Research at Intel

Instrumenting the World

An Introduction to Wireless Sensor Networks

Introduction

On an uninhabited island off the coast of Maine, tiny wireless sensors deep in the burrows of mysterious sea birds monitor the environmental factors affecting the shy creatures' comings and goings. In one of Intel's chip fabrication facilities, similar sensors measure the subtle vibrations of various machines to detect malfunctions before the equipment breaks down. At an Air Force base across the country, dozens of small sensors scattered across a bogus battlefield outperform tripwires, without the wires. Meanwhile, at the University of California at Berkeley, sensors embedded in a mock building's walls diagnose its seismic stability after a simulated earthquake.

Experimental sensor networks like these are opening up new vistas for scientists and engineers to observe physical phenomena and react to it. The building blocks of these wireless networks are "motes," self-contained, battery-powered computers that measure light, temperature, humidity, and other environmental factors. Developed by Intel Research in collaboration with the University of California at Berkeley-based Center for Information Technology Research in the Interest of Society (CITRIS), the motes self-organize into ad-hoc wireless networks. The data is then relayed from mote to neighboring mote until it reaches its desired destination for processing.

Sensor networks are a giant leap toward "proactive computing," a paradigm where computers anticipate human needs and, if necessary, act on our behalf. Instead of shuttling data between the real world and machines, the human is at the top, reaping the benefits of ubiquitous computers. Sensor networks and proactive computing has the potential to improve our productivity and enhance safety, awareness, and efficiency at the societal scale.

There are many technological hurdles that must be overcome for ad hoc sensor networks to become practical though. Nearly everything we take for granted in desktop computing is at a premium in wireless sensor networks. The individual motes are incredibly resource constrained. They have limited processing speed, storage capacity, and communication bandwidth. Their lifetime is determined by their ability to conserve power. All of these constraints require new hardware designs, software applications, and network architectures that maximize the motes' capabilities while keeping them inexpensive to deploy and maintain. Additionally, it must be easy for non-computer scientists with just basic training in the technology to extract meaningful real world data from the networks. Finally, pervasive sensor networks raise non-trivial security and privacy issues that call for collaboration between engineers, social scientists, legislators, and policymakers.

Intel Research, working with the academic community and industry, is addressing many of these significant challenges. Already, a broad spectrum of sensor network pilot applications have been demonstrated--from smart home systems that improve the quality of life for the elderly, to sensors that measure the structural health of the Golden Gate Bridge. And this is just the beginning. As sensor network technology emerges from research laboratories, the ability to instrument the world is likely to transform every facet of our lives.

The Path Toward Proactive Computing

In today's model of computing, we interact directly, one-on-one, with our desktop PCs, mobile phones, and personal digital assistants. In the near future though, the majority of computers will be embedded deep in the world around us, hidden inside our homes, roads, farms, hospitals, and factories. When we are in control of hundreds or thousands of computers each, it will be impossible for us to interact directly with each one. The time has come to transition from interactive to proactive computing. These proactive computers will anticipate our needs and sometimes act on our behalf. Sensor networks represent this paradigm shift in computing.

On a farm, sensors buried in the soil could help manage irrigation and fertilization. Smart smoke detectors will guide firefighters through a building to trapped victims. Motes in your home could monitor temperature and energy use to automatically create comfortable microclimates while cutting your utility bill.

Of course, sensing and measuring itself is not new. Engineers have been developing increasingly versatile and sensitive sensors for many years. Traditionally, the cost and bulk of sensing technology meant that only a handful of sensors could be deployed for most applications. However, data averaged from a few sensors does not truly represent the real world. How can computers anticipate our needs if they can't understand our environment? Now, thousands of sensors can be scattered throughout a single physical space, providing a much higher resolution picture of the real world than ever before. This entirely new approach to instrumentation is made possible by the intersection of several technological trends.

According to Moore's Law, the number of transistors on a microchip doubles approximately every two years, leading to faster and more powerful computers on our desktops with each generation. At the same time, microprocessors with a given computing capacity are becoming smaller and cheaper with every passing year. While silicon scaling marches on, the same semiconductor manufacturing processes are being utilized to build microscopic mechanical structures that interact with the physical world. This technology, called MEMS (microelectromechanical systems), enables the production of velocity sensors, thermometers, and even low-power radio components that fit on the head of a pin and cost just pennies each. These three hardware ingredients--microprocessors, MEMS sensors, and low-power radios--make up a sensor node, or "mote." The "mote" nickname comes from UC Berkeley's Smart Dust project, an effort funded by the Defense Advanced Research Projects Agency's (DARPA) Network Embedded Software Technology (NEST) program to shrink the devices down to dust mote size through the power of Moore's Law.

While the motes' low cost and small size are clearly desirable traits, they're not sufficient on their own to open up a wide spectrum of new sensor applications. Rather, it is the motes' ad-hoc, multi-hop networking capabilities that make it possible to deploy larger networks of these devices than ever before. This provides sensing closer to the physical phenomena and with a higher granularity than previously possible. Additionally, novel software enables the raw data collected by the sensors to be analyzed in various ways before it even leaves the network. After all, humans want information from their proactive computers, not numbers.

A New Kind of Instrument

Applying advanced networking technology to mass-produced wireless sensors yields a new kind of "instrument." The network literally becomes the sensor.

Researchers in academia and industry have already deployed dozens of sensor network pilot applications. The following is just a small sampling of those diverse projects:

- A robust sensor network on Great Duck Island off the coast of Maine aids biologists in the study of Leach's storm petrels, a species of seabird that have mysteriously selected this locale as their breeding ground. (Intel Research/UC Berkeley)
- As part of the DARPA NEST program, researchers demonstrated a sensor network at MacDill Air Force Base that can detect, classify, and track soldiers and vehicles in difficult-to-monitor open spaces such as desert battlefields. (Ohio State University)
- A sensor network deployed in an Oregon vineyard guides irrigation and planting, increasing crop yield. (Intel Research/King Family Farms/AgCanada)
- Inside an experimental smart home at Intel's Oregon campus, a sensor network is under development that could someday keep tabs on an Alzheimer's patient's vital signs while reminding him how to warm up his lunch. (Intel Research)
- On the San Andreas Fault, a network of motes equipped with seismometers calculate the depth of the fault, locate accumulating stress, and may eventually improve earthquake prediction. (UCLA Department of Earth and Space Sciences/Center for Embedded Networked Sensing)
- Motes mounted in the treetops of UC Botanical Garden's Mather Redwood Grove sample environmental data in a cross-section of the canopy to help scientists understand the massive plants' physiology. (UC Berkeley/Intel Research)

- Motes that measure vibration signatures on manufacturing equipment are being tested for “pre-emptive maintenance applications” to reduce downtime in semiconductor fabrication facilities. (Intel Research/Intel Technology and Manufacturing Group)

Anatomy of a Mote

While the particular size, type, and configuration of motes that form a network are mostly determined by the intended application, all of the devices face the same overarching design constraint. A mote is only as effective as its ability to conserve power. Ideally, each mote should be able to survive on its own for at least a year on a pair of AA batteries. Yet each reading a mote takes and every bit of data it transmits brings the device a moment closer to death. To that end, motes must be on a strict power diet.

At its core, this diet is based on enabling the motes to run at extremely low duty cycles. The mote is active as little as one percent of the time. It “wakes up” only to take scheduled readings or to transmit or receive data from neighboring devices. Every one of the mote’s hardware and software components is designed to support low duty cycles.

As semiconducting circuits become smaller, they consume less power. Simple microcontrollers like those that function as a mote’s brain can operate with just a milliwatt of power when active, or 1-10 microwatts in standby mode. A mote’s memory must also be limited due to the energy constraints. Each mote typically has less than 10 kilobytes of RAM, one hundred kilobytes of software, and a megabyte of data storage. All told, that’s approximately 10,000 times less data storage than a desktop PC.

The low power approach is continued through a mote’s sensing system. For example, commercially-available macroscale sensors such as thermistors and fog detectors show a change in voltage as, respectively, they get warmer or wetter. Analog-to-digital converters (ADCs) translate that voltage into a zero or one that the microprocessor can understand. The development of extremely efficient ADCs keep the power profile of a mote’s sensing system similar to that of the processor.

Meanwhile, MEMS provide the motes with a much broader array of low-power sensory inputs. The simplest example of a MEMS device resembles a diving board with a mass mounted on the end. Gravitational forces or acceleration cause the mass to spring up and down, forces that can easily be converted into a digital signal. These devices, called accelerometers, are commonly used in automobiles to trigger the release of airbags. A growing variety of MEMS sensors are available to detect myriad factors, from the body heat of a bird in its burrow to the presence of environmental contaminants in the air. Intel Research is also developing biochips, devices that can sense biological materials and organic chemistry.

While commercial sensors are already present in such everyday products as automobiles and washing machines, motes boast one essential capability that sets them apart from their predecessors: wireless networking using radio. Low-power transceivers enable the motes to transmit their sensor readings throughout the network. Like MEMS sensors, these low-power radios can now be inexpensively produced using conventional silicon processing techniques. This new class of RF (radio frequency) devices is one of the key enabling technologies behind 802.11 (WiFi) networks, Internet-enabled PDAs, ever-smaller mobile phones, and sensor networks.

Currently, consumer AA or “coin” batteries can keep motes alive for six months to one year. Other energy scavenging power sources are also being developed. Ambient lighting or sunlight could provide enough solar energy in applications where the motes are exposed. At an earlier stage of development are MEMS devices demonstrated at UC Berkeley that convert the ambient vibration of structural components like air-conditioning ducts and windows into enough electricity to keep the motes operational indefinitely.

Motes on the Market

Several species of motes based on the prototypes developed by Intel Research and UC Berkeley have recently become commercially available at $50-$100 each. Through re-engineering, Moore’s Law, and volume production, motes are expected to drop in price to less than $5 each over the next five years.

Crossbow Technology Inc. was the first commercial manufacturer of motes. Their latest generation of devices consists of a microprocessor, memory, storage, and an internal analog-to-digital converter, all integrated into a device roughly the size of a quarter. Various sensor boards for measuring acceleration, magnetism, light, temperature, and other factors can easily be snapped on to the processor/radio.

Crossbow is also licensed to produce Intel’s Stargate single-board gateway computer, based on the Intel X-Scale® technology. These high-end nodes can improve sensor network performance and reduce the motes’ energy consumption by offloading some of the wireless responsibilities to devices that can be plugged into power sources. The idea behind this kind of network is strikingly simple. For example, a network of high bandwidth 802.11 (WiFi) gateways like Stargate could overlay a mote-based sensor network. The structure is analogous to a highway overlaid on a roadway system. Sensor data can then enter and exit the 802.11 highway at multiple interchanges (the Intel X-Scale technology gateways) in order to bypass the side roads, the wireless motes. This approach increases bandwidth and requires less energy on average because the motes are not solely responsible for moving data through the network. The resulting system is known as a heterogeneous sensor network.

To cater to applications that require more processing and bandwidth--vibration, audio, or image sensing, for example--Intel Research developed the iMote, featuring a 32-bit central processing unit and the Bluetooth wireless standard. Bluetooth is commonly used in mobile phones and laptop computers for short-distance communication. As a result, users can employ these kinds of devices to easily interact with iMote-based sensor networks.

In the laboratory, motes are continuing to shrink in size. As part of the Smart Dust project, UC Berkeley researchers have shrunk the processing and wireless functionality of the larger motes onto a single chip just a few millimeters on a side, not including batteries. Once the incredibly-efficient radio technology behind this "Spec" mote is ready for prime time, it will be commercialized by Dust Inc., a sensor networking start-up spun out of the Smart Dust research effort.

Size Does Matter

Like all computers, motes require an operating system that manages all of the hardware and software functionality. However, commercial operating systems--Unix or Windows, for instance--require far too much processing power and storage space than a mote can offer. Over the last several years, UC Berkeley researchers have designed and honed an operating system specifically for embedded networks. Freely-available and open source, TinyOS has become the "industry standard" operating system for sensor network research and applications.

At its most basic level, TinyOS is a scheduler that manages the activities of its various modular components. First and foremost, the operating system is the final governor of power on the mote. Wireless communication is a notoriously power hungry activity. And unlike mobile phones and laptop computers, motes can't be recharged every night. In order to keep sensor networks to alive for long periods, the motes are programmed to pass their data bucket-brigade style from node to node, much like packets travel through routers in the Internet. This multi-hop approach keeps the radio's power requirements to a minimum. TinyOS also enables the motes to process some data locally and only communicate the results of that processing when an interesting event is detected.

TinyOS is also the architect of the ad hoc wireless network. The software enables each mote to discover its neighbors and perform an algorithm in concert with its peers to determine how data should be routed through the network. Finally, TinyOS is an excellent multi-tasker. It juggles the streams of data flowing in from the sensors and the network and plays traffic cop, directing the transmission of data to other nodes.

Once loaded with TinyOS, the motes must maintain their flexibility in the field. New applications may be developed over the course of a sensor network's life. For example, a biologist drawing insight from a network deployed high in a tree canopy may decide six months later that he or she would like to monitor sound as well as motion. The sheer number of nodes makes it impossible to reprogram each one individually. Instead, new programs are introduced into the network similarly to the way computer viruses spread across the Internet. As the motes communicate, they infect their kin with the new operating instructions. The programs then run inside an easily accessible and manageable "virtual machine," software within TinyOS that simulates a separate hardware computer. The beauty of TinyOS is that even with all of these capabilities, the entire operating system is just a few kilobytes in size.

Speaking A Sensor's Language

TinyOS is written in NesC, a programming language for motes developed at Intel Research and UC Berkeley. An extension of the popular programming language C, NesC (pronounced "NES-see") is a natural lingua franca for motes. Motes are a unique species of computer, primarily because they're asleep most of the time. That means their processing is event driven, occurring only when the sensors acquire data or a new message arrives. NesC supports the motes' reactivity to their environment with a component model that simplifies the creation of applications and the aggregation of data.

For example, a certain application might require a mote's average temperature over a period of time. With nesC, the timer and averaging modules are two of many reusable software components that sit between the hardware sensor and a particular application. Depending on the task, various modules can be "wired" together as necessary. Sensor readings can also be aggregated as the data is routed through the network. This approach reduces the amount of information that each mote transmits, thereby conserving power.

Still, in a massively distributed sensor network, numerous activities will often occur simultaneously and must not overwhelm the motes' limited power, processing, and memory resources. Even with these tight constraints, NesC's elegant concurrency model enables the motes to be programmed to handle many events in parallel. The NesC Compiler provides additional aid for programmers exploiting the concurrency and component model by detecting any potential problems in new software before it is deployed.

The Real World As Database

Sensor network researchers around the world have developed numerous applications using nesC and TinyOS. For heterogeneous sensor networks to be widely deployed though, it must be relatively simple to extract meaningful data from the networks. Otherwise, gathering data from a sensor network would be akin to drinking from a fire hose. TinyDB, a database system developed at Intel Research and UC Berkeley, is one such solution. Essentially, running TinyDB transforms diverse kinds of sensor networks into user-friendly virtual databases rich with useful information about the real world.

Consider this scenario: A large corporate campus is equipped with motes in every room keeping a constant vigil on light and sound. One use for the sensor network would be to locate unoccupied conference rooms by checking for noise or if the lights are on. Without an application like TinyDB running on TinyOS, the administrator of the sensor network would have to write several hundred lines of computer code to collect the light and sound information from every mote, coordinate how the data is aggregated, and forward all of the information to a PC that determines which rooms are occupied. Once written, the software would have to be installed in every mote across the campus.

TinyDB greatly streamlines the process by enabling a user to gather that same information just by posing a simple query in SQL, a common database language. Through a graphical user interface, the software describes what sensor readings are available. Meanwhile, TinyDB's declarative query language enables the user to describe the desired data – the average noise level, for example – without having to tell the software how to acquire that data. The query is then sent to the TinyDB query processor pre-installed on each mote. If a mote happens to be relaying a message related to an unfamiliar query, it simply asks the neighboring mote that sent the message for a copy of the query so it too can help gather the data.

Once a query is executed, TinyDB automatically extracts the data from the network and dumps into a traditional database. For example, in the case of the seabird-monitoring sensor network, the data hops across the island to a lighthouse where it's relayed via satellite to a Web site. The information can then be analyzed using standard tools and visualization techniques.

Vision In Motion

A new era of computing is on the horizon. The vision of proactive computing calls for billions, perhaps even trillions, of devices to be deeply embedded within our physical environment. These tiny sensors and actuators will silently serve us, acquiring and acting on a multitude of data to improve our lives, help us understand our world, and make us more productive. Of course, the ability to instrument our world poses complex questions about security and privacy. Fortunately, these are becoming active areas of cross-disciplinary research in academia and industry.

Addressing those concerns now is crucial. In the not-so-distant future, motes will evolve into devices that will not be embedded, but actually part and parcel of everyday objects. Structures will be held together with "smart bolts" that contain sensors and radios. Buildings will be constructed from "smart girders" that feed seismic stability ratings to a flat screen near the entrance. Trellis stakes will monitor the crops that they support, while gaining energy from the sun. Instrumented watches, teapots, and bathtubs will enable our elders to enjoy their lives while easing the minds of their caretakers.

That is the future of proactive computing. And sensor network research is driving us toward it.

Learn More

- Intel Research: http://www.intel.com/research/index.htm
- UC Berkeley College of Engineering: http://www.coe.berkeley.edu
- CITRIS: http://www.citris.berkeley.edu
- UCLA Center for Embedded Network Systems: http://cens.ucla.edu/
- TinyOS: A Component-Based OS for the Networked Sensor Regime: http://webs.cs.berkeley.edu/tos/
- NesC: A Programming Language for Deeply Networked Systems: http://telegraph.cs.berkeley.edu/tinydb/
- TinyDB: A Declarative Database for Sensor Networks: http://telegraph.cs.berkeley.edu/tinydb/
- Dust Inc.: http://www.dust-inc.com
- Crossbow Technology Inc.: http://www.xbow.com
- DARPA, Network Embedded Systems Technology (NEST): http://dtsn.darpa.mil/ixo/programdetail.asp?progid=42
- National Science Foundation, Research in Networking Technology and Systems: http://www.nsf.gov/pubsys/ods/getpub.cfm?ods_key=nsf04540

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