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# Vibration Measurements Using a Wireless Sensors Network

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*Non-destructive structural health monitoring of civil engineering structures is based on vibrations measurements of objects during dynamic tests or during their exploitation. Wireless sensor networks are increasingly being used for this purpose. They make flexible and inexpensive measurement systems because large cables to connect the sensors are avoided. This paper presents a vibration monitoring wireless system developed at the Faculty of Civil engineering in Belgrade. The structure and characteristics of the measurement system, based on low consumption electronic components and original embedded software real time operating system, are described.*

**Key words:** *wireless sensor networks, vibrations, accelerometers, data acquisition, low consumption*

## 1. INTRODUCTION

The developments in wireless technology, especially related to mobile telephony and the internet, have enabled the wireless sensor networks (WSN) to be used in many areas of science, engineering and everyday life [1,2]. Civil engineering is particularly suitable for WSN application, since it's much cheaper and simpler to employ such a system (compared to a wired one) on buildings, roads, railways, and especially capital objects like bridges and dams. The sensor devices are more easily placed on hard to reach spots and are more flexible than wired ones, meaning they allow for fast and easy relocation of the entire network or its parts. Most frequent objective of WSN use on civil objects is structural health monitoring (SHM), which includes recording the oscillations in different points, and gathering and processing the data to judge the structure condition [3-6]. Besides general requirements, a WSN needs to comply with specific ones for use in civil engineering, like: resistance to extreme atmospheric conditions (high humidity, high and low temperatures), resistance to electromagnetic interferences (of both natural and artificial origin), placement of sensors on large dimensions objects, reliable communication between nodes in closed spaces (out of line of sight), etc.

Development of a wireless sensor network is multidisciplinary and includes: a) choosing or developping the sensors with low consumption, yet accurate enough for a specific application, b) design of the electronic circuitry with low consumption components, c) configuration of the wireless network so that it enables fast and reliable data flow between different nodes, d) development of flexible software to control the components and the system as a whole so that it can be used for a large variety of applications, e) development of processing software to be executed high level, for specific application in civil engineering or other target area.

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## 2. HARDWARE

The wireless sensor network developed at the Faculty of Civil engineering, Belgrade, is comprised of sensor devices (nodes) placed at different measuring spots and a central (base) station. Each node contains a sensor (or multiple sensors), radio modem, battery, optionally with energy harvesting system, and accompanying electronics. Base station, which gathers and processes the data, is a standard desktop or a mobile laptop personal computer (PC).

Figure 1 shows a sensor device and its basic parts: main electronics board, board with the accelerometer, radio modem, and the housing with the antenna. Energy harvesting system and the display (not shown here) are optional. Base station has practically unlimited resources: it doesn't have to take care about energy consumption, processing power is big, and memory storage is practically indefinite for this purpose. All processing of the results except the compression prior to radio transfer, is performed at the base station.

Star network topology is used. Synchronization of the devices is performed by the beacon signal.

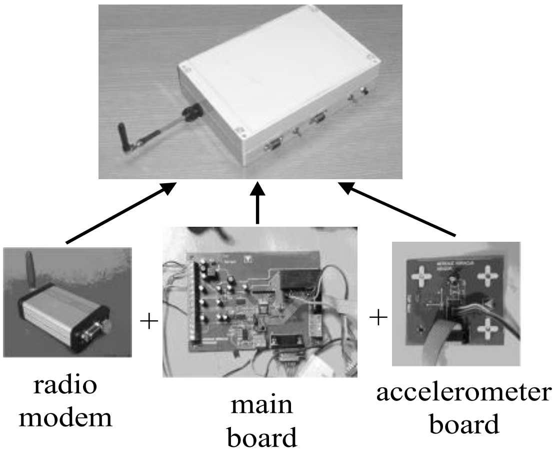


*Figure 1 - Sensor device and its basic parts*

*2.1 Main board*

The main board of a sensor node contains ADuC845 processor and supporting electronic components. It's made using surface mount technology (SMT). The processor is a member of the wide 8051 processors family. 8051 type processors have long history of use in industrial applications and are considered very reliable. One of the things that make ADuC845 suitable for particular application is relatively low consumption and the ability to enter so called sleep mode in which its consumption is about 70 μW (neglectable compared to the consumption of stabilizers and other circuitry which is powered all the time). It works with programmable pace, which goes up to 6.292 MHz. It has two 10-channel 24-bit sigma-delta A/D converters built in, with effective resolution of 19.5 to 22 bits, and sampling frequency of 1 kHz, which exceeds usual needs in civil engineering measurements, and a thermometer with $1\,^{\circ}$C resolution. The processor should be powered by 3-3.6 V voltage. Stabilizers decrease input voltage which is normally in 3.5 to 4.1 V range (knee voltage to maximum voltage of 3 NiMH batteries) down to optimal 3.3 V. Working temperature range is -40 to $+85\,^{\circ}$C. Maximum current consumption is 4.8 mA (which corresponds to about 16 mW power). UART, I2C and SPI interfaces serve to connect the processor with all peripheral parts used in this application or potentially used in any similar one. The board also contains 4 LP2986 stabilizers, external 32 kilobytes RAM M4-8T35AV with its latch control circuit, ADR2981 reference voltage source, MAX3232 driver-receiver for serial communication, LT1512 battery charging controller, and a number of basic components such as operational amplifiers, diodes, oscillators, capacitors, resistors, etc.

*2.2 Radio modem*

Radio modem PRM-4 is an external device which is connected by RS232 interface to the main board. It is an independent processor device, which communicates with the board via RS232 on one end, and sends and receives electromagnetic waves using antenna of a variable size, shape and range, on the other end. Output power of the radio signal is programmmable and this enables power saving in case large range is not needed. Maximum range in urban conditions is about 1 km, but it's dependent on artificial interferences and topology of the terrain. Baud rate of radio communication is 9600 bps and is performed at 863 MHz frequency. The modem consumes from several mA up to 40 mA during transmission.

Usual frequency of wireless modems is 2.4 GHz, but the carrier frequency of 863 MHz was chosen for better diffraction in closed spaces and less electromagnetic interferences (there is a larger number of wireless devices which work around 2.4 GHz).

The modem features its own protocol in which it uses CRC checksums and addressing masks. Similar methods are used by the embedded RTOS of the device node, so with two layers of control we can state that chance of receiving invalid data is nil.

*2.3 Accelerometer board*

The main sensor of the device is currently integrated microelectromechanical (MEMS) three-axial accelerometer LIS3LV02DL, with 12-bit resolution and the range of ±2g (can be switched to ±6g). It communicates with the main board processor using 4-wire SPI interface. The accelerometer is placed on a separate plastic board which is powered from the common power supply (normally the batteries), so that it could be separately mounted, especially during the testing period. Sampling is performed using 160 Hz frequency (frequencies available are 40, 160, 640 and 2560 Hz), so that desired oversampling is achieved for frequencies of interest in modal analysis of vibrations of big civil engineering objects, which usually don't exceed 25 Hz. One measurement lasts for approximately 20 seconds, during which time 3 times (for 3 axes) 3200 12-bit samples are acquired. The data is then compressed and sent to base station on its request using radio modem.

The experiments showed that sampling frequencies of the different accelerometer pieces, although nominally 160 Hz, aren't equal, and that they vary over 1%. That's one of the reasons why timestamping of the samples is important. Main purpose of this wireless system is modal analysis, which means oscillations in different points in space have to be compared, so relative time synchronization of samples gathered from different nodes is essential.

The program remembers start and end time of the approximately 20 second measurement. Relative time in which timers on nodes start their counting is the reception of beacon signal used to initiate the measurement cycle. Tests with storage oscilloscope have shown that standard deviation of propagation of this signal to different nodes is 6-7 μs. Relative uncertainty of frequency of the oscillator running the main board processor can be over $10^{-5}$, thus producing over 0.2 ms uncertainty in timestamps of samples near the end of a measurement period, and therefore being major cause of errors in data synchronization. But this situation may be mitigated using a number of techniques. Aged matching oscillators can be acquired with relative differences under $10^{-6}$. Even if this is not done, test of the processors using a frequency counter may be performed, and the difference in measured frequencies can be used to adjust the data by software on the base station. The downside of this method is need for the test periodical repeating, due to the fact that crystals age and change their frequencies.

### *2.4 Display*

Liquid crystal display D20486SYHLY is mounted on a separate integrated circuit, with the processor AT89C4051. This auxiliary board is placed into its own housing. It communicates with the main board using 2-wire I2C interface. Processor AT89C4051 doesn't have I2C protocol implemented, so all the coding was manually performed. LCD contains 4 rows by 20 characters and 8 buttons. Additional user-defined characters have been created.

The display can be optionally connected to the sensor device. Reasons for its use are multiple: it allows for easier development (debugging) of main board software, enables the diagnostics of node state in case it doesn't respond to radio signals, and serves for calibration of the device (setting the application parameters). Display board is powered by main power source, because I2C interface doesn't contain common ground. In case main power supply is empty, the display doesn't function.

## 3. ALGORITHM OF SYSTEM OPERATION

Sensor devices work in pulses. They spend most of the time in low consumption regime (sleep mode). Processor consumption in this regime is neglectable. Main source of consumption are stabilizers powering the processor (multiple stabilizers are employed for the purpose of precise A/D conversion in case external sensors are added to the device). They account for about 1 of about 1.5 mA (corresponding to about 5 mW) current consumption. Period of processor activation is programmable and can be anywhere between a second and 255 days (in practice, it should be expressed in minutes). Most peripheral components (most importantly the modem) are disconnected from the power supply while processor is in sleep mode. Upon activation, the processor turns the radio modem on, checks for the presence of radio signal from the base station, and if it isn't detected within several seconds, reverts to sleep mode. Base station starts periodically emitting beacon signal on the user request. This signal awakes and synchronizes the sensor nodes (measurement start is not ordered yet at this point). There are no guarantees that activation moments of nodes are approximately simultaneous, althoughugh in practice this will most often be the case, if the system is used actively. After the maximum time (defined by the user, preferably a little higher than expected period of node wake-up) has elapsed, or all requested nodes have responded, base station emits a beacon with the order to start the measurement process. All devices were in stand-by regime up to this moment, which means their awake periods have been extended to about a minute in anticipation of receiving new commands. After the measurement ends, devices go back to stand-by regime until they finish sending their data to the base station, when they go back to sleep mode.

## 4. SOFTWARE

Embedded real time operating system (RTOS) is software executed on the main board. Unlike the personal computer, where different layers of software exist, like the one written into the motherboard (BIOS), operating system (i.e. Windows), the application (i.e. a browser), and a script, macro, add-on, etc (inside the application), device of these dimensions and with fixed hardware configuration features static software. There is no possibility of loading different software modules during regular operation, so the whole set of routines, starting from most basic ones like reading the keyboard or writing dots to the display, to most complex, like data compression, is integrated and called embedded RTOS. Development of this operating system was biggest item in creation of the system, not only for complexity of the tasks, but for the lack of expensive equipment enabling real time debugging as well.

Although there exists a main program, operating system also performs a certain level of multitasking. It takes care of interrupts from several different sources, such as timers, I2C interface and serial (RS232) interface.

Several events can cause processor wake-up from the sleep mode, and the program identifies source of the wake-up to choose the path of execution. Wake-up can be: a) due to power being turned on, b) after emergency termination (reset by the watchdog timer - this is not used in normal operation, only during the development and testing period), c) caused by attaching the display and pressing the wake-up button, or d) regular scheduled wake-up by timer. If the display has caused the processor wake-up, the device enters calibration mode. It displays basic parameters (temperature, battery voltage, cause of previous wake-up, wake-up interval, error flags, and miscellaneous other variables) and expects a further key press to enter the calibration (edit) procedure, in which user can view and alter many parameters or observe the output of the accelerometer. In all other cases, source of wake-up is saved into memory and the device awaits for beacon signal for a short period of time and then goes back to sleep.

External RAM memory (the processor also contains 256 bytes „DATA/IDATA“ memory and 2048 bytes „XDATA“ memory) saves the measurement results, since it has independent embedded battery, with guaranteed lifetime of 5 years (but previous experience with similar types showed that they can last for over 10 years). This way, measurement data can be retrieved even after the device has been shut down, for instance if there was an error in communication during buffer transfer. All auxiliary data is saved as well (physical date-time of the measurement, temperature, battery voltage and relative timestamps).

To save the energy during transmission of measurement results, it is necessary to compress the data. For this, a set of routines is written which perform standard generic Huffman coding of the signal which has already been differential pulse code modulated (DPCM). This lossless method typically yields 30-70% compression ratio for real vibrations, while noise can be compressed down to about 10% (this ratio depends on accelerometer noise magnitude which varies based on a number of factors). Ratio is calculated using size of the data already packed into 12-bit fields (no unused bits).

Special challenge in application of this method is the fact that memory of the device is only 32 kB and half of this amount is already occupied by raw measurement data and other variables, so it requires rational use of resources and data overlaying. Overlaying means using same memory space for different variables which are not used in the same time. Recursive procedures necessary to create Huffman tree are time consuming so effective assembler programming is necessary in order to save time and achieve maximum energy saving. Typical compression takes several seconds (maximum compression for pure noise lasts well under a second using maximum 6.292 MHz processor tact). Compression time and ratio are, naturally, very dependent of the type of the signal.

A program for PC has been written to control the wireless network. This program controls the entire process by radio modem of the same type attached to the serial port. Prior to starting the process, user selects the devices he wishes to include. Then he „polls“ the devices, which means that PC sets its radio modem into proper regime and starts emitting „stand-by“ type beacon signals in approximately one second succession, and records if desired nodes respond to it. Nodes which wake up by the timer (regular scheduled wake-up) register this signal and enter stand-by regime. Time during which nodes are awake is normally set to about 3 seconds, to increase the chance of detecting broadcast signal, in cases when communication is not ideal (packets are lost). Nodes respond to each beacon during all the time it is being emitted from the base. Stand-by type beacon will stop being emitted once either all nodes included in the process have responded, or the time-out has been reached (predefined by the user). If all nodes responded, second beacon of a different type is emitted, to order the nodes to start the process. This process is either new measurement, transfer the results of a previous measurement, or the power test. Nodes not included in the operation will shut down upon reception of this signal.

Best synchronization is achieved if all nodes start their timers on the same beacon signal. Even in cases when perfect communication isn’t possible and this doesn’t happen, time between successive beacon signals can be recorded and post-facto correction performed on PC after the measurement.

If a new measurement is ordered, PC pauses for about 25 seconds to allow for measurement and compression. Data is acquired subsequently. All events are timestamped with physical PC time and written into a log which can be scrolled in the main window or recorded into a text file. In case old measurement data is to be gathered, the only difference is that pause is skipped. Power test is performed so that a number of packets (with predefined content) is received from a single node for each transmission power and a percentage of successful transfers (as a function of power) is recorded. Additionally, just entering standby can be ordered too, in which case PC stops sending stand-by beacons and awaits for user input (nodes will wait for about a minute before they revert to sleep).

All functions can optionally set physical datetime on the nodes, their transmission power and wake-up period.

Measurement results can be viewed on the graphic, be saved to a binary file, or exported as text for analysis in other programs. Coefficients of cross-axial sensitivity can be written into the program and automatic correction of results can be performed before the export.

## 5. TRANSVERSE SENSITIVITY TESTING OF THE ACCELEROMETERS

Due to imperfections of MEMS sensors, there is cross-axial (also referred to as transverse) sensitivity, which means that output of the sensor for an axis is caused not only by acceleration in that direction but in two perpendicular axes as well [7]. Main source of this error is mechanical misalignment (non-orthogonality) of the plates which are pressed by the proof mass.

Output of the sensor can be described like:

$$f_x = k_{x0} + k_{xx}a_x + k_{xy}a_y + k_{xz}a_z$$
$$f_y = k_{y0} + k_{yx}a_x + k_{yy}a_y + k_{yz}a_z \qquad (1)$$
$$f_z = k_{z0} + k_{zx}a_x + k_{zy}a_y + k_{zz}a_z$$

where coefficients $k_{xx}$, $k_{yy}$ and $k_{zz}$ describe main axial sensitivity and are dominant (much higher than others). $k_{x0}$, $k_{y0}$ and $k_{z0}$ are zero offsets and are sometimes omitted from the equation if it's assumed that direct component of the signal is neglected (in vibrations processing). Their determination is, however, included in the process of measuring other coefficients, and they are necessary to solve inverse equations and perform signal correction.

Transverse sensitivity testing is performed by so called tilt test, in which sensor is placed into different orthogonal positions (six of them), so that gravity acts on each axis in each direction. Due to imperfections of the surfaces and the housings, the sensor was rotated in each of the basic positions, and the results have been averaged. This eliminates effects of surfaces being sloped or sensors being not perfectly adjusted to the housings. Experiments without any external equipment yield results repeatable down to several ‰ and confirm that highest cross-axial sensitivity, defined as:

$$S_{cr.x.} = \sqrt{k_{xy}^2 + k_{xz}^2} / k_{xx}$$
$$S_{cr.y.} = \sqrt{k_{yx}^2 + k_{yz}^2} / k_{yy} \qquad (2)$$
$$S_{cr.z.} = \sqrt{k_{zx}^2 + k_{zy}^2} / k_{zz}$$

equals 2.8%, which satisfies the manufacturer's specification (up to 3.5%).

## 6. EXAMINATION OF TIME SYNCHRONICITY OF MEASURED DATA

Simultaneity of beacon signal reception on different nodes has been examined with a storage oscilloscope. Two sensor boards were programmed to flip a digital output pin signal of a processor upon reception of the beacon. These pins were connected to two oscilloscope channels. One signal edge was used to trigger the oscilloscope and the shift in time of two edges was observed. Each edge had neglectable rise and fall time (far under a microsecond) and software detection of the signal causes additional uncertainty about a microsecond. Results show standard deviation of 6-7 µs with maximum value of 20-25 µs from several hundred experiments. They vary slightly when different pairs of nodes are examined.

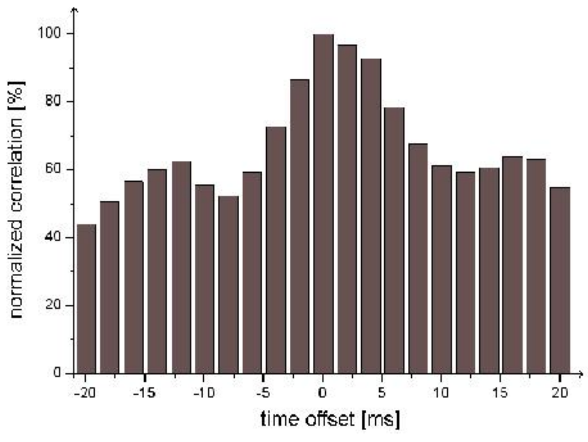


*Figure 2 - Normalized average cross-correlation function of two recorded signals as function of time shift*

In the next experiment, 36 measurements were made using two accelerometers attached as near as possible (under 10 cm) to the common plastic pad. The pad was placed on the surface and exposed to different types of vibrations. To check the concurrence of the signals, their cross-correlation function was observed. Since samples from different nodes are not simultaneous (measurement points in time are not identical and differ within sampling period range), results from one sensor were linearly approximated (based on adjacent samples) so that their timestamps match the other. Direct components of both signals were removed and data from two sensors were multiplied. If the timestamps from sensors are correct, correlation function should peak when time offset of one signal compared to the other equals zero. In reality, this can not always happen due to the facts that sensors don't record exactly the same signal since they can't be placed to exactly the same position, and their dynamic characteristics can't match perfectly. Deviations naturally occurred in these experiments. Overall result is satisfying as shown in histograms in figures 2 and 3. The first one shows cross-correlation in relative units averaged for all measurements. In some measurements, time shift of maximum correlation is zero, while in others it's not. This can not be observed in figure 2, so the figure 3 shows distribution of time offsets for which the maximum is achieved. Step in the analysis was 2 ms, which equals one third of the sampling period.

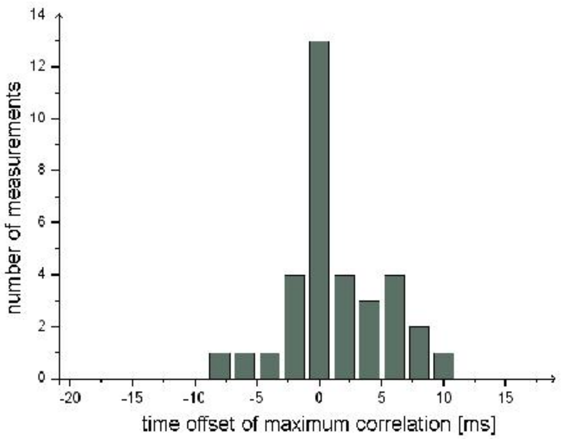


*Figure 3 – Time offset of maximum cross-correlation*

## 7. RANGE EXAMINATION

Modem range is a term which is impossible to define precisely. Probability of data packet transfer depends on its size, power of the transmission, distance between the transmitter and the receiver, types of antennas, obstacles (shape, size and position), atmospheric conditions, natural and artificial interferences, etc. Number of retries increases the chance of success. In case of sensor nodes with limited power supplies, it is necessary to choose the number of retries so to achieve compromise between the chance that a desired number of packets (ranging from 10 to 30 at 160 Hz sampling frequency in practice) is successfully transferred, and the power saving. Not only do transmission retries deplete energy reserves of a node transmitting its buffer, it also drains other nodes which have yet to transmit the data, since they are in stand-by mode until their turn to transfer the data comes. The base station software allows the user to choose maximum number of packet retries.

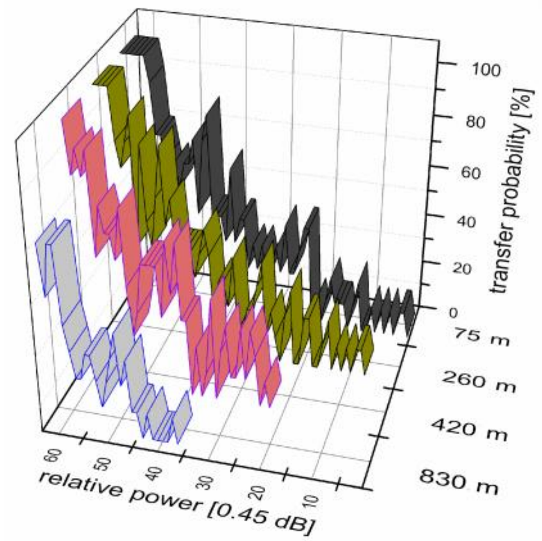


*Figure 4 – Packet transfer probability as a function of transmission and the distance*

This experiment shows the probabilities of packet full of different bytes (250 characters length) is transferred using different transmission powers of a sensor node on different distances from the base station. Ten packets were transmitted for each power, which can be adjusted in 64 steps, so 640 packets were emitted in total on a single distance. Maximum power of the transmission equals 20 mW and is equivalent to power parameter being equal to 63, and each decrement by 1 corresponds to -0.45 dB (so that zero relative power equals about 30 μW). Series of experiments showed that results do not vary as a function of supply voltage (ranging from 3.55 to 4.05 V, modem being powered directly by batteries and not through the stabilizer). However there are considerable random variations (significant drops in the rate of transferred packets) in different times of a day, which is contributed to artificial interferences. Measurements have been performed under the conditions of heavy traffic on a busy city boulevard, and the base station was located in the building of the electrical faculty. Figure 4 shows several (for clarity reasons) examples of relatively satisfying results. Conclusion is that modem range can be declared to be about 800 m in the line of sight, in the city center.

## 8. CODING

Performing a series of experiments on low powers, it soon became obvious that some packets (certain data contents) have higher chance of being transferred than others. Reason for this occurence is modem internal imperfection. In order to improve efficiency the coding was introduced. Results were satisfying.

If the transfer fails on the first attempt, nodes perform coding, and that is exclusive or (xor) operation with an 8-bit key (byte composed of different bits, such as 10101010, 11001100, etc). This byte is generated at the base station and trasmitted as a parameter to the nodes. Decoding (another xor with the same key) is performed when the packet is received. Number of retries is programmable and each retry uses a different key.

It is not unreasonable to suppose this method could be employed with variable success in other cases where a constant bit rate has to be used, and there are diffferent physical sources of disturbances in the process of signal transmission, because the coding changes number and distribution of bit transitions (0-1 or 1-0) and therefore influences spectrum of the signal, regardless of the modulation type used and the physical nature of the signal. Similar methods are usually described as data whitening [8].

## 9. CONCLUSION

A wireless sensor network for vibrations measurement on big civil engineering structure was developed and described in this article. It's composed of sensor nodes with three-axial accelerometers and a central station. Special care was taken to minimize energy consumption because of battery power supply, by choosing components with low consumption and optimal software management.

Due to original embedded real time operating system, it is possible to vary a large number of parameters, thus adapting the network to conditions of a specific measurement task. Cross-axial sensitivity of accelerometers was examined and corrected.

Time synchronicity of data from different nodes was examined and methods to improve it were introduced. Power test was designed to estimate transmission power needed for transfer of the measurement data. Efficiency of the data transfer was improved by coding (data whitening).

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## REZIME

MERENJE VIBRACIJA MREŽOM BEŽIČNIH SENZORA

*Nedestruktivno praćenje stanja građevinskih objekata se bazira na merenju vibracija objekata pri dinamičkim ispitivanjima ili u toku njihove eksploatacije. U ovu svrhu se sve više koriste mreže bežičnih senzora koje čine fleksibilan i jeftin merni sistem, jer nema razvlačenja kablova velikih dužina za povezivanje senzora. U ovom radu je opisan sistem za bežično merenje vibracija na objektima razvijen na Građevinskom fakultetu u Beogradu. Predstavljeni su struktura i karakteristike mernog sistema baziranog na elektronskim komponentama male potrošnje i originalnom softveru.*


**Ključne reči:** *bežične mreže, vibracije, akcelerometri, akvizicija, niska potrošnja*