Applications of Intelligent Sensor Networks and Wireless communication to the instrumentation of Civil Engineering Structures

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Abstract - Wireless technologies have always been of interest to physicists and this field has been active since its inception. Nevertheless, stimulated by the telecommunications and telecommunications sector in general, this domain is experiencing a renewed interest and a strong development over the last ten years. Wireless (or wireless) technologies are part of a global trend towards communication, mobility, the search for flexibility in implementation, etc. They are used in many fields of application, for the Mostly known as the internet, telephony, the medical world, industry, computers and even recently aeronautics, or less expected like civil engineering and road safety. As part of its research and development work in instrumentation, it is quite natural that for several years the LCPC Metrology and Instrumentation Division has integrated these technologies and has developed, at its level, the instrumentation of wireless technology applied to engineering civil.

Introduction

 ➢ **Structural monitoring**

Auscultation of roadways and road safety are already the subject of instrumentation based on wired sensor networks [1]. However, this wired link with a supervisory system managing a more or less essential set of sensors suffers from failures and runs up against limitations [2] of which the following are the most common:

- Waterproofing, wear and vandalism cause unacceptable connectivity failures for critical systems.
- Traditional monitoring / acquisition systems hardly manage more than one hundred sensors without using heavy acquisition and scanning arrays.
- Connectivity limits the supervision / sensor distance by nature, resulting in loss of data, signal attenuation, electromagnetic compatibility (EMC) problems, the need for rectifiers, etc.
- Sometimes the costs of the connection (purchase, installation and maintenance) are higher than those related to the measure itself and it is possible to question the financial justification.

The civil engineering sectors are therefore potential targets for networks of wireless sensors. The Scientific and Technical Network of the Ministry for Transport in General and the Metrology and Instrumentation Division of LCPC in particular have therefore naturally applied themselves over the past four years to acquiring these technologies and developing

the associated skills in order to adapt them to applications Using instrumentation. The aim of this article is to discover these technologies [3] and their potentialities, to highlight the new challenges of these transmissions without wired support [4], and then to present with some examples the first concrete achievements of the LCPC on the subject.

Definitions
  ➢ **Sensor concept**

For a better understanding of the article and the notions mentioned, it is necessary to define what is meant by sensor. Depending on the countries, companies and working communities, the sensor can represent the sensitive element of the measurement alone (the sensor) or the same sensitive element coupled with a certain intelligence, at least an electronics that plays a role In the establishment of this measure. The sensors studied in this article, whether they are wired or wireless, are complete systems including: - one or more measuring channels to which is connected an element sensitive to A physical quantity to be measured; An accelerometer, a gauge, a thermocouple, a MEMS [5] are examples; for each measuring channel, a stage which shapes the analogue information (electrical, optical, mechanical) of the sensor and converts it into digital information (bytes, logic levels); A processor whose minimum function is to acquire the data coming from each measurement channel; This processor has the capacity to integrate and execute business algorithms, or even to hide an operating system; It may be, as the case may be, a simple 8-bit microcontroller or a processor dedicated to signal processing such as a Digital Signal Processor (DSP); In some cases, the processor also provides advanced management of the electrical energy available to the sensor; Optionally a storage capacity external to the processor when its internal memory is not sufficient to meet the need for storing data and programs; RAM or FLASH memories are examples; A communication stage enabling the processor to dialogue with the supervision system, or even with other sensors; (Wired, Zigbee, Bluetooth, ISM, etc.) and can be wired (serial RS232 serial link, RS485 serial bus, Ethernet, etc.). Figure 1 shows the synoptic of a complete wireless sensor having 2 measurement channels and the links between the different stages of which it is composed
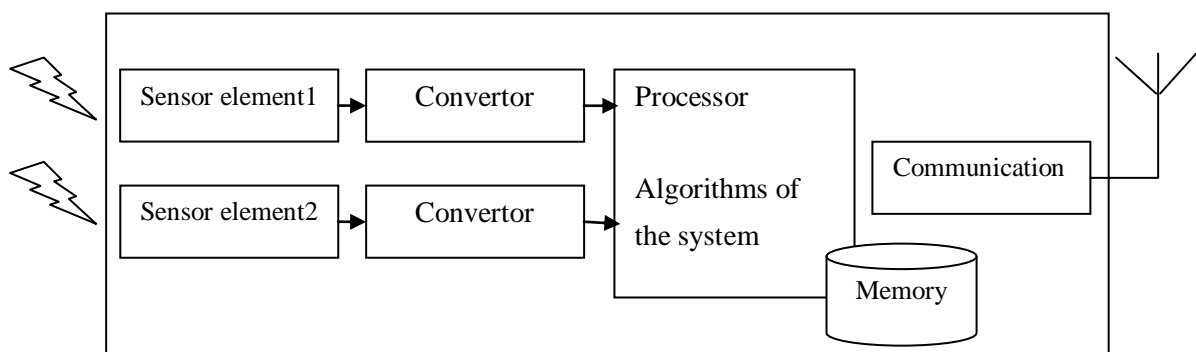

Figure.1. Typical Wireless Sensor

➢ **Intelligent sensors**

A sensor is said to be intelligent [6] as soon as it fulfils more than the function of immediate data acquisition / transmission. The simple fact that a sensor can compensate for a cut in the communication link to the supervisor, for example by storing the data until the link is restored, gives it a form of intelligence. The intelligence of a sensor is commonly due to its greater or lesser capacity to:

- Perform more or less complex algorithms on the recorded data such as calculating minima and maxima, filtering, averaging, calculating Fourier transforms interrelated correlations, etc.
- React dynamically to commands received from the supervisor such as activating a channel, modify a threshold, add another type of processing to the data, communicate with another sensor, etc.
- To react to dysfunctions in its environment such as a track that no longer responds, a threshold reached in an untimely manner that permanently disables the measurement, a faulty communication link, etc.
- Self-identify, auto-localize, self-configure, self-repair, etc. Although it is clear that a sensor only has the intelligence that has been assigned to it, a new form of structuring of this intelligence emerges in the field of embedded systems and in particular of wireless sensors, Hosting by the sensor of an operating system such as Windows or Linux in the office world, or Operating System (OS).

An OS gives the designer a simplified exploitation of the capacities of the processor and its peripherals, and allows the end user to completely reconfigure the sensor without having to manipulate or reprogram it in the laboratory. In addition, the sensor integrating an OS can be completely reconfigured hot and remote, which greatly reduces the maintenance and operating costs of the system.
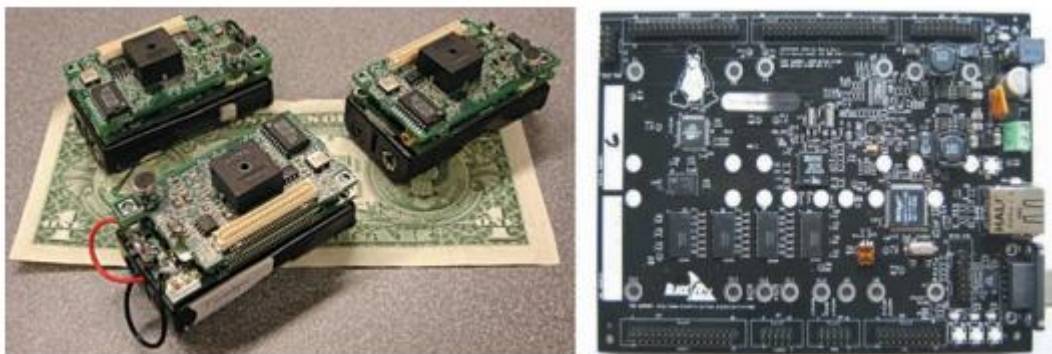

Figure.2. Some intelligent sensors incorporating OS (TinyOs and µCLinux) used by the LCPC.

■ Sensor networks The needs of structures in massive and diversified instrumentation induce the designer to develop systems whose nodes (sensors) can be organized in multiple topologies [7], that is to say according to configurations which Allow the user to physically match the instrumentation deployed in the field to the logical vision that it has since the supervision. The development of intelligent sensors and wireless sensors naturally responds

to this need by extending to infinity the scope of possible topologies. Indeed, the physical disconnection inherent to the wireless makes it possible a priori for each sensor to communicate with any other sensor present in its radio sphere of influence. Moreover, an intelligent sensor is systematically an identified or identifiable sensor, so that if the sensed data is associated with the source at the sensor identifier, the bytes can pass through any path of the network without The data loses the memory of their origin. Figure 3 gives four examples of topologies of sensor networks. The two most common topologies are star and bus topologies, in which each node knows only the supervisor and where the node-supervisor communications paths are unique and physically frozen.
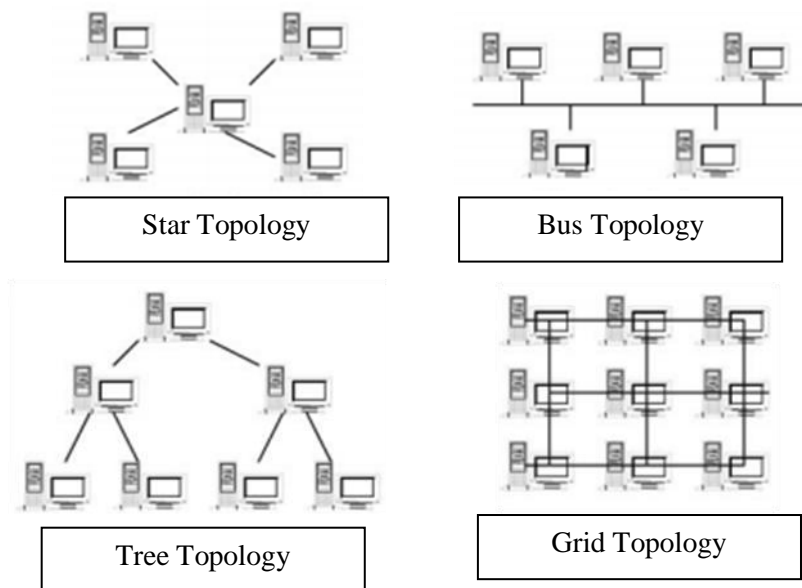

| Star Topology | Bus Topology |
| Tree Topology | Grid Topology |

Figure.3. Four topologies in which installation of wireless sensors is possible

➢ **Implementations including operating system and protocol**

The design of intelligent sensors, capable of networking and wireless communication, addresses itself globally. In particular, network operation corresponds physically to the software and hardware implementation of communication protocols at the level of each sensor and the supervisor. The communication protocols adopted are those that fall within a standard recognized by an official body such as the IEEE. Each standard, or standard, precisely describes the support and transport of data between two nodes of a network. The work of the LCPC excludes the non-perennial and expensive development of proprietary protocols in favor of sustainable and reliable protocols.

A protocol is often described as a set of layers Ensuring, each at its level, actions of encoding / decoding, transmitting, receiving, checking the integrity of the data conveyed. Each protocol - often called a stack - is implemented on hardware resources, which are electronic components. It is important to note that a single software protocol can be physically implemented in several ways. We give some examples in the following paragraphs.

➢ **TCP / IP This protocol,** or Internet Protocol, is the most widely known and widely used. It is native to all the OS of commercial PCs, such as Windows, Linux, Unix, MacOs, etc. It is also implemented in many applications such as printers or cell phones (GPRS, UMTS). The TCP / IP stack is described by the OSI model. If, in physics, the most well-known TCP / IP version is Ethernet (in the case of office sockets in RJ45 format), there are many other wireline forms (TokenRing, ATM, etc.) and non-wired [8] GPRS, UMTS, Wifi [9], Wimax, etc.).

➢ **Characteristics of protocols existing on the market**
Each protocol has its peculiarities and it is the specificities of the application that determine the criteria of choice of the protocol to be implemented.

➢ Depending on whether or not data is lost, a more or less reliable protocol and a connected protocol will be chosen.
➢ Depending on the energy capacity of the sensor, a more or less resource consuming protocol will be chosen.
➢ Depending on the range of distances between sensors, a protocol will be chosen including multi-hop, relay possibility, etc.
➢ Depending on the desired topology for the nodes, a protocol will be chosen allowing multi-hop, communication between sensors, connection of the desired number of sensors.
➢ Depending on the latency time accepted for communication, the target flow rate and the presence of deterministic time exchanges, a high-speed protocol, a deterministic protocol, will be chosen.

On the other hand, embedded operating systems always natively support a communication standard; Indeed, the interest of these OSs coming from the office world is to offer a basic mode of communication, in addition to adding a layer of software abstraction between the electronic resources of the sensor and the business application (conditioning stage, miscellaneous Ports of entry / exit, etc.). Examples include the μCLinux or Windows CE embedded native TCP / IP or TinyOS offering the 802.15.4 (Zigbee low layer, another wireless protocol).

In the design of intelligent wireless sensors, the integration of reliable and standard communication protocols is therefore possible because the electronics market now offers small turnkey protocol modules, integrable to the electronic developments of the card Sensor: in this case the processor transmits or receives data by communicating with this module via one of its input / output ports. What is more, some processors can host OS dedicated to embedded applications, which directly support a protocol communication mode: in this case, the design consists of writing the driver which allows the processor to recognize and link the lower layers of Protocol to a radio module. New technologies, new constraints and the challenges of wireless technologies It would be wrong to think that switching from a network of wired sensors to a network of wireless sensors would be effected simply by replacing the wires with radio modules And the integration of a battery-type power supply at each sensor. In reality, the realization of wireless electronic systems requires a complete overhaul of traditional design schemes. The energy aspect is often highlighted, but the energy requirements of the wireless sensor [9] are often less crucial than new constraints that appear and require the same attention.

> ➢ **Energy constraints**.

Communicating wirelessly (with radio frequency modules) usually consumes a lot of energy. The energy available at a wireless sensor is often very limited or non-existent. The more a sensor is distant (from its interlocutor) or buried (in a structure), the more energy it needs to communicate. Also in the field of wireless, should the electronic designer take into account the fact that correctly measuring the physical quantity that you want to know is as important as controlling energy consumption. There is no single, generic scheme or solution covering all possible needs. Nevertheless the designer will always seek to choose the most sober electronic components and his choice will have to be dictated, among other things, by the following considerations.

• If the instrumentation is intended for a short period of time (a few hours to a few days): Current battery technologies can overcome almost all situations, including continuous radio communications (lead and NiMH batteries), while Remaining of reasonable dimensions (a few cm3).

• If the instrumentation does not require frequent communication or measurement: the processor can really optimize the consumption by activating the acquisition / conditioning and radio communication modules only at the necessary moments. In addition, many processor families offer standby modes that allow them to consume practically nothing. The outputs of the standby states can be parameterized on event, over threshold, at a specific time, etc. For example, measurement and transmission of temperature or deformation do not require a wireless sensor operating at 100% of their capacity for 100% of the time. Thus, if one chooses batteries, provided there is room to integrate them, the sensor can take months or even years depending on the dynamics of the application.

• If the instrumentation is intended to last for a very long time and / or requires frequent radio communications, the solutions are more difficult to find. It is necessary to aim at the extreme sobriety of the sensor card, to minimize the number of electronic components, to use all the possible standby modes, to optimize the cyclical ratios of the listening or communication phases on the network, to use the network protocols dedicated to the (Zigbee, BlueTooth) by studying, in this case, the possibilities of using intermediate repeaters and reducing the distances between sensors and supervision. A complementary way is to add to the sensor one or more sources of energy recovery to charge the batteries and ensure continuous operation. For outdoor systems, solar panels or mini-windmills, piezoelectric systems, will be used to recover the energy induced by the vibrations of its environment.

Finally, tele-feeding is another form of food that offers its first solutions (but for low consumption); In this case, electromagnetic waves in specific frequency and amplitude ranges excite an integrated transducer which delivers electrical charges to the sensor (the RFID technique is the best known in this field). More generally, the best way to save energy is to limit the duration of communications and their number. Intelligent sensors can meet this need. Any system capable of processing the signal and its various algorithms as close to the source, that is to say capable of processing the measured data at the level of the sensors, will be preferred. It is at each sensor that will decide which data to transmit and at what rate. Indeed, unless the data are to be interpreted in real time, each sensor can store its own data,

possibly process it in part, and transmit it to the supervisor only in blocks and sporadically. By sending less data and less often, communications needs are reduced.

➢ **The temporal synchronization constraint**

A further difficulty arises when the sensors must be synchronized, that is to say when the data collected by sensors distinct from the network must be dated with precision. Depending on the application, synchronization may be simply desirable or a critical need. For example, if a temperature on a structure is measured, a slowly evolving physical quantity, a dating deviation of the order of one second between two distinct measurements generally does not influence the thermo-control algorithms; On the other hand, in the field of propagation of high dynamic waves (of the order of 5000 in steel or concrete), the data resulting from the sampling of these waves must often be correlated with a precision Of the order of one microsecond. Like any electronic system (computer, video recorder, etc.), the intelligent sensor integrates natively a quartz, that is to say an electronic component that allows it to count the time. Since each quartz has its own uncertainty and the sensors do not start at the same time, the time bases of the sensors cannot be perfectly in phase without a synchronization mechanism. As a consequence of construction, as well as in terms of electronic aging and temperature sensitivity, the components differing from one another, the sensors which associate several of them differ even more, and the correlation of their data therefore requires a mechanism of synchronization.

➢ **The integration constraint**

For the structural manager, the development of wireless sensors can, under certain conditions, meet real needs, in the case of hard-to-reach places where small equipment will be valuable or In the case where the sensors are to be buried in the structure itself, for example. It is difficult to provide quantified data, but after analyzes, tests, and discussions with other research organizations, a few principles can be listed for the integration of sensors.

o Less a sensor is complex in terms of processing to be performed, number of electronic functions to be implemented, etc. The more it is integrable or capable of being optimized.

o The more integrated a sensor, the less it consumes.

o If a sensor is difficult to access due to its location, it will be installed whenever the batteries need to be replaced.

o A buried sensor, eg embedded in concrete, is less accessible (up to a few meters depending on the technology) than an accessible sensor.

o A buried sensor must be either autonomous in energy for the duration of the instrumentation or remotely powered, but in this case from a relatively close source (a few tens of centimetres maximum in RFID).

o A remote sensor cannot support a complex electronics, so sensors of this type must be sober in software and hardware functions.

o The manufacture of an integrated micro-sensor dedicated to an application is very expensive (development of ASIC or FPGA) and the application must cushion this specific cost.

Conclusion

In addition to being immersed in the culture of the field, new technologies and standards have to be incorporated and new developments have to be considered. Concrete applications (modal analysis by Mote, instrumentation of a drone, etc.). The transition from wireline solutions to wireless technologies imposes new constraints. The analysis of these constraints (in terms of energy, synchronization, integration) shows that no technological evidence is emerging, given the variety of instrumentation contexts. The final application itself and the implementation criteria determine the choice of principles and technologies. What topologies, distances to cover, how long, which dimensions to respect, which target environment, etc. are just a sampling of the many questions the designer needs to ask himself in order to make the right choices. Energy being the strongest constraint, this subject is the subject of in-depth studies. The majority of the instrumentation targeted being outdoor, the solar solutions will be particularly evaluated in future.

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