how it works

IN A PACKAGE NO BIGGER THAN A GRAIN OF SAND, NEW SMART-DUST CIRCUITS COMBINE SENSING, COMPUTING, AND COMMUNICATIONS FUNCTIONS.

Smart-dust designers deliver dirt-cheap chips

By Warren Webb, Technical Editor

Imagine fully functional sensor circuits so small and inexpensive that you could afford to scatter thousands into an area of interest to sense local conditions or to detect the presence and movement of chemicals, vehicles, or even humans. These small circuits, collectively referred to as smart dust, are part of a new vision of tiny elements that combine sensing, computing, and communications. Although today's technology has not yet reached dust-particle size, several design teams, including the military, are working hard to perfect the concept and decrease the size. Some of their long-term dreams include intravenous circuits that seek out and attack cancer cells and networked sensors that are dropped from an airplane and then report troop and vehicle locations in a battlefield situation.

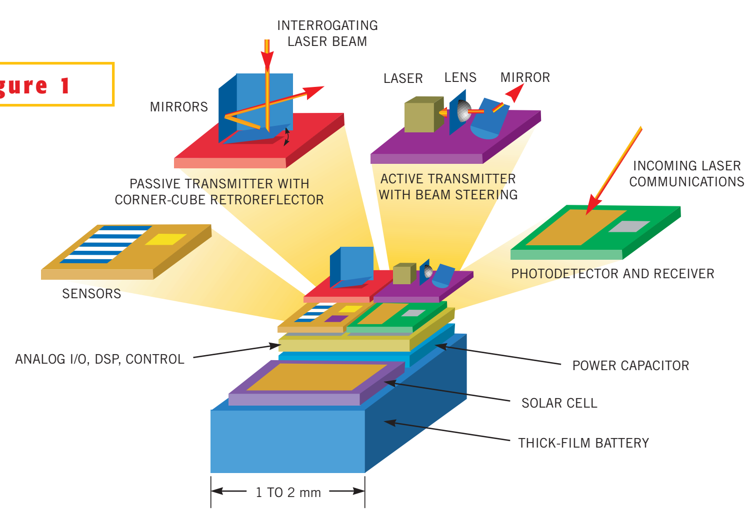
The initial smart-dust concept has been credited to researchers at the University of California—Berkeley (www.berkeley.edu). Their idea was to miniaturize conventional sensors and unite them with wireless-communications technology to form dynamic, self-organizing network devices that can deliver a stream of data from each of the sensors. Combining the data from individual sensors produces a big-picture view of the environment. Recognizing the military potential, DARPA (www.darpa.mil) funded the university and other researchers to advance the smart-dust concept with both hardware and software projects.

The objective of smart-dust devices, or motes, as they have been aptly nicknamed, is to integrate the sensor, power-supply, computing, and communications functions into a single silicon platform that can collect, analyze, and store data and then create an intelligent response. Sensors may include one or more temperature, pressure, vibration, acceleration, light, magnetic, or acoustic devices. Some of the more sophisticated sensors also include the ability to perform chemical analysis to identify airborne or liquid substances.

As the mote collects sensor-data samples, it could simply return the raw data for analysis elsewhere; however, such activity would imply a reliable and persistent communications channel, which may be unavailable. Therefore, the typical smart-dust platform includes a processor section for data analysis and storage. Along with the processor, the system needs operating software, sample-storage space, and a power supply. Obviously, a power supply in a device as small as a mote requires some serious trade-offs. Mote designers have investigated special batteries, including capacitive-charge storage, solar cells, and even isotopes, with varying success, depending on the size and expected life of the device. For example, researchers at Cornell University have created a cubic-millimeter-sized battery that can supply power for decades by drawing energy from radioactive isotopes, such as nickel-63. Power conservation is also a primary requirement in smart-dust devices and generally includes hardware or software features that suspend operation between samples and communications functions.

Data collection is worthless unless the system includes a reliable method for transmitting information back to the user. Motes use a variety of technologies, including radio frequencies, modulated light, MEMS (microelectromechanical-systems) movement, physical orientation, and color shifts to communicate their data. In addition to

Figure 1

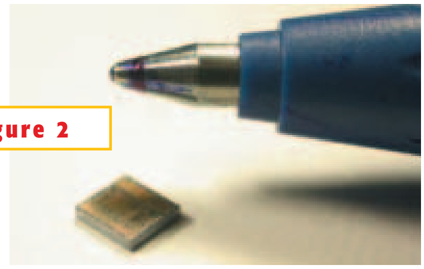


Smart-dust motes include sensing, computing, power, and communications sections. This proposed system uses optics and MEMS for communications.

their basic functions, smart-dust devices perform auxiliary duties, such as relaying information from nearby motes to decrease individual transmitter power requirements.

Figure 1 shows the original goal of the Berkeley smart-dust researchers, although they have not yet realized it in this form. The mote includes sensing, computing, power, and communications sections. In operation, the device periodically takes a reading from the sensors, filters the data, and stores the sample in memory. The system also checks the optical receiver for incoming messages that may contain new instructions or responses from previous transmissions. Based on any number of parameters, such as sample-data variations, remaining battery life, timer expiration, or remote queries, the mote transmits a message containing an identifier and the most recent sample data. Although the **figure** illustrates two types of optical MEMS transmitters, a typical application would need only one. The active transmitter uses a laser diode with beam steering to create a modulated optical source. To conserve power, the researchers also proposed a corner-cube retroreflector with three mutually perpendicular faces that you can query with a remote laser beam. Light entering a retroreflector is reflected back 180° and parallel to the original beam, regardless of its orientation to the beam. The base of the retroreflector is a MEMS flap that modulates the reflected beam.

Figure 2



Requiring only five external components, the 2×2.5-mm spec platform includes RF communications and computing functions in a single chip.

Mote designers have also incorporated RF-communications techniques into their devices. For example, mesh networks are ideal for randomly spaced smart-dust motes. Mesh networks process messages by passing packets from node to node until they reach their destination. A mesh network provides redundant paths from source to destination and automatically reroutes packets through an alternate path in case of a hardware failure or interference. Because each node requires only enough transmitted power to reach neighboring nodes, mesh networks offer substantially lower power requirements than traditional point-to-point wireless communications. In one demonstration of networking capabilities, researchers dropped a group of magnetic sensor motes along a road from an unmanned drone aircraft. The motes assembled themselves into a mesh network and began collecting magnetic information. The unmanned drone circled overhead to receive data, and researchers were able to remotely determine the speed and direction of passing vehicles.

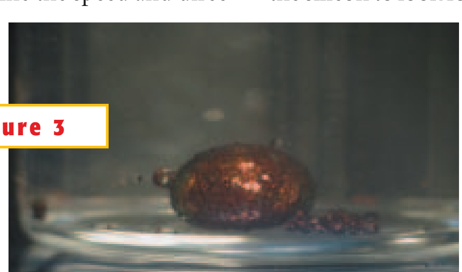
To foster participation from a variety of vendors, researchers have placed much of the smart-dust technology into the public domain. For example, Crossbow Technology (www.xbow.com), with investments from Intel (www.intel.com), works with the University of California—Berkeley and offers a family of motes and development tools for smart-dust experimentation and development. Users can select vibration, acoustic, magnetic, light, temperature, or proximity-sensor modules and easily integrate them with an RF-communications and processor module for a complete mote. Crossbow offers development kits starting at $895 that include multiple mote modules with several sensor options. The vendor also periodically offers smart-dust training seminars.

Berkeley researchers also attacked the software limitations of a resource-constrained sensor network with the open-source TinyOS operating system. Applicable to both RF- and MEMS-communications technologies, TinyOS delivers real-time scheduling and extreme power-conservation algorithms in addition to bidirectional communications. With a memory footprint of less than 4 kbytes and open-source code, TinyOS is popular among mote developers. You can download the latest version of TinyOS at http://webs.cs.berkeley.edu/tos. A companion TinyDB project offers a query processing system for extracting information from a network of TinyOS sensors.

Berkeley developers recently tested a single-chip version of the Berkeley mote, nicknamed "spec." The 2×2.5-mm chip includes a RISC core, 3 kbytes of memory, an 8-bit ADC, a radio transmitter, an RS-232-compatible UART, and 4-bit I/O ports (**Figure 2**). The team demonstrated reliable communications over a range of more than 40 ft at a data rate of 19,200 kbps. The chip requires only five external components: a 4-MHz oscillator, a 15-nH inductor, a 32-kHz crystal, a power source, and an antenna. With production costs of less than 50 cents, the chip is a major step toward the smart-dust vision.

In a completely different, nonelectronic approach, chemists at the University of California—San Diego (www.ucsd.edu) have developed tiny silicon chips that can detect and stick to a target substance. The silicon is etched to create a porous surface of unique color and then chemically modified for the specific target substance. If each side of the silicon is etched and modified to locate a different substance and then broken into flakes no bigger than a human hair, you can use the smart-dust particles to find the interface between the two substances. As many particles line up on the surface of the target for which they were programmed, the apparent color shows the direction that the particles are facing. In a demonstration, the researchers modified the silicon to look for the interface between a drop of oil and water (**Figure 3**). Researchers hope to apply the same technology to locate and treat pollution particles and cancer cells.

Figure 3



Chemists at the University of California–San Diego modified silicon to look for the interface between a drop of oil and water.

As with many new technologies, smart dust raises the issue of privacy. Governments, law enforcement, insurance companies, suspicious spouses, and others could sprinkle a few smart-dust motes on your person or vehicle and easily track your location, clock your rate of movement, detect the substances that you come in contact with, and record your conversations. Be warned.□