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Future scenarios of parallel computing: Distributed sensor networks

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Dedication to Stefano Levialdi.[1]

Abstract

Over the past few years, motivated by the accelerating technological convergence of sensing, computing and communications, there has been a growing interest in potential and technological challenges of Wireless Sensor Network. This paper will introduce a wide range of current basic research lines dealing with ad hoc networks of spatially distributed systems, data rate requirements and constraints, real-time fusion and registration of data from distributed sensors, cooperative control, hypothesis generation, and network consensus filtering. This technical domain has matured to the point where a number of industrial products and systems have appeared. The presentation will also describe the state of the art regarding current and soon-to-appear applications.

Keywords: Wireless Sensor Networks; Massively parallel processing; MEMS; Motes; Distributed sensor networks

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[1] Since the end of the 1960s Stefano Levialdi is, for the Italian community, a guide to the exciting subjects which are at the cutting edge of research in image processing initially, later in pattern recognition and computer vision, and in the last decade in visual languages and human–machine interfaces. His critical evaluation of our activity lines together with his human traits and personality, helps us to develop new high-level initiatives not only in research and in promoting the field with the organization of top-level workshops, conferences and special issues of scientific magazines, but also in growing new generations of researchers and even research communities. We are indebted to him for his open-minded view on how our field is evolving and for all our contributions, under his influence, to this progress.

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1. Introduction

With the advent of multiprocessor systems arose the problem of optimizing the computing resources (processors, memories, connections, etc). In 1983, Stefano Levialdi and one of us, in a keynote paper [1] said "… architecture and technology give the highest contribution to the overall speed gain. A good match between the architecture and a class of algorithms in IP is obtained when the data from pixel is available to the processor in order to compute the new pixel value at the clock rate of the machine, i.e. avoiding time delays due to the inter-processor communication or memory contention." Along these lines, a diagram was presented in which the existing match between classes of machines (built or sometimes just proposed), data structures, and computational structure was highlighted.

Five years later the critical issues concerning real time for vision tasks were still unresolved. The same authors continued [2]: "The complexity of these systems makes their tuning to the application difficult to achieve. Knowledge is required both from the system capabilities as well as from the task domain in order to fully exploit the available resources." In this period, an experimental law under the name of (re-evaluated) Amdahl's law, pointed out that, due to coordination overhead and serial components, the speed-up factor of a parallel architecture was very far from the theoretical maximum given by the number of processors [3,4]. But as it was explicitly expressed in [2], new speed-up strategies could allow even the overcoming of a linear scaling assumption: "Basically a linear scaling assumption may be formulated so that the time decreases proportionally to the number of available independent processors but such assumption may be overcome by the use of clever strategies such as planning in pyramidal architectures". The paper contained a real-time proposal based on reducing the data under analysis and the problem space to explore, by means of a problem solving strategy supported by a hierarchical architecture.

Nevertheless, in 1995, in the era of massively parallel systems, despite the impressive hardware evolution (in 12 years, power and memory sizes had increased by three order of magnitude) many critical systems concerning the execution of vision tasks were still unresolved, in fact [5]: "the adaptation of massively parallel machines to the users' needs is so difficult that actual performances on real application programs still remain way below their theoretical peak speed".

A perhaps hasty conclusion on this 'one long argument' was drawn 10 years later on [6] where: "we discuss the phylogenies of computer architectures for image processing along similar lines to those elicited in Mayr's framework (i.e. 'One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought') … In a similar way to the biological natural selection, the same phenomenon has appeared in computer vision architectures. The adaptation to commercial markets has driven, ex post facto, the selection process". The conclusion was that, as for dinosaurs, the massive architectures had been extinguished.

However, the same paper also added that "the winning solution to the architectural problem for image processing tasks will be to choose standard processors (with always more computation power following Moore's law) but in an effective cooperative distributed environment (taking advantage of Gilder's law)."

Indeed, this latter solution is being realized today by the new attractive technology of distributed sensor networks. Starting from compact elements composed of 'smart sensors with the ability to talk, to listen, and to interact with the data', the 'sensornet' paradigm is now progressing towards an holistic, 'massively parallel' system of motes connected in a wireless multi-hop network that may reach over 10,000 nodes with an end-to-end reliability of more than 99.9%. But, after all, what is this new platform if not a modification of the past fine-grained machines (maybe hierarchical) which just improved the I/O modality through the adoption of MEMS technology?

2. Recent developments of hardware technology

Collections of cooperating sensors have been investigated in robotics for over 30 years in the research areas of robotics, sensor fusion, and data fusion.

Wireless technology is changing the understanding of this field. Recent developments in short-ranged wireless communication (5–30 m) open completely new possibilities for sensors and computing. Large numbers of sensor platforms (10^2–10^4) are now able to communicate and share sensory capabilities, data, memory, and processing power. Wireless networks allow for a flexible and quick deployment, and an easy plug-in and out of additional nodes as the application requires. The technological innovation is investing this field at a rapid pace: wireless communication protocols are being diversified and refined, and sensor platforms are becoming smarter or smaller or both.

The effort of producing reliable wireless personal area networks (WPAN) started in the mid 1990s. In those days prominent industrial companies united into alliances to create solutions for WPAN. Meanwhile, the IEEE had formed the 802 working groups towards the same goal, and in 1999 it created group 15 to address low-power WPAN. These efforts brought to a constellation of standards which cover a wide variety of ranges and data rates. Among the others, Bluetooth and the 802.15.4 have attracted the highest interest of industry and research for distributed sensors scenarios.

Sensor platforms are likewise undergoing a revolution in design and capabilities. One line of development moves towards smarter sensors, equipped with embedded processors and memory to enhance local processing. For example, the Eye Society cameras developed at MIT Media Lab include a StrongARM SA-1110 processor running at 206 MHz and 32 MB of flash memory [7]. A second development line stresses miniaturization over computational power. The key concept in this case is that of a "smart dust", i.e. a collection of a very large number of micro sensors spread over a territory like dust and able to tackle complicated sensory tasks by creating a network and sharing information and computational resources. The Mica mote, designed by UC Berkeley, is probably the most popular micro sensor platform used in research (Fig. 1) [8].

Like what happened for computers and the Internet, we may imagine a future when sensors will be connected in an "Internet of Things". In this scenario, network/data management software will have to handle sensors of inhomogeneous technology. Starting from today algorithms, software designers should pursue a compatibility with the most exigent platforms, i.e. micro sensor platforms. A typical micro sensor platform is a small battery-powered board including a microprocessor, a memory, an RF transceiver, and an antenna. These elements are reduced to the limit of the lowest energy consumption and dimensions to make sensor nodes ubiquitous and of long-lasting autonomy. Wireless connection (most often based on 802.15.4) facilitates the deployment of sensors and provides a remote access to the local memory.

A typical distributed sensor network is composed of many sensor nodes (sources) and one collector node (sink) (Fig. 2). Data flow from sources to sink, and control messages

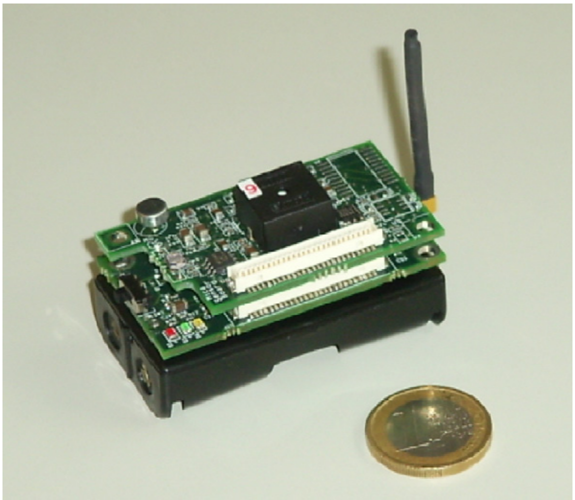

Fig. 1. MICAz sensor mote hardware.

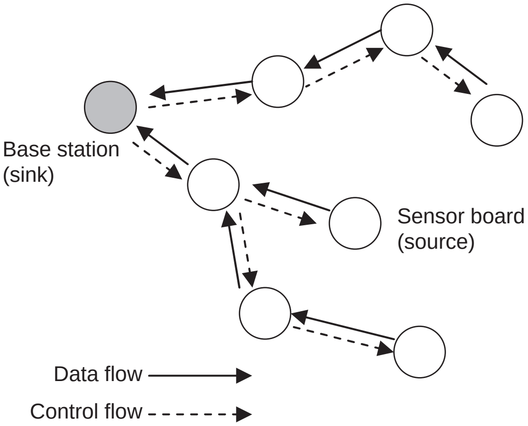

Fig. 2. Typical configuration of a simple sensor network topology.

follow the inverse direction. More elaborate architectures may include multiple sinks, heterogeneous nodes, moving nodes, or a hierarchical organization in clusters.

The sink node—or 'base station'—usually possesses more advanced hardware and acts as network access point. On the opposite, source nodes suffer from the limitations imposed by the battery lifetime: sensors, processor, and memory are generally low-performing. RF communications impose that a hardware packet management is included to avoid interrupting the CPU when a bit is received—whether significant or noisy. Also the communication protocol must cope with energy.

One important constraint of micro sensor nodes is their limited memory. For example, the Mica2 node has only 4 kB of SRAM memory for the stack, and 128 kB of program flash memory [9]. It has been argued that such limits will be overcome by Moore's law. However, most experts are convinced that in the short term new technologies will move towards a lower price per piece rather than increasing resources per node. The limited memory imposes to make drastic choices on the complexity level of embedded software [10]. The possible solutions range from ad hoc software (i.e. a single application runs and is hard-coded in the hardware), up to complex operating systems able to manage multiple applications like standard PC-OS (e.g. consider PDAs that use Windows Mobile PocketPC OS or Embedded Linux). Because of the limited hardware resources, applications can be designed to manage directly all hardware. However, an OS, even if small, is useful for application developers. Several OS have been proposed: a popular OS is TinyOS [11], an open-source operating system that implements a component-based architecture specifically designed for resource-limited WSNs; recently, more advanced OS are appearing, one example is MANTIS OS (MOS) [12], a C-based OS with a 500B footprint and automatic preemptive multithreading.

3. Distributed data management and hypothesis formation

Data management is the task of collecting data from sensors, storing data in the network, and efficiently delivering data to the users (the sinks). Accessing, processing, and transmitting data consume power. Thus, in battery-powered micro sensors, a trade-off arises between low energy consumption vs. timeliness of data delivery, accuracy, network latency, and bandwidth use.

Data management systems for WSN should be energy-efficient, scalable, and robust to failures (of hardware, of network topology, etc.). Due to unpredictable deployment, unknown network size, unreliable radio communications, and self-organizing requirements, data storage and distribution strategies should be applicable to any topology and adaptive to topology changes. Data replication and route redundancy have been identified as the elective means to provide robustness to data loss in WSN. Also, local management and processing strategies have shown advantages vs. more traditional global approaches. Local strategies pursue both energy-efficiency and scalability, because they imply short-range transmission and can be applied to hierarchical clusters in large-scale scenarios.

The strategy of data management strongly depends of the metaphor used to understand a sensor network. Up to date, the proposed paradigms are: (I) distributed database: definitely the most popular [13–16]. Data gathering is formulated as a database retrieval problem. Sensors act as distributed storage points, and are addressed on demand of the user (a sink). Sensor programming coincides with query dissemination and processing; (II) agent system: sensors are agents interacting according to social paradigms. Macro-programming is based on modifying global parameters of social behaviors and goals [17]. Agents maintain a list of task-related priorities and plan their actions (i.e. sensing and communication) in the scope of group strategies [7,18] and (III) mobile software agent: agents, in the form of programs, move across the network by replicating their code from one node to another. When an agent leaves a node, it may delete its data memory or keep it. The agent performs detection tasks locally, and spreads in epidemic fashion when an event is detected [19].

The problems described in previous paragraphs highlight the need to adopt new software paradigms for distributed computation. The naive strategy of collecting all data in a central computing node with a high computational power does not optimize the use of energy-costly transmissions. Indeed in most cases we are interested in an estimate of a small number of parameters rather than in all raw data. Instead of computing such parameters on the sink node, a better approach suggests that each node contributes to the calculus. Scalability must be pursued when designing such local approaches.

"Decentralized" and "distributed" algorithms are two common solutions. Decentralized algorithms assume that each node is linked to every other node in the network. As a consequence the total number of links is $O(n^2)$ (where n is the number of sensors), so decentralized algorithms scale with difficulty. Distributed algorithms are based on networks in which the number of links is $O(n)$ or at most $O(n\log(n))$. A fully connection scheme is therefore not allowed in distributed computing. It is interesting to notice that these two families have dramatically different performances in terms of communication costs.

As an example of distributed computing, Olfati-Saber et al. in [20] propose a new algorithm for the "consensus filter". Consensus filters are distributed algorithms that address the problem of averaging time-varying signals with a scalable Kalman filtering scheme. They consider a sensor network of size n where each node measures a signal corrupted by a Gaussian noise:

$$u_i(t) = r(t) + v_i(t), \quad i = 1, \ldots, n.$$

In most applications, $r(t)$ is a low frequency signal while $v(t)$ is a high-frequency noise. The proposed consensus filter is equivalent to a low-pass filter. The approach has been simulated in sensor networks with a regular topology (each node has a degree 6) and in a random network: each node is randomly localized with a uniform distribution (nodes have a mean degree 7.1). The authors demonstrate that the proposed distributed Kalman filter algorithms can track relatively fast varying signals.

In [21] the authors propose a distance-based fusion algorithm for the classification of moving vehicles with low communication costs. Its main characteristic is the use of source–target distance as a parameter to select the subset of reliable sensors that contribute to the final parameter estimate: sensors far from the target have a significantly lower chance to produce a reliable value.

The problem of energy consumption is tackled in [22] in a different manner. In order to obtain a long life network the authors propose an adaptive sampling based on a two steps approach. In the first step (preview step) only a subset of sensors are active and produce a raw estimate of the environment parameters. The second step (refinement step) is based on the previous results and activates the most promising nodes to refine the previous, partial results. This approach is based on a central computation and coordination node. The low energy consumption is obtained by maintaining the number of active sensors as small as possible.

A different approach is proposed in [23]. The network identifies a path connecting all sensors, so that each node is visited only once. Global average of a parameter can be evaluated in a single process flushing from the start node to the ending one. At each step the node adds only the local estimate of the parameter. The algorithm needs only $O(n)$ bits to be transmitted in the network. The authors demonstrate that such approach is less consuming than traditional data fusion algorithms.

4. An imaginative view of the future

Wireless sensor networks open visionary scenarios in the future. One of these scenarios is the so-called 'Internet of things'. Disposable or rechargeable intelligent tags can be attached to objects in order to make their identification, position, and status accessible. Internet-like searches may become possible in the real-world. Imagine, for example, a new concept for a library on a university campus. Books may be stored by different departments or in multiple labs, but still made available to the community by 'internet-searching' a title and its current position. Active position sensors on disposable objects (e.g. bottles, cans) may allow for a payback system for virtuous consumers who correctly dispose the waste [24]. If sensors are placed in public offices and shops, information on the presence of crowd or queues may help a person to schedule her tasks in a busy morning, or a customer to choose the best time to approach a shop. A person not knowing its surroundings, e.g. a tourist, may query her PDA to get an aerial view from a nearby public webcam.

Nanotechnology and nanochemistry together with wireless technology may substantially change the medical field [25]. Nanosensors would be implanted under the skin and monitor blood fluidity, seek cancer cells, and communicate data to the exterior. Such a revolution would invest prevention, surgery, and also research. For instance, a wireless link would enable receiving data from an artificial silicon retina, which is today impossible [26]. This information would shed light on the physiology of nervous stimuli from the eye to the brain.

To sum up, the last generation of massively parallel systems is represented by wireless sensor network. The critical issues of MPP which are still unresolved are completely inherited by WSN. In order to achieve efficiency and real-time performance besides the hardware-related challenges, all data will have to be stored, compressed, and analyzed. Thus, adequate software environments, task tailoring and algorithm strategies, cooperative controls and communication facilities should be provided. By all means, in many important applicative fields like border control, environmental monitoring, intelligent health-care network, urban sensing, etc. many successful solutions have already been achieved.

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