Building a Sensor-Rich World

In the late 1990s, DARPA (the US Defense Advanced Research Projects Agency) began to fund research in *sensor networks*, networks consisting of microsensors, each with local computing, networking, and sensing capabilities. The research program's long-term goal was to merge information processing with sensing and actuation to realize new systems and strategies to bring colocated perception and control to the physical, biological, and chemical environment. Subsequent DARPA programs focused on developing systems support and design tools for such large-scale, distributed-sensing systems. In the early years, sensor network research was driven by military funding and applications, such as target tracking, security perimeter monitoring, or emergency response. However, researchers quickly began to envision other applications of their technology and ideas, including environmental monitoring, industrial process monitoring and control, inventory management, and smart spaces. In the last 10 years, sensor networks have grown into an active research area, supported by journals, conferences, and workshops on sensor networking and related areas. (See the "Related Resources" sidebar for more information.)

Early sensor network nodes tended to be somewhat large and expensive. Power constraints and network connectivity posed serious deployment problems. However, technological advances have enabled the development of increasingly sophisticated commercial products. For example, this year, Hitachi unveiled RFID chips that are just 0.05 mm by 0.05 mm, the size of fine sand. They look like bits of powder. Last year, HP Labs announced Memory Spot chips, miniature computers with onboard memory and wireless capability comprising six main parts: a processor, a memory system, a memory driver, the modem, a capacitor array, and a loop antenna. With a megabyte of memory, the chip is smaller than a grain of rice (approximately 2 mm by 4 mm square). Other companies offering sensor networking products

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Related Resources

- E.H. Callaway Jr., *Wireless Sensor Networks: Architectures and Protocols*, Auerbach, 2003.
- DARPA NEST (Networked Embedded Systems Technology) Program, http://dtsn.darpa.mil/IXO/programs.asp?id=87
- DARPA SensIT Program Vision Statement, www.sainc.com/sensit.
- *Embedded Everywhere: A Research Agenda for Networked Systems of Embedded Computers*, Nat'l Academies Press, 2001.
- J.M. Kahn, R.H. Katz, and K.S.J. Pister, "Mobile Networking for Smart Dust," *Proc. ACM/IEEE Int'l Conf. Mobile Computing and Networking* (MobiCom 99), ACM Press, 1999, pp. 271–278.
- H. Karl and A. Willig, *Protocols and Architectures for Wireless Sensor Networks*, John Wiley & Sons, 2005.
- B. Krishnamachari, *Networking Wireless Sensors*, Cambridge Univ. Press, 2006.
- K. Pister, "View of Sensor Networks in 2010," http://robotics.eecs.berkeley.edu/~pister/SmartDust/in2010.
- G. Pottie and W. Kaiser, *Principles of Embedded Networked Systems Design*, Cambridge Univ. Press, 2005.
- F. Zhao and L. Guibas, *Wireless Sensor Networks: An Information Processing Approach*, Morgan Kaufmann, 2004.

Journals

- *ACM Transactions on Sensor Networks*, www.acm.org/tosn
- *International Journal of Distributed Sensor Networks*, www.tandf.co.uk/journals/titles/15501329.asp

Conferences

- ACM Conference on Embedded Networked Sensor Systems (SenSys), http://sensys.acm.org
- ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), http://ipsn.acm.org

include Crossbow, Dust Networks, Ember, Moteiv, and Arch Rock.

Moving forward

These types of new products, offered at more economical price points, have made it increasingly possible to deploy sensor networks at a scale far beyond what we could do just a few years ago. However, much work remains before sensors become truly pervasive. Sensor networks are complex systems and must draw on expertise in many fields, including power sources, microelectromechanical systems (MEMS), network protocols, low-power communication, embedded systems, information management, security and privacy, and distributed algorithms. Successfully designing, implementing, and deploying a sensor network requires clearly understanding the application's requirements and balancing a bewildering array of technologies and engineering trade-offs.

Researchers have started working on wide-area sensor networks that move beyond specialized domains and can be shared across numerous pervasive computing applications. These systems leverage deployed mobile and embedded devices, including webcams on streets and highways, wearable devices such as watches and cell phones, and sensors on cars. This gives rise to a number of interesting device, systems, and policy issues. For example, how do we extract relevant information about an ongoing wildfire from a cluster of live sensor data feeds? How do we locate sensors precisely enough to enable spatial signal processing, such as tracking a vehicle in a remote mountain pass? Or, in the realm of privacy, how do we handle multiple pieces of information linked in such a way that they paint an invasive picture of a user's life?

In this issue

We examine some of the important system issues that must be addressed to meet this vision of a sensor-rich world.

In "Mobiscopes for Human Spaces," Tarek Abdelzaher, Yaw Anokwa, Péter Boda, Jeff Burke, Deborah Estrin, Leonidas Guibas, Aman Kansal, Samuel Madden, and Jim Reich anticipate a sensor-rich world emerging from adding sensing and communications capabilities to devices already part of our daily lives, such as automobiles and cell phones. They point out that this process has already begun and will enable new applications such as *mobiscopes,* sensor networks that can achieve high-density data sampling over a wide area by using mobile sensors. The authors discuss the technical challenges posed by the design, deployment, and effective use of these mobile sensor networks.

"Data Management in the Worldwide Sensor Web," by Magdalena Balazinska, Amol Deshpande, Michael J. Franklin, Phillip B. Gibbons, Jim Gray, Mark Hansen, Michael Liebhold, Suman Nath, Alexander Szalay, and Vincent Tao, looks at the challenges arising from the volumes of data collected by the huge number of mobile and stationary sensors. In particular, they address the problems posed by streaming data sources, uncertainty from noisy or unreliable sensing, and the requirements of real-time processing. These aspects of data management will play a much more important role than they have in traditional relational databases work. Additionally, the authors highlight the growing concerns for privacy and security as more data is gathered and used to make decisions in increasingly automated systems.

Further Resources

Sensor networks are a quintessential pervasive computing technology, and they've been a frequent topic in *IEEE Pervasive Computing*. Previous magazine issues dealt with technologies of particular interest to sensor networks, such as energy harvesting, low-power radios, location awareness, data aggregation, and query processing. Two issues focused specifically on sensor networks: "First Response" applications (vol. 3, no. 4, 2004) and "Sensor and Actuator Networks" (vol. 2, no. 4, 2003).

Another useful resource is the 2006 University of Washington/Microsoft Research Summer Institute on the World-Wide Sensor Web. Approximately 40 attendees discussed how to bring to end users the wealth of sensor data collected from embedded and mobile sensors on vehicles and people. (You can access the presentations at www.cs.washington.edu/mssi/2006.) Participants also discussed the infrastructure and tools that we'll need to enable anyone to search or visualize this information. The meeting aimed to articulate the challenges involved in constructing a search engine for the physical properties of places on our planet, such as finding recurring pollution patterns. Two articles in this special issue ("Mobiscopes for Human Spaces" and "Data Management in the Worldwide Sensor Web") summarize some of the discussions and conclusions reached.

In "The Urbanet Revolution: Sensor Power to the People!" Oriana Riva and Cristian Borcea address the programming issues for distributed-sensing platforms based on vehicular systems or smart phones. To enable applications on these loosely coupled sensor networks, they propose three different approaches to programming Urbanets: a declarative model using an SQL-like interface, an imperative model that views the network as a single virtual name space, and a service migration model that moves services from node to node as the environment, system, or task changes.

This special issue also contains "Transforming Agriculture through Pervasive Wireless Sensor Networks," by Tim Wark, Peter Corke, Pavan Sikka, Lasse Klingbeil, Ying Guo, Chris Crossman, Phil Valencia, Dave Swain, and Greg Bishop-Hurley. The authors present an overview of their ongoing research in applying sensor networks to farming problems, which required creating a large-scale pervasive computing system that operates outdoors. Through their discussion of using this system for pasture monitoring, and animal monitoring and control, the authors give us novel insights into the benefits that a sensor-rich world offers and the challenges we must address to deliver meaningful applications.

Sensor networks have historically been relegated to special applications and research projects. Technological advances are making it possible to move from this restricted domain to a world where sensors and new applications abound. As we move into the consumer space, we need to consider information privacy from the very beginning.

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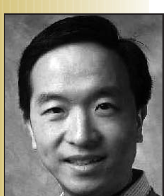

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