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Wireless sensors network for vibration measurements

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Abstract

Structural health monitoring (SHM) systems are applied for condition monitoring of machines and structures, structural integrity assessment, damage detection and structural failure prediction. Measurement data acquired by many sensors are essential for SHM, but at a same time application of many sensors located on mechanical structures causes serious technical problems due to wiring of sensors. The wiring is highly time consuming during sensors installation, may change the system output due to high structure loading and damping and often adds signal noise to measured data. To address these disadvantages, a research effort has been initiated for development of wireless modular monitoring systems which use independent wireless sensors for data acquisition and signal processing. Successful application of such sensors network is related to proper hardware and software solutions on single sensor node. The main problem in such networks is synchronization of data acquisition within the network of many sensors. In the paper the requirements for smart wireless sensors are specified and discussed. Design of wireless smart sensor for mechanical structures diagnostics is presented.

Streszczenie

Zastosowanie aktywnych układów monitorujących stan konstrukcji wymaga zainstalowania wielu czujników pomiarowych. Koszt wykonania okablowania pomiarowego w takich przypadkach jest duży, nie bez znaczenia jest również znaczny czas potrzebny na wykonanie okablowania. W celu zmniejszenia kosztów instalacji i skrócenia czasu uruchomianie systemu monitorującego stosowane są obecnie bezprzewodowe metody przesyłu danych. Rozwój tej technologii - układów scalonych, protokołów transmisji, oprogramowania, umożliwia budowę miniaturowych bezprzewodowych modułów pomiarowych, które zestawione w system pomiarowy umożliwiają diagnostykę rozległych obiektów. W artykule opisano problemy związane z zastosowaniem bezprzewodowych sieci pomiarowych, opisano budowany w KRiDM AGH system bezprzewodowy oraz wyznaczono kierunki dalszych prac dla prezentowanego systemu.

1. Introduction

There is highly motivated need for rational and economical solution for monitoring the performance of machines, mechanical and civil structures over their 'life time'. Especially the monitoring of civil structures like bridges, dams, towers, basements play important role in safety assessment and maintenance management. Monitoring systems are important source of information about operational conditions and are currently used for safety and economical reasons.

Monitoring systems play an important role in applications like: damage detection and prediction, maintenance planning and control, safety monitoring of civil constructions. Monitoring system is used to acquire data and calculate structural responses and then damage detection algorithms are employed to assess structural integrity, localize damages and predict further life time of whole structures. Damage detection algorithms that can localize the damage require application of many sensors located on monitored structure. Many of currently applied monitoring systems are wire based - such solution has many disadvantages described in following chapter.

Novel innovative solutions are based on: use of wireless communication systems for inter-sensor communication, application of micro-electro-mechanical structures (MEMS), and integration with build in microprocessor for real time implementation of damage detection algorithms.

Problems related to design and possible successful implementations of such modern systems are presented in the paper.

2. Structural Health Monitoring Systems

Classical Structural Monitoring System. Current designs of structural monitoring systems are equipped with wires, which transfer sensors measurements to a central processing unit where data is acquired and processed. The scheme of architecture of classical wire based monitoring system is shown in the Fig. 1a.

Currently wire based monitoring systems are designed as centralized system architecture with central data unit for data acquisition and data processing. Such systems are well optimized for use in small structures and stationary machinery, which can be easily tested in the laboratory. The problem arises when it is necessary to 'scale' this type of systems into large in dimension and complex structures like bridges or buildings. The potential source of problems during data processing is also measurement noise, especially when systems are located in harsh environments or connecting wires are long.

One of the most important disadvantages of traditional wire based solutions are : time consuming installation, which is estimated as 75% of total time for monitoring system installation, and high costs of placing protective conduits for wires [1].On the other hand, when it is necessary to locate many sensors on small and flexible structure then problem of wiring interaction with it gets important role in modification of structure parameters.

Wireless Structural Monitoring System. The realization of low cost and fast developing wireless monitoring systems is now possible due to the reducing price and rapid development in such technologies like: MEMS based sensors, low power microprocessors, wireless communication and integrated circuits. The scheme of architecture of wireless based monitoring system is shown in the Fig. 1b.

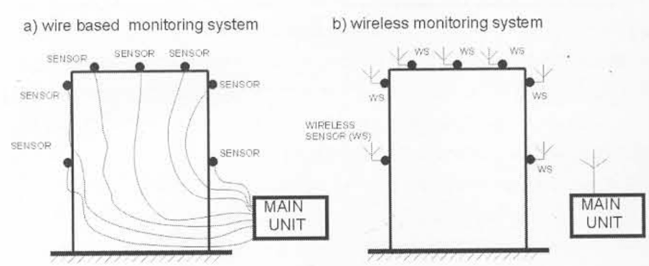

Fig. 1. Traditional and novel monitoring system a) wire based b) wireless.

The main advantage of presented system is wireless sensor inter-connection and data transfer to central unit which is also equipped with wireless interface. Wireless communication eliminates expensive wired connections which reduces cost of whole system. In addition the wireless infrastructure allows transmitting additional measurements like temperature and other environmental conditions over the same data channel. Wireless sensor network adds also flexibility to the system due to: easy change of sensor position or sensor replacement to different type. It is also possible to distribute the data processing procedures over the whole sensors network because the sensor nodes are equipped with their own microprocessors. The sensor node can compute the parameters of monitored structure on the board and transmit reduced data through network minimizing main unit computational loading. In such way the parallel processing can be realized that is important for more complex damage detection algorithms implementations.

Among many benefits this technology has also some drawbacks. The power supply source necessary at each single node can overload a structure - then is necessary to implement self powering nodes or design proper energy harvesting mainly coming from vibration of the mechanical structure. The wireless systems have reduced sample time due to requirements of energy consumption optimization. Unpredictable nature of wireless communication and some hardware features make relatively long sampling times, especially when data is acquired over the whole sensor network.

3. Wireless Sensor Networks

Architectures of wireless sensor networks. The real time data acquisition over the wireless sensor network must be carefully designed due to still quite big software overhead related to data input-output functions which are implemented on microcontroller located on single node. There exist several basic topologies of wireless sensor networks [2]. Three of them, most applicable for wireless monitoring applications, are shown in the Fig. 2.

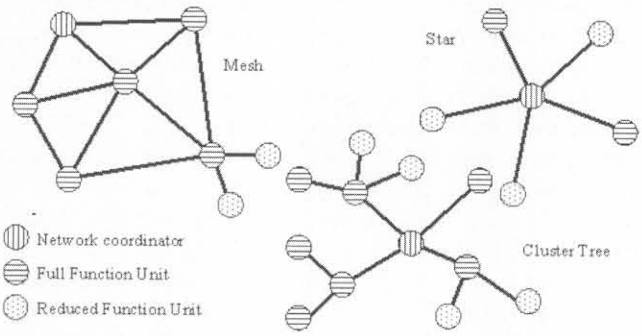

Fig. 2. Basic network topologies used for wireless data transmission

Each of presented above topologies has its own properties and features which define its ability for real time signal acquisition in damage detection systems.

"Star" topology is very similar to traditional wire based systems, except wireless connection. The data transfer from network coordinator -the main unit in network, to single node can be fast, but the central unit can communicate only with one network node at given time. In this case the data transfer time over the network can be very long. Within the network we can consider two additional types of units: a full functional unit - which makes measurements and relay transmission to another node and a reduced function unit - which makes only measurements.

There is also distance limitation between network coordinator and other units - the limitation comes from maximum distance for successful and error free radio transmission between units. However, it is quite simple using this topology to synchronize units to the central clock, which is broadcasted by network coordinator station.

Next two subtypes of topology "mesh" and "cluster" are specially designed for wireless transmission and based on solution coming form cellular telecommunication. The "mesh" topology design is dedicated for large wireless sensor structures. Energy-optimized protocols or altruist or friendly neighbors (like in IEEE 802.11 standard) define the methods of data routing. Those types of networks topologies are very suitable for solution with minimum energy consumption working over years with use of small batteries. Unfortunately, commercial standards in wireless communication, which have those topologies, like Bluetooth [3] and ZigBee [4] have limited data bandwidth and measurements synchronization possibilities. The modern ZigBee standard based on IEEE 802.15.4 protocol is designed for smart sensors working in activity time of minutes, giving extremely long battery life. The "mesh" and "cluster" topologies are designed for data transfer with minimum energy consumption and they can be applied in SHM systems, where reaction time for damage detection is not very critical.

For the designed wireless sensor unit prototype a TinyOS - free, open source operating system was chosen. The TinyOS use multi-hop routing protocol, which use described above network topologies.

4. TinyOS - Operating System For Wireless Sensors

TinyOS is an open-source operating system designed for wireless embedded sensor networks. The system was developed at Berkeley University of California [5]. It features a component-based architecture, which enables rapid implementation while minimizing code size. TinyOS's library includes network protocols, distributed services, sensor drivers, and data acquisition tools - all of which can be used as-is or be further rebuild for a custom application. TinyOS's event-driven execution model enables also power management over the network. The system has high scheduling flexibility made necessary by the unpredictable nature of wireless communication.

TinyOS application consists of a scheduler and components. Each component is described by its interface and its internal representation in manner similar to hardware representation languages like in VHDL language.

The TinyOS system, libraries, and applications are written in nesC, a new language for programming structured component-based applications. The nesC language is primarily intended for embedded systems such as sensor networks. The nesC has a C-like syntax, supports the TinyOS concurrency model, as well as mechanisms for structuring, naming, and linking software components into robust network of embedded systems. The principal goal of the operating system solution is to allow application designers to build components that can be easily integrated into complete, concurrent system, and perform extensive syntax checking at compilation time.

The TinyOS operating system is used by many scientist and commercial users. This is kind of standard platform for wireless applications. The potential application field is large and covers: security protection, monitoring, sensor networks, and robotics. Very important feature of TinyOS is possibility of programming units over the wireless network, which improves system building and testing. There are several hardware platforms which support described above operating system. An example of them is Mica board from Crossbow Technology Inc. which is shown in the Fig. 3.

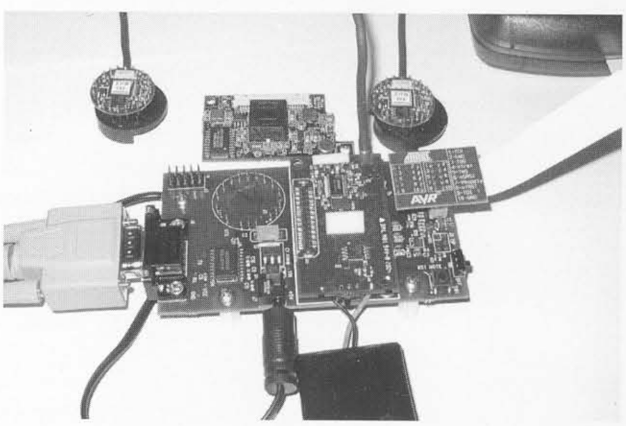

Fig. 3. Picture of Mica2, MicaDot and programming board from Crossbow.

Presented above operating system and hardware architecture were chosen as a base for smart sensor developed at AGH UST Krakow, which is described in the next chapter.

5. Wireless Sensor Unit Prototype Design

Hardware design. Currently available wireless transmitters must be equipped with high speed microcontrollers. The code execution of few mega instructions per second is required for fast transfer rates of wireless communication. On the other hand a power consumption problem arises when the system oscillator has high frequency. For this reason efficient microcontrollers of Atmel AVR family were chosen [6]. The features of Atmel ATmega32L and ATmega 128L microcontrollers are : 8 bit high-performance at low-power (2.7-5.5 V), reduction instruction set architecture (RISC), 8MHz oscillator, which gives 8 mega instructions per second with one cycle execution time, a suite of peripherals like : on-chip oscillator, timer, counter, 10 bits AD-converter, PWM channels, USART, SPI, 32 and 128 Kbytes of flash memory for program storage, 1Kbytes EEPROM, and 2K SRAM memory for additional data storage. The JTAG interface allows of simple software development and testing. Additional benefit of described microcontrollers is very low price for such advanced 'electronic brains'. The prototype unit was equipped with additional flash memory to extend of on board data storage - this feature is important in real time measurements.

As a wireless interface of sensor prototype a CC1000 single chip, low power RF transceiver from Chipcon company was chosen [7]. This chip is characterized by: on board single chip UHF transceiver working on wide ranges of ISM and SRD frequencies (315-915 MHZ), microcontroller based 5 wire interface, a set of registers for transceiver setup and tuning, very low power consumption, high sensitivity, programmable output power, small size and low supply voltage. All those features make the CC1000 suitable for almost all of wireless applications, where user defined protocols are defined. There exist ready to use small size wireless I/O modules based on CC1000, one of them from Soyter was chosen as a base of radio communication. The microcontroller board and wireless interface during software development over the JTAG interface is shown in the Fig. 4.

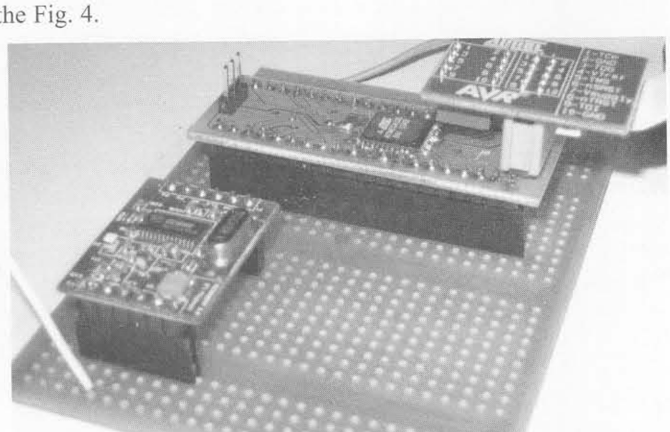

Fig. 4. Wireless sensor prototype unit during development with JTAGICE mkII.

Sensing transducers - accelerometers. Very important part of designed wireless sensor unit is sensing transducer. The prototype unit was designed mainly for vibration measurements, so as sensors the acceleration measuring sensors were chosen. One of modern accelerometers, which can be applied to wireless sensors design are: ADXL 202 - MEMS based accelerometer form Analog Devices and PB3AXN from Oceana Sensor. Measurement characteristics of accelerometers were developed giving the suitable application area for them. The ADXL sensor is used as tilt or gravity measurements with bandwidth of 50Hz. The sensor can measure in two perpendicular axes and its digital interface makes simple integration with microcontroller [8]. The PB3AXN transducer is used for high quality vibration measurements [9]. The output of this sensor is connected to ADC of ATmega microcontroller.

Software design. As it was described in previous chapter, as an operating system for wireless prototype design the TinyOS has been chosen. The complete description of environment for application development under the TinyOS can be found in [5]. Although during the system setup it was necessary to work with user defined code, which was developed with free, open source WinAVR compiler and other tools.

WinAVR environment gives programmer easy C coding capabilities. C language implementation and compiler properties were specially designed for Atmel AVR family microcontrollers, giving optimized code for fast execution of user code. Easy integration with, supplied for free by Atmel, AVRStudio 4 and JTAGICE mkII hardware debugger gives powerful environment for an application software development. It is important that all of software used in project is cost free, which strongly reduces cost of whole system.

During a software development stage the main effort was pointed out to real time measurements over the wireless network. As a result of this work the procedure for high resolution measurements over the wireless network was developed. The procedure is defined in the next chapter.

6. Real Time Synchronization Of Wireless Sensor Units Within Network

As previously mentioned, each wireless network topology has its benefits and drawbacks. The minimization of sample time must mix features of mesh and star topologies. The CC1000 RF transceiver unit is very flexible, so it is possible to setup it using dedicated software into two modes of operation:

- mesh based topology for energy preserve and data distribution over the network,
- star topology used for sampling synchronization over the network.

Developed method for high quality data synchronization consists of following steps:

1. the data between sensors is distributed in mesh type topology giving low power consumption at each node,
2. the special command, defined in applied protocol, is distributed over the network by the main unit, the command consists of operation code and additional data, which : reprogram all CC1000 transceivers to simple UART mode, all nodes except the main unit are prepared only for data receiving, this 'data' is treated as clock input for data sampling, the main unit transmits clock signal to all units at high power output,
3. during the time defined in initialization command, all nodes take measurements and store them in internal flash memory of each unit, sampling interval is generated by main unit,
4. after defined number of samples units are switched back again to mesh topology and off-line data transfer can be started.

During initial experiment the data synchronization between the main station and two receivers was tested. The schematic diagram of laboratory experiment is shown in the Fig. 5.

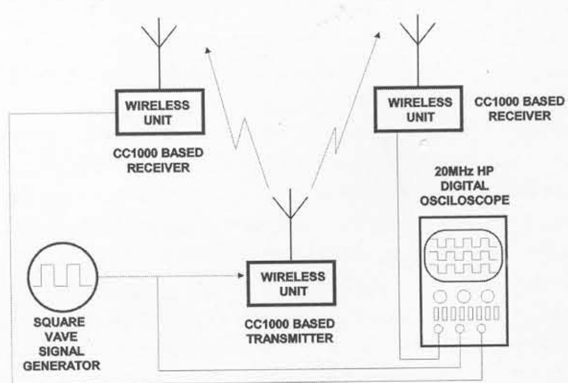

Fig. 5. Schematic diagram of data synchronization test over the wireless network

During tests data synchronization within 10 μs was achieved giving maximum sample rates about 100kHz. This method seems to be very effective during high speed real time measurements. The benefit of this method is that, the main unit can transmit the clock signal with its maximum signal strength over the network, because it can be powered from stationary power source, which eliminates problem of the power consumption at high level of signal output.

The drawback of this method is undefined setup time during the setup procedure, from mesh to star topology. This time can be experimentally obtained with aid of free SurgeView software delivered with TinyOS distribution package. This software allows fixing the data delay within nodes in network. Those delays are related to sensors distribution and propagation of wireless signal. The maximum delay time can be defined for each sensor and then proper time delay can be assumed in initialization command. There is the second method to overcome this problem: at initialization command we must setup very long time for system initialization, for example 1 second, and after this time start measurements with the first signal clock coming from the main unit.

With presented method for real time wireless measurements is possible to implement high resolution monitoring system equipped with damage detection algorithm. There exists several damage detection procedures shortly described in next chapter.

7. Damage Detection Procedure With Use Of Wireless Sensors Network

Damage detection procedures can be based on probabilistic or deterministic algorithms [10]. One of possible models, which can be applied for damage detection, is modal model of the structure. The real time modal analysis software is required to examine the system response to estimate dominant modes parameters of structure under monitoring [11]. For this purposes the real time measurements over the sensor network must be performed and the model of the structure must be calculated [12]. The results of those calculations are compared with initial data for non-damaged structure. This information is passed to damage detection algorithm, which assesses current condition of the structure.

Different method, which seems to be more efficient especially in wireless sensor networks, is method based on statistical pattern recognition described in [13]. The procedure of the damage detection is performed in following way, wireless nodes acquire the data, time history measurements are fitted it into the AR and ARX models. When residual errors between initial data and currently

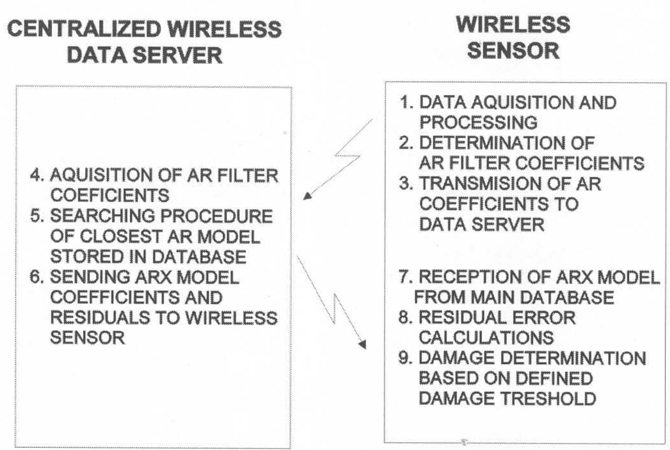

Fig. 6. Implementation algorithm for time-series based damage detection algorithm.

measured data exceed some predefined value then the damage is identified. The possible block diagram of method is defined in [14] and is shown in the Fig. 6.

Presented above algorithm have few benefits, well suited for wireless monitoring systems:

- calculations are distributed over the sensor network, which lowers the overall number of data transmitted over the network,
- only small amount of data is transferred from main unit to sensor nodes,
- calculation performed at each node can be easily performed by small microcontrollers.

One of the main disadvantages of this method is need for precise AR models during database construction. This task is especially difficult in large scale systems, where is quite difficult to obtain full information about possible system modifications and changes during normal exploitation.

8. Summary

The damage detection methods require information from many sensors located on investigated structures. The novel solutions of wireless sensor units allow minimizing the system setup costs and making the whole system more flexible. The applied at each node microcontrollers allow distributing the signal processing over the network minimizing the main unit loading comparing to classical solutions.

Modern hardware and advanced software makes possibility to build sensor networks in a simply way using block diagram technology.

In the paper the description of modern wireless monitoring systems was presented. Based on network topology overview and hardware and software solutions used in developed wireless sensor prototype, the high resolution method for sampling synchronization over the network was specified and tested giving 10 μs synchronization time. The developed software can be applied successfully for on-line modal analysis using wireless sensor networks.

Future work will carry out to validate the developed hardware and software on a real structure.

9. References

[1] J.P. Lynch and others, "A wireless modular monitoring system for civil structures", Prof. Of 2oth Modal Analysis Conference, LA, CA USA 2002

[2] A. Hać, "Wireless Sonsors Network Design" John Wiley & Sons, 2003

[3] "Specification of the Bluetooth System", ver 1.1, 22 febuary 2002

[4] Patrick Kinney "ZigBee Technology: Wireless Control that Simply Works ",Kinney Consulting LLC, Chair of IEEE 802.15.4 Task Group

[5] J. Hill, and others, System Architecture Directions for Networked Sensors Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, Berkeley, CA

[6] 8-bit AVR Microcontroller with 128K Bytes In-System Programmable Flash, ATMEL, Rev. 2467M-AVR-11/04

[7] CC1000 Single Chip Very Low Power RF Transceiver, Chipcon AS SmartRFč CC1000 Datasheet (rev. 2.2)

[8] "Low Cost 2 g/10 g Dual Axis iMEMS® accelerometers with Digital Output", USA 1999

[9] Model PB4AXN, DDC004rev. A, Oceana Sensor, Virginia USA

[10] Proceedings of the Second European Workshop on Structural Health Monitoring 2004, Ed. C. Boller, W. Staszewski, DESTech Publications, Inc., Lancaster, PA, 2004.

[11] T. Uhl, M. Bogacz, "Real time modal analysis and its application for flutter testing", Proc of ISMA2004, Leuven, 2004, pp. 1066-1076

[12] K.F. Kiefer, E. Krug, G., Ajupova, P.L. Walter, "Wireless sensors Applied to Modal Analysis", XXI IMAC Proc., 2003, pp. 253-258

[13] H. Sohn and C. Farrar, "Damage Diagnostics using time series analysis of vibration signal", Smart Material and Structures, Institute of Physics, 10, 2001, pp. 446-451

[14] J. Lynch and others, "Computational Core Design of a Wireless SHM System", Proc. Of ASEM, Pusan Korea 2002

Tytuł: Czujniki bezprzewodowe do pomiarów drgań

Artykuł recenzowany