Sensor Networks: Evolution, Opportunities, and Challenges

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Invited Paper

Wireless microsensor networks have been identified as one of the most important technologies for the 21st century. This paper traces the history of research in sensor networks over the past three decades, including two important programs of the Defense Advanced Research Projects Agency (DARPA) spanning this period: the Distributed Sensor Networks (DSN) and the Sensor Information Technology (SensIT) programs. Technology trends that impact the development of sensor networks are reviewed, and new applications such as infrastructure security, habitat monitoring, and traffic control are presented. Technical challenges in sensor network development include network discovery, control and routing, collaborative signal and information processing, tasking and querying, and security. The paper concludes by presenting some recent research results in sensor network algorithms, including localized algorithms and directed diffusion, distributed tracking in wireless ad hoc networks, and distributed classification using local agents.

Keywords**—***Collaborative signal processing, microsensors, network routing and control, querying and tasking, sensor networks, tracking and classification, wireless networks.*

I. INTRODUCTION

Networked microsensors technology is a key technology for the future. In September 1999 [1], *Business Week* heralded it as one of the 21 most important technologies for the 21st century. Cheap, smart devices with multiple onboard sensors, networked through wireless links and the Internet and deployed in large numbers, provide unprecedented opportunities for instrumenting and controlling homes, cities, and the environment. In addition, networked microsensors provide the technology for a broad spectrum of systems in the defense arena, generating new capabilities for reconnaissance and surveillance as well as other tactical applications.

Smart disposable microsensors can be deployed on the ground, in the air, under water, on bodies, in vehicles, and inside buildings. A system of networked sensors can detect and track threats (e.g., winged and wheeled vehicles, personnel, chemical and biological agents) and be used for weapon targeting and area denial. Each sensor node will have embedded processing capability, and will potentially have multiple onboard sensors, operating in the acoustic, seismic, infrared (IR), and magnetic modes, as well as imagers and microradars. Also onboard will be storage, wireless links to neighboring nodes, and location and positioning knowledge through the global positioning system (GPS) or local positioning algorithms.

Networked microsensors belong to the general family of sensor networks that use multiple distributed sensors to collect information on entities of interest. Table 1 summarizes the range of possible attributes in general sensor networks.

Current and potential applications of sensor networks include: military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structures monitoring. The sensors in these applications may be small or large, and the networks may be wired or wireless. However, ubiquitous wireless networks of microsensors probably offer the most potential in changing the world of sensing [2].

While sensor networks for various applications may be quite different, they share common technical issues. This paper will present a history of research in sensor networks (Section II), technology trends (Section III), new applications (Section IV), research issues and hard problems (Section V), and some examples of research results (Section VI).

II. HISTORY OF RESEARCH IN SENSOR NETWORKS

The development of sensor networks requires technologies from three different research areas: sensing, communication, and computing (including hardware, software, and

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Table 1
Attributes of Sensor Networks

Sensors	*Size*: small (e.g., micro-electro mechanical systems (MEMS)), large (e.g., radars, satellites) *Number*: small, large *Type*: passive (e.g., acoustic, seismic, video, IR, magnetic), active (e.g., radar, ladar) *Composition or mix*: homogeneous (same types of sensors), heterogeneous (different types of sensors) *Spatial coverage*: dense, sparse *Deployment*: fixed and planned (e.g., factory networks), ad hoc (e.g., air-dropped) *Dynamics*: stationary (e.g., seismic sensors), mobile (e.g., on robot vehicles)
Sensing entities of interest	*Extent*: distributed (e.g., environmental monitoring), localized (e.g., target tracking) *Mobility*: static, dynamic *Nature*: cooperative (e.g., air traffic control), non-cooperative (e.g., military targets)
Operating environment	Benign (factory floor), adverse (battlefield)
Communication	*Networking*: wired, wireless *Bandwidth*: high, low
Processing architecture	Centralized (all data sent to central site), distributed (located at sensor or other sites), hybrid
Energy availability	Constrained (e.g., in small sensors), unconstrained (e.g., in large sensors)

algorithms). Thus, combined and separate advancements in each of these areas have driven research in sensor networks. Examples of early sensor networks include the radar networks used in air traffic control. The national power grid, with its many sensors, can be viewed as one large sensor network. These systems were developed with specialized computers and communication capabilities, and before the term "sensor networks" came into vogue.

A. Early Research on Military Sensor Networks

As with many technologies, defense applications have been a driver for research and development in sensor networks. During the Cold War, the Sound Surveillance System (SOSUS), a system of acoustic sensors (hydrophones) on the ocean bottom, was deployed at strategic locations to detect and track quiet Soviet submarines. Over the years, other more sophisticated acoustic networks have been developed for submarine surveillance. SOSUS is now used by the National Oceanographic and Atmospheric Administration (NOAA) for monitoring events in the ocean, e.g., seismic and animal activity [3]. Also during the Cold War, networks of air defense radars were developed and deployed to defend the continental United States and Canada. This air defense system has evolved over the years to include aerostats as sensors and Airborne Warning and Control System (AWACS) planes, and is also used for drug interdiction.

These sensor networks generally adopt a hierarchical processing structure where processing occurs at consecutive levels until the information about events of interest reaches the user. In many cases, human operators play a key role in the system. Even though research was focused on satisfying mission needs, e.g., acoustic signal processing and interpretation, tracking, and fusion, it provided some key processing technologies for modern sensor networks.

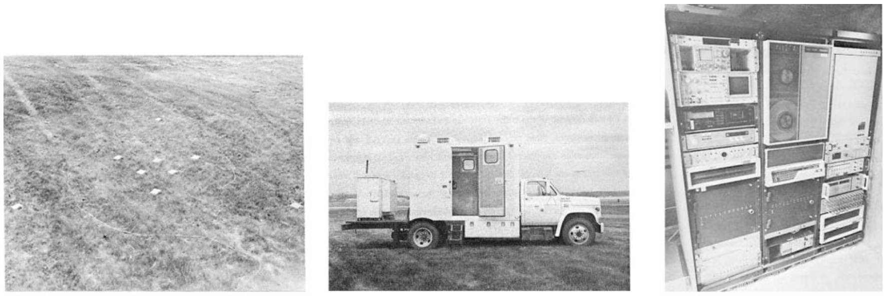
B. Distributed Sensor Networks Program at the Defense Advanced Research Projects Agency

Modern research on sensor networks started around 1980 with the Distributed Sensor Networks (DSN) program at the Defense Advanced Research Projects Agency (DARPA). By this time, the Arpanet (predecessor of the Internet) had been operational for a number of years, with about 200 hosts at universities and research institutes. R. Kahn, who was coinventor of the TCP/IP protocols and played a key role in developing the Internet, was director of the Information Processing Techniques Office (IPTO) at DARPA. He wanted to know whether the Arpanet approach for communication could be extended to sensor networks. The network was assumed to have many spatially distributed low-cost sensing nodes that collaborate with each other but operate autonomously, with information being routed to whichever node can best use the information.

It was an ambitious program given the state of the art. This was the time before personal computers and workstations; processing was done mostly on minicomputers such as PDP-11 and VAX machines running Unix and VMS. Modems were operating at 300 to 9600 Bd, and Ethernet was just becoming popular.

Technology components for a DSN were identified in a Distributed Sensor Nets workshop in 1978 [4]. These included sensors (acoustic), communication (high-level protocols that link processes working on a common application in a resource-sharing network [5]), processing techniques and algorithms (including self-location algorithms for sensors), and distributed software (dynamically modifiable distributed systems and language design). Since DARPA was sponsoring much artificial intelligence (AI) research at the time, the workshop also included talks on the use of AI for understanding signals and assessing situations [6], as well as various distributed problem-solving techniques [7]–[9]. Since very few technology components were available off the shelf, the resulting DSN program had to address distributed computing support, signal processing, tracking, and test beds. Distributed acoustic tracking was chosen as the target problem for demonstration.

Researchers at Carnegie Mellon University (CMU), Pittsburgh, PA, focused on providing a network operating system that allows flexible, transparent access to distributed resources needed for a fault-tolerant DSN. They developed



Acoustic Array Mobile Node Equipment Rack

Fig. 1. Components in the DSN test bed around 1985.

a communication-oriented operating system called Accent [10], whose primitives support transparent networking, system reconfiguration, and rebinding. Accent evolved into the Mach operating system [11], which found considerable commercial acceptance. Other efforts at CMU included protocols for network interprocess communication to support dynamic rebinding of active communicating computations, an interface specification language for building distributed system software, and a system for dynamic load balancing and fault reconfiguration of DSN software. All this was demonstrated in an indoor test bed with signal sources, acoustic sensors, and VAX computers connected by Ethernet.

Researchers at the Massachusetts Institute of Technology (MIT), Cambridge, focused on knowledge-based signal processing techniques [12] for tracking helicopters using a distributed array of acoustic microphones by means of signal abstractions and matching techniques. Signal abstractions view signals as consisting of multiple levels, with higher levels of abstraction (e.g., peaks) obtained by suppressing detailed information in lower levels (e.g., spectrum). They provide a conceptual framework for thinking about signal processing systems that resemble what people use when interactively processing and interpreting real-world signals. By incorporating human heuristics, this approach was designed for high signal-to-noise ratio situations where models are lacking. In addition, MIT also developed the Signal Processing Language and Interactive Computing Environment (SPLICE) for DSN data analysis and algorithm development, and Pitch Director's Assistant for interactively estimating fundamental frequency using domain knowledge.

Moving up the processing chain, tracking multiple targets in a distributed environment is significantly more difficult than centralized tracking. The association of measurements to tracks and estimation of target states (position and velocity) given associations have to be distributed over the sensor nodes. In the 1980s, Advanced Decision Systems (ADS), Mountain View, CA, developed a multiple-hypothesis tracking algorithm to deal with difficult situations involving high target density, missing detections, and false alarms, and decomposed the algorithm for distributed implementation [13], [14]. Multiple-hypothesis tracking is now a standard approach for difficult tracking problems.

For demonstration, MIT Lincoln Laboratory developed the real-time test bed for acoustic tracking of low-flying aircraft [15]. The sensors were acoustic arrays (nine microphones arranged in three concentric triangles with the largest being 6 m across). A PDP11/34 computer and an array processor processed the acoustic signals. The nodal computer (for target tracking) consists of three MC68000 processors with 256-kB memory and 512-kB shared memory, and a custom operating system. Communication was by Ethernet and microwave radio. Fig. 1 (extracted from [16]) shows the acoustic array (nine white microphones), the mobile vehicle node with an acoustically quiet generator in the back, and the equipment rack with the acoustic/tracking node and gateway node in the vehicle. Note the size of the system and that practically all components in the network were custom built. That was the state of the art in the early 1980s. The DSN test bed was demonstrated with low-flying aircraft, which was successfully tracked with acoustic sensors as well as TV cameras. The tracking algorithm was fairly sophisticated, since the acoustic propagation delay is significant relative to the speed of the aircraft.

Another test bed in the DSN program was the distributed vehicle monitoring test bed at the University of Massachusetts, Amherst. This was a research tool for empirically investigating distributed problem solving in networks. The distributed knowledge-based problem solving approach used a functionally accurate, cooperative architecture consisting of a network of Hearsay-II nodes (blackboard architecture with knowledge sources). Different local node control approaches were explored [17].

C. *Military Sensor Networks in the 1980s and 1990s*

Even though early researchers on sensor networks had in mind large numbers of small sensors, the technology for small sensors was not quite ready. However, planners of military systems quickly recognized the benefits of sensor networks, which become a crucial component of network-centric warfare [18]. In platform-centric warfare, platforms "own" specific weapons, which in turn own sensors in a fairly rigid architecture. In other words, sensors and weapons are mounted with and controlled by separate platforms that operate independently. In network-centric warfare, sensors do not necessarily belong to weapons or platforms. Instead, they collaborate with each other over a communication network, and information is sent to the appropriate "shooters." Sensor networks can improve detection and tracking performance through multiple observations, geometric and phenomenological diversity, extended detection range, and faster response time. Also, the development cost is lower by exploiting commercial network technology and common network interfaces.

An example of network-centric warfare is the Cooperative Engagement Capability (CEC) [19] developed by the U.S. Navy. This system consists of multiple radars collecting data on air targets. Measurements are associated by a processing node "with reporting responsibility" and shared with other nodes that process all measurements of interest. Since all nodes have access to essentially the same information, a "common operating picture" essential for consistent military operations is obtained. Other military sensor networks include acoustic sensor arrays for antisubmarine warfare such as the Fixed Distributed System (FDS) and the Advanced Deployable System (ADS), and unattended ground sensors (UGS) [20] such as the Remote Battlefield Sensor System (REMBASS) and the Tactical Remote Sensor System (TRSS).

D. Sensor Network Research in the 21st Century

Recent advances in computing and communication have caused a significant shift in sensor network research and brought it closer to achieving the original vision. Small and inexpensive sensors based upon microelectromechanical system (MEMS) [21] technology, wireless networking, and inexpensive low-power processors allow the deployment of wireless ad hoc networks for various applications. Again, DARPA started a research program on sensor networks to leverage the latest technological advances.

The recently concluded DARPA Sensor Information Technology (SensIT) program [22] pursued two key research and development thrusts. First, it developed new networking techniques. In the battlefield context, these sensor devices or nodes should be ready for rapid deployment, in an *ad hoc* fashion, and in highly dynamic environments. Today's networking techniques, developed for voice and data and relying on a fixed infrastructure, will not suffice for battlefield use. Thus, the program developed new networking techniques suitable for highly dynamic *ad hoc* environments. The second thrust was networked information processing, i.e., how to extract useful, reliable, and timely information from the deployed sensor network. This implies leveraging the distributed computing environment created by these sensors for signal and information processing in the network, and for dynamic and interactive querying and tasking the sensor network.

SensIT generated new capabilities relative to today's sensors. Current systems such as the Tactical Automated Security System (TASS) [23] for perimeter security are dedicated rather than programmable. They use technologies based on transmit-only nodes and a long-range detection paradigm. SensIT networks have new capabilities. The networks are interactive and programmable with dynamic tasking and querying. A multitasking feature in the system allows multiple simultaneous users. Finally, since detection ranges are much shorter in a sensor system, the software and algorithms can exploit the proximity of devices to threats to drastically improve the accuracy of detection and tracking. The software and the overall system design supports low latency, energy-efficient operation, built-in autonomy and survivability, and low probability of detection of operation. As a result, a network of SensIT nodes can support detection, identification, and tracking of threats, as well as targeting and communication, both within the network and to outside the network, such as an overhead asset.

III. TECHNOLOGY TRENDS

Current sensor networks can exploit technologies not available 20 years ago and perform functions that were not even dreamed of at that time. Sensors, processors, and communication devices are all getting much smaller and cheaper. Commercial companies such as Ember, Crossbow, and Sensoria are now building and deploying small sensor nodes and systems. These companies provide a vision of how our daily lives will be enhanced through a network of small, embedded sensor nodes. In addition to products from these companies, commercial off-the-shelf personal digital assistants (PDAs) using Palm or Pocket PC operating systems contain significant computing power in a small package. These can easily be "ruggedized" to become processing nodes in a sensor network. Some of these devices even have built-in sensing capabilities, such as cameras. These powerful processors can be hooked to MEMS devices and machines along with extensive databases and communication platforms to bring about a new era of technologically sophisticated sensor nets.

Wireless networks based upon IEEE 802.11 standards can now provide bandwidth approaching those of wired networks. At the same time, the IEEE has noticed the low expense and high capabilities that sensor networks offer. The organization has defined the IEEE 802.15 standard for personal area networks (PANs), with "personal networks" defined to have a radius of 5 to 10 m. Networks of short-range sensors are the ideal technology to be employed in PANs. The IEEE encouragement of the development of technologies and algorithms for such short ranges ensures continued development of low-cost sensor nets [24]. Furthermore, increases in chip capacity and processor production capabilities have reduced the energy per bit requirement for both computing and communication. Sensing, computing, and communications can now be performed on a single chip, further reducing the cost and allowing deployment in ever larger numbers.

Looking into the future, we predict that advances in MEMS technology will produce sensors that are even more capable and versatile. For example, Dust Inc., Berkeley, CA, a company that sprung from the late 1990s Smart Dust research project [25] at the University of California, Berkeley, is building MEMS sensors that can sense and communicate and yet are tiny enough to fit inside a cubic millimeter. A Smart Dust optical mote uses MEMS to aim submillimeter-sized mirrors for communications. Smart Dust sensors can be deployed using a 3 × 10 mm "wavelet"

Table 2
Three Generations of Sensor Nodes

	Yesterday (1980's – 1990's)	Today (2000 – 2003)	Tomorrow (2010)
Manufacturer	Custom contractors, e.g., for TRSS	Commercial: Crossbow Technology, Inc. Sensoria Corp., Ember Corp.	Dust, Inc. and others to be formed
Size	Large shoe box and up	Pack of cards to small shoe box	Dust particle
Weight	Kilograms	Grams	Negligible
Node architecture	Separate sensing, processing and communication	Integrated sensing, processing and communication	Integrated sensing, processing and communication
Topology	Point-to-point, star	Client server, peer to peer	Peer to peer
Power supply lifetime	Large batteries; hours, days and longer	AA batteries; days to weeks	Solar; months to years
Deployment	Vehicle-placed or air-drop single sensors	Hand-emplaced	Embedded, "sprinkled" left-behind

Fig. 2. Three generations of sensor nodes.

shaped like a maple tree seed and dropped to float to the ground. A wireless network of these ubiquitous, low-cost, disposable microsensors can provide close-in sensing capabilities in many novel applications (as discussed in Section IV).

Table 2 compares three generations of sensor nodes; Fig. 2 shows their sizes.

IV. NEW APPLICATIONS

Research on sensor networks was originally motivated by military applications. Examples of military sensor networks range from large-scale acoustic surveillance systems for ocean surveillance to small networks of unattended ground sensors for ground target detection. However, the availability of low-cost sensors and communication networks has resulted in the development of many other potential applications, from infrastructure security to industrial sensing. The following are a few examples.

A. Infrastructure Security

Sensor networks can be used for infrastructure security and counterterrorism applications. Critical buildings and facilities such as power plants and communication centers have to be protected from potential terrorists. Networks of video, acoustic, and other sensors can be deployed around these facilities. These sensors provide early detection of possible threats. Improved coverage and detection and a reduced false alarm rate can be achieved by fusing the data from multiple sensors. Even though fixed sensors connected by a fixed communication network protect most facilities, wireless ad hoc networks can provide more flexibility and additional coverage when needed. Sensor networks can also be used to detect biological, chemical, and nuclear attacks. Examples of such networks can be found in [26], which also describes other uses of sensor networks.

B. Environment and Habitat Monitoring

Environment and habitat monitoring [27] is a natural candidate for applying sensor networks, since the variables to be monitored, e.g., temperature, are usually distributed over a large region. The recently started Center for Embedded Network Sensing (CENS) [28], Los Angeles, CA, has a focus on environmental and habitat monitoring. Environmental sensors are used to study vegetation response to climatic trends and diseases, and acoustic and imaging sensors can identify, track, and measure the population of birds and other species. On a very large scale, the System for the Vigilance of the Amazon (SIVAM) [29] provides environmental monitoring, drug trafficking monitoring, and air traffic control for the Amazon Basin. Sponsored by the government of Brazil, this large sensor network consists of different types of interconnected sensors including radar, imagery, and environmental sensors. The imagery sensors are space based, radars are located on aircraft, and environmental sensors are mostly on the ground. The communication network connecting the sensors operates at different speeds. For example, high-speed networks connect sensors on satellites and aircraft, while low-speed networks connect the ground-based sensors.

C. Industrial Sensing

Commercial industry has long been interested in sensing as a means of lowering cost and improving machine (and perhaps user) performance and maintainability. Monitoring machine "health" through determination of vibration or wear and lubrication levels, and the insertion of sensors into regions inaccessible by humans, are just two examples of industrial applications of sensors. Several years ago, the IEEE and the National Institute for Standards and Technology (NIST) launched the P1451 Smart Transducer

Interface Standard [30] to enable full plug-and-play of sensors and networks in industrial environments. Factories have continued to automate production and assembly lines with remote sensing nets, implementing sophisticated on-line quality control tests enabled by the sensors. Remote, wireless sensors in particular can enable a factory to be instrumented after the fact to ensure and maintain compliance with federal safety and guidelines while keeping installation costs low.

Spectral sensors are one example of sensing in an industrial environment. From simple optical devices such as optrodes and pH probes to true spectral devices that can function as miniature spectrometers, optical sensors can replace existing instruments and perform material property and composition measurements. Optical sensing is also facilitated by miniaturization, as low-cost charge-coupled device (CCD) array devices and microengineering enable smaller, smarter sensors. The goal of this and other industrial sensing is to enable multipoint or matrix sensing: inputs from hundreds or thousands of sensors feed into databases that can be queried in any number of ways to show real-time information on a large or small scale.

D. Traffic Control

Sensor networks have been used for vehicle traffic monitoring and control for quite a while. Most traffic intersections have either overhead or buried sensors to detect vehicles and control traffic lights. Furthermore, video cameras are frequently used to monitor road segments with heavy traffic, with the video sent to human operators at central locations. However, these sensors and the communication network that connect them are costly; thus, traffic monitoring is generally limited to a few critical points. Inexpensive wireless ad hoc networks will completely change the landscape of traffic monitoring and control. Cheap sensors with embedded networking capability can be deployed at every road intersection to detect and count vehicle traffic and estimate its speed. The sensors will communicate with neighboring nodes to eventually develop a “global traffic picture” which can be queried by human operators or automatic controllers to generate control signals.

Another more radical concept [33] has the sensors attached to each vehicle. As the vehicles pass each other, they exchange summary information on the location of traffic jams and the speed and density of traffic, information that may be generated by ground sensors. These summaries propagate from vehicle to vehicle and can be used by drivers to avoid traffic jams and plan alternative routes.

V. HARD PROBLEMS AND TECHNICAL CHALLENGES

Sensors networks in general pose considerable technical problems in data processing, communication, and sensor management (some of these were identified and researched in the first DSN program). Because of potentially harsh, uncertain, and dynamic environments, along with energy and bandwidth constraints, wireless ad hoc networks pose additional technical challenges in network discovery, network control and routing, collaborative information processing, querying, and tasking.

A. Ad Hoc Network Discovery

Knowledge of the network is essential for a sensor in the network to operate properly. Each node needs to know the identity and location of its neighbors to support processing and collaboration. In planned networks, the topology of the network is usually known *a priori*. For ad hoc networks, the network topology has to be constructed in real time, and updated periodically as sensors fail or new sensors are deployed [31]. In the case of a mobile network, since the topology is always evolving, mechanisms should be provided for the different fixed and mobile sensors to discover each other. Global knowledge generally is not needed, since each sensor node interacts only with its neighbors. In addition to knowledge of the topology, each sensor also needs to know its own location [32]. When self-location by GPS is not feasible or too expensive, other means of self-location, such as relative positioning algorithms, have to be provided.

B. Network Control and Routing

The network must deal with resources—energy, bandwidth, and the processing power—that are dynamically changing, and the system should operate autonomously, changing its configuration as required. Since there is no planned connectivity in ad hoc networks, connectivity must emerge as needed from the algorithms and software. Since communication links are unreliable and shadow fading may eliminate links, the software and system design should generate the required reliability. This requires research into issues such as network size or the number of links and nodes needed to provide adequate redundancy. Also, for networks on the ground, RF transmission degrades with distance much faster than in free space, which means that communication distance and energy must be well managed. Protocols must be internalized in design and not require operator intervention.

Alternative approaches to traditional Internet methods [such as Internet Protocols (IP)], including mobile IP, are needed. One of the benefits of not requiring IP addresses at each node is that one can deploy network devices in very large numbers. Also, in contrast to the case of IP, routes are built up from geoinformation, on an as-needed basis, and optimized for survivability and energy. This is a way to form connections on demand, for data-specific or application-specific purposes. IP is not likely to be a viable candidate in this context, since it needs to maintain routing tables for the global topology, and because updates in a dynamic sensor network environment incur heavy overhead in terms of time, memory, and energy.

Survivability and adaptation to the environment are ensured through deploying an adequate number of nodes to provide redundancy in paths, and algorithms to find the right paths. Diffusion routing methods, which rely only upon information at neighboring nodes, are a way to address this [33], although such methods may not achieve the information-theoretic capacity of a spatially distributed wireless network [34]. Another important design issue is the investigation of how system parameters such as network size, and density of nodes per square mile affect the tradeoffs between latency, reliability, and energy.

C. Collaborative Signal and Information Processing

The nodes in an ad hoc sensor network collaborate to collect and process data to generate useful information. Collaborative signal and information processing over a network is a new area of research and is related to distributed information fusion. Important technical issues include the degree of information sharing between nodes and how nodes fuse the information from other nodes. Processing data from more sensors generally results in better performance but also requires more communication resources (and, thus, energy). Similarly, less information is lost when communicating information at a lower level (e.g., raw signals), but requires more bandwidth. Therefore, one needs to consider the multiple tradeoffs between performance and resource utilization in collaborative signal and information processing using microsensors.

When a node receives information from another node, this information has to be combined and fused with local information. Fusion approaches range from simple rules of picking the best result to model-based techniques that consider how the information is generated. Again there is a tradeoff between performance and robustness. Simple fusion rules are robust but suboptimal while more sophisticated and higher performance fusion rules may be sensitive to the underlying models. In a networked environment, information may arrive at a node after traveling over multiple paths. The fusion algorithm should recognize the dependency in the information to be fused and avoid double counting. Keeping track of data pedigree is an approach used in networks with large and powerful sensor nodes, but this approach may not be practical for ad hoc networks with limited processing and communication resources.

Sensor networks are frequently used in the detection, tracking, and classification of targets [13]. Data association is an important problem when multiple targets are present in a small region. Each node must associate its measurements of the environment with individual targets. In addition, targets detected by one node have to be associated with targets detected by other nodes to avoid duplication and enable fusion. Optimal data association is computationally expensive and requires significant bandwidth for communication. Thus distributed data association is also a tradeoff between performance and resource utilization, requiring distributed data association algorithms tailored to sensor nets.

Other processing issues include how to meet mission latency and reliability requirements, and how to maximize sensor network operational life. A dense network of cheap sensors may allow spatial sampling without the need for expensive algorithms. These algorithms must be asynchronous, as the processor speeds and communication capabilities may vary or even disappear and reappear. Sensor nodes must determine results with progressively increasing accuracy, and so the processes can be terminated when enough precision is gained.

D. Tasking and Querying

A sensor field is like a database with many unique features. Data is dynamically acquired from the environment, as opposed to being entered by an operator. The data is distributed across nodes, and geographically dispersed nodes are connected by unreliable links. These features render the database view more challenging, particularly for military applications given the low-latency, real-time, and high-reliability requirements of the battlefield.

It is important that users have a simple interface to interactively task and query the sensor network. An example of a human-network interface is a handheld unit that accepts speech input. The users should be able to command access to information, e.g., operational priority and type of target, while hiding details about individual sensors. One challenge is to develop a language for querying and tasking, as well as a database that can be readily queried. [35]. Other challenges include finding efficient distributed mechanisms for query and task compilation and placement, data organization, and caching.

Mobile platforms can carry sensors and query devices. As a result, seamless internetworking between mobile and fixed devices in the absence of any infrastructure is a critical and unique requirement for sensor networks. For example, an airborne querying device could initiate a query, and then tell the ground sensor network that it will be flying over a specific location after a minute, where the response to the query should be exfiltrated.

E. Security

Since the sensor network may operate in a hostile environment, security should be built into the design and not as an afterthought. Network techniques are needed to provide low-latency, survivable, and secure networks. Low probability of detection communication is needed for networks because sensors are being envisioned for use behind enemy lines. For the same reasons, the network should be protected again intrusion and spoofing.

VI. SOME RECENT RESULTS

Research sponsored by the DARPA SensIT and other programs has addressed the challenges described previously. The following are examples of some recent research results.

A. Localized Algorithms and Directed Diffusion [33]

As discussed previously, even though centralized algorithms that collect data from multiple sensor nodes can potentially provide the best performance, they are undesirable because of high communication cost and lack of robustness and reliability. In localized (or distributed) algorithms, the sensor nodes only communicate with sensors within a neighborhood. Localized algorithms are attractive because they are robust to network changes and node failures. The communication cost also scales well with increasing network size. However, localized algorithms are difficult to design because of the potentially complicated relationship between local behavior and global behavior. Algorithms that are locally optimal may not perform well in a global sense. How to optimally distribute the computation of a centralized algorithm in a distributed implementation continues to be a research problem.

Estrin *et al.* [33] developed directed diffusion routing algorithms that belong to the class of localized algorithms. Diffusion is a form of broadcast routing that does not specify a destination node address (such as the IP address in Internet protocols). Packets are forwarded to neighboring nodes, and a direction or gradient is overlaid to control the broadcast or forwarding of the packet, which eventually reaches the destination. The gradient could be based on geographic information or other attributes such as power, congestion, and other resources available in the network nodes. For example, if a user application based at location L, is interested in events occurring at and around location M, then the nodes around M would forward information packets to neighboring nodes that are in the direction of L; and intermediate nodes would also forward to their neighbors in the direction of L. Gradients can also be established in terms of information producers and consumers via publish–subscribe mechanisms, and consumer interests in specific information types propagated over the network. Intermediate nodes may cache or transform the data locally to increase efficiency, robustness and scalability.

Research results indicate the efficiency of directed diffusion. It requires considerably less energy than standard routing mechanisms such as flooding and omniscient multicast. For instance, simulation and experimental results of directed diffusion in representative sensor networks [36] indicate that multicast protocols (such as omniscient multicast [36], which is an IP-based multicast routing technique) requires less than half the energy required for flooding, and diffusion requires only 60% of the energy needed for even multicast. These savings are achieved by eliminating paths spent delivering redundant data, and from in-network aggregation such as through intermediate nodes suppressing duplicate location estimates.

B. Distributed Tracking in Wireless Ad Hoc Networks [37]

Tracking mobile targets is an important application of sensor networks for both military and defense systems. Even though target tracking has been widely studied for sensor networks with large nodes and distributed tracking algorithms are available [13], tracking in ad hoc networks with microsensors poses different challenges due to communication, processing and energy constraints. In particular, the sensors should collaborate and share data to exploit the benefits of sensor data fusion, but this should be done without sending data requests to and collecting data from all sensors, thus overloading the network and using up the energy supply.

Zhao *et al.* [38] addressed the dynamic sensor collaboration problem in distributed tracking to determine dynamically which sensor is most appropriate to perform the sensing, what needs to be sensed, and to whom to communicate the information. They developed the information-driven sensor querying (IDSQ) approach, enabling collaboration based upon resource constraints and the cost of transmitting information. Each sensor computes the predicted information utility of a piece of nonlocal sensor data and uses this measure to determine from which sensor to request data. Information utility functions employed include entropy, Mahalanobis distance, and a measure on expected posterior distribution. This approach was demonstrated with simulations as well as experimental data collected from the field.

As discussed in Section V-C, data association is needed in tracking multiple targets that are close to each other relative to the sensor measurement error. Again, distributed data association algorithms are available for networks with large nodes but are computationally too expensive to implement on ad hoc networks. An approximate approach for cheap data association (called identity management) was proposed and demonstrated in [39].

C. Distributed Classification in Sensor Networks Using Mobile Agents [40]

In a traditional sensor network, data is collected by individual sensors and sent to (possibly multiple) fusion nodes for processing. Because the bandwidth of a wireless sensor network is typically lower than that of a wired network, a sensor network's communications requirements may exceed their capacities. Mobile agents have been proposed as a solution to this dilemma [40]. In a mobile-agent-based DSN, data stay at each local site or sensor, while the integration or fusion code is moved to the data. Communication bandwidth requirement may be reduced if the agent is smaller in size than the data. If this assumption holds, then the sensor network is more scalable, since the performance of the network is not affected by an increase in the number of sensors. The network can also adapt better to the network load and agents can be programmed to carry specific fusion processes. Distributed target classification has been used to demonstrate the effectiveness of the approach.

VII. CONCLUSION

When the concept of DSNs was first introduced more than two decades ago, it was more a vision than a technology ready to be exploited. The early researchers in DSN were severely handicapped by the state of the art in sensors, computers, and communication networks. Even though the benefits of sensor networks were quickly recognized, their application was mostly limited to large military systems. Technological advances in the past decade have completely changed the situation. MEMS technology, more reliable wireless communication, and low-cost manufacturing have resulted in small, inexpensive, and powerful sensors with embedded processing and wireless networking capability. Such wireless sensor networks can be used in many new applications, ranging from environmental monitoring to industrial sensing, as well as traditional military applications. In fact, the applications are only limited by our imagination. Networks of small, possibly microscopic sensors embedded in the fabric of society: in buildings and machinery, and even on people, performing automated continual and discrete monitoring, could drastically enhance our understanding of our physical environment.

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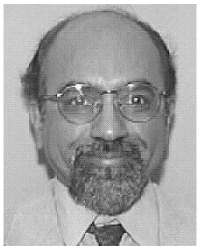

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