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WIRELESS SENSOR NETWORK USED FOR STRUCTURAL HEALTH MONITORING OF CIVIL INFRASTRUCTURE

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Abstract: *With recent developments in the field of wireless sensor networks (WSN), the author presents in this paper a solution for complex monitoring systems, that can be used to perform structural health monitoring (SHM) of different categories of bearing structures. As an experimental part of the author's research activity the author has developed a test system.*
The system under testing uses wireless sensors and the main contributions of the author to the research team's efforts are customizing the hardware to deal with the time synchronisation of information received from several sensors, dissemination of sensor configuration information, storage of acquired data and the development of a software application able to interpret and present mandatory measures that have to be taken in order to maintain structural health.

Key words: *WSN, SHM, Infrastructure.*

1. Introduction

On a global scale, a significant part of civil and commercial bearing structures are affected by certain degrees of deterioration. Due to the global crisis, it has become obvious to civil engineers the fact that there are insufficient funding solutions for immediate replacing or renovation of all affected structures. Thus, accurate information about the status of these structures is necessary in order to be able to optimize and prioritize the available resources. This information helps accurately classify which structures need replacement, which require immediate maintenance and which are in good condition and are normative compliant.

Integrating sensors into bearing structures is the main solution for performing SHM. SHM can be performed periodically or continuously based on the decision of structural engineers and experts. Both types of monitoring imply several activities like mounting the sensors, installing power supplies or the connection of sensing devices to the mains of the structure or installing cable runs for the power supply and for the transmission of the data signals. On the long term, all the above mentioned activities can imply high installation and operation costs. Moreover, long bundles of wire cables or fiber optics are subject to periodic rupture or even connector failure. Wires also limit the number of sensors that can be mounted or there may be situations where cable runs cannot be mounted on certain parts or

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sections of the structure due to the structure's shape or its purpose.

Nevertheless, the integration of sensors into bearing structures has many benefits to the owners and users of the structures, including prediction of damages or catastrophic failures, improved emergency response, increased homeland security or reduced operation costs in the long term.

As a result, in the previous decade several private research companies, universities and international standardization institutions have started the development of wireless sensor networks. These networks are composed of devices called nodes having in their composition a processing unit, a wireless communication device and one or several sensors for data acquisition.

The recommended features of a WSN node are low power consumption, fast data acquisition capabilities, reliability, long term accuracy, reduced acquisition costs, very little or no maintenance over time and the possibility for remote configuration and programming. These features are not easy to implement because real-life structural monitoring applications and problems have different requirements. Selecting the appropriate sensors and the wireless communication protocol have a strong impact on the overall performance of a node and the lifetime of the energy source.

Nowadays a single integrated circuit is able to encompass a radio communication device, a processing unit and additional digital electronics. Very good examples of such integrated circuits are produced by leading industry companies like Atmel, Texas Instruments or MicroChip [1], [2], [3].

According to the definition given in [4], a WSN is composed of a series of wireless nodes equipped with different types of sensors, placed in different locations on the structure, which communicate with one or several gateways using one or several different wireless communication protocols. A gateway or a basestation is the main collection point for the data sensed by the nodes. The data sensed by the nodes is transmitted directly or via other nodes to the gateway. In order to obtain small communication periods and thus lower energy consumption of nodes, the transmitted data is usually compressed. The data collected by the gateway is then fed as input to different software applications for further processing and information interpretation is performed by expert systems in conjunction with human experts in the structural engineering domain.

2. WSN Principles

This section encompasses a brief description of the hardware components of a WSN node, the communication possibilities available, the energy supply options and power consumption related issues.

2.1. Node Components

The basic hardware components that make up a WSN node are presented in Figure 1 and are compliant with the descriptions given in [4]. It can be observed that the components are modular and this architecture empowers the node's design with versatility and flexibility to requirements from different SHM applications.

The sensing devices are mounted on the prototyping board of the wireless node and can range from simple temperature, humidity, noise or dust sensors to more complex sensors able to detect cracks, crack propagation, linear displacements, accelerations or ultrasound sensors capable of distance measurement [5], [6]. The data acquired by the sensing devices is than fed into the conditioning module. This module is necessary because the sensed signal may be too weak or too noisy to be fed directly into the data storage devices. The most common circuits used for signal conditioning are conditional bridge circuits.

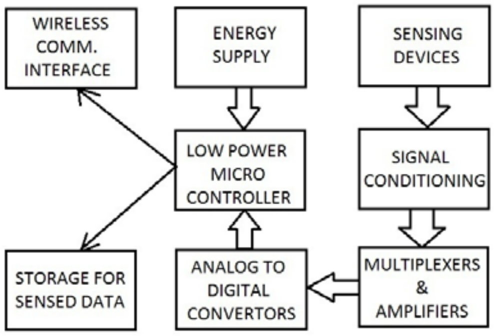

Fig.1. *Structure of a WSN node*

Multiplexing and amplifying circuitry is used in order to boost the conditioned signal which at the conditioning circuit's outputs can be as low as 10μV with corresponding temperature drifts of 0.1μV/ºC. The most common circuits used at this point are precision operational amplifiers. Multiplexers are used in order to combine the inputs from several sensing devices and then feed them as input to the analog digital (A/D) converters.

The A/D converters are responsible for performing the digitization of the analog signals. The input signals are converted from an analog voltage range into a sequence of binary digits using several output channels of the A/D converters. Common resolutions for the A/D converters are 12, 14 or 20 bits.

The majority of nodes currently available on the market use 8-bit AVR RISC-based microcontrollers with operating frequencies between 8 - 16 MHz, capable of running in temperature conditions between -40ºC and + 85ºC which fit the majority SHM scenarios. The micro-controller has the following main functions [7]: WSN protocol management, sensor data acquisition management, power supply management, transmission of data from the sensor interface to the physical communication layer and read/write controller operations for the local storage media.

The microcontroller units are directly coupled with different types of wireless communication interfaces. These include the IEEE 802.15.4 compliant interface, GSM/GPRS interface, Bluetooth or IEEE 802.11 interfaces.

In addition, the nodes provide the possibility for local data storage by using a flash memory mounted on the board. In the majority of node implementations SD, miniSD or microSD cards are used. These cards have capacities ranging up to a few GBs but they also have some strict timing constraints [8]. Due to these constraints some of the sensor data can be stored to the flash memories if the timing constraints are not too strong for the flash memory write delay to comply to. For example, the flash storage is suitable for temperature sampling which is performed once every few minutes as opposed to acceleration sampling which may take place several times a second.

From the point of view of the energy supply, several options are available including: batteries (Li-Ion or Li-polymer rechargeable), fixed or flexible solar panels, auxiliary 3V no-rechargeable batteries or the possibility of connecting an AC/DC adapter to the mains, depending on the monitoring application.

2.2. Wireless Communication Options

A wireless sensor networks usually has no or very little infrastructure. It is composed of a given number of nodes ranging from a few to tens or even thousands working together in order to obtain information about the bearing structure under monitoring. Several standards and protocols have been developed to sustain the specific requirements of wireless sensor networks communication including: IEEE 802.15.4/ZigBee standard compliant [2], [9], IEEE 802.11 b/g /Wifi standard compliant, GSM/GPRS, Bluetooth and RFID/NFC.

2.3. Energy Supply and Power Consumption

One of the major concerns in designing feasible WSN deployments for bearing structure's SHM are the node power consumption and the available options for power supply of the node. According to studies performed in [4] and [11], from the total power consumption of a node, an average of around 80% is spent by the wireless transmitter/receiver, around 4-5% by the sensing devices and the rest is consumed by the processing unit and on board electronics.

Generally, SHM applications are continuous or span over long periods of time (e.g. one or several years). Thus, it is desirable that the energy source is able to serve the node without servicing for the entire monitoring period. In addition, a proper operational scheme has to be designed for the hardware of the node and tuned algorithms have to be implemented at the operating system and application level in order to minimize power consumption.

The most important concerns are with the wireless transmission/reception part and the related algorithms, due to the fact that it is the most power consuming component of the node. The following actions must be considered during implementation [4]:

- Implementation of strict power management strategies and functioning modes (sleep mode, power-down mode, suspend mode);
- Reduction of transmitted/received data through the use of compression algorithms and through data reduction;
- Reducing the frequency of data transmissions;
- Reducing the wireless transceiver duty cycle;
- Transmission of data only when sensor events occur (e.g. transmit displacement data or temperature data only when an increase/decrease of the sampled data occurs);
- Reduce the administrative overhead of the transmitted data (reduce the amount of data that is not related to the sensed data).

Significant research has been performed on the topic of energy sources for wireless sensing nodes. In the typical scenario, when the energy source of a node is almost depleted, the node will shut down and will disconnect from the network. This can have a limited or significant impact on the SHM system depending on the node placement and the initial redundancy considered in the network design [12]. As a solution, researchers have sought energy harvesting solutions besides energy conservation techniques and algorithms.

The typical energy source for a wireless node is a rechargeable or non-rechargeable battery. The most common rechargeable batteries used in the nodes are Li-Ion or Li-polymer. The second category is preferred due to lower manufacturing cost, adaptability to a wide variety of packaging shapes, reliability, and ruggedness. In addition, the self-discharge rate is lower at around 5% per month as compared to 8% for classical Li-Ion batteries.

Even if rechargeable batteries are used in the design, they need servicing at certain time intervals by either replacing the batteries or recharging them. By using energy harvesting there exists a solution for online recharging. Energy harvesting involves the replenishing of the energy capacity of a nodes energy source. Research has been conducted on different methods like use of solar energy, vibration, thermal energy, acoustic noise or fuel cells [11], [13], [14].

The current mature energy harvesting technology is using solar cells and panels. There exist rigid solar panels capable of supplying 500mA at a voltage of around 7V and flexible solar panels capable of supplying 100mA at the same voltage. The acquisition cost is still high with prices starting from 20-25 Euros/pc. Even if it is a mature technology, solar energy harvesting has the main drawback that the results of the harvesting are proportional to the existing sunlight or to the existing artificial light.

3. WSN Architecture

The network architecture of a WSN depends greatly on the type of structural health monitoring application to be implemented. Several factors influence the architecture chosen for in situ deployment including but not limited to the type of structure under monitoring, structural dimension, structural materials or expose of nodes to natural elements.

In the following subchapters first a presentation of the most commonly met topologies for wireless sensor networks is detailed, followed by a description of node roles and details about the software architecture and its main components.

3.1. WSN Topologies

One of the most common topologies used in civil engineering structural health monitoring applications is the star topology, where all the sensor nodes transmit information directly to a special station called gateway [15]. The gateway or the basestation acts a direct data sink which receives all the information from the wireless nodes and can be accessed using a variety of internet communication options including Wi-Fi, GSM/GPRS or broadband technologies. A star topology is presented in Figure 3.

Another topology used in case of monitoring applications that need strong connectivity between sensing nodes is the mesh topology, already presented on Figure 2(b). In this topology nodes are connected to one another, to the closest neighboring nodes as well as to one of several gateways (data sinks). Such a topology ensures that the redundancy criteria are met, but at a higher cost, due to additional hardware and energy cost in terms of wireless communication volume.

In all topologies the data sink nodes or the gateways require a computing device with enough processing power and enough storage space. In addition, they must act as a remote gateway for the users of the structural heath monitoring system in order to allow remote connectivity, retrieval of data and data analysis software tools to run interpretation algorithms on the data. Last but not least, they must allow the structural expert to perform custom queries on the sensed data according to the criteria that he or she considers fit for the purpose of the monitoring.

Mesh topologies are especially appropriate for monitoring bridges and tunnels due to the fact that in these applications the primary concerns are to acquire data about the long-term changes in performance in a number of different locations on the structure. This requires a wireless sensor network composed of closely positioned nodes that sample data at a low time frequency of the order of minutes or even hours [16]. Due to the fact that in such monitoring application, nodes are closely positioned, it is not feasible to use wireless transmitters that need the power to communicate directly to the gateway. It makes sense using multi-hop communication inside a mesh topology whose nodes can communicate with one another as well as to the gateway in order to minimize the requirements in terms of transmission distance and thus reducing the overall energy consumption of the nodes.

3.2. Node Types

In bridge or tunnel monitoring, as well as for other types of applications for bearing structures health monitoring, typically the following types of nodes are used: environmental nodes, deformation nodes, accelerations nodes [16], crack and crack propagation nodes [6], [18] and inclinometer nodes [17].

3.2.1. Environmental Nodes

Usually the steel wires and strands that compose the main cables of a bridge are exposed to the natural elements and it is important to have relative humidity information at the surface of the cables. This information can be obtained by directly mounting the sensors on the surface of the cables. In addition, environmental nodes are equipped with temperature sensors, particle and light sensors.

Humidity sensors can measure 0-100%RH with an accuracy of ±4%RH (at 25ºC, range 30 ~ 80%), <±6%RH (range 0 ~ 100) and a response time under 15s according to [18]. The temperature sensors can measure temperatures in the range between -40ºC and +125ºC with a stepping of 0.5ºC and an accuracy of ±2ºC (range 0ºC ~ +70ºC), ±4ºC (range -40 ~ +125ºC). These properties are sufficient to study temperature gradients across the cable length or at boundary regions. The light sensors have a spectral range between 400 - 700 nm and operate in environments with temperatures between -30ºC and +70ºC with a energy consumption closely to 0μA.

3.2.2. Deformation Nodes

Deformation nodes are nodes equipped with sensors able to measure the amount of deformation of the monitored structural element. In [17] the research team presents a fiber optics based sensor capable of performing the measurement. The idea behind this sensor is that it differentially measures the time required by a laser impulse to travel through a fiber optic wrapped around the monitored structural element. If the structural element suffers deformation, the time needed by the signal to travel becomes longer.

Some advantages of this type of deformation measurement device are the facts that it is a minimally invasive measurement method, it does not suffer from electromagnetic noise and it can be used to measure the deformations of a wide range of elements, for example from a single 1 foot element up to an entire structure [17].

Supplementary, this type of node contains a temperature sensor in order to measure the instantaneous temperature in order to perform coordination to the amount of deformation at the measurement point.

3.2.3. Acceleration Nodes

The majority of nodes can be equipped with an acceleration sensor. Acceleration sensors are capable of measuring accelerations in the range: ±2g (1024 LSb/g) / ±6g (340LSb/g) at frequencies of 40Hz/160Hz/640Hz/2560Hz [6]. Acceleration data is high-volume data and has to be stored immediately after sampling. Acceleration nodes are able to sustain a 500Hz sampling rate while writing the data on the microSD card without loses. This requires nodes designed to support bursts of high-rate data having strict reliability requirements.

The acceleration sensor in the case of a wireless node is a MEMS device (micro-electro-mechanical system) with dimensions in the scale of maximum 1 millimeter. These are low-power inexpensive alternatives to classical sensors very suitable for implementation in an energy-constrained wireless sensor node.

3.2.4. Crack and Crack-Propagation Nodes

These nodes are equipped with sensors capable of detecting the appearance of cracks and measure the magnitude and 2D orientation of these cracks. Crack detection gages have lengths between 15 and 56 mm and widths between 3 and 6 mm [18]. The operation temperature typical to this type of sensor is between -195ºC and 120ºC.

The sensor consists of a small conductive strand with a very low resistance value embedded in a fiber-glass film. In the case of a crack development, the sensor shall break thus interrupting a closed electric circuit. This event will be signaled to the node's central processing unit. In order to mount such a sensor to a surface, it has be fixed using a special adhesive. The use of a protective coating is recommended in long term installations.

The crack-propagation sensor that is mounted on this type of node has the same operation principle, with the difference that it is composed of a small conductive strand which contains several parallel grid lines that break progressively with the propagation and enlargement of a crack's width. Several options are available for the distribution of the grids. There are be sensors having: 10-grid lines with 0.25 mm between grids, 20-grid lines with 0.25 mm between grids, 20-grid lines with 0.51 mm between grids, 20-grid lines with 2.03 mm between grids, 20-grid lines with 1.27 mm between grids or other formats depending on the specifics of the structural health monitoring application in terms of crack propagation data [18].

3.2.5. Inclinometer Nodes

These nodes are equipped with sensors able to measure the inclination sustained by structural elements. These nodes are especially used in the case of bridge, tunnel or road structural elements with relatively high success in determining the changes that appear at the relative position of structural elements.

4. Software Running on WSN Nodes

On top of the hardware of wireless sensor nodes runs a very compact operating system (OS). This is a distributed operating system and must be perceived as an operating system working on the entire network as a whole. Abstracting the capabilities of the hardware is a basic OS responsibility.

The majority of OSs are developed using the nesC programming language which makes them portable on many types of hardware platforms.

The basic services provided by the OS are:

- hardware abstraction;
- timers/alarms;
- memory management;
- sensor primitives;
- communication primitives.

One of the main goals of a hardware abstraction is to provide programmers with the facility of easy traversing the software/hardware boundary by allowing some software components to be replaced by hardware components with real hardware modules and vice versa.

Timers and alarms are used by applications running on top of the OS in order to get an event or a piece of data when the timer expires. Alarms are used to signal the applications running on top of the operating system about events that have occurred and must be processed immediately by the monitoring software applications.

The memory management function is responsible for the allocation of memory to the structural health monitoring applications running on top of the operating system. It is also responsible for the efficient allocation of memory in order to reduce memory waste. The fact that the memory resources of the node are reduced as compared to smart phones for instance, has to be noted at this point.

The sensor primitives provide an abstract interface to the physical hardware sensors and the underlying node platform. At least five functions of this interface can be called by a monitoring application: sensor activation, sensor deactivation, get sensor value, configure sensor and get sensor status. In addition, when sensors are deactivated, the sensor API has support for turning off the power to the sensors, thus conserving energy of the sensor board.

Communication primitives are abstracted under the form of messages. Messages are preceded by a small identifier that is attached to each message, specifying the action that needs to be taken on the receiver's side when a given message has been received followed by sensed data, timestamps and other data fields. Usually the nodes transmitting the information are the sensing nodes and the receivers of information are the sink nodes. Nevertheless, communication can take place in the other direction too, for configuration and administrative related tasks.

In the test setup used in our research, the structural health monitoring applications are developed directly on top of the operating system by making use of the operating system's functions. Still, there exists in other implementations of monitoring application another layer between the OS and the user applications. This layer is called a middleware layer and performs further abstractions on top of the OS's abstractions [17].

5. Conclusions

Intelligent monitoring of bearing structures by using wireless sensor networks proves to be a cost-effective solution that can be deployed on a wide range of infrastructure projects including but not limited to water-supply and aerial sewage infrastructure, bridges, tunnels, towers or road segments. They can supply civil engineers with real-time critical data on the health status and the performance degree of the monitored structures.

In the test phase our research team is implementing a structural health monitoring application on a sewage-pipe in Cluj County. The pipe is suspended using wire ropes. Monitoring is performed on the health of the bearing cables by obtaining information about relative humidity, accelerations and deformations. This is done by using three types of wireless sensing nodes: environmental, acceleration and deformation nodes.

Environmental nodes sample humidity, temperature and dust readings. The purpose is to analyze the daily, weekly and seasonal temperature readings and match them to the contractions of the bearing cables. Humidity readings are performed in order to determine the exposure of sustaining and connection elements and braces to corrosion. Relative humidity values above 60% accelerate corrosion processes.

The acceleration nodes are recording information about the vibrations induced in the bearing cables by wind and nearby traffic. The analysis of acceleration records will be done by a custom application and will help understand the dynamic behavior of the suspended bearing structure. From the theoretical point of view, the vibration response of the test structure is not random, but it is situated along some frequencies known as natural frequencies.

Deformation nodes supply an average

value of the last 20 deformation readings. This average is performed due to irrelevant character of single samples. These tend to fluctuate. Elongation of the vertical sustaining cables is an indication of deterioration and will be automatically detected and signaled by a software application under development.

Using a combination of data supplied by environmental, acceleration and deformation nodes a monitoring application will be developed in the next research phase, which will, hopefully, be able to perform strain analysis on the bearing cables. Nevertheless, there is a wide research field left uncovered when discussing about structural heath monitoring applications based on intelligent networks composed of wireless sensing nodes.

An ongoing development of the test WSN, an image acquisition node is being tested. This node is responsible with gathering images of the wire cables. The images are then fed to a new software application embedded into the existing package. The application uses advanced object detection and recognition algorithms for processing the input images.

Currently a database of undamaged cables (wire ropes) is being populated followed by the implementation of machine learning algorithms that will be able to compare new images of cables to the existing models and decide with a high degree of certainty if the images contain damaged cables and the degree of the damage.

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