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A Survey of Applications of Wireless Sensors and Wireless Sensor Networks

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***Abstract*— Wireless sensors and wireless sensor networks have come to the forefront of the scientific community recently. This is the consequence of engineering increasingly smaller sized devices, which enable many applications. The use of these sensors and the possibility of organizing them into networks have revealed many research issues and have highlighted new ways to cope with certain problems. In this paper, different applications areas where the use of such sensor networks has been proposed are surveyed.**

I. Introduction

RECENT research in many scientific areas, like physics, microelectronics, control, material science etc. and the collaboration of scientists which used, traditionally, to work towards totally different directions, has lead to the creation of the Micro-Electro-Mechanical Systems, commonly referred to as MEMS [1]. MEMS have succeeded in augmenting the limits of what was considered to be a System-On-a-Chip (SoC). Indeed, MEMS have enabled chips, which were formerly assumed to carry only logic functions, to sense the real word and even to react. Measuring of physical parameters and actuating is now possible via integration of sensors and actuators to silicon.

MEMS are not the only part of the silicon industry that has made astonishing strides. RF technology and digital circuits have also progressed spectacularly. Lower power and higher frequency trancievers are implemented on chips, while digital circuits tend to shrink and be fabricated more and more densely.

The collaboration and synergy of *sensing, processing, communication* and *actuation* is the next step to exploit the inheritance of this new technology. The possibilities and challenges offered by this field both in theory and in practice are widely recognized and many research teams and companies are active in the design and implementation of units that encompass these four attributes. Devices of this kind, which are created either as prototypes or as commercial products, are generally referred to as "*motes*". A mote is an autonomous, compact device, a sensor unit that also has the capability of processing and communicating wirelessly. Despite the autonomy they present, the big strength of motes is that they can form networks and co-operate according to various models and architectures. These networks, known as *wireless sensor networks*, have been the focus of considerable research efforts in the areas of communications (protocols, routing, coding, error correction etc), electronics (energy efficiency, miniaturization) and control (networked control system, theory and applications).

In this paper, we try to survey the numerous applications that utilise wireless sensors, or wireless sensors networks and classify them in appropriate categories. As the ongoing interest for this research area is intense, we feel that a recording of these recent applications and trends will be useful for perceiving new applications, or relevant research problems, especially from the point of view of control and systems science.

II. Existing Applications and Research

Although the number of implementations of wireless sensors is great, there is no exact standard defining a "mote". The term "mote" implies a small sized platform, but no absolute separation can be done. Irrespective of the exact type of platform, already known applications can be categorised under some general headings: military applications, environmental monitoring, commercial or human centric applications and applications to robotics.

A. Military applications

Military applications are very closely related to the concept of wireless sensor networks. In fact, it is very difficult to say for sure whether motes were developed because of military and air defense needs or whether they were invented independently and were subsequently applied to army services. Regarding military applications, the area of interest extents from information collection, generally, to enemy tracking, battlefield surveillance or

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target classification [2], [3]. Classification algorithms use, for instance, input data that come from seismic and acoustic signal sensing. For example, mines may be regarded as dangerous and obsolete in the future and may be replaced by thousands of dispersed motes that will detect an intrusion of hostile units. Then, the prevention of intrusion will be the response of the defence system. An application related to this scenario, developed by the University of Virginia, is presented in [4].

Another demonstration, described in [5] deals with multi–vehicle tracking in the framework of a pursuit-evasion game. There are two competitive teams: the pursuers and the evaders. A third part is a sensor network which is used to help pursuers locate their opponents. The sensor network informs the pursuers about the relative positions and movements of the enemy units. So, the sensors network augments the "vision" of the pursuer team and reveals their rivals.

Ohio State University has also demonstrated an application of this kind. The name of this project is "A line in the Sand" [6] and refers to the deployment of ninety nodes which are capable of detecting metallic objects. The ultimate objective was the tracking and classification of moving objects with significant metallic content and specifically the tracking of vehicles and armed soldiers. Other beings (e.g. civilians) were ignored by the system.

Finally, Palo Alto Research Center also tries to spot "interesting" vehicles (that is vehicles marked by a specific way as important) using motes equipped with microphones or steerable cameras [7]. The objective is to coordinate a number of this kind of sensors in order to keep sensing the track of a chosen moving object minimizing any information gaps about the track that may occur.

In spite of the fact that the above research refers to wartime scenarios, its results can also be used during pace time. Peacetime applications such as homeland security, property protection and surveillance, border patrol, etc. are activities that perhaps in future sensors networks will undertake.

B. *Environmental monitoring*

Another major category of possible applications is what is called "*environmental monitoring*".

1) Indoor environmental monitoring and emergency services

Research centers, like SABER (Sensors and Buildings Engineering Research Center), have already focused on this type of application [8]. Researchers and graduate students at CITRIS installed fifty matchbox-size "Smartdust Motes" throughout Cory Hall, which houses the Department of Electrical Engineering and Computer Sciences of U.C. Berkeley [9] to monitor light and temperature. The capability of sensing temperature, light, status of frames (windows, doors), air streams and indoor air pollution can be utilised for optimal control of the indoor environment. Moreover, a major waste of energy occurs through unnecessary heating or cooling of buildings. Motes can help in using heaters, fans and other relevant equipment at a reasonable and economic way, leading to a healthier environment and greater level of comfort for residents.

The use of motes to improve the environmental conditions inside buildings has also preoccupied the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). A wireless network was deployed in an office building at Pacific Northwest National Laboratory, Richland, Washington, to survey the advantages and drawbacks of wireless technology in operation of heating, ventilation and air condition (HVAC) systems [10], [11].

Other indoor applications can be mitigation of fire and earthquake damages as it is envisioned in [8]. Fire and smoke detection is something common, nowadays, in buildings and in most countries it is imposed by relevant laws. The existence, also, of light-signals indicating exits is, usually, obligatory in big buildings. However, these two systems do not cooperate in case of a fire. The installation of sensor networks in buildings can lead to the integration of these two systems. So, the role of a sensor network is to guide the trapped residents through the safest route and save their lives.

Sensor networks may also be useful after an earthquake. In addition to systems like the ones described above for fires, civil engineering research has shown that the inspection of structures based on vibrations is possible [12]. Based on this observation, the incorporation of wireless sensors inside cement blocks during construction, or their attachment to structural units makes sense. The recording of vibrations during the life of a building can function as the identity of the building; as associate professor Steven D. Glaser says "smart buildings admit their faults" [13]. The inspection of a building after an earthquake, by the use of this system, will not be restricted to evaluation of cracks and damages, but will be accompanied by real data. Computation of average and maximum values of vibrations maybe done by each mote, so the inspection can be done faster and the determination for any repairs can be more precise. Glaser's team (U.C. Berkeley's Richmond Field Station seismic research laboratory) is conducting experiments with 15 motes installed in a wood framing of a three-story model apartment. The construction is supported by a "shake table" that simulates earthquakes [14].

2) Outdoor Monitoring – Application to Ecology

Outdoor monitoring is another vast area for applications of sensors networks. One of the most representative examples is the deployment of a sensor network consisting of 32 nodes on Great Duck Island (GDI), [15]. This network was used for habitat monitoring. The sensors that were used were able to sense temperature, barometric pressure, and humidity. In addition, passive infrared sensors and photoresistors were used. The aim was to monitor the natural environment of a bird (storm petrel) and its behaviour according to climatic changes. For that reason, some motes were installed inside birds' burrows, to detect the bird's presence, while the rest were deployed in the surrounding area. Data are aggregated via sensor nodes and are passed through to a gateway. The role of the gateway is to transmit data using a higher-level network to a local base station (database). The database is accessible through the internet and is replicated to another remote location for safety. This application provides an example for monitoring using a heterogeneous, multi-level network.

The University of Hawaii has also been occupied with the study of the environment [16]. They have focused the research in Volcano National Park, trying to discover why some species can only live in a specific region. The outcome of this study would be very useful when trying to prevent endangered species from extinction. Each unit (called POD) is equipped with environmental sensors and, in some cases, with a high-resolution digital camera. These platforms were based on "Tephranet" developed by MIT's Media Lab research team. Each sensor unit collects it own data and also forwards data coming from other units toward an internet node. A characteristic of the topology of this deployment is that motes are separated into two sub-networks, one dense, to monitor the selected territory, and another sparse, to serve primarily as a link between the first group and an internet gateway (but also collect data in the vicinity of its nodes).

In related work, North Carolina State University is conducting a study of the red wolf, another endangered species [17]. The plan is to attach a node to each animal, in order to record information about its condition and behaviour. The inability of motes to transmit over large distances and their energy constraints implies that it is unfeasible to keep all the motes on-line at all times. To overcome this problem, the network contains two types of nodes: mobile and static. The concept is that a moving mote collects and stores information until the animal runs across a static mote. The static mote triggers the communication capabilities of the moving mote and the latter establishes a connection and uploads the stored data.

Research, regarding habitat monitoring, has also been conducted by Wang et al. [18], [19]. The nodes that have been used during these experiments are not size optimised (PDAs) and they manipulate acoustic signals. Here the emphasis is on exploiting the computing capabilities of a mote, comparing the input with a reference signal. In that way a mote uses more of its resources.

Other applications pertaining to outdoor monitoring that have been implemented concern environmental observations and forecasting weather phenomena. Following their successful implementation on GDI, Mainwaring et al. have deployed another sensor network at the James San Jacinto Mountains Reserve in Idyllwild, California. The aim is environmental observations. In contrast to the GDI network, in this application the time scales are much slower (climatic changes are expected to be sluggish) and the area covered is vast (29 acres).

Instrumentation of natural spaces has also been studied by the UCLA Center for Embedded Networked Sensing (CENS) [20]. CENS has developed Networked Infomechanical Systems (NIMS) and has applied them to the Wind River Canopy Crane Research Facility in the Wind River Experimental Forest, Washington. NIMS comprise a heterogeneous network. That is a mixture of fixed and mobile motes. The aim is for fixed motes to support mobile ones (energy distribution, sensor calibration). The particular deployment at the Wind River is to probe the interaction between the atmosphere and the forest canopy. Efforts to save environmentally sensitive lands are now supported by a robust ally: motes.

A much earlier implementation of sensor networks was ALERT (Automated Local Evaluation in Real Time), [21], a system developed by National Weather Service in 1970's. ALERT is a precursor of modern sensor networks and it is used in monitoring of rainfalls and flooding prediction in California and Arizona. For that reason, the system is equipped with temperature, water level and wind sensors. Despite the fact that this application uses sensors nodes, these cannot be regarded as motes strictly speaking, because they lack processing capabilities. Raw data are collected and accessed through GUIs. However, the application is currently operational and could be upgraded to use motes.

Finally, CORIE [22] is another system that was deployed on the California River by the OGI School of Science & Engineering of the Oregon Heath & Science University. CORIE is another example of a heterogeneous system. Some nodes are installed and connected (hard-wired) along the estuary and a wireless one drifts on the river. The mobile node sends data to the fixed nodes. Sensors measure parameters which describe water or atmospheric conditions. It should be noted that these nodes are large compared to standard mote platforms. The aims of surveillance vary and can be both ecological (e.g. observation of salmon habitat) and economical (hydropower management, navigation improvements).

To sum up, wireless sensor networks are ideal for remote monitoring and event detection in geographically large regions or inhospitable areas.

3) Outdoor Monitoring – Applications to agriculture

Proposals have also been developed to deploy motes to agriculture, to enhance the efficiency and growth of cultivations. Intel Corporation in cooperation with Intel Research Berkeley Labs have studied the case of deploying a sensor network in a vineyard [23], [24]. The original idea was that a survey of microclimates would improve productivity and would be useful for farmers. Consequently, the prototype platforms were equipped initially with temperature sensors. However, interviews with farmers led to the conclusion that another source of raw data was practically useless for them. The perspective changed as a result. The sensor network turned out to be a component of a system that could be useful for every participant in the wine making process, from the time of growing the grapes to wine production and marketing. Many activities like filling out of timesheets, automatic calculation of salaries overtimes and billing, time-programming and monitoring of tasks such as pruning (by attaching sensors to tools such as pruning shears), targeting of chemicals and pesticides to selected points (by forecasting diseases through monitoring of temperature and humidity) and harvest timing (observing the ripeness of grapes).

Vineyards are also an area of interest for Accenture Technology Labs. Similar work has been performed by their R&D team in a field test in Pickberry Vineyard [25]. A 30 acre area was covered by sensors measuring humidity, wind, water, as well as soil and air temperature. Millennial Net's motes were used for this purpose. Irrigation management is one of the aims. Water usage can be controlled in a more efficient and economic way by monitoring moisture on soil, air humidity and weather forecasting. Other goals of the system are frost detection and warning and, as before, pesticide application and disease detection.

Generally, crop management, lowering costs and increasing quality is in the scope of applying sensors network technology to agriculture.

C. *Support for logistics*

Inventory control is a major problem for big companies. Management of assets (pieces of equipment, machinery, different types of stock or products) can be a predicament. The problem is highly distributed, as these companies expand all over the world. A promising way to achieve asset tracking and cope with this problem is believed to be the use of RF ID tags and wireless sensor networks. British Petroleum (BP), participating in CoBIs program and Accenture Technology Labs have invested in research in this area. BP in [26] describes smart surrogates. The application refers to warehouses and storage management of barrels. The concept is that motes attached to barrels will be capable of locating nearby objects (other barrels), detecting their content and alerting in case of incompatibility with their own (danger of a chemical reaction), aging effects of the enclosure etc. This will enhance safety and guarantee product quality. British supermarket Tesco PLC has, also, applied first generation systems of this kind for inventory control [27]. BP and Accenture Technology Labs have also used wireless sensor networks for fleet management [28]. Tracing of lorries and railcars and tracking of parameters regarding carried goods is possible through motes and the GPS system. So, telemetry and wireless sensing can be combined to build smart objects and vehicles.

Other industries are also interested in wireless sensors. Intel research, for example, deploys a network of this kind to monitor the condition of semiconductor fabrication equipment [29], [30]. Motes in this case sense vibrations. More specifically, the plan is to make feasible the detection of faulty parts, which need repair or changing, by analysing their "vibration signature". Rockwell Automation has, also, contributed to this effort, as well as to another scheme: Monitoring of vibrations that occur in a ship (a tanker named Loch Rannoch) of BP, which travels in dangerous seaways, like those of the North Sea. This project, now in its initial steps, has studied whether the deployment and connectivity of motes is feasible in such a harsh environment [26], [31].

Another industrial case study was carried out by Helsinki University of Technology [32]. The study deals with the use of motes, in particular the "weC Mini Mote" of Berkeley, to the process of paper production. The sensors are fitted into the rolls used in the paper drying stage. The role of the motes is to measure temperature in order to control the heating rolls. In [32] the research was focused on transmission security.

Other examples in industry are Shell Oil Co, which monitors the condition of pumps at gas stations, York International Corp., which installs ventilation systems and Tyco Thermal Controls LLC [27]. York Int. tries to program maintenance of installed systems depending on customer needs, while Tyco aims to reduce the installation costs of laying wires by replacing them with motes in pipe-heating systems. BP, in addition, uses RF ID tags for the inspection of equipment at a refinery in Toledo, Ohio. In that case, the tags do not form a wireless network, but report to handheld equipment as inspection personnel pass in the vicinity [26]. The same company plans to use this technology for tracking "lone" personnel in hazardous regions in their facilities at Hull (UK).

Researchers at UC Berkeley have also proposed a similar application based on "wearable motes". The integration of a mote to a part of the equipment that firemen wear, not only makes the coordination of fire-extinguishing easier and more effective, but can also act as a supplementary safety measure by revealing the exact location of each fireman. In case of an accident, rescue crews can act more effectively.

Delivery and distribution systems are another area of applications for wireless sensors. Again BP, in [26], describes the advantages of using this technology for managing the delivery of liquefied petroleum gas (LPG) to its clients. The content of each customer's tank is monitored so that the supply department of the company knows the remaining quantity. That is useful in programming the trips of supply tank-trucks and consequently increases the efficiency of the delivery system. BP in cooperation with Andronics, has deployed this system in the north of England and already equipped around 2000 tanks.

Electric energy systems can also benefit from deploying motes to households and, generally, to consumers of electric power. Such a scheme is being investigated in CITRIS [33]. "Electric economy" always deals with maximum values of electricity consumption. This value has to be kept as low as possible for economic reasons relevant to production. Peaks in electricity demand can be diminished by attaching wireless sensors as components of smart appliances. In a program envisioned by CITRIS, Smart Energy Distribution and Consumption is deployed in three stages. First, the end user monitors their appliances and finds out defective or energy exorbitant-consumers. Next, feedback is employed between end user and supplier (real-time pricing). Finally, measuring of environmental parameters slips into the system operation. In this phase the indoor environmental monitoring application described earlier is encountered.

D. *Human-centric applications*

Health science and the health care system can also benefit from the use of wireless sensors. Intel's research concerns senior citizens and their problems [27]. Cognitive disorders, which perhaps lead to Alzheimer's, can be monitored and controlled at their early stages, using wireless sensors. Intel in Portland and in Las Vegas is carrying out such an experiment (Proactive Health Research). The nodes can be used to record recent actions (taking medication, last visitor, etc.) and remind senior citizens, indicate the person's real behaviour, or detect an emerging problem. Related research, conducted by Intel and the University of Washington, uses RF ID tags to examine patient behaviour and customs by recording the frequency with which they touch certain objects. The application includes a display, which will help the "caregiver" extract information about the indisposed person discreetly and without hurting their feelings. Finally, motes can also be used in order to study the behaviour of young children. For example, the aim of the study reported in [34] was to analyse children behaviour, by monitoring sensors enclosed inside toys.

Another medical application refers to human vision restoration [35] by retina prosthesis. Sensors are implanted to human organs to support a function and they require the capability to communicate wirelessly with an external computer system, which carries out the advanced processing. Energy limitations do not allow this computing to be carried out on-board the sensors. Other applications of wireless sensors to healthcare that have been proposed include tracking and monitoring doctors and patients, or tracking drug usage inside hospitals [36].

E. *Applications to robotics*

Many applications coupling motes and robots have been proposed. For example, Robomote is a tiny robot developed by the USC Center for Robotics and Embedded Systems to promote research in large-scale sensor network where robots participate [37]. Applications already implemented [38] are the detection of level sets of scalar fields (like isothermal or isobar curves) using mobile sensor networks and imitation of the function of bacteria for seeking and discovering dissipative, gradient sources [39]. The objective was the tracking of a light source with simplified algorithms. In addition, a solution to the "coverage problem" by robots and motes is proposed in [40]. The initiative here is the attempt to have dense measurements over a wide area. The collaboration of both static and mobile networks is accomplished by mobile robots, which explore the environment and deploy motes that act as beacons. The beacons help robots to define directions.

Intel is also conducting research in this area. The point of view for Intel is mobile robots that act as gateways into wireless sensor networks. Actions that aim to serve and support the operation of a sensor network are described in [41]. Examples of tasks are: sustaining the energy resources of the sensor network indefinitely, maintaining and configuring hardware, detecting sensor failures and appropriate deployment for connectivity among nodes.

Another relevant work [42] concerns localization of nodes in a sensor network by means of mobile robots. This approach tries to solve the problem of unifying a network that is separated because of disconnected groups of sensors (clusters). Of course, in all these cases robots are integrated parts of the sensor network.

In the range between robotics and medical applications is the virtual keyboard developed by U.C. Berkeley. The virtual keyboard is a system of wearable motes sensing acceleration. Six motes are attached to a glove, one for each finger and one at the wrist. The objective is the understanding of the relevant movements of fingers so that gestures can be recognized [43]. Applications could be a wireless wearable mouse/keyboard, or a pointing device, hand motion and gesture recognition for the disabled, virtual musical instruments and work training in a simulated environment.

III. CONCLUSION

The possible use of wireless sensor motes and networks extends over a vast area of human activity. Although, most of the applications are still under research and few completed products or services have become available for public use, there is remarkable effort and progress. New scientific fields like pervasive computing have, already, appeared. As most of the applications are focused on monitoring, the distributed sensing seems to enable the parameterization of the physical environment and the integration of it to established forms of information propagation (like the internet). Apart from these, adding the parameter "mobility" creates another dimension to the information system.

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