

Bogdan FABIAŃSKI*
Krzysztof NOWOPOLSKI*
Bartłomiej WICHER*

THE SYSTEM OF STREAMING AND ANALYSIS OF SIGNALS FROM MEMS ACCELEROMETERS

In the article, a dedicated testing environment for MEMS acceleration sensors is shown. The system is able to collect data from multiple devices with different physical interfaces, send them through parallel streaming, archive, and analyze it. The architecture and operational algorithms of individual components, such as complex synchronization methods in the data streaming process is described. This data streaming is finally realized by Ethernet interface which becomes a bridge between the PC system running the dedicated application and the sensor board. In the last section of the article, quality indicators of acceleration sensors signals are presented. These indicators indicate primarily a useful signal to noise ratio with respect to the measurement resolution.

KEYWORDS: MEMS technology, gravity sensors, data streaming, digital signal processing, data acquisition, STM32L microcontrollers

1. INTRODUCTION

The article issues related to solving the problem of gravity field sensors signal data streaming that will be used for the purpose of particular sensors quality indication are discussed. The base of this topic selection - from practical point of view - is system prototyping that would be able to classify the status of machine based only on acceleration signals. Such systems are used for diagnosing of machines moving parts (e.g. electric machines [1, 2]), in transportation (detection of critical to the transported cargo integrity: falls, impacts [3]), in the anti-theft systems (detection of unauthorized doors/windows opening attempts [4, 5]). Common MEMS (Micro Electro-Mechanical Systems) ICs mass production technology used by many producers meaning that the economic barrier is broken resulting in dynamic growth of potential applications. Generally research problems in the field are focused on appropriate signal processing – including increasingly using of artificial/machine intelligence (e.g. fuzzy logic, neural networks) [6, 7]. More

* Poznan University of Technology.

sophisticated signal processing is necessary in the cases where difference between normal and fault operational state of machine is not trivial. The good quality of source signals determines appropriate system work in global scale, often determines effective operation in general. This is why the selection of suitable MEMS ICs should be based on a comparison of operating in real conditions and not only on parameters pointed in related datasheets. The article shows an attempt to create such a dedicated testing environment for MEMS acceleration sensors that will be able to signal data parallel streaming, archiving, and analysis from multiple devices (often with different physical interfaces). The paper describes architecture and operational algorithms of individual components, so the complex synchronization methods in the data streaming process. This data streaming is finally realized by Ethernet interface which becomes an bridge to the PC system and to the dedicated application. The purpose for the PC application is to control streaming process, to archive and analysis of signal data in a user friendly environment. Finally there are presented a quality indicators of acceleration sensors signals in the way of selected analytical formulas. These formulas indicate primarily a useful signal to noise ratio with respect to the measurement resolution.

2. SYSTEM HARDWARE ARCHITECTURE

2.1. System overview

The system – as mentioned in the introduction to the article – is using for parallel measurement data streaming from several different MEMS chips. In the Figure 1 system overview that realize this idea is presented. Several main nodes (elements) of the system can be extracted. from Ethernet and RS-485 networks point of view These points are also independent hardware devices.

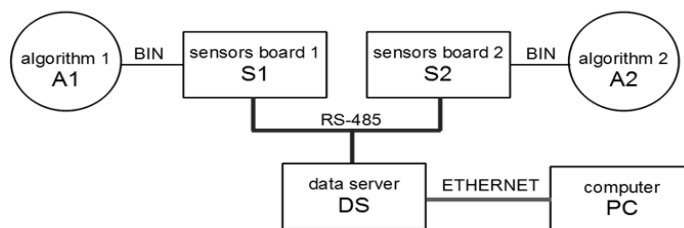


Fig. 1. System general structure overview

The most important parts are: sensors boards S1 and S2, where magnetic field sensors are mounted and where the data origin is placed. The S1, S2 and embedded data server are connected together with RS-485 interface lines (UTP – Universal Twisted Pair, on which differential signal is propagated). The

advantage of RS-485 is that it can be applied in almost all, even simple MCU (Microcontroller Unit) based on UART peripheral (Universal Asynchronous Receiver Transmitter) and dedicated line driver (e.g. MAX485, SP485) with relatively large cable length (there is about 20 meters of UTP cable used in the laboratory bench that S1, S2 are connected with data server – DS).

Role of the DS module is to provide data via Ethernet interface based on TCP/IP stack (UDP protocol transmission) what makes the system easy to connect to any PC, where a dedicated application is running. PC application makes the system much more efficient, so detection of improper work (malfunction) is possible thanks to the easy to use interface and built-in functions (e.g. convert into the data compatible with Matlab environment).

2.2. Data source boards

The algorithm boards A1, A2 (Figure 1) are not essential in the article main subject, but are very useful in practice. Algorithm boards are stand-alone, independent devices supplied by the battery and equipped with only one MEMS sensor chip each. These boards are the effects of further system development and are able to detect intrusion (e.g. via door) based on the vibration signals analysis. In other words, A1 and A2 are “intelligent classifiers” able to distinguish between normal behavior and intrusion attempt. These boards were evaluated with strong emphasis on practical application and were used to test classification algorithms, moreover two different algorithm may be tested in the same time.

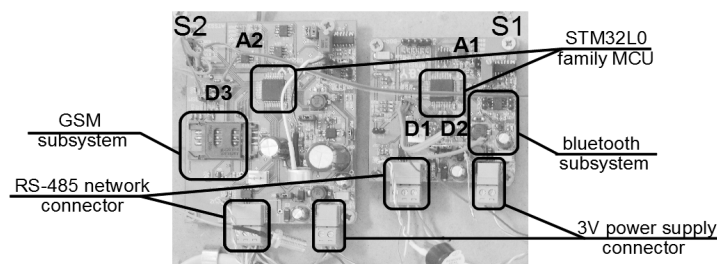


Fig. 2. MEMS signal source boards

The system core, S1 and S2 boards are presented in the Figure 2. Power supply and RS485 interface connectors are present on both PCBs. Greater system flexibility was obtained by splitting the data source into two separate boards. Besides, research on MEMS chips, GSM and Bluetooth interfaces was conducted on the laboratory stand (appropriate sections are pointed in the Figure 2). System is driven by STM32L0 ultra-low-power microcontroller unit (88 μ A/MHz in run mode, 1.65 V to 3.6 V power supply) [8]. The boards S1

and S2 are equipped with embedded SPI and I²C interfaces for communication with MEMS sensors. The following MEMS chips (from the same price level) were verified: LIS352AX (signed as A1 in the Figure 2, analog interface), MMA7361LC (A2, analog interface), LIS3DH (D1, SPI interface), LIS35DE (D2, SPI) and MMA8451Q (D3, I²C interface).

The reason to add this boards to the system was to enable real-time evaluation of intrusion detection algorithms by on-line system state acquisition. Computation results are sent by simple binary interface (described as BIN in Figure 1) and added to the RS-485/Ethernet data .

2.3. Independent signal analyzer units

In the Figure 3 independent signal analyzer units A1 and A2, connected via binary interface to S1 and S2 boards, are presented. In the A1 and A2 boards two different algorithms (even in the meaning of logical structure of these algorithms) are implemented, what makes a real-time objective assessment of intrusion detection quality (at the same scenario) possible. Such a structure may be used in the automatic algorithm parameters selection in the test cycle (with application of fuzzy logic, theory of artificial neural networks learning or other analytical methods).

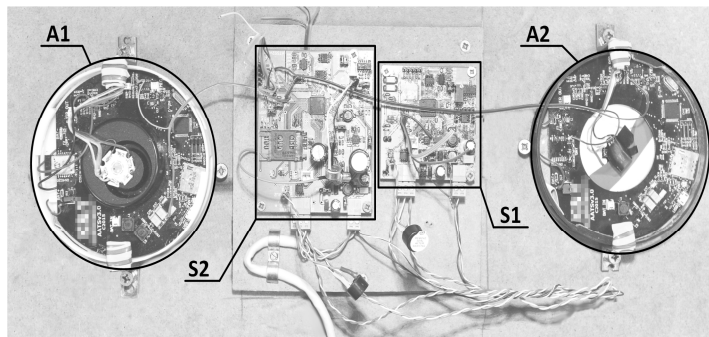


Fig. 3. Independent signal analyzers units

2.4. Ethernet server and PC system

Figure 4 shows the Ethernet server and rest of the laboratory setup elements. As mentioned before, DS (from Figure 1) operate as a RS485<->Ethernet interface translator. The RS485 frames are aggregated to bigger packages (over 1 kB) and are sent via Ethernet to PC system, where are intercepted by a dedicated application. Since the RS485 communication is fully synchronized by DS and data contains time information, Ethernet transmission delays have no impact on the further analysis in data integration.

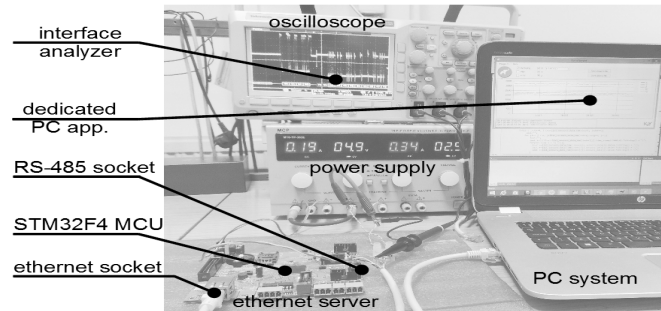


Fig. 4. Laboratory stand with Ethernet data server

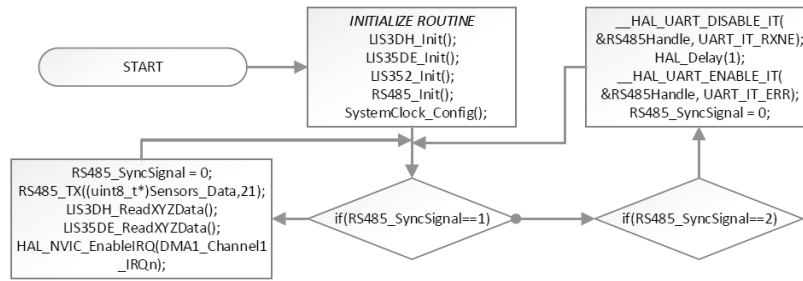


Fig. 5. General program flowchart in S1 MCU (main part)

Data server is a custom made design powered by STM32F4 MCU, with computational power much more than in the MCUs in previously mentioned boards and required Ethernet interface [10]. Oscilloscope is provided with embedded interface module, which allows to decode signals on SPI, I²C and RS485 (see Figure 5 oscilloscope screen) interfaces.

3. SOFTWARE AND COMMUNICATION

3.1. Embedded software

The new STM32 family MCUs are supported by producer only by HAL standard peripheral library (HAL STL) which differs from STL (as new library is on the higher abstraction level). This library is used in the project embedded software development. HAL STL simplifies some instructions but is also much less flexible on the other hand. The program flowchart related to S1 board MCU is presented in the Figure 5. After the initialization procedures (one analog, two digital SPI interfaced MEMS, clocks and RS485 peripheral), system listens on the Rx channel of the RS485, waiting for the sync signal from the DS board. When complete “sync1” signal is received (condition `RS485_SyncSignal==1` is

true), then last acquired sample is sent (thanks to that solution, there is no delay caused by the new SPI data grabbing or analog channels conversion). After about 1 ms, DS sends “sync2”, what halts the RS485 receive line (that eliminates possibility of receiving false “sync” signal as an unfortunately MEMS data stream combination).

Proposed synchronization mechanism works well and stable at 1Mbps network speed rate. The embedded program in S2 has a similar structure, besides there are I²C and analog interfaces to the MEMS chips. Synchronization system is presented as timetable in subsection 3.3.

Data server (Ethernet server) is based on an older, more flexible STL peripheral library, connected with FreeRTOS real-time operating system and LwIP TCP/IP stack. Communication to the PC via Ethernet is realized by UDP protocol on transport layer of ISO/OSI model. When high data rates are required and time determinism is more important than packet transfer certainty, UDP is better than TCP (datagram lost does not delay or hangs all the transmission).

3.1. PC application

MEMS laboratory data server PC application shown in the Figure 6 is a one-windowed form with several controls groups. There is a turn on/off button (Figure 6-a) which causes sending an appropriate message via Ethernet to the DS board that starts/stops data streaming. In the control section (top of the window) there are others controls: (b) causes averaging of 16 samples before displaying on the screen (prevents from graphic system overloading when plotting), (c) - when checked results of the AI1/AI2 board computation is shown, (d) - display the data associated with X,Y or Z component of gravity field.

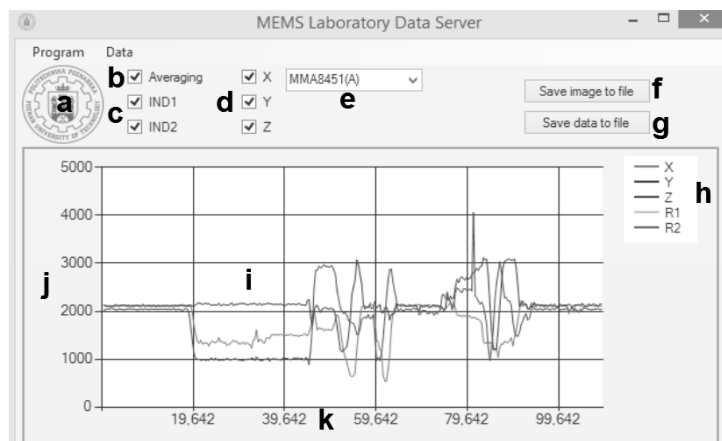


Fig. 6. PC application

Only one data source can be shown at one time - this is selected by (e) control. Acquired data is shown in the center of the window (i), while (k) is the time independent time-based plot variable (in seconds), (j) is value of the measured acceleration (raw, binary data) and (h) is the plot legend. The plot can be saved into the PNG formatted image (f) or to text data formatted in CSV (g), which is easily importable to other environments such as Matlab, Excel or OpenOffice Calc. Application is developed in Visual Studio C# IDE Environment with use of only embedded libraries/controls.

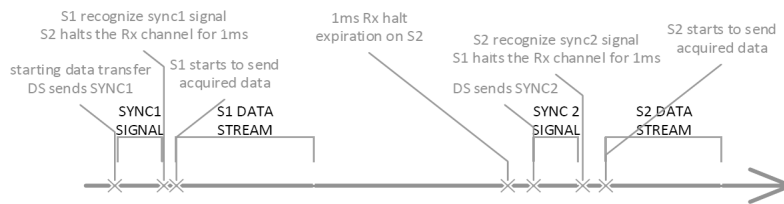


Fig. 7. RS485 transmission cycle timeline

3.2. Communication

The timeline of the RS485 transmission cycle is presented in the Figure 8, with detailed timestamps and intervals description on it. Figures 8–10 show transmission process on the SPI, I²C and RS485 interfaces of the system.

The Ethernet server sends the concatenated data after every forty RS485 transmission cycles. The transmission cycle becomes complete when after “sync1” signal, DS receives expected amount of data from S1 and when S2 sends strict data bytes after “sync2” frame.

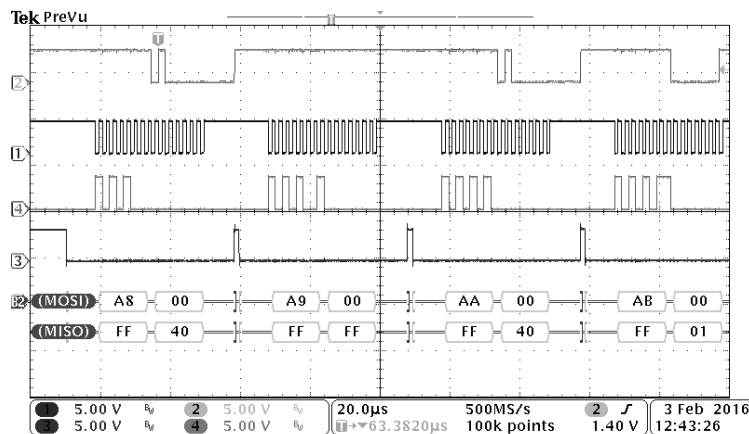


Fig. 8. SPI interface with MEMS sensor example; 1-CLK; 2-MISO; 3-CS; 4-MOSI lines

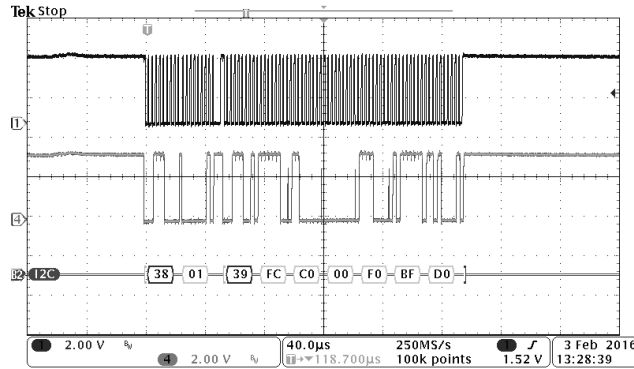


Fig. 9. I²C interface signals with MEMS sensor example; 1-SDC; 4-SDA

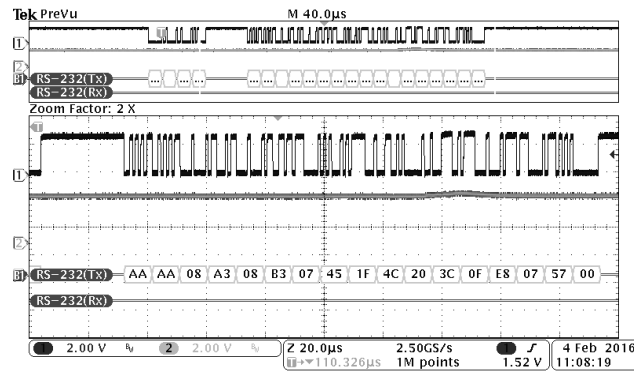


Fig. 10. RS485 signal interface example (UART side) - response of the S2 board in the zoom section

4. SENSORS ANALYSIS

4.1. Methodology

MEMS quality analysis bases on testing extortions which are same to all the sensors (as mounted on very limited space). S1 and S2 are mounted on a common wooden board. The board is then mounted on the test door, which a specially crafted movement simulate typical behavior (several scenarios). All data samples in each scenario are saved into a CSV file from dedicated PC application and then prepared to be plotted and to analyzed in Matlab environment. Matlab plots are converted into TEX files in PS-Tricks format and then to PDF before putting in rasterized PNG format into the article. That makes the presented waveforms as high quality and clarity to interpret as possible.

4.2. Measurement results

In the Figures 11–13, time a domain waveform from each axis is presented. Two scenarios (the same for each sensor) were taken into account: opening the door (waveforms on the left) and multiple hitting the door (waveforms on the right). The waveforms present raw reading from X, Y and Z axis – upper, middle and lower figure, respectively.

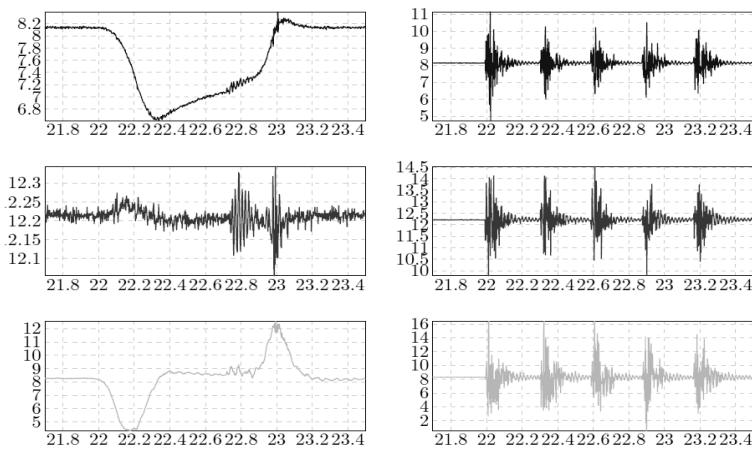


Fig. 11. Time domain (the x axis is [s]) raw waveforms obtained from MMA8451 accelerometer (I²C interface). The y axis is multiplied by 10⁴, readings from X, Y, Z accelerometer axis – upper, middle, lower waveform respectively

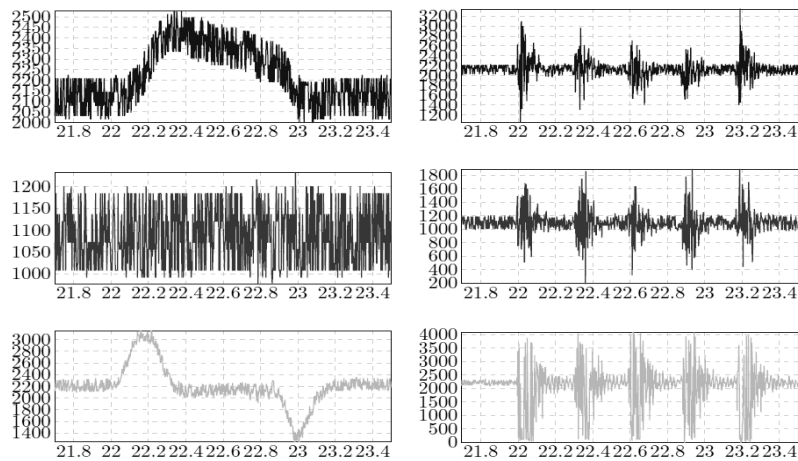


Fig. 12. Time domain (the x axis is [s]) raw waveforms obtained from LIS35DE accelerometer (SPI interface), readings from X, Y, Z accelerometer axis – upper, middle, lower waveform respectively

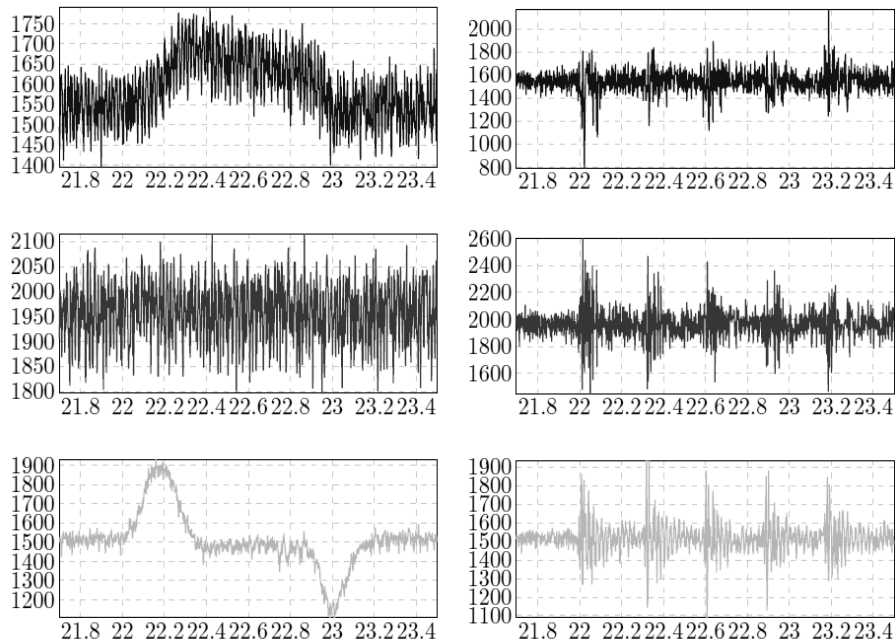


Fig. 13. Time domain (the x axis is [s]) raw waveforms obtained from LIS352A accelerometer (analog interface). readings from X, Y, Z accelerometer axis – upper, middle, lower waveform respectively

4.3. Quality indicators

In order to determine the quality of the sensors, the authors decided to calculate the following statistical indicators for each axis: noise level (standard deviation of the signal when no extortion was applied) and relative noise level (the ratio of the noise to the reading range). The results are presented in Table 4.1. The MMA8541 sensor achieves the best dynamic and the lowest noise.

Table 4.1. Statistic coefficients – no extortion

<i>SENSOR</i>	<i>LIS35DE</i>			<i>LIS3DH</i>			<i>LIS352A</i>			<i>MMA7361</i>			<i>MMA8451</i>		
	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>	<i>X</i>	<i>Y</i>	<i>Z</i>
Standard deviation	68	67	68	13	10	12	59	63	27	84	101	98	10	9	11
Relative noise level $\cdot 10^{-4}$	17	16	17	13	10	12	14	15	6	20	25	23	0,6	0,6	0,6

5. CONCLUSIONS

As it was presented in the previous chapters, a complete multi-sensor measurement system was designed, tested and ran. The data sever collected measurements from two subordinate systems by RS-485 protocol and sent these information via Ethernet to PC. The collected data may be viewed and stored in a common file format for future analysis by using dedicated PC application. According to the assumed quality indicators, MMA8451 accelerometer was found as the best of five tested sensors. This sensor chip was implemented in the independent algorithm executors called A1 and A2, where the burglary detection system was running simultaneously. What is more, the data acquisition system simultaneously received the data from MEMS and from the AI units, so that an easy evaluation of the burglary detection algorithms was also available. The described measurement system revealed, that a stable communication with different protocols coupled is possible and may be successively used for development of complex digital signal processing algorithms where MEMS accelerometers are the data sources.

REFERENCES

- [1] A. Getman, C. D. Cooper, G. Key, H. Zhou, and N. Frankle, "Detection of mobile machine damage using accelerometer data and prognostic health monitoring techniques," in *IEEE Workshop on Computational Intelligence in Vehicles and Vehicular Systems, 2009. CIVVS '09*, 2009, pp. 101–104.
- [2] M. Iorgulescu, R. Beloiu, and M. O. Popescu, "Vibration monitoring for diagnosis of electrical equipment's faults," in *2010 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, 2010, pp. 493–499.
- [3] W.-C. Cheng and D.-M. Jhan, "Triaxial Accelerometer-Based Fall Detection Method Using a Self-Constructing Cascade-AdaBoost-SVM Classifier," *IEEE J. Biomed. Health Inform.*, vol. 17, no. 2, pp. 411–419, Mar. 2013.
- [4] G. Vakulya and G. Simon, "Low power accelerometer based intrusion and tamper detector," in *Multi-Conference on Systems, Signals Devices (SSD), 2014 11th International*, 2014, pp. 1–6.
- [5] V. Ahmed and S. A. Ladhake, "Novel Ultra Low Cost Remote Monitoring System for Home Automation Using Cell Phone," in *2011 International Conference on Computational Intelligence and Communication Networks (CICN)*, 2011, pp. 569–573.
- [6] Y. Song, S. Shin, S. Kim, D. Lee, and K. H. Lee, "Speed Estimation From a Tri-axial Accelerometer Using Neural Networks," in *29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2007. EMBS 2007*, 2007, pp. 3224–3227.
- [7] J. G. Lim, S.-Y. Kim, and D.-S. Kwon, "Neural network based motion segmentation for accelerometer applications," in *2011 IEEE Symposium on 3D User Interfaces (3DUI)*, 2011, pp. 109–110.

- [8] “STM32L052R8 Ultra-low power ARM Cortex-M0+ MCU with 64 Kbytes Flash, 32 MHz CPU, USB - STMicroelectronics.” [Online]. Available: <http://www.st.com/web/catalog/mmc/FM141/SC1169/SS1817/LN1844/PF254256>. [Accessed: 11-Feb-2016].
- [9] Fabiański, B. “Embedded System of Critical Information Management.” *Poznan University of Technology Academic Journals. Electrical Engineering* No. 76 (2013), pp.:143-149

(Received: 16. 02. 2016, revised: 8. 03. 2016)