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The system of MEMS sensors data streaming and signal quality analysis

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In the article, a dedicated testing environment for MEMS sensors is presented. The system serve real–time measurements from several, different interfaced sensors, what gives opportunity to collect the data and – furthermore – its off–line analysis. To complete the main challenge what is MEMS ICs integration in one platform, a special hardware layer is applied together with operational algorithms. Two low–level boards are connected to the embedded server by RS–485 lines. This data server translates RS–485 signals and communicates with dedicated PC program by an Ethernet interface. Such a solution made possible to parallel streaming, archive, and analyze of data in a convenient way. The architecture and operational algorithms of individual components, such as complex synchronization methods in the data streaming process is described. Proper system design is verified by presenting selected signal waveforms grabbed in an experimental tests. In the end introduced two signal quality indicators resulting in comparison of different MEMS ICs. Summary table of computed indicators is shown with its analysis.

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

1. Introduction

The article issues are related to solving the problem of signal data streaming from several MEMS (Micro Electro–Mechanical Systems) sensors at the same time (in real–time regime). Such a data, grabbed parallel at the same environment state, same place and time will be used for sensors quality indication. Computed quality coefficients leads to the selection of best suited IC for target application. In general, the end–user application for the presented in the article system is a machine state classifier which bases only on acceleration signals. Before the target implementation, it was considered that the good way was to identify best fitted MEMS sensor(s) from experimental tests in real environment close to expected one in target implementation. Presented system serve such a testing possibilities. Example application – burglary alarm – that bases on the article considerations is introduced in [1], but practical implementations of MEMS based systems are more common. They may be used for diagnosing of machines moving parts (e.g. electric machines [2, 3]), in transportation (detection of critical to the transported cargo integrity: falls, impacts [4]), in the anti–theft systems (detection of unauthorized doors/windows opening attempts [5, 6]).

Common mass production technology of MEMS ICs used by many producers meaning that the economic barrier is broken what results in dynamic growth of potential applications. It may be noticed, based on the literature analysis that research problems in the field are focused on appropriate signal processing – including increasingly using of artificial/machine intelligence (e.g. fuzzy logic or neural networks) [7, 8]. More sophisticated signal processing is used in the cases where difference between the normal and fault operational state of machine is not trivial. The good quality of measurement signals determines appropriate system work in global scale and 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 data–sheets.

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. Hardware architecture of the system

2.1. System overview

The system – as mentioned in the introduction to the article – is used for parallel measurement data streaming from several different MEMS integrated circuits. In the Figure 1, the system overview that realize this idea is presented. Several main nodes (elements) in the set may be extracted. These nodes represents independent hardware devices.

The most important parts from the Figure 1 are sensors boards: S1 and S2, where intertial sensors (accelerometers) are mounted and where the data source is placed. The S1, S2 and embedded data server are connected together with RS–485 interface lines. Physical connection is done by using UTP (Universal Twisted Pair) cable, a common, cheap and well suited to the differential signal propagation. The advantage of RS–485 is that it can be applied in almost all, even simple MCU (Micro–Controller Unit) with UART (Universal Asynchronous Receiver Transmitter) peripheral. Together with dedicated line driver (e.g. MAX485, SP485) relatively (to the simple serial interfaces as SPI, I2C, RS–232) long cable may be used . There is about 20 meters of UTP cable used in the laboratory bench on which S1,S2 are connected to the 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. As an example, PC user application may convert the data to the format compatible with Matlab environment. DS platform origins from project described in more details in [9].

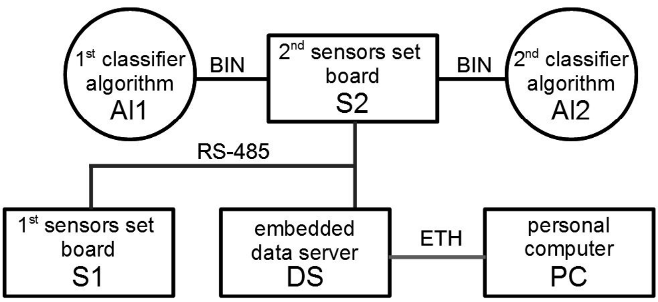

Fig. 1. General structure of data streaming system

Figure 1 presents general structure of data streaming system, where S1, S2, DS and PC nodes are main elements. However, AI1 and AI2 system nodes are elements added later and helps in target application developing. The core of the streaming and analysis system is marked in the Figure 2 (as primary laboratory setup).

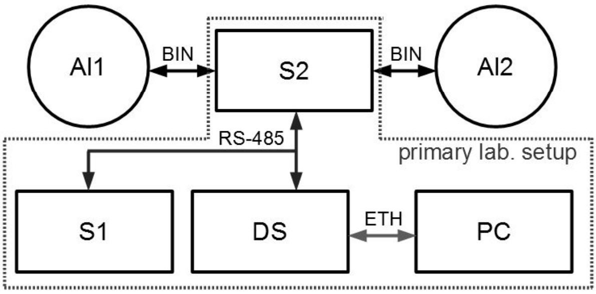

Fig. 2. Primary laboratory setup

2.2. Data source boards – S1 and S2

The system main parts: S1 and S2 boards are presented in details in the Figure 3. Power supply and RS485 interface connectors are present on both PCBs. System flexibility was obtained by splitting the data source into two separate boards. Applied GSM and Bluetooth interfaces (appropriate sections are pointed in the Figure 3) made possible to test some high–level communication solutions and to implement new program libaries for appropriate modules. System is driven by STM32L0 ultra–low–power microcontroller unit (current consumption at 88 μA/MHz in run mode, supply voltage in range 1.65 V to 3.6 V) [10]. Boards S1 and S2 are equipped with embedded analogue, SPI and I2C interfaces to serve wide spread of MEMS sensors accessible on the market. The following MEMS chips (from the same price level) were verified: LIS352AX (signed as A1 in the Figure 3, analog interface), MMA7361LC (A2, analog interface), LIS3DH (D1, SPI interface), LIS35DE (D2, SPI) and MMA8451Q (D3, I2C interface).

S2 board – as distributes shorter RS–485 frame than the S1 – translates AI1/AI2 binary interface and add thi signals to the transmitting data. This allows to include results of AI1/AI2 operation in primary communication regime and real–time evaluation of classiffication algorithms by analysis in PC enviroment.

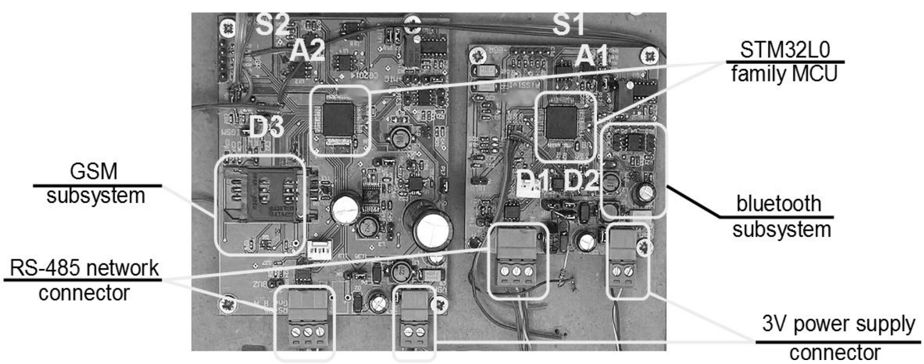

Fig. 3. MEMS signal source boards: S1 and S2

2.3. Independent signal analyzer units – AI1/AI2

The AI1, AI2 boards (for Figure 1 and Figure 4) are not essential for the article main subject, but are very useful in practice. These 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 analysis of protected surface vibrations (movements). In other words, AI1 and

Al2 are "intelligent classifiers" able to distinguish between normal behavior and intrusion attempt. These boards are evaluated with strong emphasis on practical application and are used for testing of classification objective. Two different, competitive DSP algorithms may be tested in the same time.

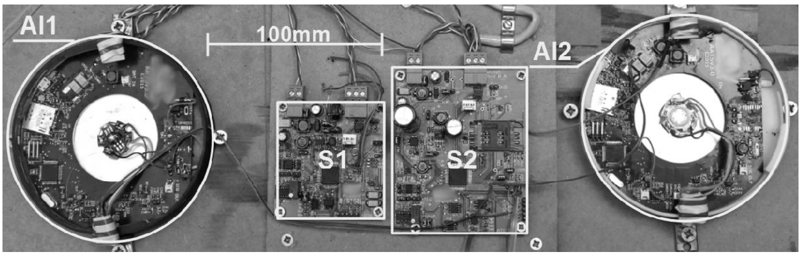

Fig. 4. Photography of independent signal analyzer units (Al1, Al2) connected to S2 board by binary interface

Presented structure may be used not only for validation, but also in closed–loop parameters adaptation of working algorithms (in application of fuzzy logic, theory of artificial neural networks learning or in other analytical methods).

2.4. Ethernet server and PC system

Figure 5 shows the Ethernet server and rest of the laboratory setup elements. As mentioned before, DS (see Figure 1) operate as a RS485 to Ethernet interface translator. The RS485 frames are aggregated to bigger packages (over 1 kB) and are sent via Ethernet to PC system. Packets are then intercepted by a dedicated application. Since the RS485 communication is fully synchronized by embedded data server, time–stamps are included in the process of Ethernet packet formulation. Such a solution made the data analysis system independent from Ethernet transmission delays.

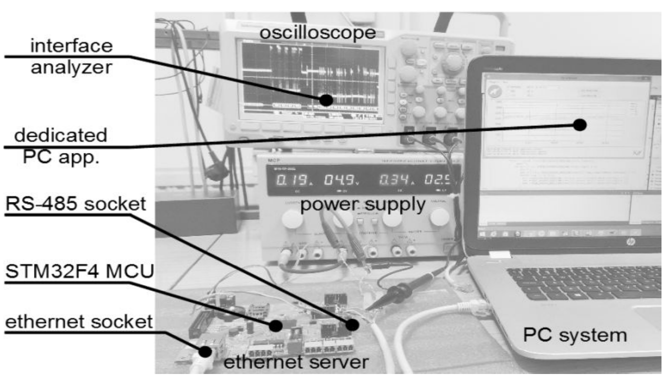

Fig. 5. Laboratory stand with Ethernet data server

Embedded data server (DS) is a custom made design, powered by STM32F4 MCU with much more computational power than in the MCUs in previously mentioned boards, as Ethernet interface is required [10].

The oscilloscope from Figure 5 is provided with embedded interface module, which allows to decode signals on SPI, I^2C and RS485 interfaces (see Figures 9–11 as the oscilloscope screens).

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 6. 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).

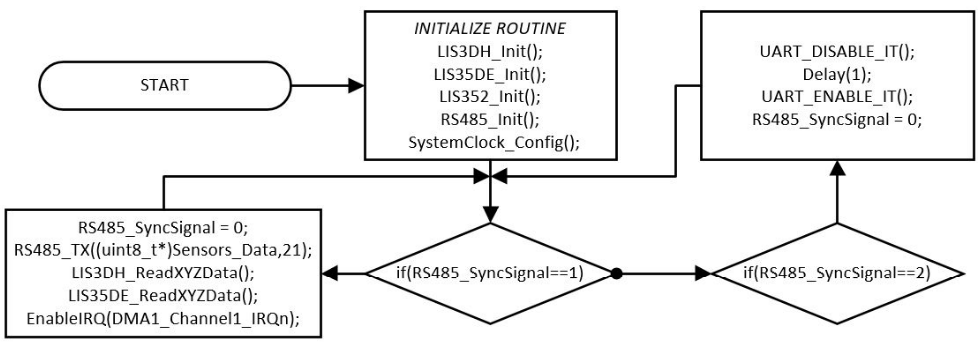

Fig. 6. General program flowchart in S1 MCU (main part)

Proposed synchronization mechanism works well and is stable at 1Mbps network speed rate. The embedded program in S2 has a similar structure, besides there are I^2C and analog interfaces to MEMS chips. Synchronization system is presented as timetable in the subsection 3.3.

Embedded data server (Ethernet server) bases on an older, more flexible STL peripheral library connected together 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).

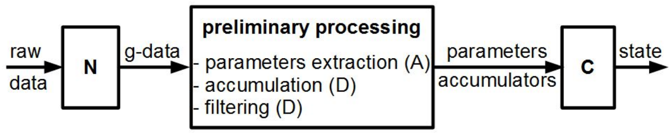

Fig. 7. Diagram of MEMS signal processing in Alx boards

The application of burglar alarm introduced in [1] and applied in Al1 and Al2 boards works in the regime presented in the Figure 7. Raw data collected by using of low–level interface (SPI, I2S, analog channel) are normalised to the absolute G–value in normalisation block (N). Then, by using selected algorithms based on the operation of bigger data sets (data vectors) calculated indicators are carrying information about the nature of the signal, its dynamics and other time/frequency domain dependencies. Finally, the prepocessed values are base for the classificator core (C block) that concludes output state by using different methods (e.g.: FL, ANN, ANFIS, DDSP, SVM).

3.2. PC application

Dedicated PC application, which is shown in the Figure 8 is a one–windowed form with several controls groups. There is a turn on/off button (Figure 6–a) which causes sending an appropriate command 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 Al1/Al2 board computation is shown, (d) – display the data associated with X,Y or Z component of acceleration/rotation. Only one data source can be shown at one time – this is selected by (e) control. Acquired data is showed in the center of the window (i), while (k) is the time base of plotting variable (in seconds), (j) is value of the streamed acceleration value (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 Calc. Application is developing in Visual Studio C# IDE Environment with use of only embedded libraries/controls.

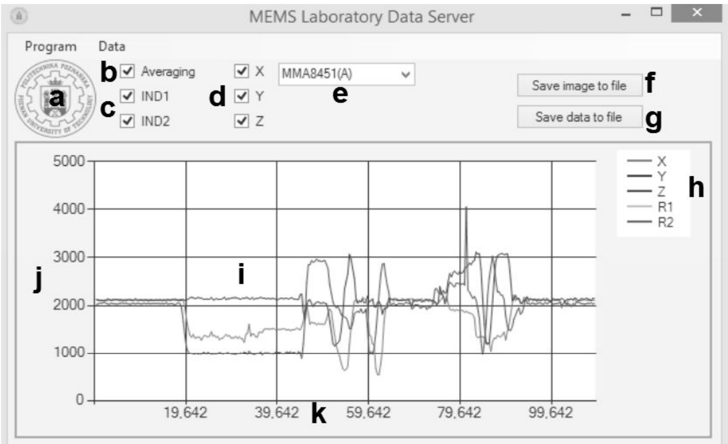

Fig. 8. Windows of the PC application

3.3. Communication

The time–line of the RS485 transmission cycle is presented in the Figure 9, with detailed timestamps and intervals description on it. Figures 10–12 show transmission process on the low–level interfaces as SPI, I2C and RS485.

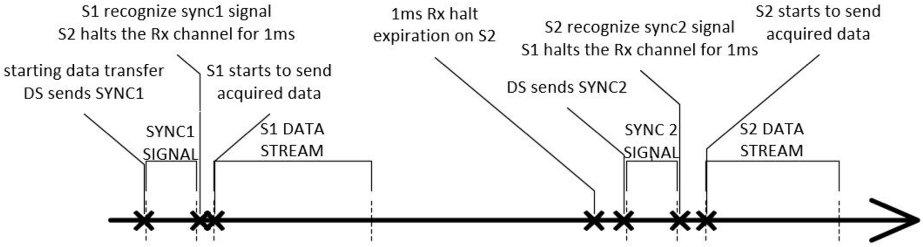

Fig. 9. RS485 transmission cycle timeline

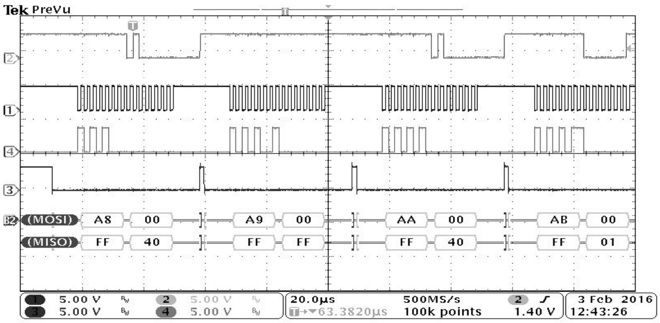

Fig. 10. SPI interface with MEMS sensor example; 1 – CLK; 2 – MISO; 3 – CS; 4 – MOSI lines

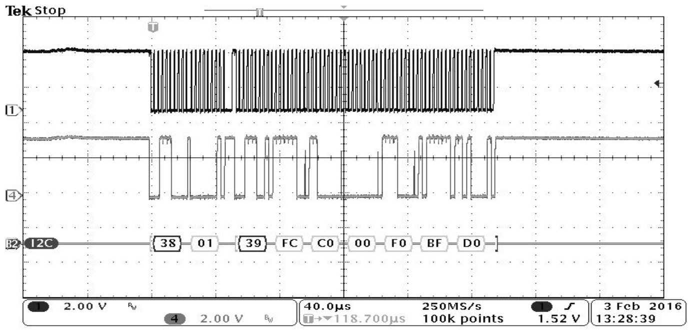

Fig. 11. I^{2}C interface signals with MEMS sensor example; 1 – SDC; 4 – SDA

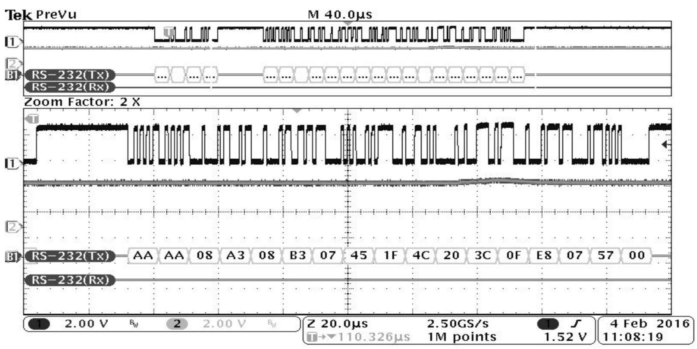

Fig. 12. RS485 signal interface example (UART side) – response of the S2 board in the zoom section

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

4. Analysis of sensors quality

4.1. Methodology

MEMS quality analysis bases on testing extortions which are same to all the sensors (as all are mounted on very limited space, on the same platform). The system platform (S1/S2 and Al1/Al2 on same surface) is then mounted on the test door. From test door an RS–485 interface cable traces signals to the data server what guarantee movement freedom. Specially crafted movements simulate typical behaviors (several scenarios). All data samples in each scenario are saved into a CSV file from dedicated PC application and then prepared to plot and to analyze in external environment. Matlab plots are converted into TEX files in PS–Tricks format and then compiled in LaTeX environment to PDF before putting in rasterized PNG format. That makes the presented waveforms as high quality and clarity to interpret as possible.

4.2. Measurement results

In Figures 13–15, a time domain waveforms of acceleration from each axis of selected sensor is presented. Two scenarios (the same for each sensor) were taken into account when presenting: 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 – in upper, middle and lower figure, respectively.

In order to determine the quality of the sensors, it was 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 computation results are presented in Table 4.1. The MMA8541 sensor achieves the best dynamics and the lowest noise ratio.

Table 4.1. Computed coefficients measured at idle state

SENSOR	*LIS35DE*			*LIS3DH*			*LIS352A*			*MMA7361*			*MMA8451*		
AXIS	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
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

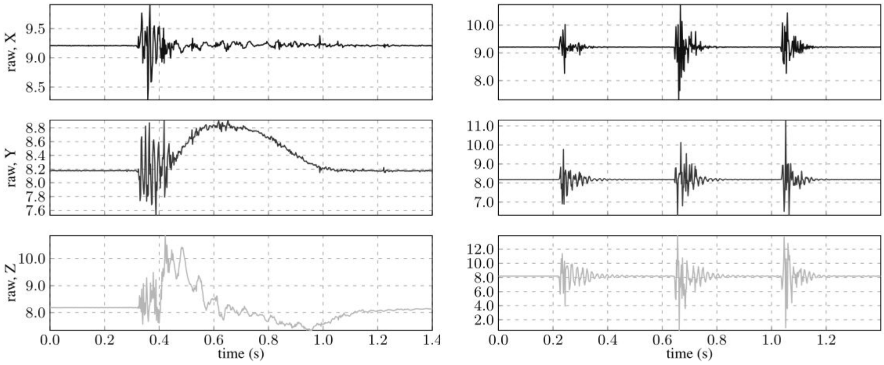

Fig. 13. Time domain, raw waveforms obtained from MMA8451 accelerometer (I^2C interface); the values are reduced by factor of 10^{-3}, readings from each axis

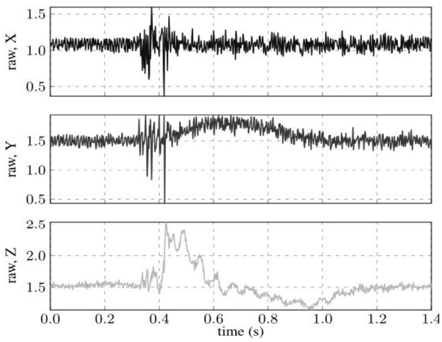

Fig. 14. Time domain, raw waveforms obtained from LIS35DE accelerometer (SPI interface); the values are reduced by factor of 10^{-3}, readings from each axis

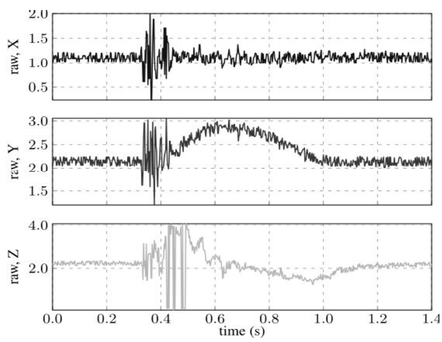

Fig. 15. Time domain, raw waveforms obtained from LIS352A accelerometer (analog interface); the values are reduced by factor of 10^{-3}, readings from each axis

5. Conclusions

As it was presented in the previous chapters, a complete multi–sensor measurement system was designed, tested and verified on proper operation. The data sever collected measurements from two subordinate systems by using RS–485 interface and sent these information via Ethernet to PC. I was confirmed, that proposed and described in details synchronization mechanism gave stable transmission from sensors to the PC. Introduced very useful validation system of application level algorithms in real–time regime. It was shown that 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 systems were running simultaneously. What is more, the data acquisition system simultaneously received the data from MEMS and from the Al units, so that an easy evaluation of the burglary detection algorithms was also available. The described measurement system revealed, that a stable communication with use of different interfaces is possible and may be successively used for development of complex digital signal processing algorithms where MEMS accelerometers are in the role of sensors/data sources.

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