- Smart buildings Admit their Faults
- RoboMote
- Brainy Buildings Conserve Energy
- DARPA SensIT demo
- Tracking vehicles with a UAV-delivered sensor network
- Plant Care
- Traffic Pulse(r) Technology
- Condition-based monitoring of machinery
- Military Surveillance