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Portable bioimpedance monitor evaluation for continuous impedance measurements. Towards wearable Plethysmography Applications

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Abstract —**Personalised Health Systems (PHS) that could benefit the life quality of the patients as well as decreasing the health care costs for society among other factors are arisen. The purpose of this paper is to study the capabilities of the System-on-Chip Impedance Network Analyser AD5933 performing high speed single frequency continuous bioimpedance measurements. From a theoretical analysis, the minimum continuous impedance estimation time was determined, and the AD5933 with a custom 4-Electrode Analog Front-End (AFE) was used to experimentally determine the maximum continuous impedance estimation frequency as well as the system impedance estimation error when measuring a 2R1C electrical circuit model. Transthoracic Electrical Bioimpedance (TEB) measurements in a healthy subject were obtained using 3M gel electrodes in a tetrapolar lateral spot electrode configuration. The obtained TEB raw signal was filtered in MATLAB to obtain the respiration and cardiogenic signals, and from the cardiogenic signal the impedance derivative signal (dZ/dt) was also calculated. The results have shown that the maximum continuous impedance estimation rate was approximately 550 measurements per second with a magnitude estimation error below 1% on 2R1C-parallel bridge measurements. The displayed respiration and cardiac signals exhibited good performance, and they could be used to obtain valuable information in some plethysmography monitoring applications. The obtained results suggest that the AD5933-based monitor could be used for the implementation of a portable and wearable Bioimpedance plethysmograph that could be used in applications such as Impedance Cardiography. These results combined with the research done in functional garments and textile electrodes might enable the implementation of PHS applications in a relatively short time from now.**

I. INTRODUCTION

The application of Electrical Bioimpedance (EBI) technology for respiration function monitoring is one of the earliest non-invasive monitoring applications of EBI measurements and is commonly known as Impedance Pneumography (IP). Already in 1969, NASA used IP to monitor the breathing of the astronauts during the Apollo XI mission. Since then, EBI technology has improved to a great extent and it can accurately correlate with volume estimations obtained from spirometers [1]. Respiratory volume and flow signal extracted from IP during tidal breathing contains pathological signs of Chronic Obstructive Pulmonary Disease (COPD), cystic fibrosis, or asthma among others.

As a result of extensive applied research efforts in the last decade funded by the European Commission, such as advances in textile and monitoring technology have produced textile sensors and measurement garments [2, 3] which have enabled personalised health monitoring applications based in EBI measurements.

Few years ago, Analog Devices introduced the first System-on-Chip (SoC) solution that perform complex impedance measurements, named the AD5933 [4], and the development of an Analog-Front-End (4E-AFE) enabled the measurement of Bioimpedance using a tetrapolar configuration [5]. The AD5933 has been used successfully in EBI applications ***e.g.*** an implantable impedance spectroscopy [6] or Body Composition Assessment using Textile Electrodes [7].

In this work, the performance of the AD5933+4E-AFE for continuous impedance measurements was evaluated for the implementation of impedance plethysmography applications, such as IP or Impedance Cardiography (ICG). The maximum continuous impedance estimation frequency and system performance error were assessed. Finally, the Transthoracic Electrical Bioimpedance (TEB) measurements were recorded, and the signal was processed to obtain the respiration and cardiac signals.

II. MATERIALS

A. AD5933-Based Bioimpedance Measuring Device

The AD5933 from Analog Devices Inc. [4] is a SoC solution that incorporates all the necessary components to perform complex impedance measurements. Thanks to the tetrapolar Analog-front-End [5, 7], the AD5933 SoC can perform Bioimpedance measurements in the range 5-270 kHz [7]. The AD5933-Based Bioimpedance Meter (AD5933-EBIM) used in this work, shown in Figure 1, it is a battery operated portable tetrapolar spectrometer controlled by a Microchip PIC24FJ microcontroller. It uses Bluetooth technology to transfers control messages and data between

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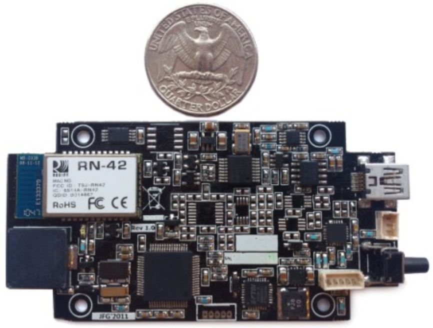

Figure 1 AD5933-EBIM main board picture.

device and a PC station. The AD5933-EBIM dimensions are 50x90x15 mm, and 70 gr of weight including the battery and a plastic box.

1) AD5933-EBIM Modifications

The 4E-AFE was modified to optimise the instrumentation for thoracic bioimpedance measurements. The injected current was configured to 400 μA_{RMS} and the input instrumentation amplifier gain to 26 v/v. The system was calibrated using a 2R1C circuit, selected to model a typical thorax impedance response which it was formed by a resistor of 150 Ω 0.1% in series with a capacitor of 10nF 1%, both in parallel with a resistor of 75 Ω 0.1%. The system was calibrated for the impedance frequency analysis points of 50, 100, 200, 300 and 400 kHz. The AD5933 was programmed to have one settling time cycle, starting frequency equal to the analysis frequency, frequency increments equal to zero and number of increments equal to one [4]. The I2C serial interface clock was configured for a frequency of 400 kHz.

III. METHODS

A. Theoretical impedance estimation time

The theoretical total sample time for a single measurement t_{SAMP} was calculated using the Equation 1.

$$t_{SAMP} = t_{AD5933Prot} + t_{SetCycles} + t_{Z\,Conv} \tag{1}$$

In Equation 1, the time t_{ZConv} is the time for the AD5933 to estimate the impedance values, and it is approximately 1 ms for a system clock of 16 MHz [4]. The time $t_{AD5933Prot}$ is the total time to perform all the I2C protocol instructions; to read the estimated impedance value registers, send the repeat instruction time and to check the impedance status measurement status. The time $t_{AD5933Prot}$ will depend on how the AD5933 is accessed and also which I2C frequency clock is selected. The time $t_{SetCycles}$ is the programed Settling Cycles Time, and it is calculated by the multiplication of the total number of the settling cycles and the period time of the impedance excitation signal.

B. Experimental impedance estimation time

The experimental impedance measurement estimation time was measured using a polling test program, which performed a continuous impedance measurement for a specific number of sample points, checking continuously the "Conversion-Done" bit in the AD5933 status register in order to reach the maximum speed. After setting the AD5933 initial measurement configurations, the "Start-to-Measure" command was sent, and the program was continuously checking the conversion status bit to determine if the impedance conversion has been done. When a conversion was done, the real and imaginary registers were read and a "Repeat-Frequency" command was sent. An output test pin was digitally toggled every time that a conversion was done, and using an oscilloscope the total impedance measurement time could be obtained. The total time for two sets of 10 and 100 sample points was obtained, using two impedance excitation frequencies, 50 kHz and 100 kHz.

C. System accuracy

The system accuracy was evaluated for the measurement of a 2R1C circuit model, which it was formed by a resistor of 71.5 Ω 0.1% in series with a capacitor of 10 nF 1%, both in parallel with a resistor of 90.1 Ω 0.1%. The AD5933-EBIM was configured to perform a continuous impedance measurement in the 2R1C circuit for frequencies of 50, 100, 200, 300 and 400 kHz, recording a total of 30 seconds for each excitation frequency. The average magnitude and standard deviation were calculated, as well as the magnitude error for each excitation frequency.

D. Thoracic electrical Bioimpedance measurements

After obtaining the practical impedance estimation frequency, a set of 180 seconds of TEB measurements in one subject were obtained using an impedance sampling frequency of 400 Hz and an injecting impedance signal frequency of 100 kHz. The tetrapolar Lateral Spot Electrode Configuration [8] and repositionable EKG Ag/AgCl 3M Electrodes were used to perform the measurement while the patient was in sitting position and relaxed. The experimental measurements were on humans were approved the regional Ethics committee of Gothenburg, ethical approval number 274-11.

The TEB measurements were processed using MATLAB to obtain the respiration and cardiac signals. The respiration signal was obtained filtering the impedance magnitude signal using first a low pass FIR filter at 10 Hz to eliminate the high frequency noise, and after a low pass interpolated FIR filter [1] at 0.5 Hz. The Cardiac Signal (ΔZ) was obtained applying first a linear detrend and zero-mean function to the impedance magnitude signal, then that signal was filtered using a band pass FIR filter with cut frequencies at 0.9 Hz and 7 Hz, also its first derivative signal (dZ/dt) was calculated.

IV. RESULTS

A. Impedance estimation frequency tests

The results for the experimental impedance estimation time tests are shown in Table I. The maximum estimation time was similar for all the tests with an averaged value of 1.791ms, a maximum impedance estimation frequency of approximately 550 Hz. Using the Equation 1 and for an output frequency of 50 kHz. Using the Equation 1, the theoretical impedance sampling time gives a value of 1.895 ms, which it is very close to the measured time.

TABLE I IMPEDANCE ESTIMATION TIME RESULTS.

Z Freq.(kHz)	Measurements (number)	Total Time (ms)	$Z\ F_{sampling}$ (Hz)
50	10	17,98	556,2
50	100	179,10	558,3
100	10	17,94	557,4
100	100	179,11	558,3

B. System measurement performance

Table II shows the results for 30 seconds of measuring on a 2R1C circuit model. The magnitude error was low for all impedance excitation frequencies, with a maximum magnitude error of 0.26 % at 400 kHz. The maximum Standard Deviation (STD) was 0.04 Ω at 50 kHz.

C. TEB results

A 23 seconds recording of the TEB signal Z_{raw} is shown in Figure 2. In the signal Z_{raw}, the cardiac and respiratory components could be observed as well as high frequency content due to the AD5933 impedance estimation error. The filtered respiratory signal Z_{resp} is also displayed in Figure 2 with a dashed line. The respiration interval appears to be approximately 3.5 seconds per cycle, giving an average respiration rate of 17 breaths per minute.

The original detrended Impedance Signal (Z_d), the cardiac signal (ΔZ) and its first derivate (dZ/dt) are shown in Figure 3 for a sequence of 6 seconds of the original measurement. The beat-to-beat interval as extracted from the plots is approximately 0.91 seconds giving a heart rate of 66 beats per minute. Some parameters for Impedance Cardiography analysis [9] can be extracted from Figure 2 and Figure 3 such as the increment difference for ΔZ signal with a value of 0.17Ω, the peak value for dZ/dt which is 1.55 Ωs^{-1}, or the baseline thoracic impedance Z_0 value of 29.4 Ω.

V. DISCUSSION

The first performance tests over a 2R1C circuit showed that the AD5933-EBIM could perform continuous impedance measurement for a maximum frequency of 550 Hz and with a magnitude error below 0.26%. The difference between the theoretical and the practical value it could be due to AD5933 specifications where the parameter t_{ZConv} time is not well specified by the manufacturer or the current microcontroller code among other factors. Studies carried out by Schwan [10] suggest that the sampling frequency must be around 1 kHz, but most plethysmography devices uses sampling frequencies around 500 Hz [11, 12].

TABLE II 2R1C MEASUREMENT PERFORMANCE RESULTS
SAMPLING FREQUENCY = 200HZ, MEASUREMENT TIME = 30S

$Z\ F_{measurement}$ (kHz)	Impedance Magnitude			
	Mean (Ω)	STD (Ω)	Error (Ω)	Error (%)
50	66,142	0,037	0,094	0,142
100	57,532	0,010	0,101	0,174
200	47,792	0,018	0,029	0,060
300	44,100	0,006	0,053	0,121
400	42,541	0,009	0,109	0,257

The obtained TEB signal Z_{raw} plotted in Figure 2 exhibited a good performance before any signal processing. In Z_{raw} the cardiac and respiratory components could be observed, also there was a high frequency content due to the AD5933 impedance estimation error among other external factors. The obtained respiratory and cardiac signals displayed good performance, enabling the possibility to be used in applications such as pulmonary flow [13], respiratory volume changes [1] or ICG assessment among others.

VI. CONCLUSIONS

The obtained results suggest that the AD5933-EBIM is suitable for continuous impedance plethysmography applications. These results together with the ability of AD5933-EBIM to perform spectroscopy measurements open new opportunities for several EBI applications where the tissue characterisation and plethysmography applications are required.

The integration of the AD5933-EBIM with measuring garments could allow the development of novel personalised health monitoring applications for patients suffering diseases such as COPD. Complementing the system with a ECG recording with the TEB measurements, and integrating the measuring system into a garment with textile electrodes [14] would be a step forward to wearable ICG monitoring devices.

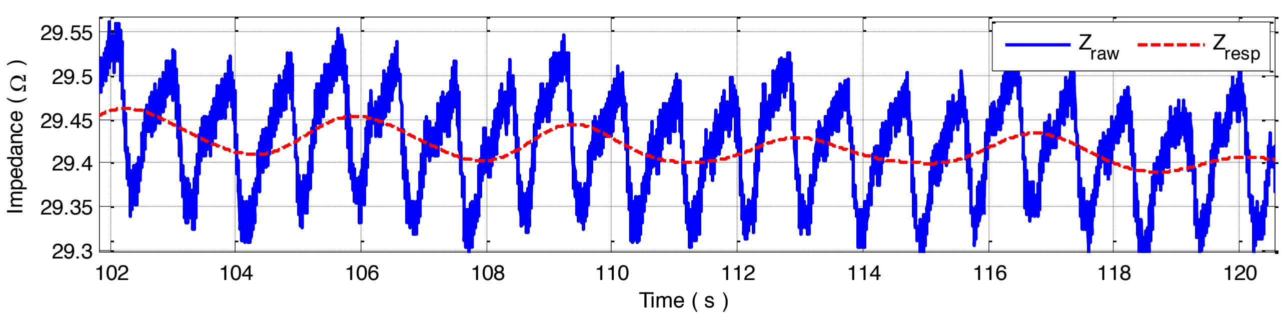

Figure 2 Raw impedance magnitude signal (Z_{raw}) and impedance respiration signal (Z_{resp}).

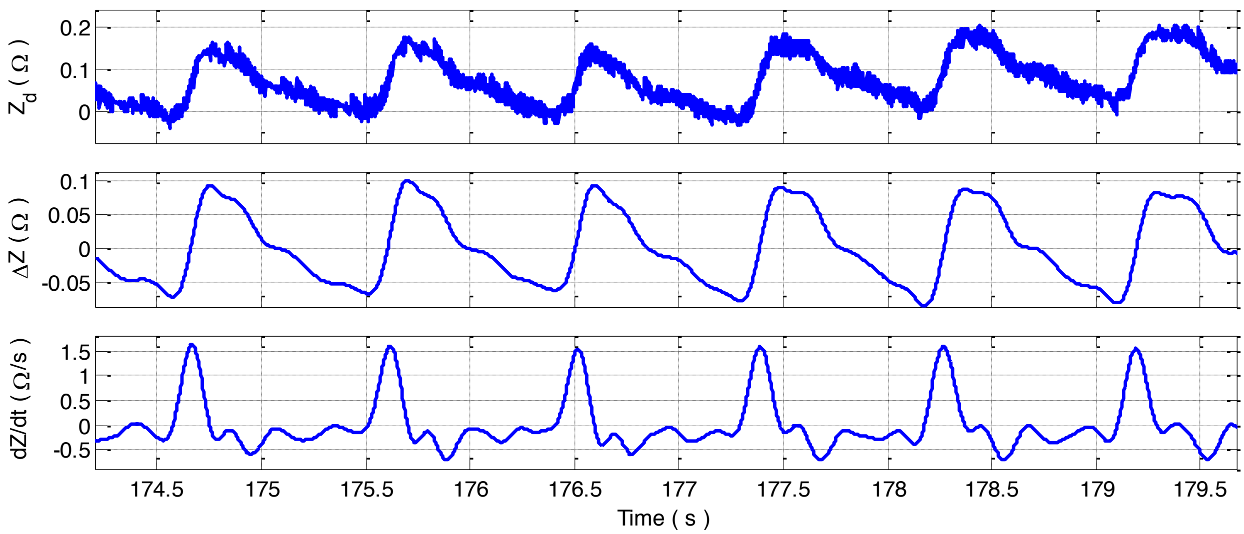

Figure 3 Detrended impedance magnitude (Z_d), filter impedance magnitude (ΔZ) and first derivative (dZ/dt) plots.

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