Sensor Networking: Concepts, Applications, and Challenges[1)]

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Abstract Sensor network has experienced world-wide explosive interests in recent years. It combines the technology of modern microelectronic sensors, embedded computational processing systems, and modern computer and wireless networking methodologies. In this overview paper, we first provide some rationales for the growth of sensor networking. Then we discuss various basic concepts and hardware issues. Four basic application cases in the US. National Science Foundation funded Ceneter for Embedded Networked Sensing program at UCLA are presented. Finally, six challenging issues in sensor networks are discussed. Numerous references including relevant papers, books, and conferences that have appeared in recent years are given.

Key words Sensor networks, wireless communication, embedded processing, information processing, environmental monitoring, health care system, robotics, automated manufacturing

1 Introduction

At the end of the 20th century, the Internet has been able to provide a large number of users with the ability to move diverse forms of information readily and thus has revolutionized business, industry, defense, science, and education, research, and human interactions. The technologies of information processing in the last fifty years that made the Internet possible included modern microelectronics resulting in low-cost PCs and servers and world-wide telecommunication and computer networking infrastructure. In the last ten years, sensor networking combines the technology of modern microelectronic sensors, embedded computational processing systems, and modern computer and wireless networking methodologies. It is believed that sensor networking in the 21st century will be equally significant by providing measurement of the spatial-temporal physical phenomena around us, leading to a better understanding and utilization of this information in a wide range of applications. Sensor networking will be able to bring a finer-grained and fuller measurement (using acoustic, seismic, magnetic, infrared, imaging, *etc.* data) and characterization of the world around us to be processed and communicated, so the decision makers can utilize the information to take actions in near-real-time.

In the last few years, there have been much world-wide interests in the basic and applied research and deployment of sensor networks (*e.g.*, the cumulative number of "hits" on Goggle Scholar by the fall of 2005 on "sensor networks" is over 350,000.) In the last three years, there were numerous annual conferences and workshops held around the world on sensor networks (*e.g.*, some of them include). Many technical monographs and books dealing with sensor networks have appeared (*e.g.*, some of them include[1~10]). Several Special Issues of journals dealing with various aspects of sensor networks have also been published (*e.g.*, some of them include[11~15]). These statistics and information all indicate that sensor networking has extensive interests.

In this overview paper, Section 1 provides an introduction to the sensor networking problem. Section 2 considers the recent explosive interests in sensor networks. Section 3 discusses various concepts and hardware issues. Section 4 reviews four main basic application cases in the NSF funded CENS program[16] at UCLA. Section 5 lists six challenges in sensor networks. A brief conclusion is included in Section 6. The references include numerous relevant papers, books, and conferences that have appeared in recent years.

2 Explosive interests in sensor networks

Sensor network as a concept and in realization appeared only in the last five years or so due to the accumulations of enabling technologies of the last fifty years. The concept of a programmable digital computer was originated in the 1940s. In the 1950s, mainframe electronic digital computers were built. They were expensive and were only available in few educational, governmental, and commercial research organizations. At this time, basic concepts of digital communication also became known. In the 1960s, mini-computers became popular and digital computations were made available to more

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users. In that period, satellite and terrestrial microwave communication made the transmission of large amount of digital data possible. The concept of the transmission of data over a network of many nodes distributed over large areas was pioneered by researchers of the Arpanet. In the 1970s, microprocessors significantly reduced the cost of digital computations, and the availability of low-cost DSP chips also made digital processing possible for many applications. Commercial and military communication and computer networks were spread around the world. In the 1980s, PCs appeared and the beginning of the Internet allowed researchers at few research and large commercial organizations to easily communicate with others. In the 1990s, optical communication networks and the availability of the WWW browser allowed the explosive growth of world wide communications among individuals through the Internet. In this period, advances in embedded processors and wireless communication technology led to the creation of ad hoc networks and explosive world-wide usage of cellular telephony. In 2000s, with all the above available technologies, sensor networking was made possible.

A sensor network consists of dozens/hundreds/thousands of nodes (possibly randomly distributed), each with a sensor (*e.g.*, acoustic, seismic, magnetic, chemical, image, video, temperature, *etc.*), a low-power embedded processor (of varying processing capability), a radio (*e.g.*, a low-power transceiver of varying capability and range), a battery often of limited energy and size, and a program controlling one or more nodes and possibly some parts of the network to perform some given task. The slogan of a few years ago, "The network is the computer," is now, "The network is the sensor."

2.1 Sensor networks connect the physical world to the virtual world

In the last fifteen years, the Internet using computer networks had connected the digital computers of the world into a virtual world. Sensor networks provide the capability of connecting the physical world (using the sensors in the sensor networks) to the digital world through the Internet to the virtual world. Sensor networks enhance the explosive impact of the Internet many folds by bringing the phenomena of the physical world under greater understanding and control.

At present, the European SENSOR consortium with over thirty-five participating institutions in fifteen countries is using sensor networks to study the understanding of the multi-functional use of land. The U.S. National Science Foundation (NSF) is supporting several large research efforts using sensor networking. NEON (National ecological observatory network) is estimated to be a $500 millions project over many years. An observatory may track birds and weather over a forest canopy. Another one may track invasive species causing agricultural losses, while a third one may monitor the biosphere associated with climatal changes. The Earthscope project is estimated to cost $200 millions and its purpose is to erect 3,000 stations to track faint tremors, measure crustal deformation and make three-dimensional maps of the interior of the earth. The Neptune project, also estimated to cost $200 millions, will place 2,000 miles of cables with sensors, cameras, and tetherless robots in the depth of the Pacific Ocean from California to Canada. Its goal is to study from the depth to the surface for the total understanding of the ocean environment. NSF has also funded a ten year research program of approximately $40 millions at CENS (Center for Embedded Networked Sensing) at UCLA starting in 2002 to study the impact of densely embedded sensing for scientific applications. Details on some of the projects of CENS will be discussed in Section 4.

Many other applications of sensor networks have been proposed and implemented. It may include robotic control in manufacturing and industrial inventory management of products. It may perform personal health monitoring of senior citizens in their homes. Sensor network has been used for environmental pollutant monitoring on land, water, and air. It can be perform habitant monitoring in open spaces. Sensor networks can monitor plants in precision farming. It can monitor structural integrity of buildings. It can detect, localize, and track vehicles and people for commercial and military surveillance and reconnaissance applications.

2.2 Commercial aspects of sensor networks

An ideal sensor network node (often called a mote) is shown in Fig. 1. It may consist of one or more sensors, a microprocessor/controller, programs to perform its desired operation, a RF transceiver, and a battery supply. To keep cost low (*i.e.*, costing less than $1), it needs to use a fully integrated single chip CMOS design of less than $1cm^3$ in volume. To achieve ultra low-power, it needs to use less than one milliwatt of power.

At present there are several dedicated hardware companies including Crossbows, Millenial Net, Eaton, oteIV, *etc.*, selling various types of mote nodes, sub-systems, and services in sensor networks. Intel makes the Stargate sensor node. Recently, IBM announced the formation of a new business unit to invest $250 million over five years to support products and services in sensor networks. Microsoft also has an active R&D efforts in sensor networks. Fig. 2 shows a forecast of the number of motes produced from 2005 to 2010. Indeed, the sales volume is of such motes may exceed that of other wireless handheld devices.

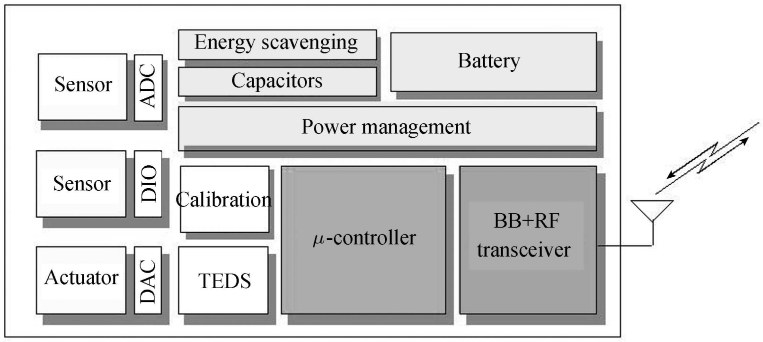

Fig. 1 Single chip wireless sensor node

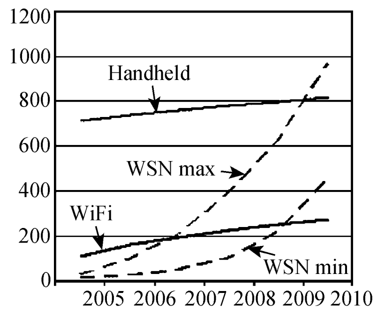

Fig. 2 Sales forecast in integrated wireless sensor nodes

3 Concepts and hardware in sensor networks

In this section, we will introduce various concepts and hardware in sensor networks. They include sensor principle and hardware; sensor signal processing and communication; sensor network methodology; network position and synchronization; sensor network energy management; sensor network data management; sensor network node architecture; and sensor network data integrity and security.

Sensors act as the "eyes and ears" of the sensor networks in accepting inputs from the physical world. Acoustical sensor (microphones) may be low cost condenser microphones or calibrated microphones (*e.g.*, LinearX M31 and M53 microphones). Chemical sensors may detect CO_2 or nitrates. Sensors to detect vibrations can use low-cost geophones or more accurate and expensive bi-axial or tri-axial accelerometers. Sensors to detect magnetic fields can utilize magnetometer. Low-cost image and video sensors use CCD sensing devices. All of the previously listed sensors have existed for many years and are capable of sensing various physical phenomena. These conventional sensors are commercially available and have well defined costs, sizes, and sensitivities. However, state-of-the-art MEM-based sensors are often much smaller, have greater sensitivities and have lower power needs, but often are available only from laboratories in experimental batches. For practical system applications, there are tradeoffs between commercially available low-cost sensors versus "super performance" but expensive, unavailable, and unproven MEM-based sensors.

There are many issues in sensor signal processing and communication. The ADC (analog-digital-converter) bit requirement depends on the type of signals encountered by the sensors. The issue of communication transmission energy per bit versus processing energy cost per bit is an important matter in sensor networks. In some applications, it is possible to perform more local processing at the nodes instead of transmitting the raw information bits for processing at a central node. Often it is desirable to perform distributed processing than centralized processing in wireless sensor networks. There is active research in tradeoff studies in low-bits, low-power, and distributed processing algorithm in sensor networks.

A sensor network can be organized in a star, ring, tree, or ad hoc manner. An important initial organization requirement of a network is to discover connectivity among the nodes so communication links can be established. Network routing procedure shows which links are desirable from the communication energy and node reserve energy points of view. Latency and congestion are issues of importance in routing. Models for information channels (*e.g.*, broadcast, multiple-access, cooperative relaying, etc.) and theoretical rate-flow capacity results for maximum data transfer in the sensor network are areas of active research.

Spatial-temporal relationships for physical phenomena can be observed by densely distributed nodes in a sensor network. In order to determine the location and time of events of one or more sources of interest as they evolve in space and time, the nodes must know their own positions (and in time if the nodes are also moving). Sensor network constraints of distributed versus central processing, low-power processing, and limited physical placements of the nodes all make these solutions to be challenging.

The energy management of a sensor network is crucial for its longevity. Energies to power a node may include a solar cell with about 0.006 mwh/cm^2 indoor and about 15 mwh/cm^2 outdoor power densities. A lithium-ion battery has about 300 mwh/cm^3 power density, while a fuel cell can provide about 4,000 mwh/cm^3 power density. Since a CMOS transistor′s power $P = (1/2)CV^2f$, where C is the capacitance, V is the voltage, and f is the clock frequency, by reducing V and f, the power P can be reduced. Table 1 shows some typical processor energy needs of an ASIC, FPGA, and microprocessor in 1999 and 2005 to perform one basic operation. We notice a one order of magnitude decrease in power consumptions for all three types of processing devices[8].

Table 1 Comparisons of processor energies for three types of devices for 1999 and 2005

Processor energy	ASIC	FPGA	Microprocessor
1999	1 pJ/op	10 pJ/op	1,000 pJ/op
2005	0.1 pJ/op	1 pJ/op	100 pJ/op

It is interesting to compare the communication versus the processing energy needs. One needs about 0.35 joule of energy to transmit 1 kilobits of data using DPSK under a Rayleigh fading channel having a fourth-power propagation loss using an antenna at 15 cm above the ground. On the other hand, one needs only 10-6 joule of energy to process 1 kilobits of data with a 100 MIPS processor. Thus, if a processing algorithm permits, it is more energy efficient to process locally rather than transmit the data for processing at another node[8].

In sensor network data management, there can be a nearly “infinite” amount of data generated from a physical source if observed over a sufficient long period. Thus, one can only collect a transient amount of data needed by the user at a given period. The data needs to meet certain fidelity criterion which varies greatly depending on applications. In some applications, there may be an advantage to fuse data collected from distributed sensors rather than depending on individual sensor data. Since the physical phenomena are often unknown or changing with time, one may need to use adaptive data collection procedures with respect to variable sampling rate and spatial sampling density. Fig. 3 shows

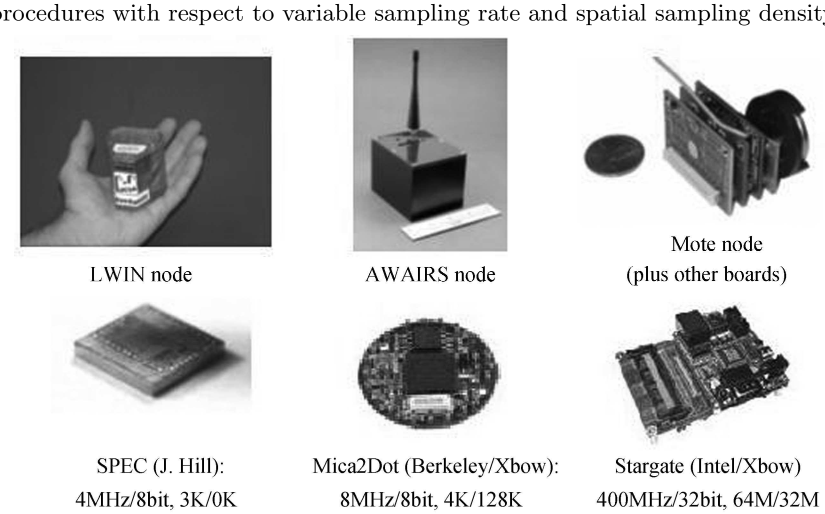

Fig. 3 Shows 6 sensor nodes (LWIN, AWAIRS, Mote, SPEC, Mica2Dot, and Stargate)

six sensor nodes fabricated at research institutions and commercial companies in recent years.

Sensor network data integrity and security involve many complex and challenging issues. There is the issue of secrecy which denies the information to an unauthorized user. In authenticity, one wants to validate the correctness of the source generating the information. In integrity, one wants to verify the data from a source that is not modified accidentally or maliciously. Scalability involves the issue of whether a network can grow with varying number of nodes and users. Robustness of a network depends on its proper operation when network parameters change significantly.

4 Four CENS case studies

In this section, we consider the four CENS case studies of ecosystem and bio-complexity, contaminant transport for environmental protection, marine microorganism monitoring, and seismic structure response.

4.1 CENS ecosystems-bio-complexity study

Networked Info-Mechanical Systems (NIMS) is a robotic 3-D aerial access sensing system, shown in Fig. 4, with coordinated mobility enabling self-aware diverse sensing on the bio-complexity factors of a heavily forested area at James Reserve in San Jacinto Mountain in California. NIMS infrastructure enables efficient dense sampling of microclimate (*e.g.*, temperature, humility, precipitation, sun light, *etc.*) over a given volume.

At James Reserve, acoustical sensors are used to study individual and specie properties of Acorn Woodpecker birds in their natural environment as shown in Fig. 5. The arrays using beamforming for detection, localization, tracking, and classification applications. Data from the arrays are used to verify bio-complexity conjectures.

Fig. 4 NIMS sensor system deployed at James Reserve, CA

Fig. 5 Collection of Acorn Woodpecker data using acoustical arrays at James Reserve, CA

4.2 CENS contaminant transport study

Fig. 6 shows four images of a contaminant transport environmental monitoring system located at Palmdale, CA. State-of-the-art nitrate microsensors have been fabricated. Partially processed sewer water used for agricultural irrigation purpose is monitored with respect to nitrate infiltration into the ground water. Instead of using extensive number of expensive deep hole drilled with placed underground sensors, only few are used for calibration purposes for a distributed array of densely placed sensors on the surface are used for real-time monitoring and extrapolation of the underground pollutant.

4.3 CENS marine microorganism study

Many coastal areas around the world are often heavily polluted. An important goal is to understand and predict the behavior of marine microorganisms. One approach is to correlate the environmental conditions with microorganism abundances at the small spatial and temporal scales that are relevant to the organisms. Previously known approach has not been proven to be useful. However, sampling the environment with densely populated high resolution sensors and identifying microorganisms in-situ in near-real time may provide important new ways to understand this problem.

4.4 CENS seismic structure response study

Earthquakes impact many areas of the world. An important impact of earthquake is its damage to buildings and cause of injury and loss of life in such buildings. The moderate 1994 Northridge, CA earthquake caused 57 deaths and over $40 billions of financial losses. Despite years of study, the interaction between ground motions and structure and foundation responses are still not well known.

Current seismic networks have sparsely separated sensors. The purpose of this study is to use densely placed seismic sensor to sample wave field without spatial aliasing and monitor and correlate structure deformations to ground motions.

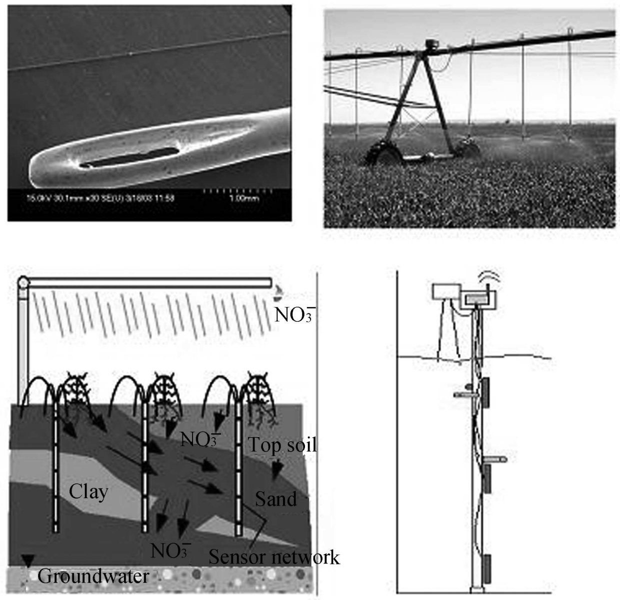

Fig. 6 Four images of the sensor and real-time pollutant monitoring system

5 Challenges

In this section, we list six fundamental challenges in the research, development, and commercial aspects of sensor networks.

1) Application specific – Problems in sensor networks are highly application specific, as can be seen from the four case studies described in Section 4. It is essentially impossible to design a sensor network system that is near optimum for many applications. It is clear that sensor networks will form basic building blocks of many societal infrastructures (*i.e.*, electric power network, water and natural gas networks, transportation network, *etc.*). All these systems posse both a challenge in that innovative design needs to be used to tackle each new sensor network application, but also presents the massive manufacturing of few generic sensor network systems to reduce their costs.

2) Cooperative operation of the sensor network – How do all the sensor nodes operate in an organized and systematic manner to exploit the correlated information available across all parts of the network? This cooperation may involve different level of fusion of the results obtained after distributed processing across the entire network.

3) Node and source localization – In many sensor networks, the location of the sensor nodes must be determined. This problem has been addressed by many researchers, but reliable and practical solutions for many applications are still quite challenging. The detection, localization, and tracking of multiple sources have been considered for many years in aerospace applications, but are even more challenging in sensor networks with limited resources for real-time applications.

4) Poor wireless communication links – Low-powered RF transmission under severe multipath propagation conditions limits the reliability of most wireless sensor networks over single links. Reliable multihop links are even more challenging. Research and development efforts to solve these problems need to be considered from the theoretical system as well as practical hardware points of view.

5) False positive issue using sensor network – Many deployed sensor networks often produced the "false positive" result. That is, the network declared some critical state (thus resulting in the need to take some important actions) from the measured data in the network, when the true situation does not warrant such actions. This "crying wolf scenario" lowers the confidence of the use of sensor networks for some applications. At present, this problem and not necessarily the technical nor cost of such sensor network systems are preventing wider deployments. Clearly, better hardware at the node level as well

as better decision algorithm need to be utilized to reduce the frequency of this problem.

6) Battery limitation – Many sensor networks operate in remote locations with no AC power supply. Their physical locations may present the usage of solar cells to charge the batteries. Thus, higher energy density batteries muse be used for these situations. Active research and development in various small form factor fuel cells may lead to their availability in the near future.

6 Conclusions

The overview paper considered some basic issues in sensor networking. It is clear that sensor networking is only at its infancy. Much challenging work in research, development, and application will be performed in sensor networks in the coming years.

7 Acknowledgments

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