THE SYSTEM FOR EMG AND MMG SIGNALS RECORDING FOR THE BIOPROSTHETIC HAND CONTROL

Submitted: 2nd January 2017; accepted: 2nd August 2017

Andrzej Wołczowski, Michał Błędowski, Jerzy Witkowski

DOI: 10.14313/JAMRIS_3-2017/25

Abstract:
The process of biosignal acquisition has a significant impact on the reliability of the control of the multi-functional hand prosthesis. The paper discusses the nature of EMG and MMG signals and noise associated with their registration. The measuring system developed on the basis of these premises, as well as the measurement procedure are described.

Keywords: *bioprothesis, EMG, MMG, signal recognition, biosignals measurement*

1. Introduction

A rehabilitation understood as a branch of medicine aims to improve the health status and the life quality of patients. For this purpose, are commonly used technical devices, an example of which are prostheses used by handless patients [1]. Increasingly popular in this area are bioprostheses controlled by signals retrieved from the patient's body [2, 3]. The information about the patient movement intentions contained in these signals, after proper recognition, control the prosthesis. Recognition process, due to the time required for execution leads to the discrete control by subsequent decision commands [4, 5, 6, 7].

As carriers of information about the patient's intentions most often electromyographic (EMG) and/or mechanomyographic (MMG) signals are used – rarely electro-encephalographic (EEG) signals [8, 9, 10].

Currently, designing of robotic hand is a challenge in two aspects:

- to design of a multi-articulated anthropomorphic construction, mimicking the human hand in terms of shape, weight and mobility of fingers, but also feeling of sensory interaction with the grasped object [7];
- building the control system, able to recognize the various intentions of a man (depending on the situation and type of object to be gripped) and pass them in the form of specific control commands to prostheses motor control [4, 6, 11, 12].

The recognition process can be divided into four main stages (Fig.1).

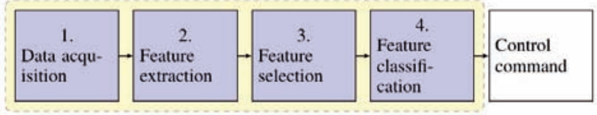

Fig. 1. Diagram of the recognition process

(1) On the first step bio-signals from the human body are measured. In the case of EMG and MMG signals, they are recorded on the surface (on the skin) of the prosthetized limb stump (the so-called surface electromyography/mechanomyography that is completely non-invasive) [5, 6, 8].

The signals are analyzed after registering to reduce their size by extraction (2) of appropriate features. There are many methods of signal analysis, which use different areas of the signal. For example, in the frequency domain frequently used method is the Short-Time Fourier Transform (STFT), and the time and frequency domain method of discrete wavelet transform (DWT) [14]. Features pass the selection and/or reduction process (3) using methods such as principal component analysis (PCA) [15] or the factorization of matrix and tensor (TF) [16]. The final stage of the decision-making process is the classification (4), which distinguishes the class of the expected movement – that determines the decision to control [8, 9, 10].

The basic problem at hand prosthesis control is reliability in interpreting user intent. Wrong recognition causes movement of the prosthesis inadequate for a situation which disorganize user action and in extreme cases can be dangerous both to user and his surroundings. Therefore, it is crucial to achieve high reliability of recognition (close to 100%).

The task of the artificial hand is to help the user in his everyday life. Depending on the type of object and the intended manipulating-gripping action, the hand should allow to diversification of its ability up to a dozen different grips. Unfortunately, along with enlarging the repertoire of possible movements of the prosthesis decreases drastically the reliability of the recognition process. Reliability depends on each step of the process component (in a simplified, general reliability is taken as the probability of correct operation. It is the product of the reliability of every subsequent steps). Therefore, it is important to optimize each stage. Optimization of the extraction, feature selection and classification were dedicated several studies [6, 10, 16, 18]. In this article we focus on the problem of optimizing the registration process of bio-signals – understood as the pursuit of registration signals (including the construction of a measurement system) that ceteris paribus, maximizes the reliability of recognition. Destiny of developed system is not only registration bio-signals for many people and for different movements but also creation a databases of signals, which allows to experimental testing of methods of analysis bio-signals (including methods of extraction and feature selection and classification).

In chapter 2 was described physiology of bio-signals, factors disturbing theirs registration, methods to eliminate / reduce disturbance and premises for construction of the recognition system. Chapter 3 describes the recognition system and registration procedure which allow both repeatability and high value of movements discrimination of recorded signals. Chapter 4 summarizes the obtained results.

2. Bio-Signals – the Nature and the Problems of Measurement

2.1. The Nature of Bio-Signals

The activity of skeletal muscle is accompanied by the appearance of the electric potentials, so-called myo-potentials. They are the result of movement of (Na+) and (K+) ions flowing in and out from the surrounding environment to the interior of muscle cells stimulated to contraction.

The contraction of the monofilament is accomplished on an all-or-nothing, and the strength and shrinkage rate of the whole muscle depend on the number of activated fibers. The individual muscle fibers are activated by the incoming to them axons of motor neurons (called motoneurons). A single motor neuron can connect to multiple muscle cells. The cells activated simultaneously by a common motor neuron are called the motor unit of the muscle. The activity of individual motor units in the working muscle varies randomly in time. They are alternately activated (recruited) and released, but their number remains constant and is proportional to the required muscle strength.

The myocyte excitation is accompanied by a change in electrical potential between the inside of the cell and its environment from -60 mV to +50 mV. This potential change can propagate through the surrounding tissues, reaching up to the surface of the limb. Superposition changes potentials of all active muscle cells can be registered on the skin over the active muscles, as the surface electromyographic signal A superposition of potential changes from the all active muscle cells can be registered on the skin over the active muscles as the surface electromyographic signal (EMG signal).

The rms value of the EMG signal from human skeletal muscle, depending on their level of excitation, may be between 0–1.5 mV, and assumes the highest value in the range of 50–150 Hz.

Changes of the potentials for the individual myocytes have the same waveform, but their superposition on the body surface, due to the spatial filtering of signals in the tissue (different damping of different frequency components), critically depends upon the spatial position of active muscle cells with respect to the locations of measurement electrodes on the skin. Hence the form of the EMG signal carries information about which muscles are active. Various movements of fingers engage different muscle groups of the forearm, so ultimately EMG signals carry information about the type of hand movement.

Another type of signals associated with the activity of skeletal muscle are mechanical vibrations. These vibrations are formed during the activation of the individual fibers in the muscle motor units, changes muscles outer geometry – during shrinkage, and friction of moving relative to each other muscles as well as from the movement of tendons and joints. The vibration, similarly as myo-potentials, spread through the limb tissues and reach the surface, and there they superposition can be registered using a microphone or a vibrometer placed on the skin, as a mechanomyo-graphic signals (EMG signals). As in the case of EMG signals, the form of MMG signal reaching the skin surface also depends on the active muscles, and thus carries information about the type of movement.

Due to the different nature of the two types of signals the contained therein information (or lack of information caused by interference) can complement each other giving the synergy effect. This will be explained in section 2.2.

2.2. The Problems Accompanying the Biosignal Registration

As it has been stated in Chapter 1, the biocontrol is based on the classification of measured biosignals. To each recognized class of signal a particular decision control of the prostheses movement (or the movement other technical devices) is assigned. To the recognition of the information contained in the biosignals could be reliable the character of signals recorded during the same hand movement should always be the same (unchanged). However, both discussed above physiological phenomena which underlie the formation of bio-signals and their measurement process itself, they do not provide a constant form of signals.

The physiological cause of EMG and MMG signal changes are the changes in the recruitment pattern of motor units due to fatigue/weakness of muscle.

The fatigue is a result of changes in the concentration of electrochemical metabolites in the environment of muscle fibers (outside the fiber membrane accumulate K^+ ions). Conduction velocity is reduced and the signals change The speed of propagation is reduced and the signals change Fatigue can be detected by monitoring the mean or median frequency or distribution envelope of signal (RMS). This phenomenon must be considered in the measurement methodology.

While the external causes related to the EMG signal measurement process are:

- external electromagnetic fields overlapping the signal, and
- changes in the conditions of electrode contact with the skin (resulting from changes in skin conductance due to perspiration, changes in the composition of sweat, changes in adhesion of the electrodes, etc.).

The electromagnetic smog (usually at a frequency of 50 Hz electricity network, but also in mobile telephone, radio and TV bands) can induce on the skin a noise amplitude of 103 times greater than the useful signal. In turn, changes in electrode contact with the skin affected by the change ratio of the amplitude of the registered signal to noise ratio.

In the case of MMG signals, the primary source of interference is the outside noise, and (in the case of a prosthesis) the sounds coming from the activity of the prosthesis and its interaction with the grasped object.

These phenomena are changing patterns of classes used by the recognition algorithm, increasing the spread within the class of measured signals and thus impairing the reliability of signals recognition and control decision making. So, during the constructing of the measurement circuit you should aim to reduce these noise.

The ambient noise can be effectively eliminated by using a differential measuring system. Such a system consists of two active electrodes placed directly over the examined muscle and a reference electrode placed as far as possible, over the electrically neutral tissue (directly above the bone, joint, etc.).

The signals obtained from the active electrodes (measured relative to the reference electrode) are subtracted from each other and amplifies. The common part of these signals, which is composed of background noise is thus removed, and the useful signal contained in the difference of these signals is amplified. The idea of differential measurement is shown in Fig. 2

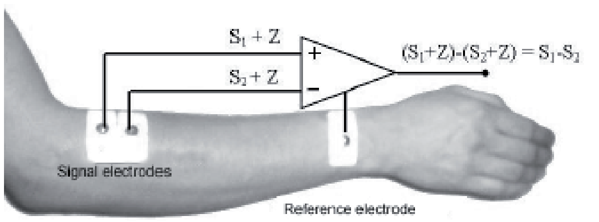

Fig. 2. The Idea of differential measurement; S1, S2 – useful signal, Z – noise

Others of interference said, related with measurement process (from the adhesion of the electrode to the skin and the movement of the cables connecting the electrodes of the measuring amplifier), can be significantly reduced by the use of high impedance amplifier, many times higher than skin impedance, and a low output impedance – and position it directly at the electrodes. In this way, there is the concept of "active" electrodes, integrated with a preamplifier that delivers the signal resistant to external interferences [6, 19].

Another problem are the interference from overlapping signals (crosstalk) from other skeletal muscles – eg. as a result of performing the grip during the movement of the whole arm (for example, reaching for an object at a high shelf) [18]. This applies to both electrical and mechanical signals. It should be noted that unlike the invasive measurement (consisting in the stick of electrode in the determined site in muscle), which allows you to register a signal from only one place, the surface measuring, by its nature, records the superposition of the signals generated by all active myocells of the human body. This phenomenon is illustrated in Section 2.1. The components of EMG (and MMG) signals derived from the active muscles of the forearm, from the point of view of the motion recognition, are the desirable elements while the other components derived from skeletal muscle are the interference. These disturbances are eliminated at the classification stage [18].

In commercial embodiments of prosthetic hand most often are used the measuring systems based on two electrodes [16, 17].

The presented above considerations indicates that each measuring electrode, regardless of its location on the hand stump, records signals from all active muscles, however, as a result of spatial filtration, the greater amplitude in the registered signal have components derived from the muscles closer to the electrode.

So we can expect that for the given repertoire of prosthesis movements and for the individual amputations case, there are such locations of electrodes for which the recorded signals provide the best efficacy of movements discrimination. An important part of the optimization of biosignals registration process is thus to determine on the forearm the electrode position. In the presented approach the experimental selection based on the number of redundant electrodes (measurement system channels) and determination of the best located electrodes by analyzing the effect of information obtained from the individual channels on the recognition quality, was proposed.

3. Bio-Signals Acquisition

3.1. Measurement Setup

Measuring (Fig. 3) circuit consists of analog parts which includes the differential probe with high input impedance, gain of 10V/V and CMRR ratio (Common Mode Rejection Ratio) about 80 dB. Next stage of analog circuit consist of filtering amplifier of gain of 100 V/V and transfer function shown in Fig. 4. Before last step of amplification a 50 Hz notch filter is applied, to prevent the successive stage from saturation in case of hazardous area. Transfer function of microphone amplifier has the same shape but maximum gain of about 20 V/V and is devoid the notch filter.

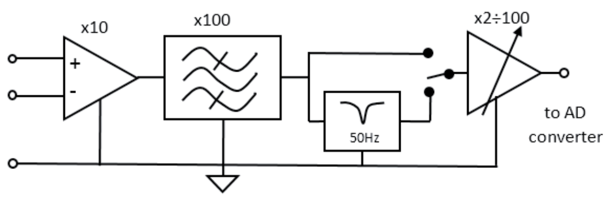

Fig. 3 Analog part of measurement experimental setup

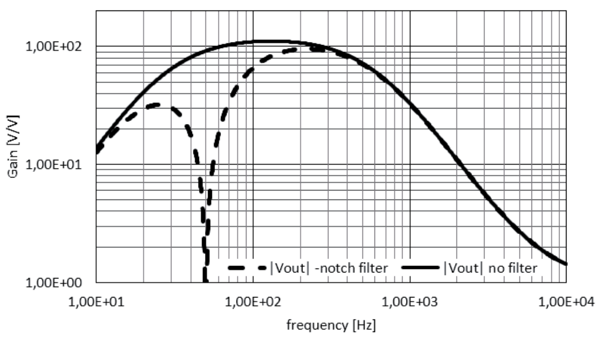

Fig. 4. Transfer function of filtering part of analog circuit with activated and disactivated 50Hz notch filter

In presented results the total gain of analog circuit was adjust for about A = 10×100×15 = 15 000 V/V.

Including the premises described in Chapter 2, a 16-channel system for recording biosignals was designed. The system consists of:

- 8 integrated measurement probes enabling simultaneous recording 8 points in both signals EMG and MMG;
- 16 channel filters-amplification system (8 for EMG and 8 for MMG signals);
- Set of 16 analog to digital converter (PCIE-1816 by Advantech).

Technical details developed measuring system is described in [19]. Each probe includes two metal strip electrodes (Ag wire) directly connected to the differential EMG preamplifier circuit, and electret microphone collecting MMG signals. These components are integrated in the housing (see Figure 5) constituting:

- a support structure for them; and simultaneously,
- isolator for EMG electrodes; and
- acoustic chamber for the microphone MMG.

The analog parts of measuring system is shown in Fig. 3. The probe contains a high input impedance differential amplifier, of 10 V/V gain and CMRR ratio (Common Mode Rejection Ratio) about 80 dB, for EMG signal. Each probe cooperates with two channels of filtering and amplifying system consisted of filtering amplifier, for EMG signal of gain of 100 V/V and for MMG signal of gain of about 20 V/V, and transfer function shown in Fig. 3.2. Before last step of amplification a 50 Hz notch filter is applied to prevent the successive stage from saturation in case of hazardous area.

The Characteristics of the EMG and MMG amplifier circuit show graphs 6 and 7. An amplifier of the EMG signal (with a probe – 10 V/V) amounts about 14000–15000 V/V, and the microphone channel about 10–20 V/V.

For more detailed investigation of dynamic of EMG signals the analog-digital conversion with sample frequency of 10 kHz and 16 bit resolution was applied.

Fig. 5. Integrated EMG, MMG probe: (a) inner view – EMG front-end circuit, (b) electrode and acoustic chamber view

Examples of power density vs frequency are shown in Fig. 6. In this case the notch filter was not activated and fringes of 50 Hz are clearly seen. Although the power of these fringes is small, according to the authors, the filter should be used in practical solutions to avoid blocking final amplifier and AD converter, in any hazardous environment.

Applying the notch filter the total signal power (in bandwidth of 500 Hz) can drops. This is shown in Fig. 7. As seen 50 Hz fringes are affectively suppressed but the total energy drops by 1.5 to 2.4 dB.

To check the effective signal bandwidth, a cumulative sum of power density was investigated. Results are shown in Fig. 8. It is seen that 95% of the signal energy is included in the frequency range from 30 to 250 Hz and 99% do not excide range above 300 Hz.

One can conclude that in practice the sampling frequency can by reduced down to 1 kHz leaving 500 Hz effective bandwidth. It was also checked that in this case a aliasing power (from band 500 hz to 1 kHz) is about 30 dB below the signal power.

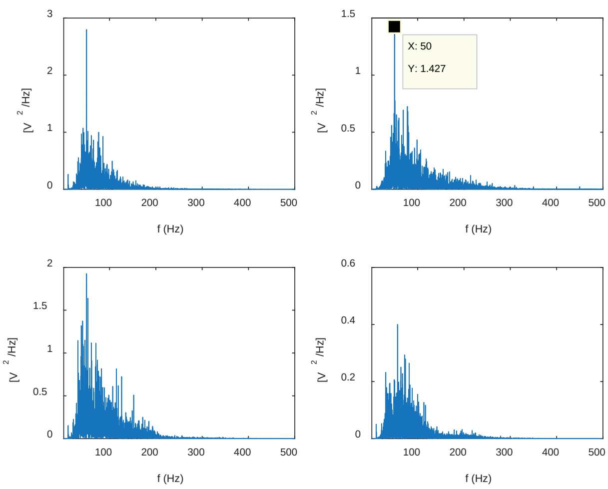

Fig. 6. Examples of power density EMG signals. Notch filter not active. Energy of the signals are (left to right and down): 7.01; 8.6; 7.00; 12.8 V²

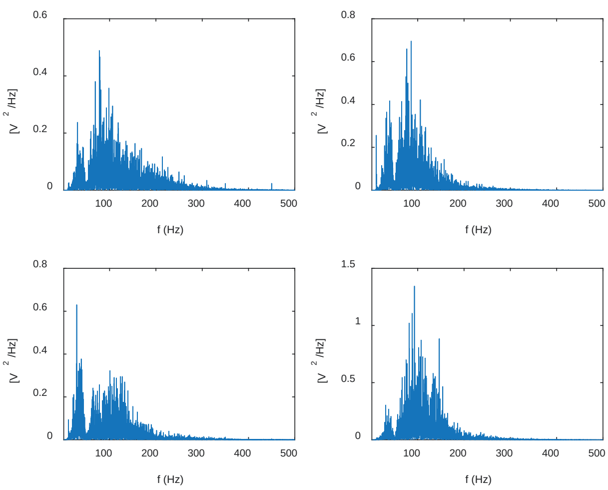

Fig. 7. Examples of power density EMG signals. Notch filter active. Energy of the signals are (left to right and down): 4.4; 4.9; 4.4; 9.0 V²

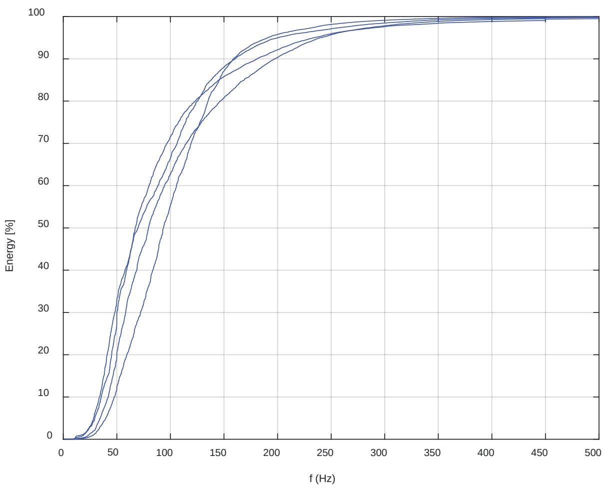

Fig. 8. Cumulative sum of power density for four examples of EMG signals like in Fig. 7

To check a dynamic range of EMG signals noise of the output voltage was investigated. Fig. 9 shows the power of noise of the EMG signal in case when muscles are relaxed. It is seen that the noise of relaxed muscle is higher (2 to 6 times) than that calculated from catalog data of used amplifier (28nV/√Hz) and Johnson's noise for 100 kOhm resistor in temperature of 300K (40nV/√Hz). So the dynamic range of EMG signal can by estimated to (signal power from Fig. 7 to noise power from Fig. 9) 20–26 dB witch is quite small value. It means that the resolution of AD converter of 16 bits is oversized and in practical application can be significantly reduced.

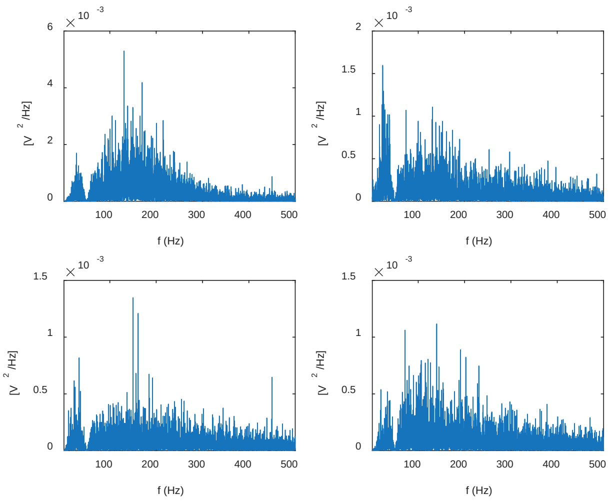

Fig. 9. Noise power density for relaxed muscles. Energy of the noise are (left to right and down): 0.06; 0.026; 0.017; 0.02 V^2

Filter-amplifier circuits of the system were placed in a one housing and by means of multi-core signal cable combined with a analog-to-digital card PCIE-1816 – Advantech (inserted in the PC). The card has 16 independent, 16-bit, A/C transducers. Sampling the signal in each channel is proceeded with a frequency of f = 1 kHz (sampling period T_f = 1 ms). Card driver buffers in interior memory 20 next samples for each of the 16 channels and saves them to a text file. When the driver is initiated, a buffer address (to which the driver has to prescribe a number of samples from the card) and a procedure address (the procedure rewrites the data from the buffer to a text file – 16 samples of 20 value) have to be put. Next data samples are saved to database every 20 ms. For a single measurement (it lasts by default 2 s) there are samples, which are rewritten 100 times.

3.2. Measurement Software

The second part of the developed measuring stand is a data acquisition software combining both hardware requirements and a methodology of measurement.

To register bio-signals the EMG_Rejestrator software was developed. The software works together with the controller of PCIE-1816 card of described above system. It was written in C++ programming language and the Qt libraries. The program allows, at the stage of measurement, the pre-analysis, and elimination of those measurements, which differ from the others, allowing to record only the correct data. An assessment is made by the person supervise the experiment, based on observations of how the movement was made and on overview of the graphic form of the registered signal.

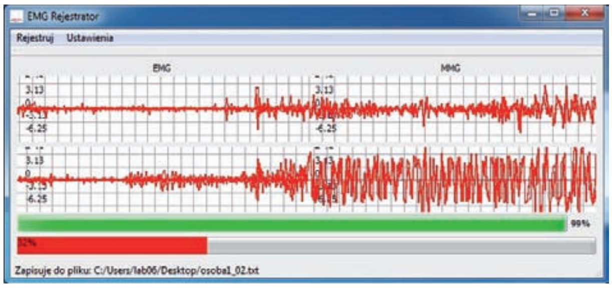

Fig. 10. Main window of EMG_Rejestrator

Recorded signals are presented up to date on the screen in the form of time charts. They are stored in the memory buffer and after the completion and acceptance the measurement they are transcribed to a text file database. The program assists in the run of the experiment:

- Allowing to establish the registration parameters and the type of experiment (the measurement of EMG and/or MMG; the time of single measurement; the time of rest; the way of scaling charts; the number of measurements repetitions; the data file name);
- Visualizing the recorded signals, signaling by sound the beginning of measurement and displaying a progress bar during the measurement;
- Waiting for approval after the measurement;
- Activating the progress bar of time of rest and preparing to make next move
- Counting the measurements and after established number of repetitions finishing acquisition.

EMG_Rejestrator application communicates with the user through an intuitive, graphical interface. The main application window can be divided into 4 sectors:

– The top menu bar, where the research can be begun (option "Rejestruj" – Fig. 11a) or settings of

applications can be changed (option "Ustawienia" Fig. 11a);
- Below the menu bar there are presented 16 charts, 8 for EMG and 8 for MMG signals. During registration signals are presented in real time, so that the operator can control the correctness of the study.;
- Under charts, there are two progress bars: green which determines the progress of current measure, which by default takes 2 seconds and red which determines the progress of the break/rest, which lasts for 3 seconds;
- At the bottom of the window, during the test, there are shown the name of the file and the number of current measurement.

Fig. 11. Menu of EMG_Rejestrator; a – settings or recording; b – begin of recording

In experiments dedicated to recognizing hand movements based on bio-signals, an analog system (filters and amplifiers) was used closed in a common housing and, connected via a multi-wire cable with 16-bit analog-to-digital converter (ADC) r PCIE-1816 by Advantech. Sampling frequency of f = 1 kHz was used (sampling period T f = 1 ms). ADC driver caches in memory 20 consecutive samples for each of the 16 channels and saves them to a text file at the address given by the program recorder. To initiate the PCIE driver, several information are requested: address of a buffer (in the recorder) to which the driver has to prescribe a set number of samples, and the address of the procedure, which rewrites the data from the buffer to a text file (16 strings samples after 20 value). This means another portion of the data recording to a text file every 20 ms. For a single measurement (for each repeat each test movement), of duration of default 2 s, collected by the card samples are rewritten 100 times.

3.3. Methodology of Measurement

At the time of a single measurement, the tested person performs one iteration of the movement, including:
- Preparation of grip (lifting and moving the forearm in the direction of the gripped object and position of fingers on the object);
- Griping (clamping fingers on the object and lifting the object).

Putting aside the gripped object is realized in the "rest phase". The application signalizes the beginning of each measurement with a sound and a green progress bar displaying on the screen. The end of the progress bar indicates the end of the registration of a movement. The person putts aside gripped object and prepares for the next measurement. At that time an supervisor evaluates and accepts (by pressing any key) or rejects the measurement (by pressing Escape). The assessment is made based on an observations of how a movement was made and on graphic form of a time course of signal. This initial analysis allows to avoid errors due to inattention or mental fatigue and write only valid data.

An approval runs red progress bar (Fig. 10), which lasts 3 seconds. The result of an accepted measurement is stored in a text file in the previous specified directory. If the movement was not accepted the result is not saved. It is activated the progress bar of "break" and the movement and measurement of signals EMG/MMG are repeated.

3.4. Placement of Electrodes

The task of the developed measuring system is the registration of bio-signals for many people and for different hand movements. It causes the need for multiple clamping of electrodes in next studies. Therefore, when the placement of electrodes was chosen, there was need to obtain good reproducibility of deployment. The adopted arrangement of electrodes was show in Fig. 12. Electrodes are arranged in two rows (upper and lower side of forearm) of 4 electrodes in every row, in such a way as they form a straight line running from the thumb (sensor 1) to the elbow (sensor 4) and from the small finger (sensor 5) to the elbow.

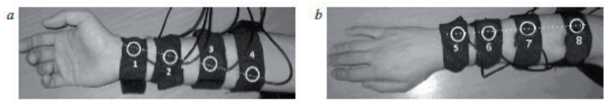

Fig. 12. Placement of electrodes on forearm: inside and outside

4. Conclusions

The paper presents the concept of the construction of the measurement stand for concurrent recording EMG and MMG signals, developed at the Faculty of Electronics of Wroclaw University of Science and Technology. The purpose of the stand is the registration of bio-signals for many people and for different movements, leading to the creation of Signal Base, that allows the experimental study of biosignal analysis methods (including methods of feature extraction and selection, and classification).

The results of the measurement session carried out with the developed position, confirm the correctness of the adopted assumptions (in the design of integrated probes, measuring circuits, and also software and the procedures for carrying out measurements) which are the result of years of research of the authors into the use of biosignals in the construction of human-machine interface.

The developed measuring system eliminates the most known artefacts meet in data acquisition of EMG and MMG signals.

As for the quantitative estimation, the noise own electronic circuit (parameter of used front-end amplifier), and Johnson noise of "body" modeled as resistor are smaller than that of relaxed muscle signal. Signal to noise ratio (dynamic) understood as the ratio of EMG signal of active muscle to relaxed muscle is quite small and can be estimated to 20–26 dB. This conclude that the 16-bit resolution ADC seems to be oversized in this application.

Electromagnetic smog high-frequency (radio-frequency, cellular, Wi-Fi etc.) have been effectively eliminated by filtration, and screening systems. It was shown that bandwidth of EMG signals do not excite about 300 Hz, so the sampling frequency as low as 1 kHz is sufficient in practice.

The most difficult to eliminate in medical measurements is 50 Hz hum (USA 60 Hz). It generally has two components – a common of large amplitude and a differential - much smaller. Common component was reduced by:

- placing pre-amplifier directly with electrodes, which reduces the possibility of capacitive coupling,
- the use of a differential amplifier having a high CMRR.

Differential component of the hum was eliminated applying 50 Hz active notch filter which can be activated in hazardous electromagnetic environment to prevent next stage amplifier from saturation.

The integration of probes measuring two different modalities enables the study of the impact of the synergy of different information to improve the efficiency of further process steps to recognize human intentions. The solution is not free of drawbacks. Certain problems by producing acoustic noise and restricting movement in the conducted experiments bring the cables connecting probes with amplifying circuits. The current works are aimed to replace these wires by wireless communication which will result in autonomous probes.

AUTHORS

Andrzej Wołczowski – Chair of Cybernetics and Robotics, Electronics Faculty, Wroclaw University of Technology, ul. Janiszewskiego 11/17, Wrocław, Poland. E-mail: andrzej.wolczowski@pwr.wroc.pl.

Michał Błędowski* – Chair of Cybernetics and Robotics, Electronics Faculty, Wroclaw University of Technology, ul. Janiszewskiego 11/17, Wrocław, Poland. E-mail: michal.bledowski@pwr.wroc.pl.

Jerzy Witkowski – Chair of Electronic and Quantum Electronic Systems, Electronics Faculty, Wroclaw University of Technology, ul. Janiszewskiego 11/17, Wrocław, Poland. E-mail: jerzy.witkowski@pwr.wroc.pl.

*Corresponding author

REFERENCES

[1] E. Biddiss, T. Chau, "Upper-limb prosthetics: Critical factors in device abandonment", American J. of Physical Medicine and Rehabilitation, vol. 86, no. 12, 2007, 977–87. http://dx.doi.org/10.1097/PHM.0b013e3181587f6c.

[2] B. Hudgins, P. Parker, R. N. Scott, "A new strategy for multifunction myoelectric control", *IEEE Trans. Biomed. Eng.*, vol. 40, 1993, no. 1, 82–94. http://dx.doi.org/10.1109/10.204774.

[3] A. Wołczowski, "Smart hand: the concept of sensor based control". In: *Proceedings of MMAR conference*, Miedzyzdroje, 2001, 783–790.

[4] A. Wołczowski, M. Kurzyński, "Human-machine interface in bioprosthesis control using EMG signal classification", *Expert Systems*, vol. 27, 2010, no. 1, 53–70. http://dx.doi.org/10.1111/j.1468-0394.2009.00526.x.

[5] A. Wolczowski, J. Jakubiak, "Control of a multi--joint hand prosthesis – an experimental approach". In: *Proc 9th Int Conf Computer Recognition Systems CORES 2015*, ser. Advances in Intelligent Systems and Computing. Springer International Publishing, 2016, chapter 52, 553–563. http://dx.doi.org/10.1007/978-3-319-26227-7_52.

[6] M. Kurzynski, M. Krysmann, P. Trajdos, A. Wolczowski, "Multiclassifier system with hybrid learning applied to the control of Bioprosthetic hand", In: *Computers in Biology and Medicine*, vol. 69, 2016, 286–297, 2016. http://dx.doi.org/10.1016/j.compbiomed.2015.04.023.

[7] A. Wolczowski, M. Kurzynski, "Control of hand prosthesis using fusion of biosignals and information from prosthesis sensors". In: *Computational Intelligence and Efficiency in Engineering Systems*. Eds. G. Borowik, chapter 19, Springer Int. Publishing, 2015, 259–273. http://dx.doi.org/10.1007/978-3-319-15720-7_19.

[8] M. Kurzynski, A. Wolczowski, "Multiple Classifier System Applied to the Control of Bioprosthetic Hand Based on Recognition of Multimodal Biosignals". In: *Proc. of 15th Int. Conf. on Biomedical Engineering*, chapter 147, Springer Int. Pub., 2014, 577–580. http://dx.doi.org/10.1007/978-3-319-02913-9_147.

[9] Y. Su, C.R. Allen, A. Wołczowski, G.D. Bell, "Telerobotic control using instructions from human hand motion". In: *Robot Control 2003. (SYROCO '03). Proc 7th IFAC Symposium*, vol. 2, ed. by I. Dulęba and J. Z. Sąsiadek. Oxford, UK, Elsevier, 2004, 527–532. http://dx.doi.org/10.1016/S1474-6670(17)33448-1.

[10] M. Kurzynski, A. Wolczowski, T.G. Amaral, "Control of bioprosthetic hand based on EMG and MMG signals recognition using multiclassifier system with feedback from the prosthesis sensors". In*: Proc. of 2nd Int. Conf. on Sys. and Cont.*,

[11] Marrakech, Morocco, June 2012, 280–285.[11] T.V. Camata, J. L. Dantas, T. Abro, et al., "Fourier and wavelet spectral analysis of EMG signals in supramaximal constant load dynamic exercise". In: Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE, August 2010, 1364–1367. http://dx.doi.org/10.1109/IEMBS.2010.5626743.

[12] N. F. Güler, S. Kocer, "Classification of EMG signals using PCA and FFT", *Journal of Medical Systems*, vol. 29, no. 3, 241–250, 2005. http://dx.doi.org/10.1007/s10916-005-5184-7.

[13] A. Cichocki, R. Zdunek, A. Phan, S. Amari, *Nonnegative Matrix and Tensor Factorizations: Applications to Exploratory Multi-way Data Analysis and Blind Source Separation*, Wiley and Sons, 2009. http://dx.doi.org/10.1002/9780470747278.

[14] H. M. Al-Angari, G. Kanitz, S. Tarantino, C. Cipriani, "Distance and mutual information methods for EMG feature and channel subset selection for classification of hand movements", *Biomedical Signal Processing and Control*, vol. 27, May 2016, 24–31. http://dx.doi.org/10.1016/j.bspc.2016.01.011.

[15] A. Wołczowski, J. S. Witkowski, *Stanowisko badawcze do akwizycji biosygnałów*, Report of the Institute of Computer Engineering, Control and Robotics of Wroclaw University of Technology 2013, Ser. PRE no. 47, Wrocław, 2013. (in Polish)

[16] W. Sobczak, W. Malina, Metody selekcji i redukcji informacji, WNT, Warsaw, 1985. (in Polish)

[17] C.J. De Luca, *Electromyography. Encyclopedia of Medical Devices and Instrumentation*, John Wiley Publisher, 2006, 98–109.

[18] bebionic, http://bebionic.com/the_hand/grip_patterns/key_grip

[19] ottobock, http://www.ottobock.pl/

[20] delsys http://www.delsys.com/