DATA ACQUISITION SYSTEM FOR ELECTRODERMAL ACTIVITY RECORDING

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Electrodermal Activity Recording (EDA) is a non-invasive technique used for study the body reactions to various stimuli and has many applications in biomedical field (dermatology, endocrinology, psychopathology, neurology, etc.).

This paper presents a data acquisition system that performs skin conductance measurements. The design has been oriented to provide the following key features: small size, connectivity with a personal computer, electrical safety, possibility for adding new functionalities and low cost.

These characteristics were obtained by using of a digital signal processor which performs most functions through software and allows reduction of hardwired analog electronics to a minimum.

Keywords: Data Acquisition, Digital Signal Processing, Electrodermal Activity

1. Introduction

The study of electrodermal phenomenon has its beginnings in 19-th century, when the first experiments that demonstrated the link between sweat glands and the electrical current expressed in the skin were conducted [1]. Galvanic skin response or electrodermal activity (EDA) is a technique with a rich history as a handy and relatively noninvasive tool used to study the body reactions to various stimuli, being an indicator of physiological and psychological arousal. The autonomic control mainly regulates the internal environment, in order to maintain the body homeostasis [2]. It is considered that the skin is an organ that responds preponderantly to the action of the sympathetic nervous system through the eccrine sweat gland [3]. For this reason, the data acquisition made in the skin can get information about the attitude of the body's "fight or flee".

There are two ways of recording of electrodermal activity [4]:

- endosomatic method that involves measurement of skin potential (without of application of external voltage/current);
- exosomatic method that measure skin conductance using either direct or alternating current excitation signal.

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High-quality electrodermal recordings are offered by numerous available commercial devices, the best known and most used being the BIOPAC system [5]. We can also enumerate other devices with different features and applications: Flexcomp System, a physiological monitoring device with a wide range of applications in psychology, psychiatry, clinical research, physical therapy, primary care, and sports medicine [6]; SenseWear, a physical activity monitor [7]; SC5 24 bit Skin Conductance system from PSYCHLAB [8]; wearable sensors systems for long term assessment of electrodermal activity [9], [10]. However, these devices are either too expensive or use simple direct current excitation for conductance measurement.

In this paper we present a data acquisition system that we developed in order to give a high quality but low-cost solution for electrodermal activity recording.

2. Data acquisition system description

The design of EDA data acquisition system has been oriented to provide high quality measurements, electrical safety, low cost and ability to add new functionalities. The way of achieving this is to implement as many functions as possible in software and keep the hardware to minimum complexity.

2.1. The method for skin conductance measurement

The simplest way to measure skin conductance is to apply a known DC voltage (0.5V) between two electrodes and measure the current that occurs between them. Electrodes are placed on intact palmar skin of the same member. The contact between electrode and tegument is not perfect, hence a small resistor in range of 200Ω up to 1KΩ is introduced in the circuit. Because resistance of the skin is of the order of 100KΩ, the contact resistance can be neglected [4].

This simple method does not allow obtaining accurate measurements due to presence of parasitic potentials that appear at skin-electrode interface (Fig.1).
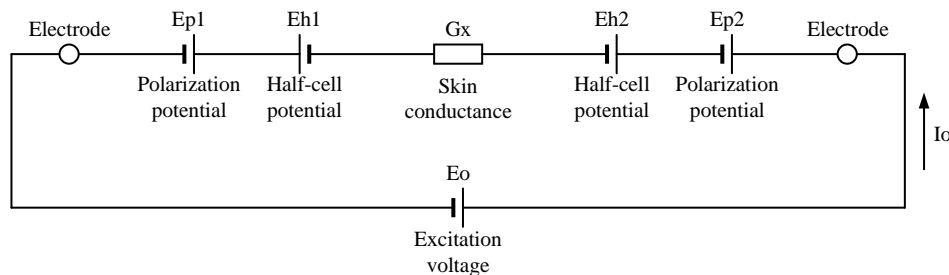

Fig. 1. Skin-electrode interface model

Half-cell potential is a voltage that appears between a conductive electrode and surrounding conductive electrolyte. In real measurements, although the electrodes are identical, the two half-cell potentials *Eh1* and *Eh2* do not cancel each other because the salt concentrations on the skin may vary between electrodes positions.

Electrode polarization effect is another cause for measurement errors and consists in development of a counter electromotive force opposed to the applied voltage at each skin-electrode interface (*Ep1* and *Ep2*).

In the presence of these voltages, estimated conductance (Gx^*) will be:

$$Gx^* = \frac{Io}{Eo} = \frac{(Eo - Ep1 - Ep2 + Eh1 - Eh2)Gx}{Eo} \neq Gx \qquad (1)$$

that is different from the real conductance *Gx*.

A simple solution to this issue is to perform conductance measurements using low frequency AC (20 Hz). In this way, DC voltages caused by electrode potentials are eliminated and the low frequency of the excitation voltage allows having conductance measurements very close to DC. In this case, excitation voltage *Eo* and measured current *Io* are sinusoidal quantities that can be represented by complex phasors.

Admittance represents the ratio between the current and voltage phasors and can be represented as a complex number as follows:

$$Yx = \frac{Io}{Eo} = Gx + j\,Bx \qquad (2)$$

where:

    Io, *Eo* – are complex phasors of current and voltage, respectively;
    G   – represents conductance;
    B   – corresponds to susceptance;

Complex phasor of an AC signal can be determined by processing the measured signal using a two-phase lock-in amplifier [11] (Fig. 2).
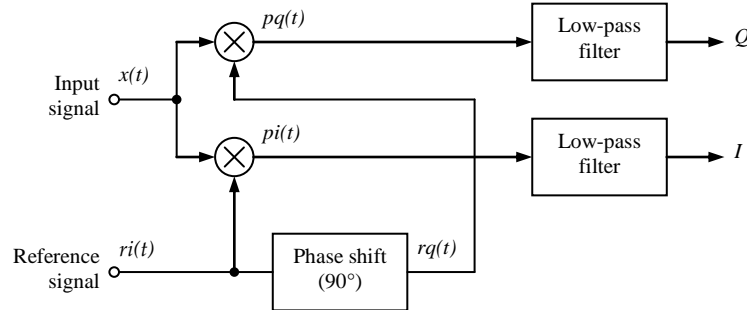

Fig. 2. Lock-in amplifier block diagram

Input signal *x(t)* is composed by the AC signal that must be analyzed and some noise. The reference signal *ri(t)* is a sine wave with same frequency as the AC signal, the phase shift block creates another reference signal *rq(t)* in quadrature with *ri(t)*.

The phasor of the AC signal is *I+jQ* and its angle is relative to the phasor of the reference signal *ri(t)*

The block diagram of admittance estimation is presented in Fig. 3:
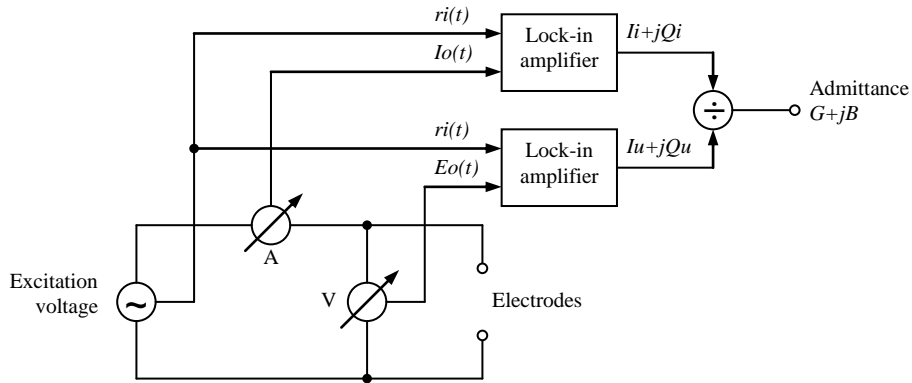

Fig. 3. Admittance estimation using two-phase lock-in amplifiers

In order to implement the two-phase lock-in amplifiers using digital signal processing, excitation voltage *Eo(t)* and electrode current *Io(t)* are sampled by an Analog to Digital Converter that offer discrete-time signals Eo_k and Io_k. Sampling frequency was set to 20 KHz for a very good accuracy of signal acquisition process.

Reference signals samples ri_k and rq_k used inside of the two-phase lock-in amplifiers and for excitation voltage generation are generated using a look-up table as following:

$$ri_k = sine\_tabtab[k \bmod 2000], \quad rq_k = sine\_tab[(k+500)\bmod 2000] \quad (3)$$

where:

$$sine\_tab[k] = \sin\left(\frac{2\pi k}{2000}\right), \quad k = 0\ldots1999 \tag{4}$$

The main difficulty in lock-in amplifier implementation is the low-pass filter that requires a large amount of arithmetic computation. In order to solve this issue, we propose an alternative that consists in replacing the low-pass filter with a simple moving average operation [12] that has a similar effect of reduction of high frequency components. The window size of the moving average filters was set to 2000 samples (10 ms equivalent) in order to obtain complete rejection of power grid disturbances at both 50 Hz and 60 Hz frequencies.

2.2. Hardware design

The design has been oriented to provide high measurement precision with minimum number of electronic components. The way of achieving this is to implement as many functions as possible in software. In order to make this approach possible, we develop the conductance acquisition system based on a 16-bit microcontroller that contains all hardware resources required by signal generation, acquisition and processing. As result, the hardwired analog processing was reduced to a minimum (Fig. 4):

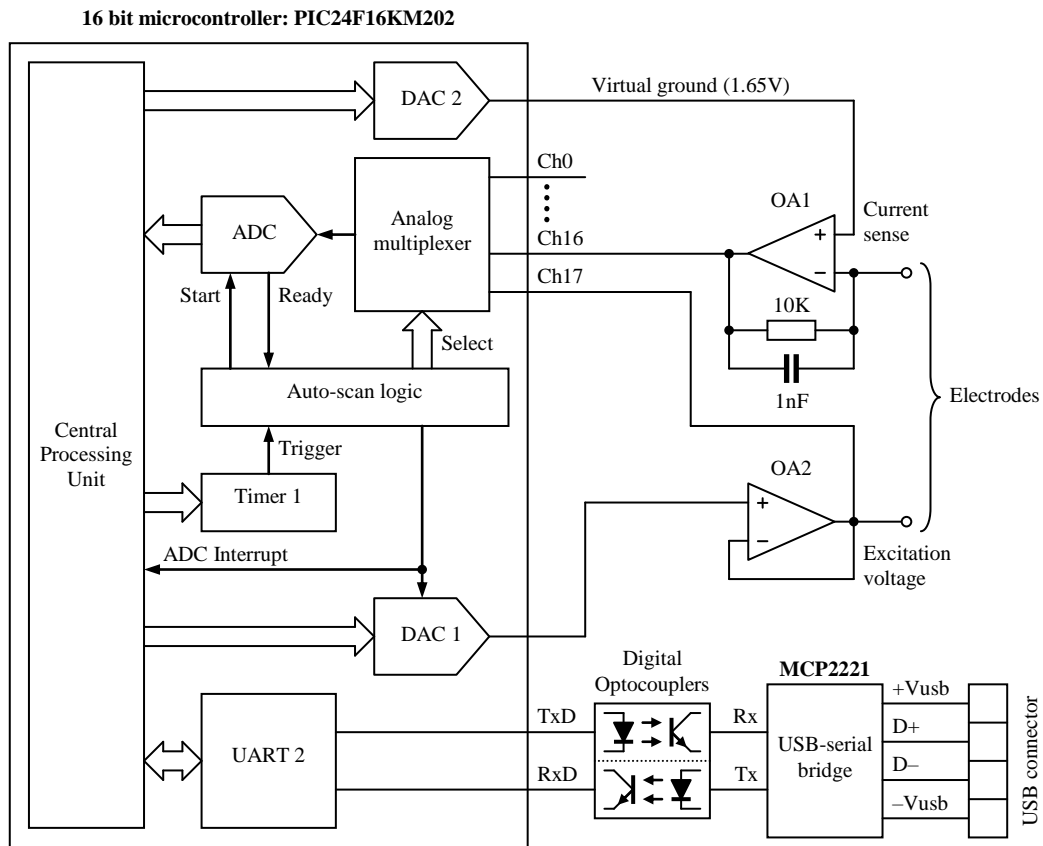**16 bit microcontroller: PIC24F16KM202**

Fig. 4. Electrical diagram of conductance acquisition system

The hardware design consists of 5 main functional modules:
- Central Processing Unit;
- Signal acquisition system;
- Excitation voltage generator;
- Communication interface;
- Power supply unit.

Central Processing Unit is included entirely inside the microcontroller and consists of a 16-bit processor able to perform 16 million operations per second; a 16KB program memory implemented using Flash technology and a 1KB data memory.

Signal acquisition system is used to measure the excitation voltage applied to the electrodes and the current that flow between them. It is based on the ADC (Analog to Digital Conversion) module included in the microcontroller and has a minimal external circuit for signal conditioning.

Excitation voltage is taken directly from the active electrode and applied to one of the ADC input channels (Ch17). The current that flows between electrodes is converted into a voltage by a transimpedance amplifier implemented with operational amplifier OA1 (first section of a MCP6002 circuit) and applied to another ADC input channel (Ch16).

The feedback resistor of the transimpedance amplifier sets a gain of 10mV/μA. In order to reduce the noise, we added a capacitor connected in parallel with the feedback resistor. This capacitor creates a low-pass characteristic with a cutoff frequency of about 16KHz.

Because all analog circuits (both integrated inside the microcontroller as well as external operational amplifiers) are powered by a single voltage supply it is impossible to process negative voltages. In order to allow processing of alternating voltages and currents that can have positive and negative values we implemented a "virtual ground". This means that all voltages in analogic chain are referenced to a potential equal with half of the supply voltage. This potential is generated by a Digital to Analog Converter (DAC2) integrated inside the microcontroller that is programmed to generate a constant voltage of 1.65V (half of the 3.3V supply).

Acquisition of the two input voltages (from channels 16 and 17) is performed by the integrated ADC module. This module has an auto-scanning function that allows sequential acquisition of multiple channels. Using this feature, we can continuously acquire the two input channels in the following order: Ch16-Ch17-Ch16-Ch17-…

The auto-scan logic of the ADC module generates an interrupt request after each input scan completion (every two ADC conversions). The trigger for ADC conversion is generated by a timer circuit at a 40KHz rate. As result, each input channel is measured 20000 times per second.

Excitation voltage generator provides the excitation voltage to the active electrode. Hardware resources used by excitation voltage generator are an integrated Digital to Analog Converter (DAC1) and a low output impedance buffer implemented by the second operational amplifier (OA2) connected in voltage follower configuration.

The Digital to Analog Converter is configured to use a double-buffer updating mechanism that allows very precise updating of the DAC output by using a trigger signal. We used the scan completion signal generated by the ADC module as trigger for DAC updating.

Communication interface provides data transfer between admittance recorder device and a personal computer used for storage and interpretation of measured data. Since most personal computers has only USB ports and the microcontroller does not include an USB interface we used an USB-to-serial bridge circuit (MCP2221) that implements a virtual UART (Universal Asynchronous Receiver/Transmitter) over an USB port.

Due to electrical safety reasons, we isolated the admittance recorder circuits from the USB to serial bridge that is electrically connected to the personal computer. This isolation is implemented by two digital optocouplers (6N136) placed on UART transmission (TxD) and reception (RxD) signals. This isolation also contributes to reducing noise generated by the computer power source that could be transmitted through the USB interface.

Power supply unit consists in four AAA batteries and a low-power voltage regulator (LP2951) that provides the supply voltage for microcontroller and operational amplifiers (3.3V). We chose to use batteries instead of an AC power adapter due to same electrical safety and noise reduction reasons as in case of electrical isolation of USB interface.

2.3. Software implementation

The software application is composed by:
- ADC Interrupt Service Routine (ADC_ISR);
- Main program loop.

ADC Interrupt Service Routine(ADC_ISR) is generated by ADC module 20000 times per second and performs excitation signal generation and estimation of the *Eo* and *Io* complex phasors.

In order to generate excitation voltage, ADC_ISR must update the Digital to Analog Converter (DAC1) synchronously with the sampling rate. Signal samples correspond to ri_k reference and are obtained from the look-up table according to equation (3).

Estimation of the *Eo* and *Io* complex phasors is performed by a digital implementation of the two-phase look-in amplifiers presented in Fig. 3.

Ratio between current and voltage phasors are computed in the main program loop because complex division operations takes too long to be implemented inside an Interrupt Service Routine.

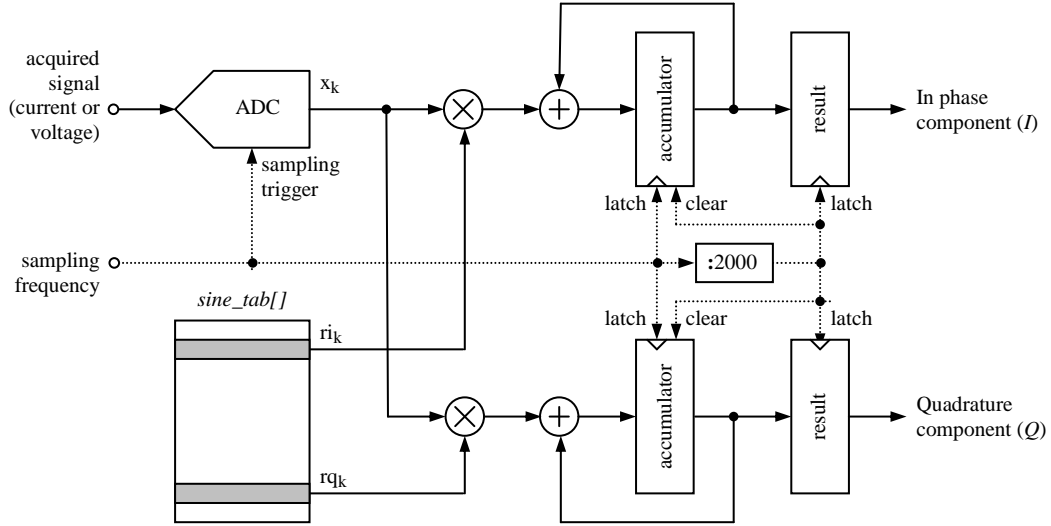Figure 5 presents the digital implementation of the lock-in amplifier using simple moving average filtration.

Fig. 5. Digital implementation of signal phasor estimation

At every sample period, reference signals ri_k and rq_k are generated using *sine_tab[]* and the actual sample of acquired signal (x_k) is multiplied with corresponding reference value. Each product is than accumulated in a variable (accumulator) and at every 2000 samples, accumulated values are transferred to a result variable and the content of the accumulator is cleared.

Communication between the phasors estimation code located in ADC Interrupt Service Routine and admittance calculation code located in the main program loop is performed using a two-buffer mechanism (Fig. 6):
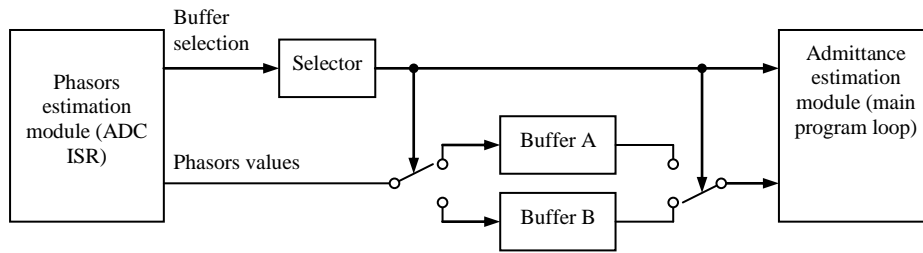

Fig. 6. Double buffer communication mechanism

At one time, phasors estimation module from ADC Interrupt Service Routine uses one buffer while the admittance estimation module from main program loop uses the other buffer. When first module completes the accumulation of the 2000 values for each phasor component, buffers are exchanged between modules. The module to buffer association is indicated by a

variable (selector) that is updated by phasors estimation module and monitored by admittance estimation one.

For high efficiency implementation (required by small sampling time constrains), the code was developed using assembly language and all calculations were made using fixed-point arithmetic.

Main program loop implements conductance computing as the ratio between complex current and voltage phasors and communication function. The code was developed in C language.

Conductance is computed in the main program loop every time when a new set of current and voltage phasors are available by the following formula:

$$Gx = \frac{\mathrm{Re}(Io)\,\mathrm{Re}(Eo) + \mathrm{Im}(Io)\,\mathrm{Im}(Eo)}{\mathrm{Re}(Io)^2 + \mathrm{Im}(Eo)^2} \tag{5}$$

Data communication between the conductance acquisition system and the personal computer used for data analysis and results presentation is performed through an asynchronous serial interface (UART2) included in the microcontroller structure. This interface is connected to the personal computer by an USB-to-serial bridge that emulates a virtual communication port.

The communication protocol is very simple: the host computer sends an interrogation and, as result, the conductance acquisition system responds with a message that contains the requested data. Communication protocol is implemented as a finite state machine inside the main program loop

There are two possible interrogations that consist in single character messages as following:

- '#'– identification request;
- '*' –EDA data request;

The response to the identification request is the character string "EDA". This kind of interrogation is useful for detection of device connection and identification of the virtual port assigned by the operating system.

In case of an EDA data request, the response consists in 100 conductance values transmitted at a rate of 10 values/second.

The reception of a new EDA data request during transmission of the response to a previous interrogation will reset the number of transmitted values to another 100.

The format used for conductance values is:

XXX.YY <CR><LF>

where *XXX* is the integer part represented by 3 decimal digits, *YY* is the fractional part as 2 decimal digits and *<CR><LF>* are the Carriage Return and Line Feed characters (codes 0x0D and 0x0A).

3. Results

Conductance data acquisition hardware was designed using Eagle 7.10 CAD software (schematics and layout). Printed circuit board (PCB) dimensions were selected according to a standard instrumentation case (1598BBK – Hammond Manufacturing) and uses Through-hole assembly technology (Fig. 7).

Fig. 7. Conductance data acquisition system (PC Board)

Conductance data acquisition system was initially tested by measuring a 10KΩ calibrated resistor that has a complex admittance of *100μS+j 0μS*. In order to obtain real measurements, we added a calibration procedure inside the software application. This procedure multiplies the estimated admittance with the ratio between the ideal and measured admittance of the calibrated resistor:

$$Y\_calibrated = Y\_measured \frac{100\mu S}{Y\_resistor\_measured} \tag{6}$$

After calibration, we tested measurement accuracy over the whole range of conductance values (0 to 100μS) using a set of 11 test resistors. First, all the resistors were measured in order to find their exact values (R_{real} / G_{real}) using a precision multimeter (BK5492B – B&K Precision). Second, same resistors were measured using the proposed device, and 200 conductance samples were averaged to remove effects of noise ($G_{measured}$).

For each resistor we computed relative error as:

$$Error = \frac{G_{real} - G_{measured}}{G_{real}} \cdot 100 \quad [\%] \tag{7}$$

Test results are presented in the following table:

Table 1

Measurement accuracy test results

R_{real} [KΩ]	G_{real} [μS]	$G_{measured}$ [μS]	Relative error [%]
200.78	4.9806	5.0050	-0.4914
100.26	9.9741	9.9999	-0.2585
50.097	19.961	19.948	0.0648
33.387	29.952	29.922	0.0989
25.042	39.933	39.880	0.1331
20.022	49.945	49.847	0.1964
16.683	59.941	59.815	0.2099
14.300	69.930	69.771	0.2276
12.519	79.879	79.662	0.2708
11.123	89.904	89.638	0.2952
10.014	99.860	99.556	0.3047

It can be noticed that relative errors are very small (less than 0.5%) that confirms obtaining of a good accuracy.

Another test performed on the conductance data acquisition system was an evaluation of measurement noise. This kind of test is required because electrodermal activity analysis involves detection of small conductance variations during a continuous recording and a high level of noise makes this process very difficult. Noise tests were performed by measuring a 100KΩ resistor (G=10μS) and consists in recording 1000 conductance in order to obtain effective value of the measurement noise (Eq. 8):

$$A_{noise} = \sqrt{\sum_{k=0}^{999}\left(G_k - \overline{G}\right)^2} \qquad (8)$$

where:

G_k – represents the conductance sample no. *k*;

$\overline{G}$ – correspond to mean value of all 1000 samples;

Noise amplitude test was performed in three different situations:

Resistor connected and no human interaction with it – this test indicates the level of noise generated by the circuits inside data acquisition system or received by them from the environment. Noise amplitude was 10.52nS that correspond to a signal-to-noise ratio SNR=79.5dB.

Resistor connected and human contact on input terminal – this test indicates the effects of the noises induced by the human subject that acts like an antenna for all electromagnetic disturbances. Noise amplitude was 71.71nS, (SNR=62.8dB).

Resistor connected and human contact on excitation output terminal – in this case noise amplitude was 6.39nS, (SNR=83.9dB). It can be noticed that, noise amplitude is smaller than in case of no human contact. A possible explanation is that touching the output terminal, the human subject is connected to a circuit point that presents a low impedance path to the device ground. Therefore, the human subject became an electromagnetic shield that decreases the influence of external disturbances that affects electronic circuits inside the conductance recorder.

4. Conclusions

In this paper we presented a data acquisition system designed for skin conductance recording. The key elements of its design were high measurement precision, low cost electrical safety and possibility for adding new functionalities. All of these requirements were achieved by implementation of most signal processing functions through software, therefore analog processing circuits were simplified to a minimum.

In future, this approach will allow extending system capabilities to more complex measurements like skin admittance evaluation at several frequencies. This feature will offer the possibility to evaluate more electrical parameters of the skin tissue that are very useful in many biomedical research fields.

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