DESIGN OF A PROGRAMMABLE BIOELECTRICAL IMPEDANCE SYSTEM FOR BIOMEDICAL APPLICATIONS

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Abstract: The design of a portable, versatile and programmable bioelectrical impedance system is presented. The device uses inexpensive off-the-shelf components to perform multi-frequency current injection and voltage measurements through skin electrodes. The impedance measurement system can be configured as multi-frequency bioelectrical impedance analyzer as well as acupuncture point detector, for localizing pathologically changed acupuncture points on the body. In order to improve the accuracy and the flexibility of the measurements, a programmable wide frequency bandwidth current source has been designed. It allows to generate sinusoidal and square waveforms with a frequency up to 1MHz and amplitude values in the range of $[12\mu A_{pp} - 1.2mA_{pp}]$. The measured signals can be amplified with a programmable gain and converted with 16 bits of resolution before being transmitted to a PC through USB transmission for further processing.

1 INTRODUCTION

Multi-frequency bioelectrical impedance analysis (MBIA) is a non-invasive technique to assess body composition and to determine fluid distribution across cell membranes, based on the property of tissues to conduct electrical alternating current (Kyle et al., 2004). At low frequencies (lower than 100kHz) cell membranes represent a barrier to the flow of electric current, so bioelectrical impedance measurement can be used to estimate extra-cellular water (ECW). In contrast, at frequency over 100kHz, electric current permeates cell membranes and flows through cell so, bioelectrical impedance can be used to estimate total body water (TBW). Changes in tissue perfusion can cause dehydration, arterial hypotension, edema and cerebral intraventricular hemorrhage (Mayer et al., 2005). These events induce variations of the bioimpedance electrical characteristics, whose on-line monitoring could be of great diagnostic relevance in clinical investigation and patient care (Ricciardi and Talbot, 2007). In line with this aim, several bioelectrical impedance instruments have been developed recently, mostly based on the Direct Digital Synthesis (DDS) technique for multi-frequency stimulus signal generation (Seoane et al., 2008; Cheng et al., 2006; Hartov et al., 2000). Moreover, according to several studies and research experiments, skin impedance measurements can be used also to locate acupuncture points (APs) and to guide diagnosis and treatment strategies on those points (Reichmanis et al., 1976). The assumption that the skin resistance shows differences among APs and the surrounding tissues, is under debate and is currently controversially discussed in the literature (Kramer et al., 2009). Consequently, a low-cost device has been developed in order to evaluate the phenomenon of electrical skin resistance changes before and during acupuncture and to obtain precise and objective information about this topic. In addition, the system can be configured as multi-frequency bioelectrical impedance analyzer for BIA purpose, allowing rapid and accurate measurement of the electrical impedance over a wide frequency range.

2 SYSTEM DESIGN

A schematic diagram of the bioelectrical impedance system is shown in Figure 1. Basically, it consists of four main parts: electrodes, multi-frequency current source, voltage measurement circuitry and digital system controller. A painless and constant amplitude electrical current I_{inj} flows through tissue via a pair of current electrodes. The voltage drop across tissue im-

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pedance is detected by a pair of voltage electrodes, amplified by a programmable-gain instrumentation amplifier and then, directly digitized using a 16-bit analog-to-digital converter or first sent to the peak detector input, in order to convert only peak levels of the signal. The bioelectrical impedance system has been realized using a COTS-based (Commercial Off-the-Shelf) design and it is supplied by the +5V USB power bus.

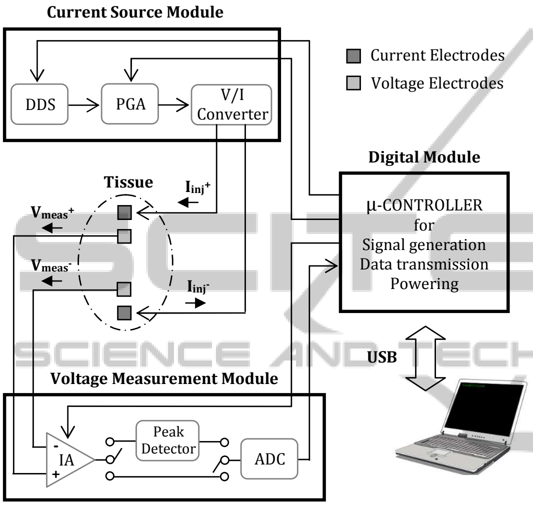

Figure 1: Block diagram of the bioelectrical impedance system.

Current Source Module. The current source module has been designed using a direct digital synthesizer (DDS) in combination with a programmable variable gain amplifier/attenuator and a V/I converter. The Analog Devices DDS chip AD9833 has been chosen for its ability to generate constant amplitude sine waves in the frequency range from 0Hz to 12.5MHz. Since the AD9833 architecture does not provide waveform amplitude adjustment, a programmable attenuation/amplifying circuit have been integrated in the circuit in order to make use of the entire voltage range ($0V-3V$). By means of two digitally controlled potentiometers R_1 and R_2 (ISL22316, Intersil), DDS output signal can be amplified or attenuated in amplitude from −47dB to +47dB. The voltage-to-current (V-I) converter has been realized using a simple operational amplifier (OPA343, Texas Instruments) in a non-inverting configuration, using the tissue impedance as feedback resistor. It converts the amplified/attenuated voltage signal into the controlled current I_{inj} required for the tissue excitation. As shown in equation 1, the excitation current is independent of the tissue resistance and can reach values from $12\mu A_{pp}$ to $1.2mA_{pp}$. Excitation levels and frequencies are digitally controllable from a personal computer via a Universal Serial Bus (USB) controller interface.

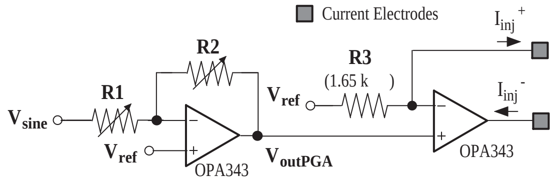

Figure 2: PGA and V-I converter circuits.

$$I_{inj} = \frac{(V_{outpga} - V_{ref})}{R_3} \tag{1}$$

Voltage Measurement Circuitry. The voltage measurement module is composed of a programmable-gain instrumentation amplifier (IA), a peak detector and a 16-bit successive-approximation analog-to-digital converter (ADC). As shown in Figure 3, a three-amplifier implementation of the instrumentation amplifier has been designed. The output signal V_{meas} is indicative of a difference between the pair of input signals (V_{in}^{+} and V_{in}^{-}) received from the two detection electrodes, as reported in equation 2. The voltage gain of the circuit is programmed by a digitally controlled potentiometer R_4 (ISL22316, Intersil), and varies from 1.8 to about 200. The voltage V_{meas} measured by the instrumentation amplifier, can be directly converted into digital samples using 16-bit AD7694 (Analog Devices) ADC or sent to the peak detector input, in order to convert only peak levels of the signal when very high frequencies are used. The AD7694, in fact, can only reliably convert signals below $5kHz$. The peak detector has been implemented using an op-amp configured as a voltage follower, whose output is used to charge the capacitor C_1 through diode D_1. Once that the chosen signal is converted, it is sent to the PC to be stored in a data file.

$$V_{meas} = (V_{in}^{+} - V_{in}^{-}) \cdot (1 + 2 \cdot \frac{R_4}{R_5}) \cdot \frac{R_7}{R_6} \tag{2}$$

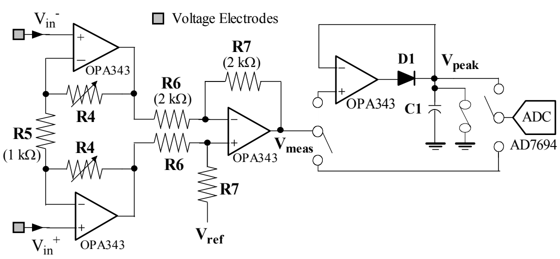

Figure 3: Voltage measurement circuitry.

Digital System. The digital module is responsible of monitoring several aspects of the system. It is based on the Universal Serial Bus (USB) controller PIC18F4550 (Microchip), chosen principally for its low cost and relative ease of programming. The function of the microcontroller is to manage communication between PC and modules of the bioelectrical impedance system. The PIC18F4550 contains a full-speed and low-speed compatible USB Serial interface Engine that allows fast communication between any USB host and the microcontroller itself.

3 OPERATING MODES

The system supports two different operating modes: multi-frequency bioelectrical impedance analysis and acupuncture stimulation with point finding. In order to evaluate circuitry functionalities before in-vivo laboratory trials on animals, two additional Test operating modes have been integrated in the system. The dummy resistor R_{tissue} simulates the tissue impedance during the testing operation modes.

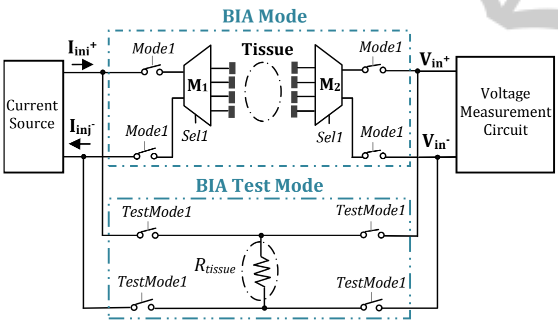

Figure 4: System reconfigurability: switch network for BIA and test.

When the BIA operating mode is selected, the system is enabled to estimate resistance values from each arm and leg. The tissue resistance R_{tissue} is given by equation 3. Typically the electrical resistivity of human tissues, except fat and bone, varies from 150 to 675Ω in the frequency range $[100Hz - 10MHz]$ and the whole-body impedance value is around 500Ω (Faes et al., 1999). Thus considering this range, a resistance of 499Ω has been chosen to simulate the tissue impedance during BIA Test operating mode.

$$R_{tissue} = \frac{(V_{in^+} - V_{in^-})}{I_{inj}} \tag{3}$$

During the APs research working mode, a probe electrode is passed over the skin while a second electrode is held in the hand of the patient to complete an electrical circuit therethrough. The tissue impedance presented between the two electrodes will depend on the placement of probe electrode on the patient's body. As the probe electrode is passed over the patient's skin, the detected impedance will vary narrowly around a nominal magnitude with substantial variations occurring within skin moisture conditions. Significantly variations in tissue impedance, however, will be detected only when the pointed electrode localizes an acupuncture point. The tissue resistance R_{tissue} in the APs research operating mode is given by equation 4. Since skin impedance at APs can ranges from $10k\Omega$ to $10M\Omega$ (Colbert et al., 2008), to verify the APs finder electronic system functionalities, the tissue impedance has been replaced with a resistive component of $49.9k\Omega$ in the Acupuncture Research Test operating mode.

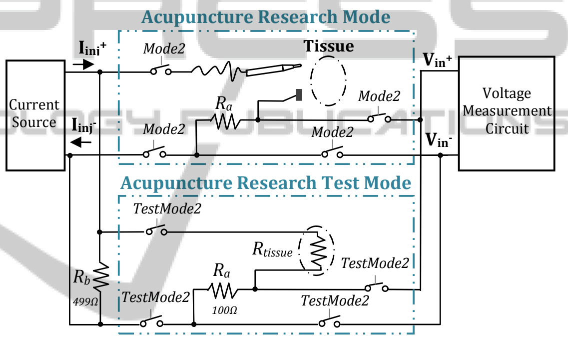

Figure 5: System reconfigurability: switch network for acupuncture research and test.

$$R_{tissue} = \frac{R_b \cdot (I_{inj} - \frac{V_{in^+} - V_{in^-}}{R_a})}{V_{in^+} - V_{in^-}} \cdot R_a - R_a \tag{4}$$

4 PRELIMINARY RESULTS

A preliminary phase of experiments has been carried out configuring the circuitry in test modes with the aim of validating the electronic system design. The BIA test has been conducted by injecting a stimulus current of $600\mu A_{pp}$ at three different frequencies through R_{tissue} and by measuring the voltage drop across it when a gain of 2 is set in the IA circuit. The results are expressed graphically in Figure 6 and demonstrate system's ability to measure according to equation 3, a magnitude impedance of 499Ω in a wide range of current signal frequencies. The same value $(V_{in^+} - V_{in^-}) = 299.4mV$ is in fact obtained at $10Hz$, $100Hz$ and $1kHz$. The APs test has been performed by setting the current source to generate a stimulation signal I_{inj} of $990\mu A_{pp}$ at $50kHz$. The value of

$(V_{in^+} - V_{in^-})$ can be reconstructed with good accuracy by subtracting the offset (1.5V) from the peak detector output and multiplying the result by two. As shown in Figure 7 a value of $0.978mV_{pp}$ is obtained for $(V_{in^+} - V_{in^-})$. Substituting this value into equation 4, as expected the resulting impedance is $R_{tissue} \simeq 49,9k\Omega$.

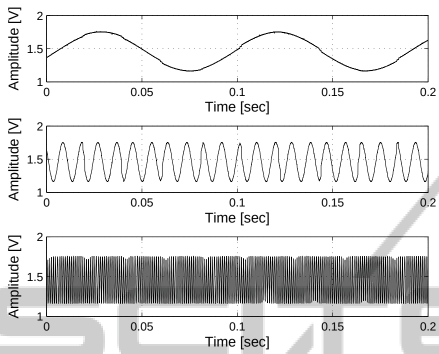

Figure 6: Results of BIA test mode operation: voltage $V_{meas} = 2 * (V_{in^+} - V_{in^-})$ measured at $10Hz$, $100Hz$ and $1kHz$.

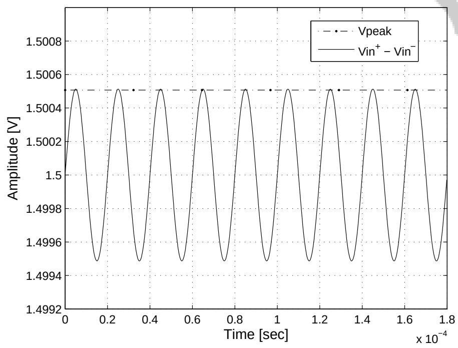

Figure 7: Peak detector output voltage when a current I_{inj} of $990\mu A_{pp}$ at $50kHz$ is provided as stimulus and the respective signal $(V_{in^+} - V_{in^-})$ reconstruction.

5 CONCLUSIONS

A portable system for multi-frequency bioelectrical impedance analysis and acupuncture point stimulation and detection is presented. The device has been designed and implemented using COTS-based electronics. Preliminary results demonstrate the capability of providing electrical stimulation of skin, injecting sinusoidal current pulses with programmable parameters. Since it has not still been possible to realize in-vivo experiments, preliminary tests have been performed using a dummy resistor to simulate the tissue impedance. The measurement system is able to record signals below $100\mu V_{pp}$ at low and high frequencies. It also provides programmable amplification to realize highly sensitive measurements.

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