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Implementation of and Electrical Bioimpedance Measurement System

for Renal Function Monitoring

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ABSTRACT

Peritoneal Dialysis is a treatment for patients suffering from renal failure that allows out-patient care. This means that the patient only needs to visit the hospital for consultation and not for treatment, increasing considerably the comfort of the patient, while reducing remarkably the cost per patient.

In order to increase the level of medical supervision obtained with the periodic visits to the clinic, televisit has been put into practice in some hospitals. But these televisits are based on indirect and qualitative indicators of renal failure, and therefore they are just valid for detection of situations near limit cases, such as well over-hydrated or dehydrated.

Electrical Bioimpedance Measurements have been proved to constitute an appropriate method for assessment of body composition, and therefore they can provide with direct indicators of body fluid distribution. Such ability of EBI technology allows the detection of body fluid unbalance caused by renal dysfunction, and therefore, nephrology televisits would benefit tremendously from EBI measurements.

This project is based on the AD5933 Impedance Network Analyzer of Analog Devices, and the main task is to develop a software application that controls the evaluation board in which it is implemented, and allows the storage of the EBI measurements in EDF+ files that will facilitate the management of medical data when applied to televisit. These files are uploaded to XML format in order to be sent to a remote server, where a software application will have been implemented for medical consultation.

PREFACE

This final degree work has been done in Borås, Sweden, during the course 2007/2008 under the European Exchange Program Socrates in execution of the Erasmus agreement between Högskolan I Borås and Universidad Politécnica de Madrid, and more specifically the agreement between the Institutionen Ingenjörshögskolan and the Escuela Universitaria de Ingeniería Técnica de Telecomunicación.

The project work has been supervised by Dr. Fernando Seoane Martinez.

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Sonia

Borås, 30 Mayo 2008

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LIST OF ACRONYMS

ADC - Analog-to-Digital Converter
AFE - Analog Front-End
DDS - Direct Digital Synthesizer
DES - Data Encryptation Standard
DFT - Discrete Fourier Transform
EBI - Electrical Bioimpedance
EDF - European Data Format
FIPS - Federal Information Processing Standard
SSH - Secure Shell
USB - Universal Serial Bus

CHAPTER 1

INTRODUCTION

1.1 Introduction

This project is based on the implementation of and Electrical Bioimpedance Measurement System for Renal Function Monitoring. This system allows renal failure patients undergoing peritoneal dialysis treatment to carry out their own measurements at home and send them to a remote server for medical consultation.

1.2 Motivation

More than one million people in the World suffer from chronic renal failure and are under dialysis treatment.

Dialysis treatments normally occur three times a week and last a few hours at a time. Most commonly, patients travel to a medical centre to have their treatment, what means a lot of time spent in the medical centre and on the way there, something predictably unpleasant for all patients. To avoid such a waste of time, and what is more important, to increase the quality of life of the patients, home dialysis therapy is becoming an option for some of them.

Peritoneal Dialysis is the alternative treatment to Haemodialysis for patients with renal failure, and allows out-patient care, what means the patient only needs to visit the hospital for consultation. This situation not only increases considerably the comfort of the patient, but also reduces remarkably the cost per patient.

The only drawback is that the mortality rate is slightly higher for patients following peritoneal dialysis than haemodialysis and it has been found that peritoneal dialysis patients show signs of over-hydration. This indicates that the medical supervision obtained with the periodic visits to the clinic does not provide with the same level of healthcare as the one obtained with haemodialysis.

In order to increase the level of medical supervision, televisit has been put into practice in some hospitals. But these televisits are based on indirect and qualitative indicators of renal failure, and therefore are only valid for detection of situations near limit cases, such as well over-hydrated or dehydrated.

Under these circumstances, the implementation of a system based on direct indicators of renal failure seems necessary. It would increase remarkably the amount of valid information available for the nephrologist, providing him this way with a complete monitoring system.

Electrical Bioimpedance Measurements have been proved to be an appropriate method for assessment of body composition, and therefore they can provide with direct indicators of body fluid distribution. Such ability of Electrical Bioimpedance technology allows the detection of body fluid unbalance caused by renal dysfunction and this is why nephrology Televisit would benefit tremendously from Electrical Bioimpedance measurements.

1.3 Goal

The main goal of this project is to provide the patients undergoing peritoneal dialysis with the same level of healthcare as the one obtained with haemodialysis treatment.

The secondary goal is to reduce the costs per patient, since their visits to the medical centre can be reduced.

1.4 Work done

This project implements a software application for an Electrical Bioimpedance Measurement System for Renal Function Monitoring. This software application controls a full-featured evaluation board that has the AD5933 Impedance Network Analyzer of Analog Devices integrated on it. The evaluation board is adapted for biomedical applications through the connexion to an Analog Front-End (AFE) circuit **[1]**.

With this system, patients suffering from renal failure undergoing home peritoneal dialysis treatment can carry out their own measurements at home in a very easy and comfortable way. These measurements, together with another data about the patient, are stored in EDF+ files and sent, under XML format, to a remote server. In the server it has been implemented a software application for medical data consultation.

The software has been developed in Visual Basic .NET and is divided into two parts: the Home Monitoring Application and the Web Server Application. The Home Monitoring Application operates in two modes: Full Control Mode and Wizard Mode. In Full Control Mode the software sets several parameters of the EBI measurements that will run the Wizard Mode. The Wizard Mode guides the patient through the necessary steps to complete the measurements, although it has been done with demonstration purposes only and does not consider the mandatory aspects of Human Factors Engineering and Usability, which are completely out of scope of this project. The Web Server Application allows the medical staff to consult the information sent.

1.5 Structure of the Thesis Report

The thesis report is organised in six different chapters. Chapter 1 is the introduction part of the thesis. Chapter 2 gives a brief background of Bioimpedance Measurement and explains how it is used for monitoring renal function. Chapter 3 describes the materials used, and the methods applied in data storage and in order to get a secure communication. Chapter 4 describes the software application, explaining its two different parts: Home Monitoring Application and Web Server Application. Chapter 5 contains the results obtained, including a discussion. Then in the last Chapter it follows the conclusions and proposed future work. Finally, all the references have been included.

1.6 Out of Scope

In every biomedical application, one of the most important factors is the safety of the patient. The Bioimpedance measurement system implemented in this project introduces an alternating current in the patient’s body during the excitation stage. Therefore, it would be necessary to introduce an isolation block between the electrodes and the measurement system that protected the patient from any damage caused by the electrical injection, specially considering that the system can be connected to the general electric network. But this part of the system has not been implemented in this project.

As it has already been mentioned, The Wizard Mode has been done with demonstration purposes only and does not consider the mandatory aspects of Human Factors Engineering and Usability, which are completely out of scope of this project.

CHAPTER 2

BIOIMPEDANCE MEASUREMENT BACKGROUND AND CLINICAL APPLICATIONS

2.1 Electrical Properties of the Biological Tissue

2.1.1. Antecedents of Electrical Bioimpedance Measurement

The history of Electrical Bioimpedance measurements in biological tissues date back to the end of XVIII century, with the experiments carried out by Galvani **[2].** Electrical Bioimpedance measurements give information about the tissue, as long as the event under analysis presents a change in dimension, in its dielectrical properties or in its conductivity. According to **[3]**, it was not until the beginning of XX century when the structure of biological tissues was studied focusing on their passive electrical properties, what proved that biological tissues are conductors and their impedance changes with frequency.

Basically Electrical Bioimpedance measurements can be classified within two types. One is the study of the Bioimpedance changes over time that are associated to a physiological or pathophysiological process e.g. Impedance cardiography that studies the circulatory system or impedance pneumography that monitors the respiration. The objective of this application is to find qualitative and quantitative information about the changes of impedance produced by composition or structural changes. The second type pursues the determination of characteristics of the body tissues, such as: hydration, oedema, volume of body fluids, intra and extracellular volume, fat percentage, and in general terms, the state of the tissues and the cells composing them.

The instrumentation used in Bioimpedance measurement is very affordable. Besides, it uses a non-ionizing technique that can be applied non-invasively. These facts have encouraged its possible application in several areas. However, this measurement is influenced by many factors, including the geometry, the tissue conductivity and the blood flow, among others **[4].** Using multiple electrodes (typically 16) it is possible to obtain enough conductivity data about the volume to generate images of a body section, what is called Electrical Impedance Tomography or Bioimpedance Tomography, but its spatial resolution is very poor in comparison with other medical imaging modalities currently in use.

Electrical Impedance Spectroscopy is used for the characterization of healthy and pathological tissues based on spectrum of their electrical properties. This approach is very popular nowadays because spectral measurement provides with much more information about the tissue than a single frequency measurement.

2.1.2. Electrical Bioimpedance Definition

The Electrical Impedance of a material is the opposition that the material offers to the flow of electrical charges through it. If the material is of biological origin, then such opposition is called Electrical Bioimpedance.

The impedance (Z) is a complex number defined by Ohm´s law as the ratio between the measured voltage (V) and the total current flow (I).

Due to the nature of tissues, the impedance may vary with the frequency of measuring signal. The impedance will decrease as the frequency increases. The relationship between the impedance and frequency is nonlinear. The higher the frequency, the lower is the impedance.

In the case of a homogeneous and isotropic object, the impedance is a function of its electrical properties (conductivity and permittivity), but also depends on geometric factors determined by the cell factor.

$$Z = k\frac{1}{\sigma + jw\varepsilon_0\varepsilon_r} = k\frac{1}{\sigma^*} = k\rho^* = k(r + jx) = k\left|\rho^*\right|_{phase(\rho^*)} \qquad \textbf{(2.1)}$$

Where:

k = Cell Factor (m-1), σ = electrical conductivity (S/m), j = imaginary symbol,

w = frequency, ε_0 = permittivity of vacuum, ε_r = relative permittivity

Instead of using the complex conductivity $(\sigma^* = \sigma + jw\varepsilon_0\varepsilon_r)$, the complex impedivity can be defined $(\rho^* = r + jx)$. The real part of the impedivity is the resistivity and the imaginary part is the reactivity.

Historically, impedance measurements were expressed as resistivity, due to the small magnitude of the imaginary part, which is not considered. This is a correct approximation, especially at low frequencies (1 kHz or lower). However, at high frequencies the imaginary part increases and the impedivity must be considered as a complex number. As the term impedivity is not commonly used, the term specific impedance and its polar representation ($|Z|$ magnitude and Φ phase angle) will be used. The previous equations are only valid in the case of a homogeneous and isotropic object.

2.1.3. Electrical properties of Biological Tissues

Living organisms are composed by cells. Therefore, the cell is defined as the fundamental unit of life. Most cells are joined to each other by means of an extracellular matrix or by direct adhesion of one cell to the other constituting different unities. These cell associations give rise to the tissues.

The main component of the cells is their cellular membrane, the structure of which is based on a lipid double layer in which proteins are distributed, allowing the formation of channels to exchange ions with the exterior, *Figure 2.1*. Due to its molecular components, the cellular membrane acts as a dielectric interface and can be considered as the two plates of a capacitor.

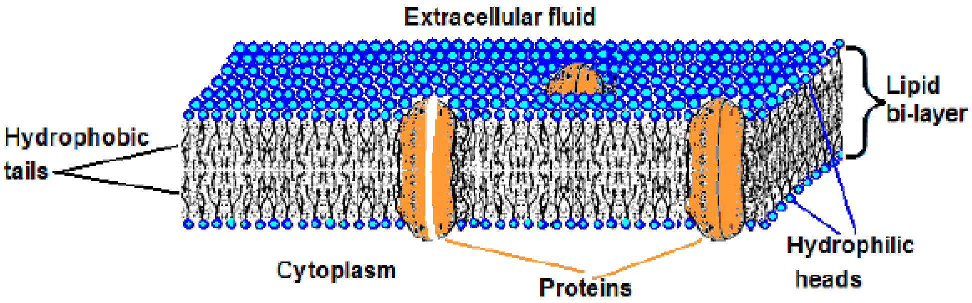


Fig.2.1 Cellular membrane diagram

Therefore, when a constant electric field is applied, the electrically charged ions move and accumulate in both sides of the membrane. However, when the field is alternating, an alternating movement of electrons appears at both sides of the cellular wall, producing a relaxation phenomenon.

The dielectric relaxation phenomenon in the tissues is the result of the polarization of several dipoles and the movement of the charges that induce a permittivity and conductivity phenomenon. The charge carriers are mainly ions and the main source of dipoles are the water polar molecules in the tissues.

The electrical behaviour of biological tissues reveals a dependency of the dielectric parameters with the current frequency, due to the different relaxation phenomena that take place when the current flows through the tissue.

When the frequency of the applied electric field increases, the conductivity of most of the tissues rises from a low value in direct current, which depends on the extracellular volume, to a constant level that keeps between 10 and 100 MHz.

This increase in conductivity is associated to a decrease in permittivity, from a high value at low frequency, in four relaxation windows: α, β, δ and γ, as it is shown in *Figure 2.2*. Each of these steps characterizes a type of relaxation that occurs in a specific frequency range and is characteristic for each tissue.

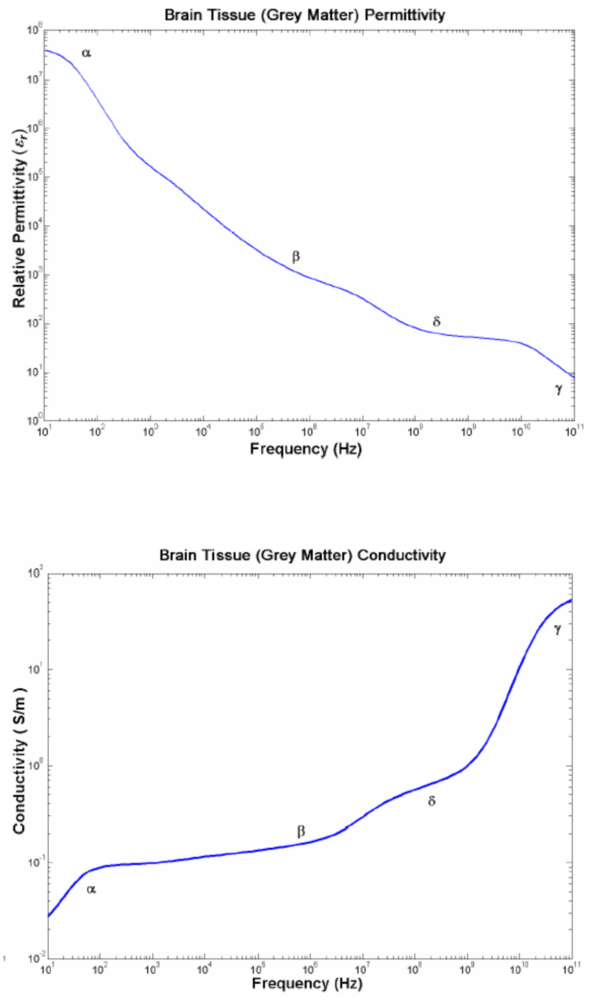


Fig.2.2 Ideal representation of permittivity and conductivity in brain tissue (grey matter) as a function of the frequency

2.2 Types of Bioimpedance Measurements

2.2.1 Electrode Systems

Electrodes are essential elements in the Bioimpedance measurements. They are an interface between the electronic current in the measurement system and the ionic current in the biological tissue. This discontinuity in the media is resolved by means of movement of electrons in the metallic part of the electrodes and oxidation-reduction reactions in the ionic part of the electrode.

2.2.2 Electrode Impedance

The electrode impedance can be modelled by the combination of a resistance (R) and a reactance (X) in series, the value of which decreases when frequency increases.

$$Z_e = R - jX \quad \textbf{(2.2)}$$

This impedance is commonly called polarization impedance, and even though the electrode impedance parameters can be identified, a model with accurate values can not be determined.

2.2.3 Different Electrode Measuring Methods

There are two very common measurement methods in EBI: 2-Electrode Method or bipolar method and 4-Electrode Method or tetrapolar method. A variant of these two methods is the 3-Electrode Method. Each of them is described next.

2.2.3.1 Two Electrode Method

In this method, an electrical current (I_0) is forced into the tissue through two electrodes, which present an impedance (Z_e), the value of which is usually higher than the impedance under analysis (the one of the tissue between the electrodes), *Figure 2.3*. The voltage detector is connected to the tissue through the same injecting electrodes thus the voltage that appears between them (V_0) contains the voltage drop caused by the Ze. Therefore, the measured impedance is:

$$Z = \frac{V_0}{I_0} = Z_{e1} + Z_{e2} + Z_x \quad \textbf{(2.3)}$$

If the electrodes have the same characteristics, then:

$$Z_{e1} = Z_{e2} \quad \textbf{(2.4)}$$

And therefore, the measured impedance is:

$$Z = \frac{V_0}{I_0} = 2Z_e + Z_x \quad \textbf{(2.5)}$$

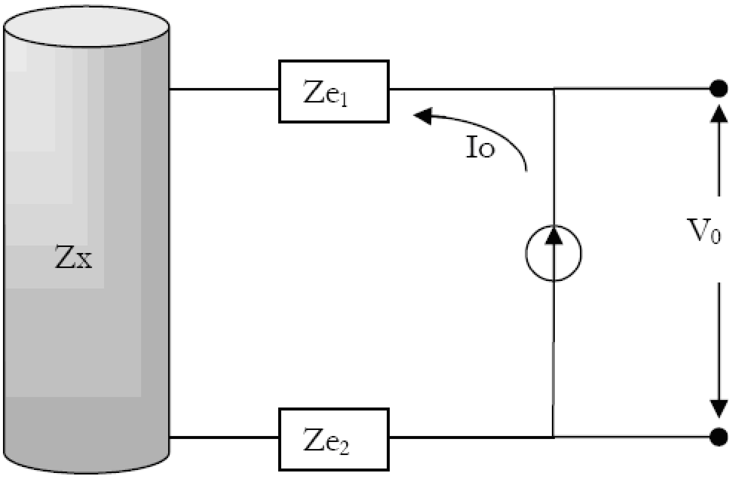


Fig.2.3 Two Electrode Method

When carrying out measurements with superficial electrodes (Skin Surface electrodes) it must be considered that the skin impedance (Z_p) is in series with the electrode impedance (Z_e). That gives rise to an electrode-skin contact impedance (Z_{ep}) much higher than the tissue impedance, *Figure 2.4.*

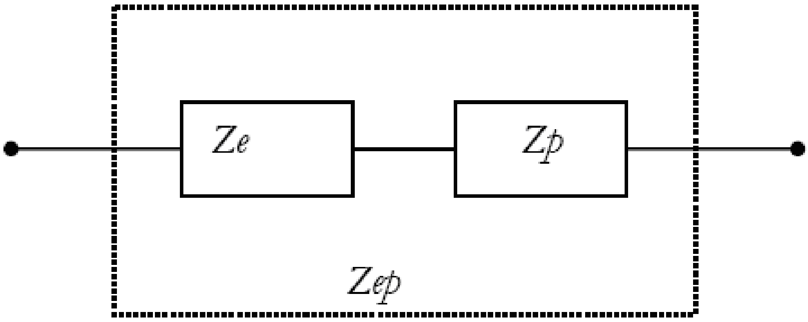


Fig.2.4 Diagram of the contact impedance (Z_{ep}) in superficial measurements

In the frequency range of β-dispersion, the typical value of the skin impedance (Z_p) can be between two and ten times the value of the tissue under analysis **[5].** Then in order to obtain values of electrical impedance that can be used to provide with information about the tissue, the contribution of the skin impedance must be removed. This is done using the 4-Electrode Method.

2.2.3.2 Four Electrode Method

This method consists on applying a current (I_0) through two electrodes and detecting the voltage between other two different electrodes, *Figure 2.5.*

With this method, the impedance of the electrodes is eliminated from the impedance measurement. This is true as long as the electrodes have relative low impedance compared to the input impedance of the voltage detector circuit. In the case of superficial measurements, the skin impedance is also reduced, because it is in series with each electrode.

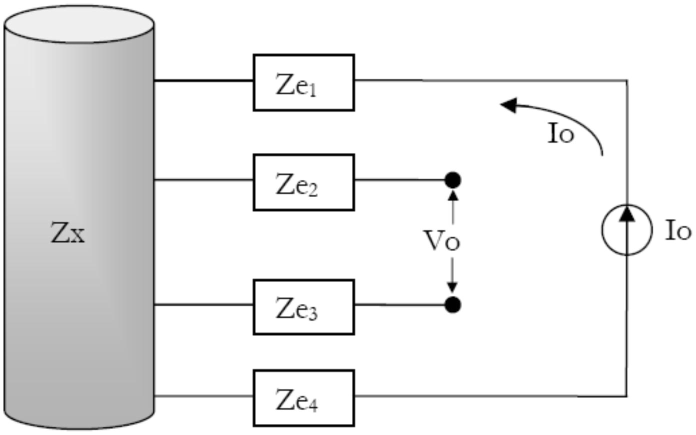


Fig.2.5 Four Electrode Method

2.2.3.3 Three Electrode Method

This method consists on applying a current (I_0) through two electrodes: a current injector electrode (Z_{e1}) and a reference electrode (Z_{e2}). This current flows through the tissue. The voltage (V_0) is detected between a third electrode (Z_{e3}) and the reference electrode (Z_{e2}), *Figure 2.6*.

The voltage measured (V_0) corresponds to the potential difference caused by the current applied to the impedance under analysis (Z_x) and the second electrode (Z_{e2}).

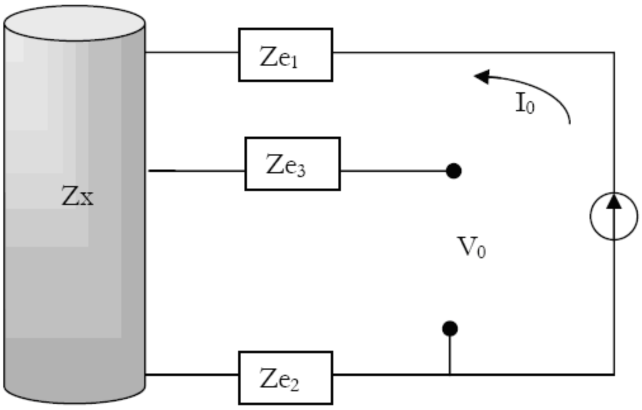


Fig.2.6 Three Electrode Method

Since the 3 Electrode Method is sensitive to the second electrode impedance (Z_{e2}) and to the impedance of the skin under this electrode, it has been used to measure the skin moisturizing**,** in the characterization of electrodes and in the calibration of electrical impedance systems**.**

2.3 Electrical Bioimpedance and Oedema

Electrical Bioimpedance measurements have been used for many years to study the electrical properties of biologic tissue and to measure physiological events, being applied in several clinical areas, including body composition. The assessment of oedema formation from EBI measurements is based on the dependency of the electrical properties of tissue on its structure and intrinsic constituents, i.e. alterations in the tissue structure produce a modification of its electrical properties.

When the renal function is impaired in the kidneys, an immediate physiological consequence is an excessive accumulation of liquid in the rest of the body, and consequently oedema is formed. Oedema is considered by the physician a common indicator of renal failure, and therefore visual inspection by the physician is a regular practice to detect such kidney function impairment. Such an inspection is usually performed targeting the limbs, legs and arms, targeting the inspection for peripheral oedema.

There are several methods of assessing extracellular swelling, and the EBI measurement approach is one of the more comfortable ones, due to the fact that the electrical properties of tissue can be measured non-invasively and without tightening the skin**.** Some studies about the excess of fluid in chronic HD patients, using Bioimpedance spectroscopy measurements, where performed. The experimental results suggested that HD patients keep their excess fluid volume primarily in the extracellular compartment (interstitial fluid). Bioimpedance spectroscopy together with a stable measurement of lean tissue can determine the degree of relative excess hydration. Due to the capacitance effects of the cell membrane, the tissue impedance depends on the measurement frequency. As a consequence, the accuracy of measurements by means of multiple frequency Bioimpedance spectroscopy analysis is superior to the accuracy of measurements based on a single frequency for the prediction of extracellular water. Some authors suggest that the best frequency range to assess extra-cellular fluid is up to 10 kHz and the range between 50-100 kHz is a suitable measurement range for a successful assessment of extra- and intra-cellular fluid.

Concluding, the monitoring principle of the EBI measurement system implemented in this thesis work lays as follows: during renal failure the amount of interstitial fluid in the limbs increases, causing extracellular oedema. The consequent interstitial swelling modifies the electrical properties of the tissue, and by means of the combination of non-invasive EBI measurements with skin-surface electrodes and EBI spectroscopy analysis, the ongoing swelling can be detected. Therefore changes in the EBI of the limbs may be used as an efficient indicator for early detection of renal failure.

CHAPTER 3

MATERIALS USED AND METHODS APPLIED

3.1. Evaluation Board for the Impedance Converter Network Analyzer AD5933

The hardware of this project is an EBI spectrometer based on the AD5933 Impedance Converter Network Analyzer. This hardware was developed in a previous thesis work by Ferreira and Sanchez **[6].** The base of the software application is the software for the evaluation board of the AD5933 circuit developed by Analog Devices to interface. The evaluation board functional block diagram is shown in *Figure 3.1*.

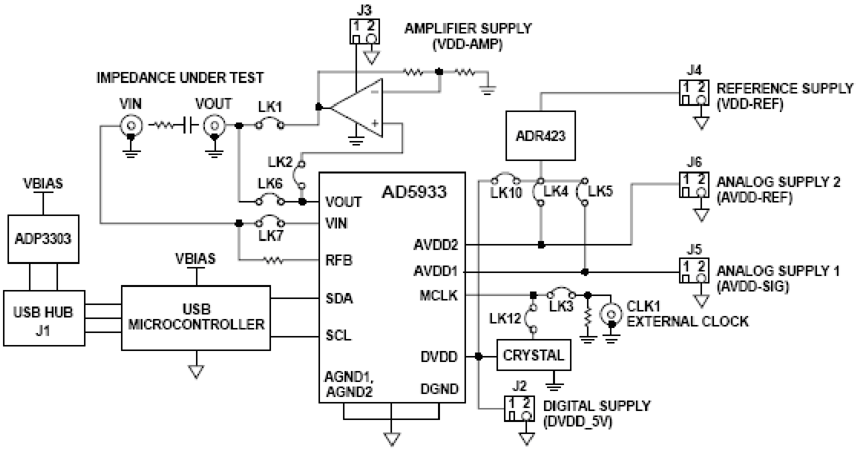


Figure 3.1. AD5933 Evaluation Board Block Diagram

The AD5933 circuit is a high precision impedance converter system that combines an on-board frequency generator with a 12-bit, 1 MSPS analog-to-digital converter (ADC). Its functional block diagram is shown in *Figure 3.2*.

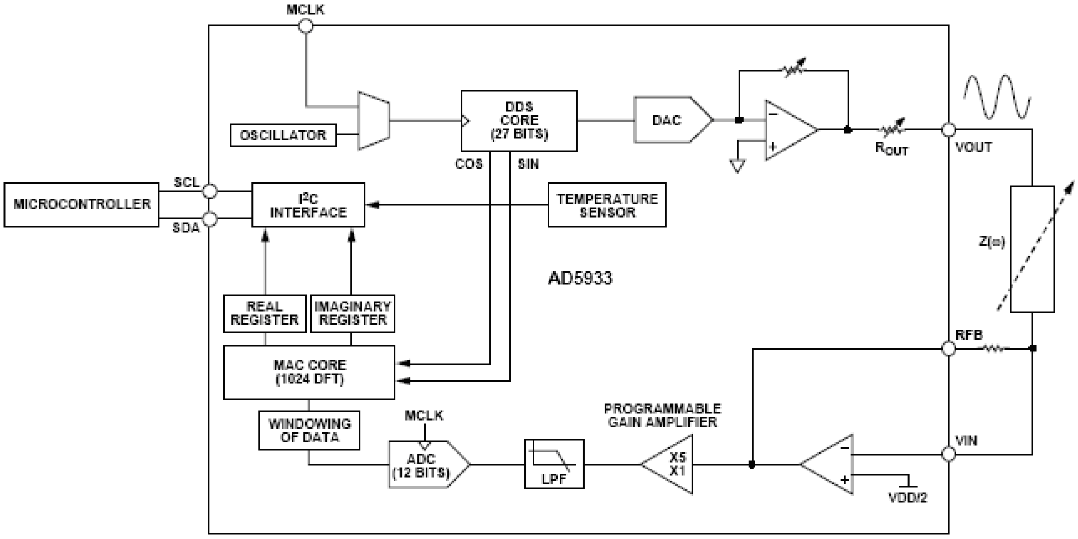


Fig.3.2. AD5933 Block Overview

The frequency generator allows an external impedance load to be excited with a known frequency. The response signal from the impedance is sampled by the on-board ADC, and a discrete Fourier transform (DFT) is processed by an on-board DSP engine. The DFT algorithm returns a real (R) and imaginary (I) data-word at each output frequency. The magnitude and relative phase of the impedance at each frequency point along the sweep are calculated using these coefficient pairs.

The AD5933 circuit permits the user to perform a frequency sweep with a user-defined start frequency, frequency resolution, and number of points in the sweep. In addition, the device allows the user to program the peak-to-peak value of the output sinusoidal signal as an excitation to the external unknown impedance connected between the VOUT and VIN pins.

The excitation signal for the transmit stage is provided on-chip using Direct Digital Synthesizer (DDS) techniques which permit subhertz resolution. The AD5933 Analyzer offers a frequency resolution programmable by the user down to 0.1 Hz. As a response to the voltage excitation, certain current flows through the load. This current will be sensed at the receive stage and its value will be used to estimate the impedance value. The clock for the DDS is generated from either an external reference clock which is provided by the user at MCLK or by the internal oscillator.

The AD5933 Analyzer also contains an internal temperature sensor with 13-bit resolution and operates from a 2.7 V to 5.5 V supply.

The user can power the entire circuitry from the Universal Serial Bus (USB) port of a computer.

Interfacing to the AD5933 circuit is through a USB microcontroller, which generates the I2C signals necessary to communicate with the AD5933 circuit. The user interfaces to the USB microcontroller through a Visual Basic® graphic user interface located on and run from the user PC. *Figure 3.3* shows a picture of the Evaluation Board for the Impedance Converter Network Analyzer AD5933.

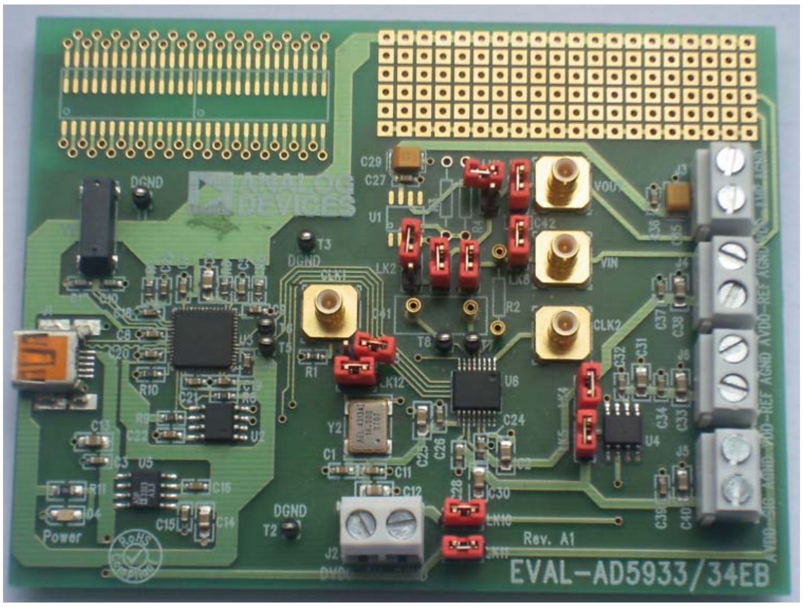


Fig. 3.3. Evaluation Board for the Impedance Converter Network Analyzer AD5933

The evaluation board is connected to an Analog Front-End (AFE) circuit **[1]**. It has a double finality: ensuring that the safety conditions for the patients are fulfilled, what means that the electrical signals are below any safety threshold and no DC current is introduced in the body; and adapting the AD5933 operation from a 2-electrode measurement system to a 4-electrode measurement system, so that the system can be used in applications of spectral characterization. The patient is connected to this front-end through the electrodes.

Figure 3.4 shows a picture of the whole measurement system. An important aspect to take into account in order to implement a system that fulfils all the security conditions for the patient is the power supply. The power source must be decoupled from the general electric network in order to avoid possible electrical shocks on the patient. As the system is fed with the voltage provided through the USB port of the evaluation board, the electrical decoupled depends on the device connected to the evaluation board. Considering that the power source of the system is a computer, it should be used a laptop disconnected from the network, working with its battery supply.

Fig.3.4 Bioimpedance Measurement System for Renal Function Monitoring

3.2. Standardization in data storage: EDF files

In order to interpret unequivocally the data from the measurements of the patients, it is necessary to store them following a certain standard, a standard that has to be known by the whole medical community. Therefore, the personal data of each patient, together with the Bioimpedance measurement data are stored under the EDF+ standard.

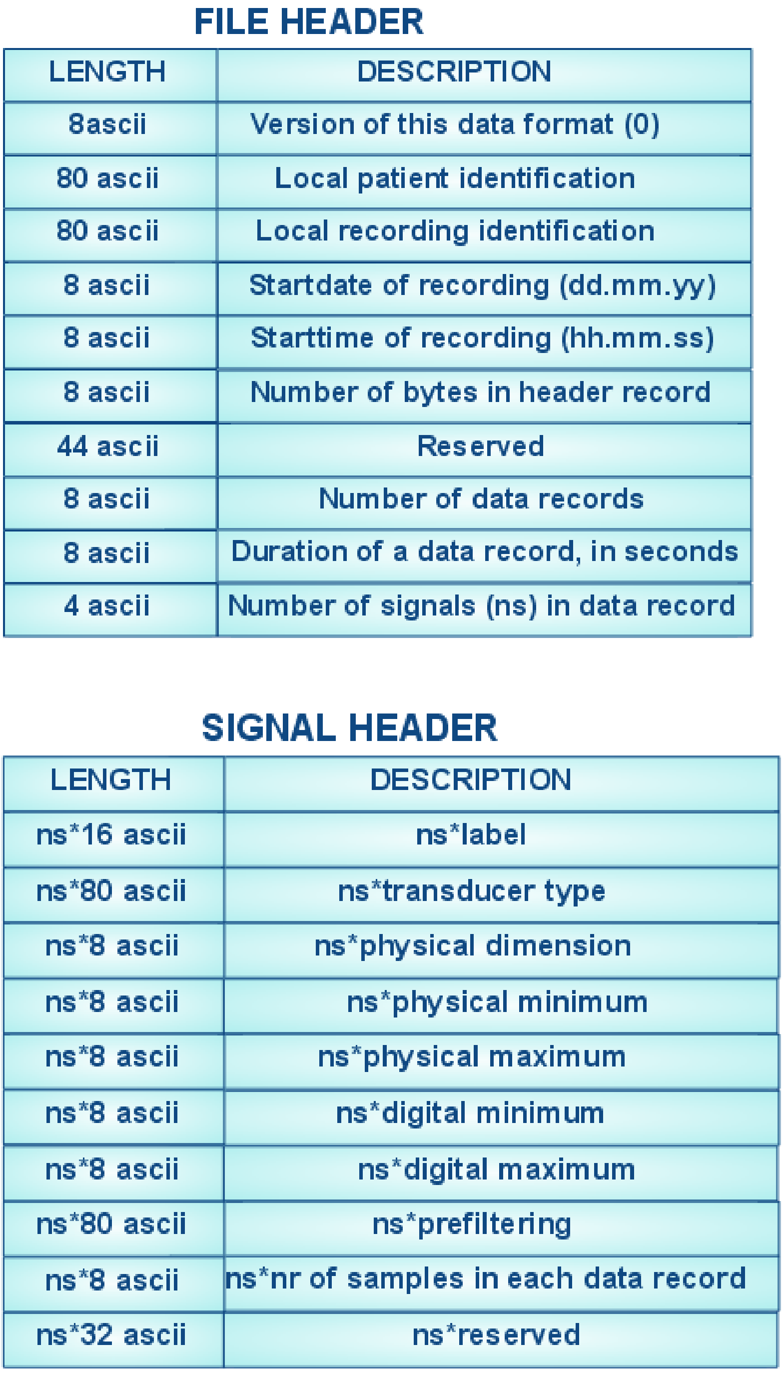
The European Data Format (EDF) is a simple and flexible format for exchange and storage of multichannel biological and physical signals. It was developed in Leiden in April 1990 by a few European 'medical' engineers who were working with sleep analysis algorithms. And extension of EDF, named EDF+, was developed in 2002 and is largely compatible to EDF. But EDF+ files can also contain interrupted recordings, annotations, stimuli and events. Therefore, EDF+ can store any medical recording such as EMG, Evoked potentials, ECG, as well as automatic and manual analysis results such as deltaplots, QRS parameters and sleep stages. The medical recording in this case is the Electrical Bioimpedance measurement.

The EDF+ file is stored in ASCII and has a header record, which is divided into two headers:

- The file header: it contains ten different fields with the version of the format, the patient identification, the recording identification, starttime of the recording, number of bytes in the header, and information about the data records. In this case, there is just one data record.

- The signal header: there is one for each of the signals in the data record. It also has ten fields with information about the type of transducer used, the physical dimension, the minimum and maximum values obtained in the measurement, the pre filter used and the number of samples in the data record.

The value of each signal obtained in the measurement is stored just after the last field of its corresponding signal header, in the field data record. All the fields of the EDF+ file headers, with their lengths, are explained in detail in the *Figure 3.5*.



FILE HEADER

LENGTH	DESCRIPTION
8ascii	Version of this data format (0)
80 ascii	Local patient identification
80 ascii	Local recording identification
8 ascii	Startdate of recording (dd.mm.yy)
8 ascii	Starttime of recording (hh.mm.ss)
8 ascii	Number of bytes in header record
44 ascii	Reserved
8 ascii	Number of data records
8 ascii	Duration of a data record, in seconds
4 ascii	Number of signals (ns) in data record

SIGNAL HEADER

LENGTH	DESCRIPTION
ns*16 ascii	ns*label
ns*80 ascii	ns*transducer type
ns*8 ascii	ns*physical dimension
ns*8 ascii	ns*physical minimum
ns*8 ascii	ns*physical maximum
ns*8 ascii	ns*digital minimum
ns*8 ascii	ns*digital maximum
ns*80 ascii	ns*prefiltering
ns*8 ascii	ns*nr of samples in each data record
ns*32 ascii	ns*reserved

Fig.3.5 Header record in a EDF+ file

In order to analyze the EBI data with any of the methods for Body composition, the EDF+ files should contain personal data and the height, race, age and sex of the patient. Therefore the sex and the date of birthday are stored in the Local patient identification field, as the EDF+ standard states. The height and race of the patient are stored in the field Reserved on the file header.

The EDF+ file is encrypted for local storage, and encapsulated under the XML format to be uploaded to the remote server.

3.3 Communication security

EDF+ files contain personal data of the patients, together with the results of their Bioimpedance measurements. According to privacy laws about clinical data, confidentiality has to be kept all over the process, since the EDF+ files are stored in the local machine. In order to have a secure communication, the communication is done through a Secure Shell (SSH) channel.

3.3.1 Data Encryptation Standard (DES)

Data Encryption Standard (DES) is a cipher, and it is the method used to encrypt the EDF+ files. DES is a wide spread method for encrypting information, selected as an official Federal Information Processing Standard (FIPS) for the United States since 1976.

DES is an archetypal block cipher, an algorithm that takes a fixed-length string of plaintext bits and transforms it through a series of complicated operations into another ciphertext bitstring of the same length. In the case of DES, the block size is 64 bits. DES also uses a key to customize the transformation, so that decryption can supposedly only be performed by those who know the particular key used to encrypt. The key ostensibly consists of 64 bits; however, only 56 of these are actually used by the algorithm. Eight bits are used solely for checking parity, and are thereafter discarded. Hence the effective key length is 56 bits, and it is usually quoted as such.

The algorithm's overall structure is shown in Figure 3.6. There are 16 identical stages of processing, termed rounds. Before the main rounds, the block is divided into two 32-bit halves and processed alternately; this criss-crossing is known as the Feistel scheme. The Festal structure ensures that decryption and encryption are very similar processes. The only difference is that the subkeys are applied in the reverse order when decrypting. The rest of the algorithm is identical. This greatly simplifies implementation, particularly in hardware, as there is no need for separate encryption and decryption algorithms.

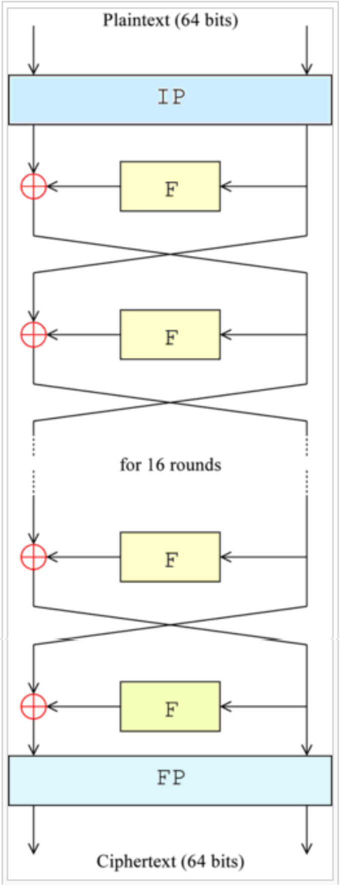


Fig.3.6. Feistel Structure of DES

The red + symbol denotes the exclusive-OR (XOR) operation. The F-function scrambles half a block together with some of the key. The output from the F-function is then combined with the other half of the block, and the halves are swapped before the next round. After the final round, the halves are not swapped; this is a feature of the Feistel structure which makes encryption and decryption similar processes.

3.3.2 Secure Shell (SSH)

To implement a secure communication, the client and server applications must encrypt and decrypt the data with a common key only known by them. The protocol used to implement the secure communication is Secure Shell or SSH protocol. It is a network protocol that allows data to be exchanged over a secure channel between two computers. With this protocol, XML files are encrypted just before sending them to the remote server; and decrypted once they arrive there.

The major features of the SSH protocol are:

- Privacy of the data, via strong encryption
- Integrity of communications, guaranteeing they haven't been altered
- Authentication, i.e., proof of identity of senders and receivers
- Authorization, i.e., access control to accounts

Forwarding or tunnelling to encrypt other TCP/IP-based sessions

SSH uses public-key cryptography to authenticate the remote computer and allow the remote computer to authenticate the user, if necessary. SSH is typically used to log into a remote machine and execute commands, but it also supports tunnelling, forwarding arbitrary TCP ports and X11 connections. It can transfer files using the associated SFTP or SCP protocols.

An SSH server, by default, listens on the standard TCP port 22. A SSH client program is typically used for establishing connections to an SSHD daemon accepting remote connections. Both are commonly implemented on most modern operating systems, including Mac OS X, Linux, FreeBSD, Solaris and OpenVMS. Proprietary, freeware and open source versions of various levels of complexity and completeness exist.

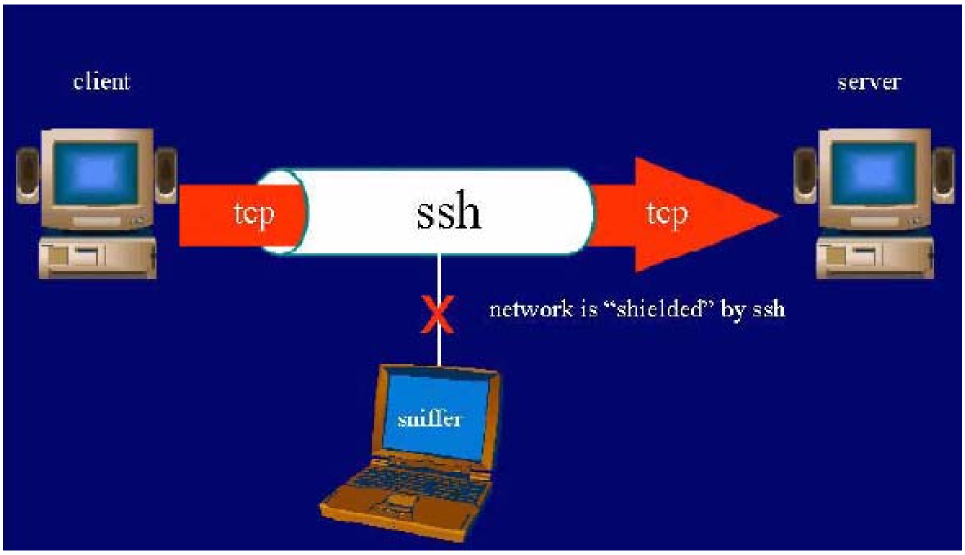


Fig.3.7 SSH Security System

CHAPTER 4

SOFTWARE APPLICATION

4.1 Introduction

The software application implemented in this thesis work is based on the core of the software for the evaluation board for the AD5933 circuit. In order to adapt the code to the project specifications, some functionalities were added, and some existing ones were deleted or modified.

The original code had been written using Visual Basic 6.0, and the idea was implementing the new software application in Visual Studio.NET. The reason was a matter of compatibility with new applications: new applications are not developed in Visual Basic 6.0 anymore, and the new application is intended to be compatible with any possible new application.

So the first step was updating the original code to .NET. First, it was done with Microsoft Visual Basic 2005 Express edition. Just as expected, there were many errors in the conversion obtained with the automatic migration. All of them could be solved pretty easily except one of them. It was related to the communication between the computer and the evaluation board through the USB port. This version of Microsoft Visual Basic 2005 can not be used in a communication through USB port. So this version had to be changed to Microsoft Visual Basic 2005 Full edition. Finally, the application could be implemented successfully with this programme.

4.2 Basis of operation

Over this section it will be explained the operation of the AD5933 Impedance Converter Network Analyzer and the way the original software from Analog Devices operates with it in order to perform the measurements. It will also be explained the changes that the Analog Front-End added in the system has caused in the original software.

4.2.1 Frequency Sweep

The impedance spectroscopy measurement is done frequency by frequency. *Figure 4.1* shows the operation flow of the impedance sweep performed by the AD5933 Impedance Converter Network Analyzer.

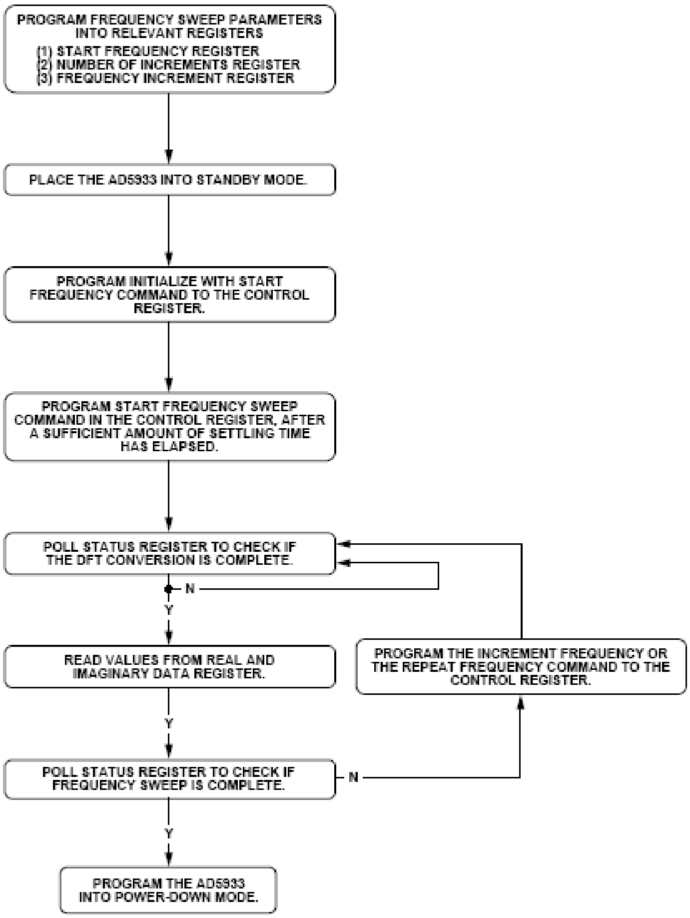


Fig.4.1 Frequency Sweep Flow Chart

4.2.2 Impedance Estimation Procedure

For the impedance estimation, the AD5933 Analyzer performs a Discrete Fourier Transform (DFT) over the sampled current signals and the reference sinusoidal signals from the DDS on the DSP core. The DSP calculates a 1024 points- DTF transform for each frequency point contained in the frequency sweep, obtaining the real and imaginary components. Since the sinusoidal signals from the DDS represent the voltage applied on the load and the sampled signals represent the corresponding current to such a voltage excitation, the impedance can be directly estimated by applying Ohm’s law in the frequency domain:

$$\frac{V(\omega)}{I(\omega)} = Z(\omega) = \frac{1}{Y(\omega)} = \frac{V_{out}(\omega) - V_{in}(\omega)}{I_{load}(\omega)} \tag{4.1}$$

Notice that with such a current measurement it has been used the 2-Electrode method, what means that the estimated impedance corresponds to the load between the exciting leads.

Finally, the DFT transform provides with the Fourier coefficients of the relationship between the voltage signal controlling the excitation and the current signal through the load. From each pair of Fourier coefficients, the magnitude and phase can be calculated at each frequency point. It is doing using the following equations:

$$Magnitude = \sqrt{R^2 + I^2} \tag{4.2}$$

$$Phase = Tan^{-1}(I / R) \tag{4.3}$$

The magnitude represents the ratio between the voltage generated by the DDS and the current through the load, and the phase the time delay between both signals.

4.2.3 Calibration

The calibration process is a mechanism applied on the impedance measurement process to compensate for systematic errors caused by the electronic components in the injection and measurement channels, i.e. time delays, attenuation, differences between the frequency response of the measurement channels, etc.

In the AD5933 circuit, the voltage signal used as a reference is transmitted to the DSP straight from the DDS, while the exciting voltage applied on the load, and true responsible for the current flow through the load, is the signal at the Vout output. Such pin is after a DAC converter and a voltage buffer and it is most likely that from the DDS to the Vout pin the signal has suffered certain delay scaling. Therefore the signals used as reference in the DSP core are not exactly representing the value of Vout. If the DSP did not consider this situation, the impedance calculation would have a systematic error due to the scaling and phase shifting that occur in the electronics building the exciting stage.

In order to obtain the correct impedance value, this scaling and delay must be compensated and removed from the final calculation. The AD5933 Analyzer does it by a calibration process. The AD5933 circuit allows two different calibration modes: Single Frequency Point calibration mode and Multi Frequency Point calibration mode.

4.2.3.1 Single Frequency Point Calibration

In this calibration process, a load with a known impedance value is placed between the exciting leads. The AD5933 Impedance Network Analyzer chooses the frequency value that is just at the middle point of the measurement frequency range as the single calibration frequency. Then a voltage signal excites the calibration load, and the corresponding current is sensed. This way, the calibration impedance value can be estimated. Since the calibration impedance is known, it can be calculated a calibration factor in order to compensate the difference between the estimated impedance and the real calibration impedance value. This calibration factor is represented by two Fourier complex components, representing a scaling and a phase adjustment, and is denominated Gain Factor. Further impedance measurement over unknown loads will be corrected with this factor in order to obtain their correct values.

4.2.3.2 Multi Frequency Point Calibration

In this mode the calibration process is done in the same manner as in the previous mode, but with one exception. The excitation is done at every single frequency point contained in the spectroscopy measurement. This way the Gain Factor is calculated at each frequency.

In both modes the Gain Factor is obtained using the following equation:

$$GAIN\ FACTOR = \frac{CALIBRATION\_ADMITTANCE}{Calibration\_Magnitude} \qquad \textbf{(4.4)}$$

And the measured impedance is shown by the next equation:

$$UNKNOWN\_IMPEDANCE = \frac{1}{GAIN\ FACTOR \times Unknown\_Magnitude} \qquad \textbf{(4.5)}$$

The Analog Front-End adds electronic components at the output of the Impedance Network Analyzer in both the injection channel and the measurement channel. This extra electronic stage introduces more systematic errors, but fortunately the calibration through the Gain Factor calculation also compensates for them.

Since the scaling and delay produced by the DAC and the buffer are frequency dependent and the Single Frequency Point calibration only calculates the Gain Factor at one frequency, this calibration mode only performs an appropriate compensation at the calibration frequency. For a proper compensation in a multifrequency measurement, the calibration prior the measurement must be done using the Multi Frequency Point calibration mode. Furthermore, considering the nature of the electronics in the Analog Front-End, i.e. active components with non ideal frequency response, the decision taken was ruling out the Single Frequency Point calibration mode from the measurements, and not including this option in the new software application.

4.2.4 Changes introduced by the Analog Front-End circuit

The Analog Front-End circuit introduces new elements in the impedance network that influence the impedance calculation method implemented by the Impedance Network Analyzer. The software provided by Analog Devices to process the impedance measurements must be adapted to the new operation conditions. The mentioned differences between the calculation process used with the AFE (four-electrode technique) and the one used with the original configuration (two-electrode technique) are explained in the following lines:

The DSP core provides Fourier components of the injecting signal and the measured signal to evaluate the unknown load. With the original configuration Xreference is the applied voltage and Xmeasured is the resulting current. And the ratio between them provides the impedance value according to Ohm’s Law:

$$X(f) = \frac{X_{reference}}{X_{measured}} = \frac{V_{out}}{I_{load}} = Z(f)\,[\Omega] \qquad \textbf{(4.6)}$$

Z(f) is the data provided by the Impedance Network Analyzer to the Host-PC.

But the AFE modifies such relationship. Now Xreference refers to the injected current into the load provided by the voltage to current converter while Xmeasured refers to the resulting voltage drop in the load sensed by the instrumentation amplifier in the AFE. Since the function of the DSP core in the Impedance Network Analyzer can not be modified, the impedance estimation implementation with the AFE changes to

$$X_{reference} = I_{load} \times R_{current\ source} \qquad X_{measured} = \frac{V_{load}}{R_{out\ front-end}} \tag{4.7}$$

Obtaining:

$$X(f) = \frac{X_{reference}}{X_{measured}} = \frac{I_{load} \times R_{current\ source}}{V_{load} / R_{out\ front-end}} = \frac{I_{load}}{V_{load}} \times R_{current\ source} \times R_{out\ front-end}$$

$$X(f) = Y_{load} \times R_{current\ source} \times R_{out\ front-end}\ [\Omega] \tag{4.8}$$

Where the units continue being Ohms corresponding to impedance, but *X(f)* corresponds to the admittance value of the load instead. This change forced to modify the software provided by Analog Devices in order to process correctly the coefficients provided by the Impedance Network Analyzer and this way obtain the correct impedance value of the load.

The original software executed the following two actions in order to calculate the Impedance under measurement:

$$GAIN\ FACTOR = \frac{CALIBRATION\_ADMITTANCE}{Calibration\_Magnitude} \tag{4.9}$$

$$UNKNOWN\_IMPEDANCE = \frac{1}{GAIN\ FACTOR \times Unknown\_Magnitude} \tag{4.10}$$

Now, the calculation method with the Front-End is:

$$GAIN\ FACTOR = \frac{1}{CALIBRATION\_ADMITANCE \times Calibration\_Magnitude} \tag{4.11}$$

$$UNKNOWN\_IMPEDANCE = GAIN\ FACTOR \times Unknown\_Magnitude \tag{4.12}$$

So this characteristic has been taken into account in the software application when treating the real and imaginary values obtained from the DFT transform.

4.3 Software Application for Renal Function Monitoring

The new software application is divided into two parts: the Home Monitoring Application and the Web Server Application. With the Home Monitoring Application, patients can carry out their own Bioimpedance measurements at home. The results obtained, together with some personal data about the patient, are stored in EDF+ files and sent, under XML format, to a remote server, where all the files are stored.

The Home Monitoring Application operates in two different modes: Full Control Mode and Wizard Mode. In Full Control Mode the software sets several parameters of the EBI measurement that will run the Wizard Mode. The Wizard Mode guides the patient through the necessary steps to complete the measurements.

In the web server, it has been implemented a Web Server Application where XML files can be read by medical staff. *Figure 4.2* shows the whole software application architecture.

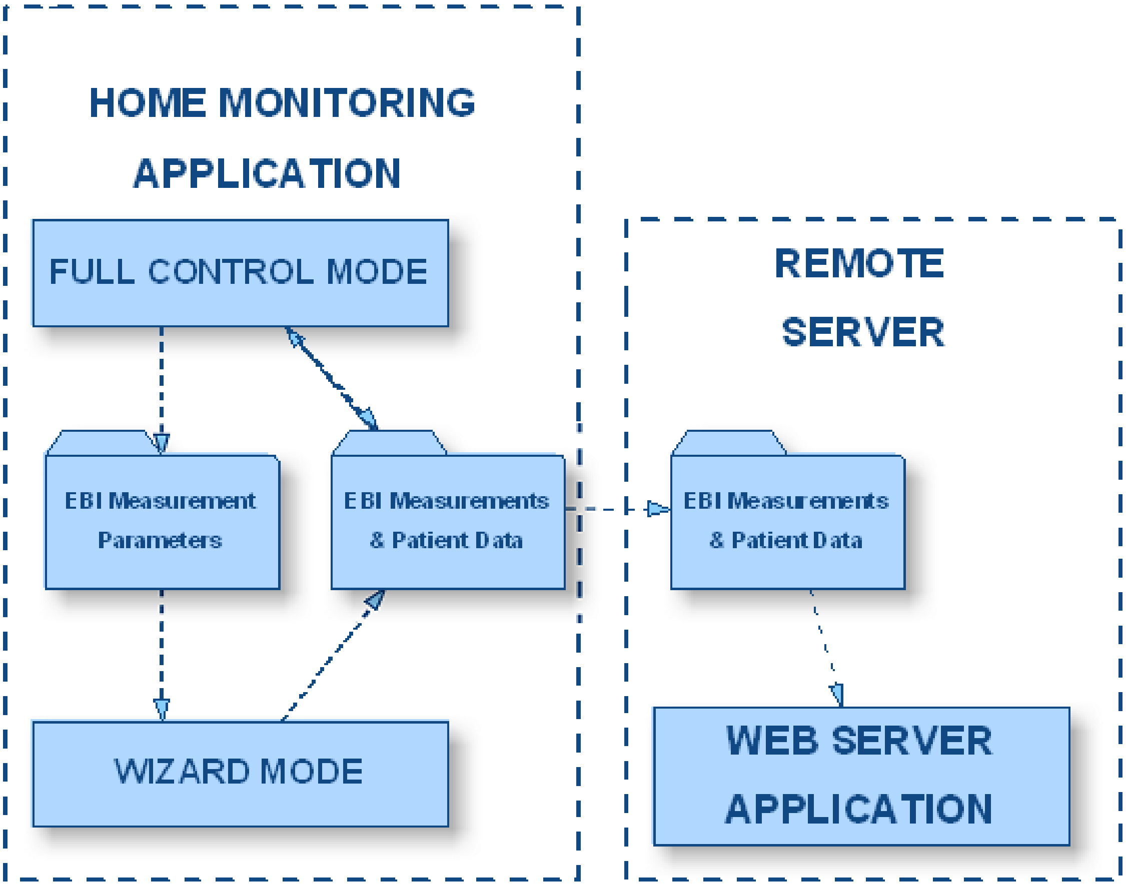


Fig.4.2 Software Application Architecture

4.3.1 Home Monitoring Application

As it has already been mentioned, the Home Monitoring Application is divided into two different parts: Full Control Mode and Wizard Mode. Both of them will be explained over this section.

4.3.1.1 Full Control Mode

In Full Control Mode, the software provides the functionalities of Bioimpedance measurement, data visualization and data file management. This last one includes storing the information in EDF+ files and displaying these files, and creating XML files and sending them to the remote server. In this mode, a script with several parameters of the EBI measurement is generated. These parameters are introduced by the user, and will run the Wizard Mode later.

Full Control Mode is aimed at a medical technician who would set the EBI parameters just once, and then the patient would use the Wizard Mode on his own as many times as necessary, until the parameters had to be changed again. This is why in the EDF+ file that is generated with every measurement, there is a field with an identification of the person that checks the parameters. In the field Local Recording Identification of the file header, the code that specifies the responsible technician is stored.

In Full Control Mode, functionalities are divided into two groups: Measurement Options and File Options. *Figure 4.3* shows the first interface of the program, where the user can make the first choice

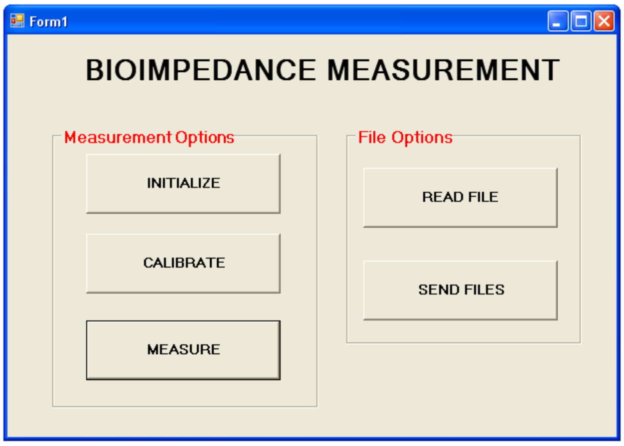


Fig.4.3 First Interface in Full Control Mode

If the user clicks on Read File, a new interface will ask him to choose between one file and two files. This interface is shown in *Figure 4.4*. Every time a measurement is taken, a new EDF+ file is generated, encrypted and stored in the application. And it keeps there after the application is closed. That means the user can read files that were stored in previous uses of the application.

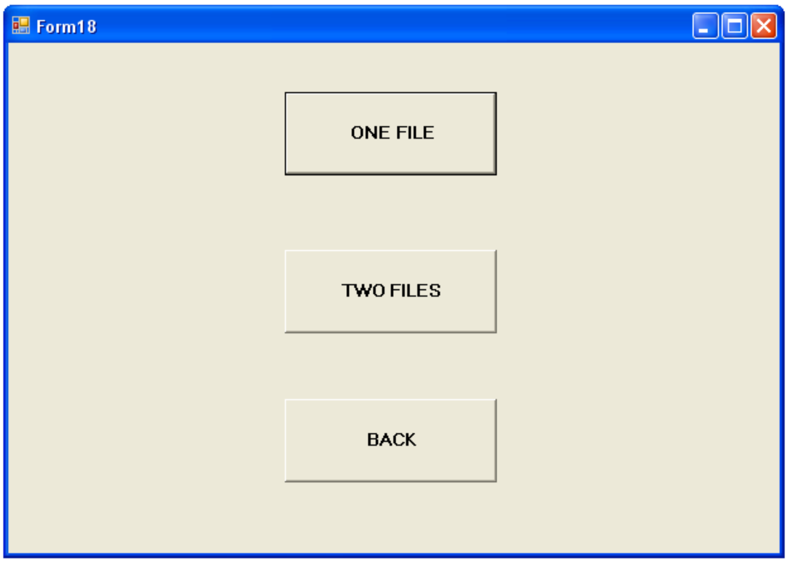
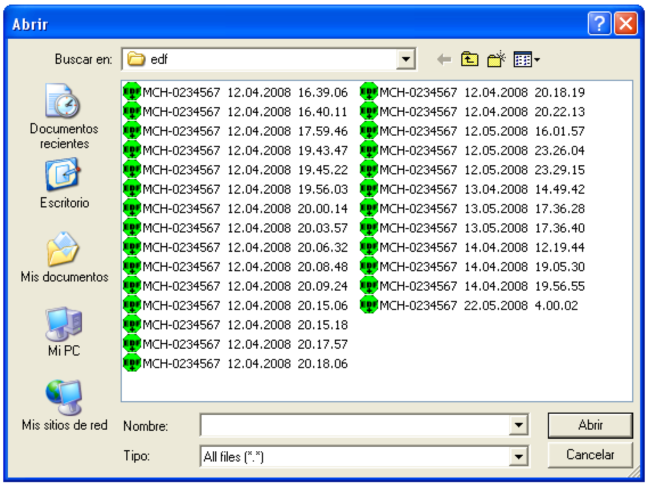


Fig.4.4 Interface where the user decides whether to read one file or two files

If the user wants to read only one file, a dialog box with the names of all the EDF+ files stored in the application will appear. This dialog box will request the user to choose one file; if the user clicks on Two Files, then the same dialog box will appear twice, so that the user can select two files. *Figure 4.5* shows the dialog box.



Buscar en: edf

```
MCH-0234567 12.04.2008 16.39.06
MCH-0234567 12.04.2008 16.40.11
MCH-0234567 12.04.2008 17.59.46
MCH-0234567 12.04.2008 19.43.47
MCH-0234567 12.04.2008 19.45.22
MCH-0234567 12.04.2008 19.56.03
MCH-0234567 12.04.2008 20.00.14
MCH-0234567 12.04.2008 20.03.57
MCH-0234567 12.04.2008 20.06.32
MCH-0234567 12.04.2008 20.08.48
MCH-0234567 12.04.2008 20.09.24
MCH-0234567 12.04.2008 20.15.06
MCH-0234567 12.04.2008 20.15.18
MCH-0234567 12.04.2008 20.17.57
MCH-0234567 12.04.2008 20.18.06
MCH-0234567 12.04.2008 20.18.19
MCH-0234567 12.04.2008 20.22.13
MCH-0234567 12.05.2008 16.01.57
MCH-0234567 12.05.2008 23.26.04
MCH-0234567 12.05.2008 23.29.15
MCH-0234567 13.04.2008 14.49.42
MCH-0234567 13.05.2008 17.36.28
MCH-0234567 13.05.2008 17.36.40
MCH-0234567 14.04.2008 12.19.44
MCH-0234567 14.04.2008 19.05.30
MCH-0234567 14.04.2008 19.56.55
MCH-0234567 22.05.2008 4.00.02
```

Tipo: All files (*.*)

Fig.4.5 Dialog box that requests the user to choose a EDF+ file

If the user chooses reading just one file, a new interface will ask him to choose the kind of display he wants to see. The options are: resistance as a function of frequency, reactance as a function of frequency or resistance vs. reactance. Figure 4.6 shows the interface where the user is requested to choose one of them.

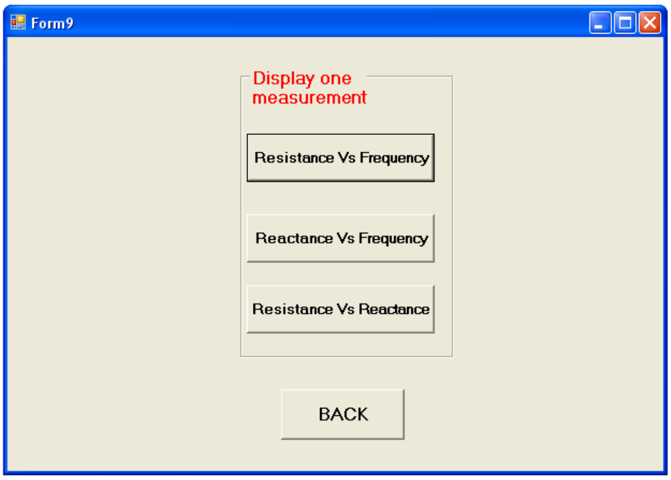


Fig.4.6 Interface that requests the user to choose a kind of display for just one file

Depending on the option chosen by the user, *Figure 4.7*, *Figure 4.8* or *Figure 4.9* will be shown. These three figures show information from a single measurement, and therefore, belong to the same EDF+ file.

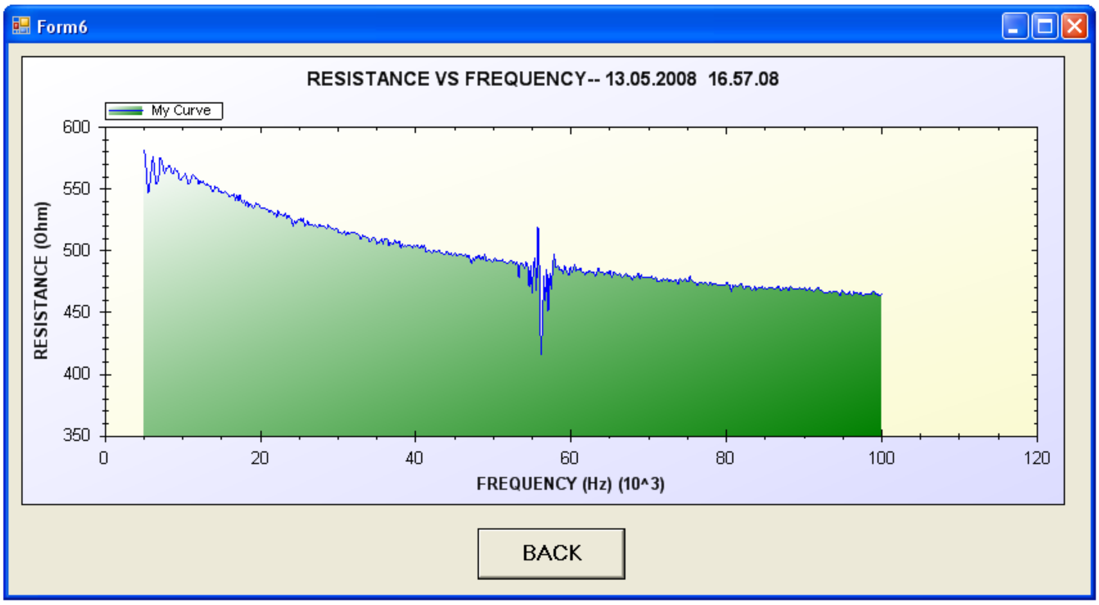


Fig.4.7 Resistance as a function of the frequency. Bioimpedance measurement taken over the whole body of a male

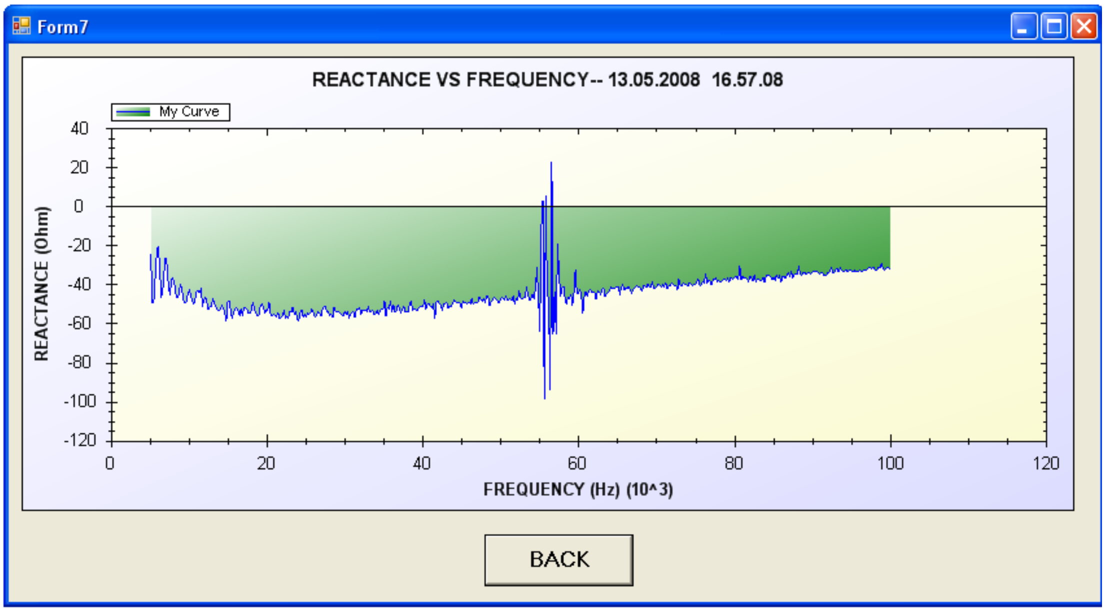


Fig.4.8 Reactance as a function of the frequency. Bioimpedance measurement taken over the whole body of a male

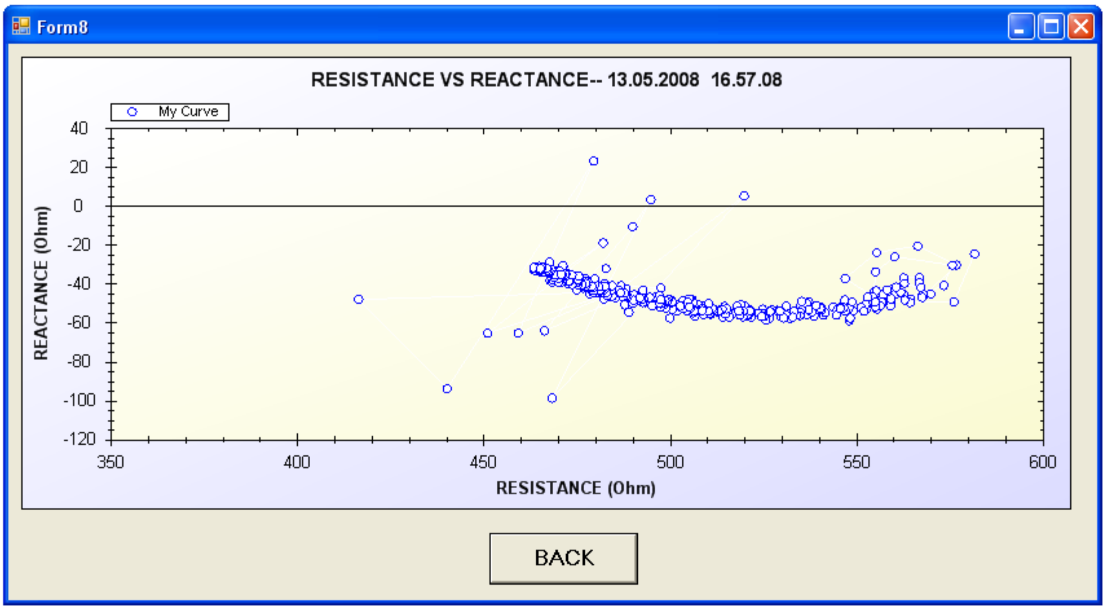


Fig.4.9 Resistance vs. reactance. Bioimpedance measurement taken over the whole body of a male

When the user chooses reading two files, a different interface requests him to choose the kind of display he wants to see. The options are the same as for one file, but they are referred to two files, so two different measurements can be compared. *Figure 4.10* shows this interface.

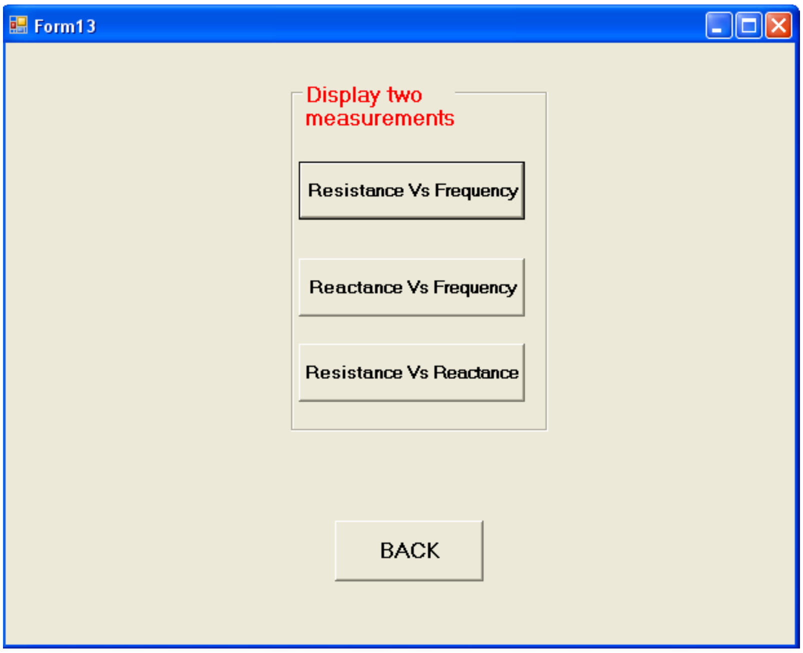


Fig.4.10 Interface that requests the user to choose a kind of display for two files.

Depending on the option chosen by the user, *Figure 4.11*, *Figure 4.12* or *Figure .13* will be shown. In these three figures, we can compare information from two different measurements, both of them taken from the same person.

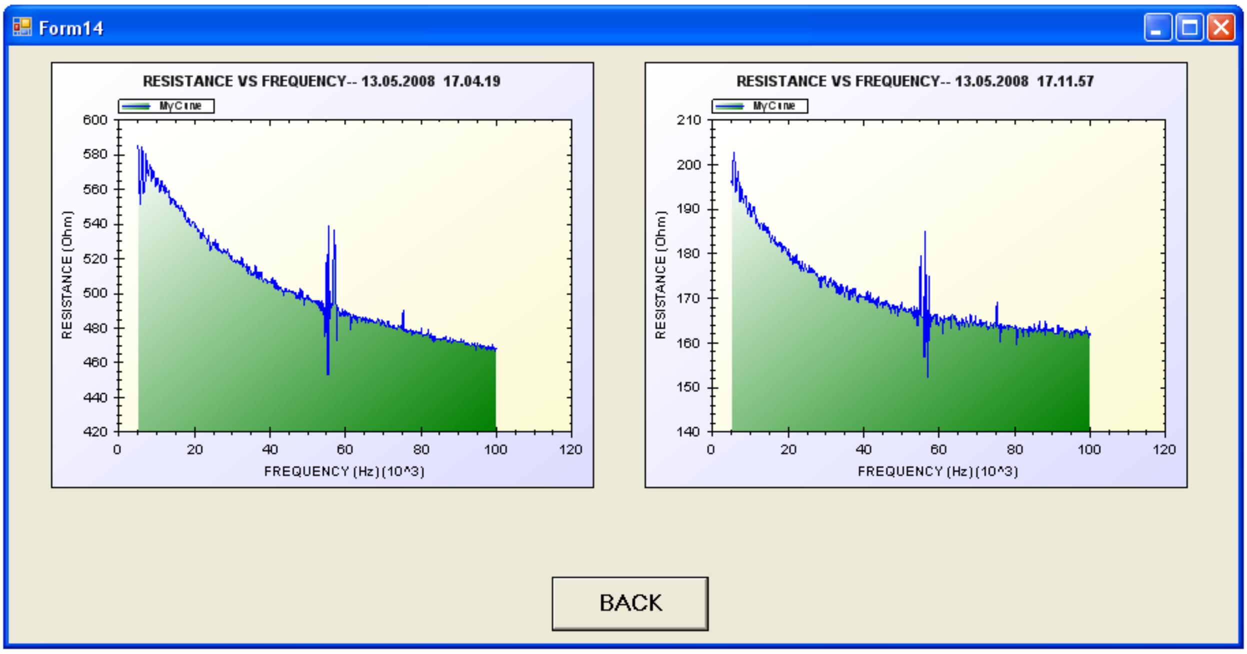


Fig.4.11 Resistance as a function of the frequency. Left display: Bioimpedance measurement taken over the whole body of a male. Right display: Bioimpedance measurement taken over the left leg of the same person.

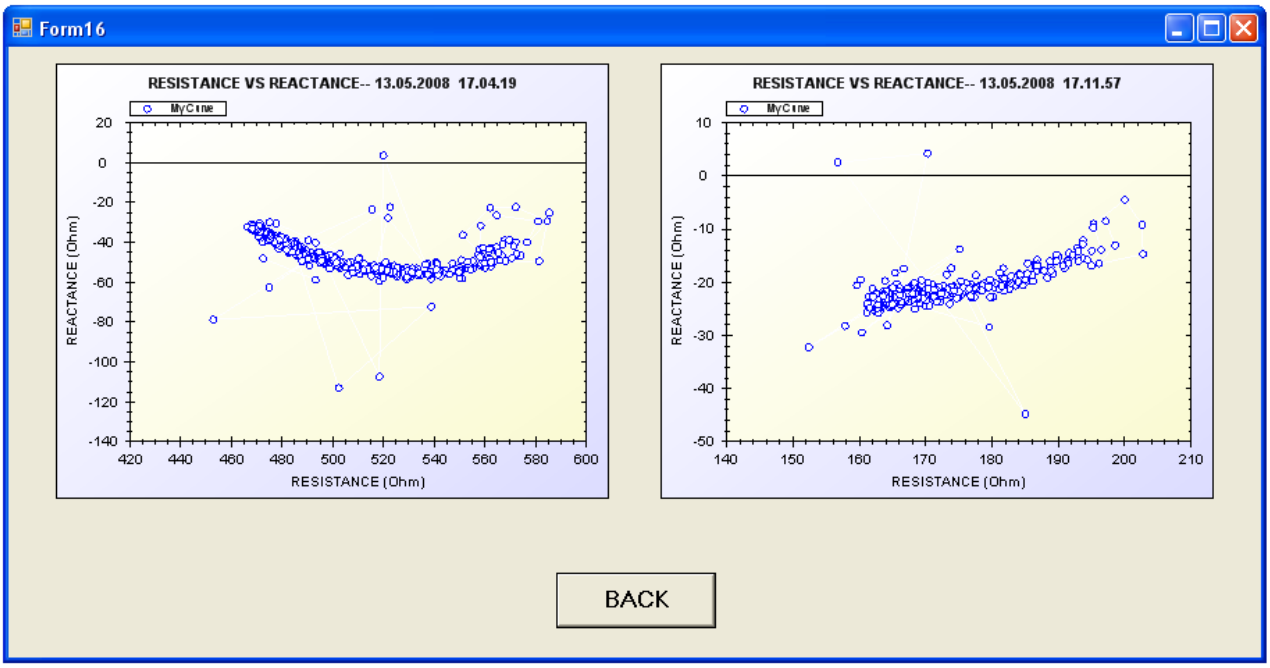


Fig.4.13 Resistance vs. reactance. Left display: Bioimpedance measurement taken over the whole body of a male. Right display: Bioimpedance measurement taken over the left leg of the same person.

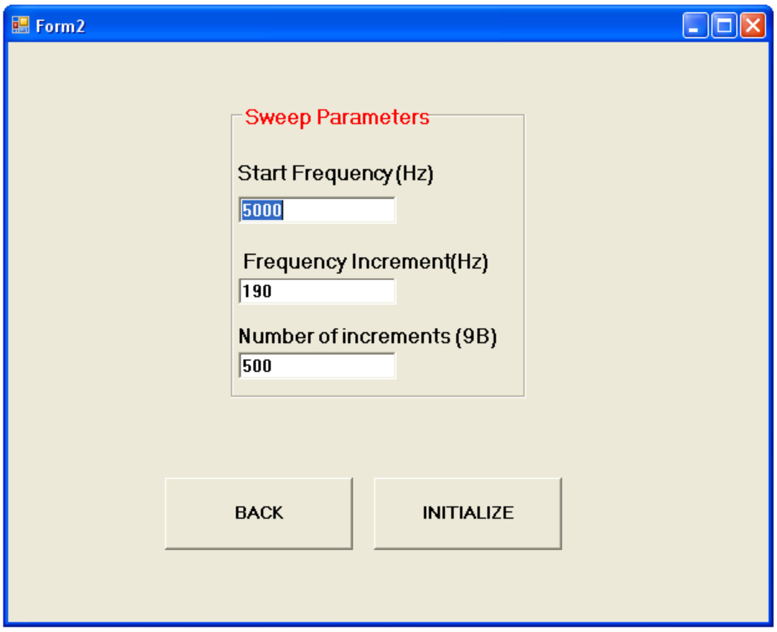
When the user chooses Send Files, all the XML files stored in the application are sent to the remote server. To implement this functionality, another application that was developed in a previous thesis work by García **[7]** has been used. If the files can not be sent, either because the internet connection is not available or because the server application is down, they keep stored in the local machine for a next trial. *Figure 4.14* shows the message that is shown when the files can not be sent.


Information could not be sent to the server. You can try next time you use the program

Fig.4.14 Message that indicates the files can not be sent to the remote server

It is important to stress that the evolution board is not needed to carry out all the file management functionalities that have just been explained. This gives rise to a higher portability of the system: with the original software application from Analog Devices, the evaluation board had to be always connected to the computer. With the new application, the evaluation board is only required for the Measurement Options.

There are three Measurement Options: Initialize Calibrate and Measure. The only one available when non measurement has been taken is Initializing. This functionality consists on programming the three parameters that fully describe the frequency sweep: the Start Frequency, the Frequency Increment, and the Number of Increments. The Number of Increments refers to the number of frequency points in the sweep, and can not be higher than 511. All these parameters are defined by the user. *Figure 4.15* shows the interface that requires the user to introduce them.



Sweep Parameters

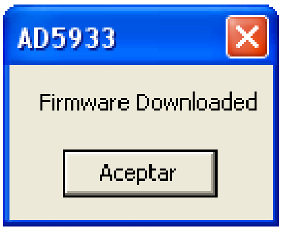
Start Frequency (Hz): 5000

Frequency Increment(Hz): 190

Number of increments (9B): 500

Fig.4.15 Interface that requires the user to introduce the initializing parameters

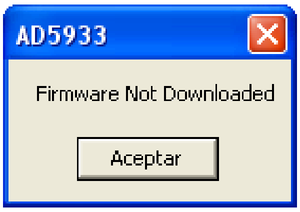
Once the parameters are introduced, and the user clicks on Initialize, the communication between the AD5933 circuit and the computer starts. *Figure 4.16* shows the message that indicates the communication has been established.



Firmware Downloaded

Fig.4.16 Message that indicates the communication between the AD5933 circuit and the computer has been established.

If the communication can not be established, i.e. when the evaluation board is not connected to the computer, the message shown in *Figure 4.17* indicates about this special situation.



AD5933

Firmware Not Downloaded

Fig.4.17 Message shown when the communication between the AD5933 circuit and the computer can not be established

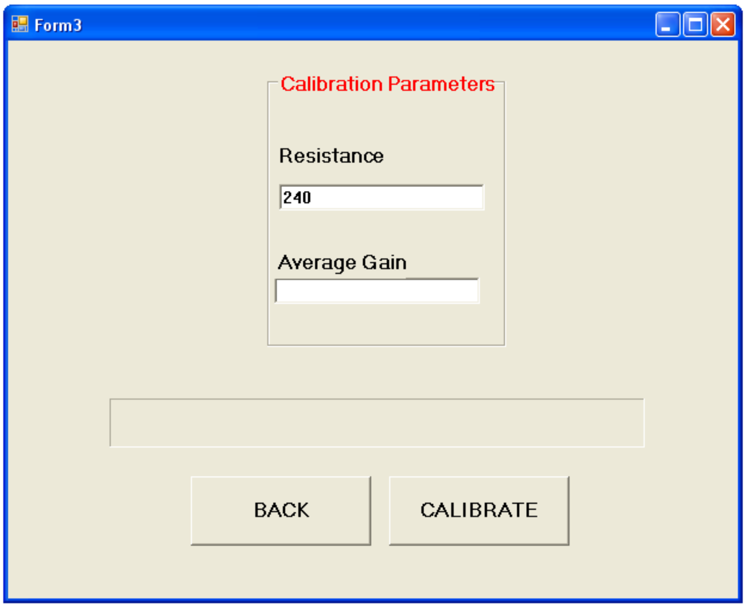
If the communication is possible, the initialization process takes place. *Figure 4.18* shows the message that indicates the initialization process has been completed.

AD5933

Initialization complete

Fig.4.18Message that indicates the initialization has been completed

The next step in the measurement process is to Calibrate. As explained before in this chapter, the application uses the Multi Frequency Point calibration mode. To carry out this process, the user must introduce the value of the calibration load that is connected between the exciting leads. *Figure 4.19* shows the interface where the user is requested to introduce the calibration load value.



Form3

Calibration Parameters

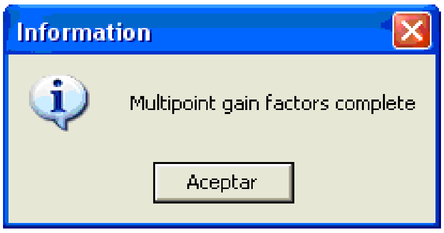
Resistance

240

Average Gain

Fig.4.19 Interface where the user must introduce the calibration load value

A message like the one in *Figure 4.20* indicates that the calibration process has been completed.

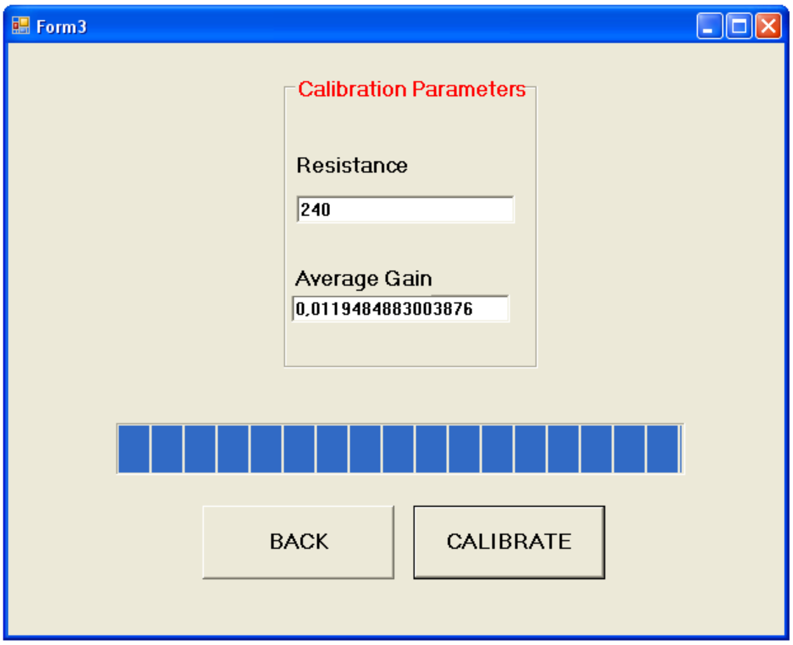


Information

Multipoint gain factors complete

Fig.4.20 Message that shows the calibration process has finished

As we can observe in *Figure 4.21*, the application shows the average Gain Factor.



Resistance: 240

Average Gain: 0,0119484883003876

Fig.4.21 Interface that shows the average Gain Factor

The last step in the measurement process is to Measure. The system is now ready to do it, so the user only has to click on Start in the interface shown in *Figure 4.22*.

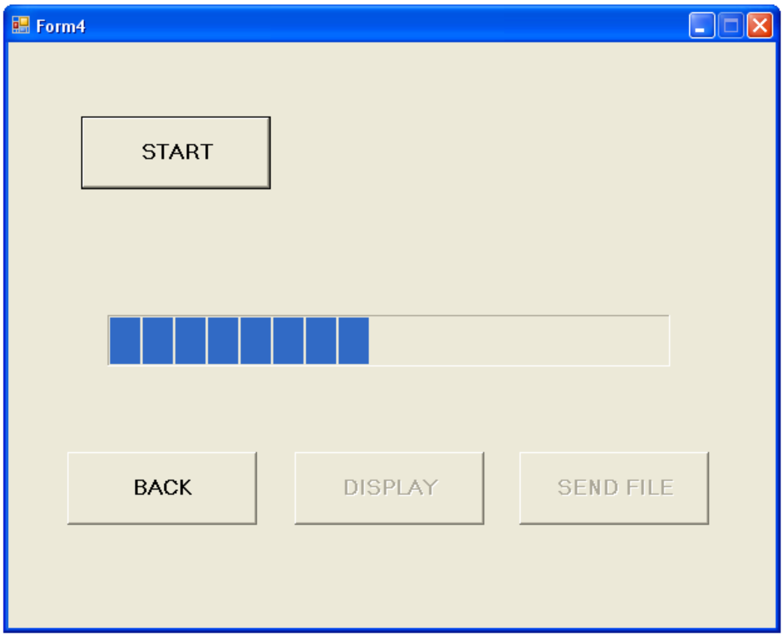
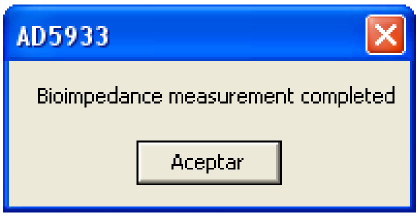


Fig.4.22 Interface where the user can start the measurement

Figure 4.23 shows the message that indicates the measurement process has been completed.



Bioimpedance measurement completed

Fig.4.23 Message that indicates the measurement process has finished

Once the measurement process has been completed, the user can see the results. If he clicks on Display, a new interface like the one shown in *Figure 4.24* will request him to choose between displaying just the last measurement, or comparing it with another measurement that was previously made and keeps stored in the local machine.

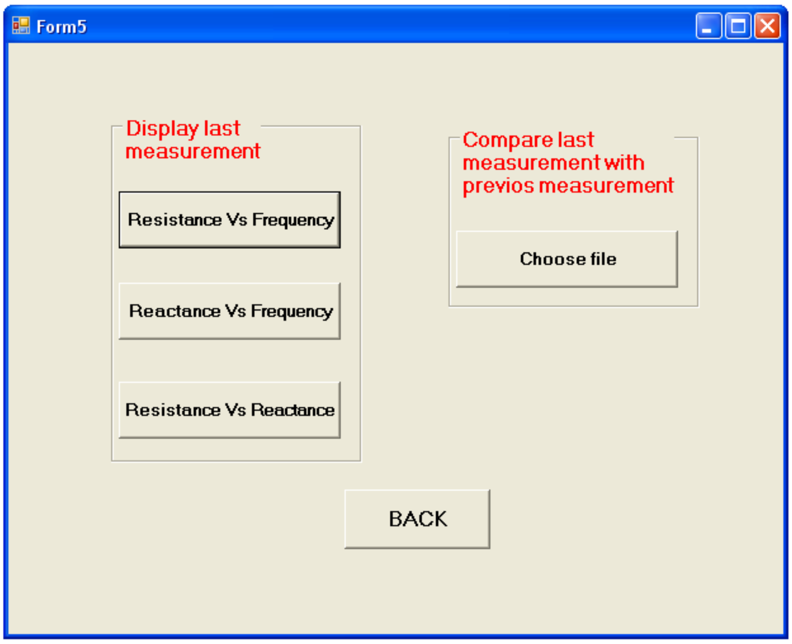


Fig.4.24 Interface where the user decides whether to display only the last measurement, or to compare it with a previous one.

In both cases, the display options are the same that were explained for the File Options. In case the user only wants to display the last measurement, and depending on the kind of display chosen, *Figure 4.25*, *Figure 4.26* or *Figure 4.27* will be shown.

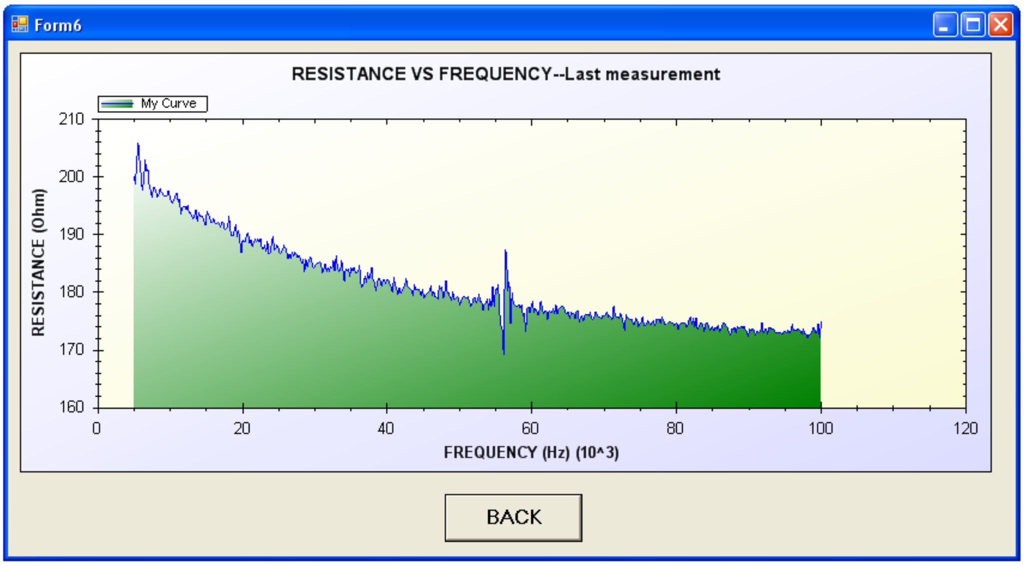


Fig.4.25 Resistance as a function of the frequency. Bioimpedance measurement taken over the left forearm of a female.

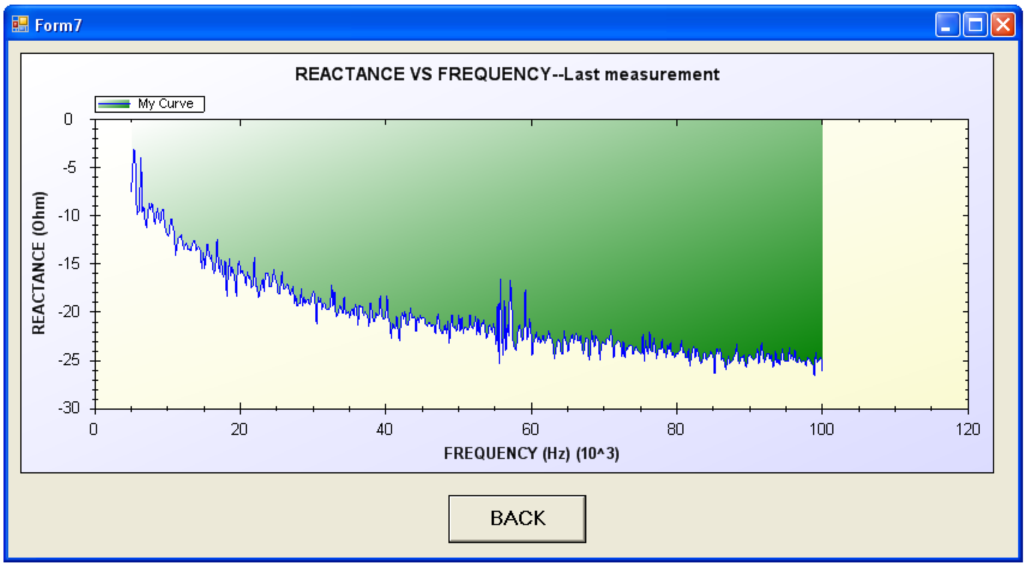


Fig.4.26 Reactance as a function of the frequency. Bioimpedance measurement taken over the left forearm of a female.

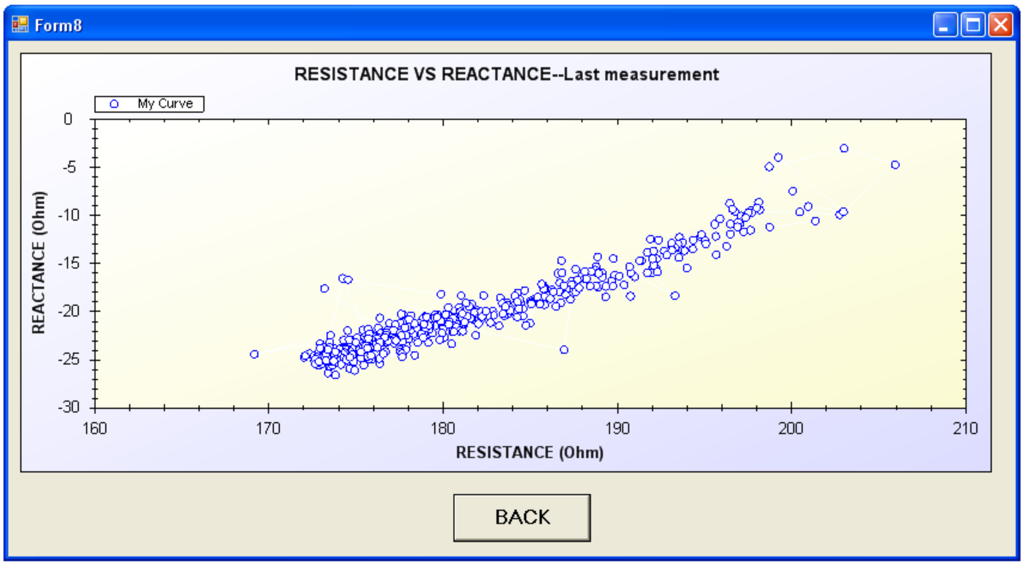


Fig.4.27 Resistance vs. reactance. Bioimpedance measurement taken over the left forearm of a female.

If the user chooses displaying the last measurement together with a previous measurement, the dialog box shown in *Figure 4.5* will request him to choose a file, and once it is done, he will have to choose the kind of display in the interface shown in *Figure 4.10*. Depending on his election, *Figure 4.28*, *Figure 4.29* or *Figure 4.30* will appear.

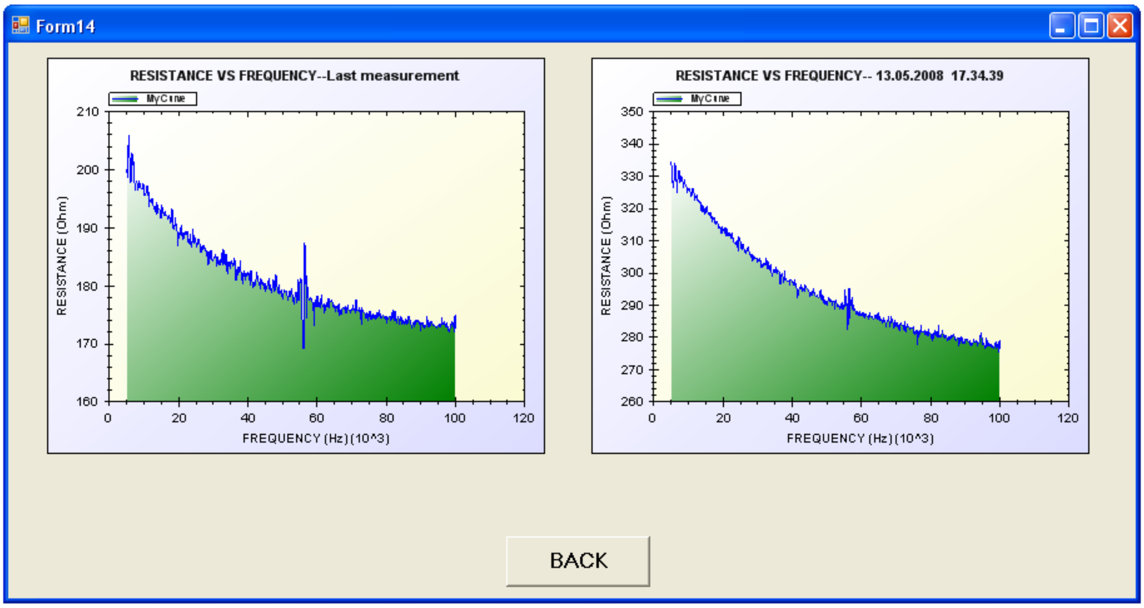


Fig.4.28 Resistance as a function of the frequency. Left display: Bioimpedance measurement taken over the left forearm of a female. Right display: Bioimpedance measurement taken over the whole same arm.

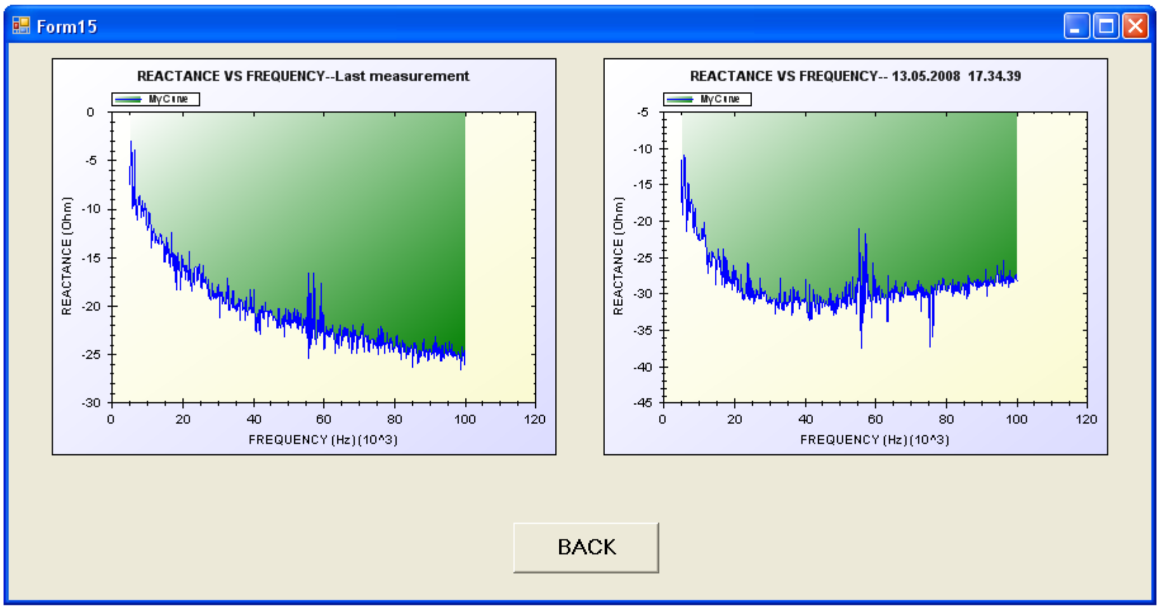


Fig.4.29 Reactance as a function of the frequency. Left display: Bioimpedance measurement taken over the left forearm of a female. Right display: Bioimpedance measurement taken over the whole same arm.

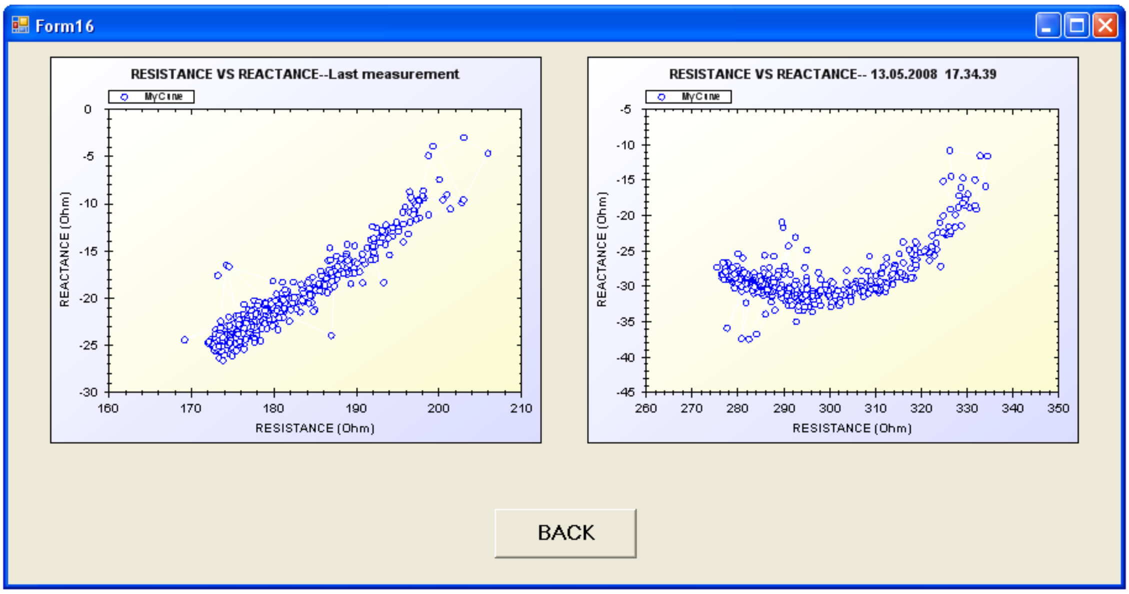


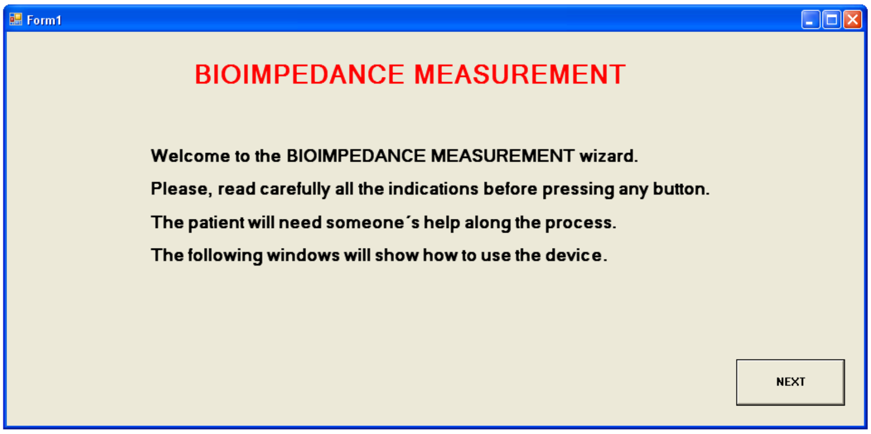
Fig.4.30 Resistance vs. reactance. Left display: Bioimpedance measurement taken over the left forearm of a female. Right display: Bioimpedance measurement taken over the whole same arm.

If the user chooses Send File, the same procedure as explained for File Options will take place.

4.3.1.2 Wizard Mode

The Wizard Mode is aimed at patients undergoing peritoneal dialysis. The measurement process could be completed by the patient at home just by following the easy instructions provided by this part of the application. Notice that this part of the application has been done with demonstration purposes only and does not consider the mandatory aspects of Human Factors Engineering and Usability, which are completely out of scope of this project.

Figure 4.31 shows the first interface of the Wizard Mode. It informs the patient that help is required during the process.



BIOIMPEDANCE MEASUREMENT

Welcome to the BIOIMPEDANCE MEASUREMENT wizard.
Please, read carefully all the indications before pressing any button.
The patient will need someone´s help along the process.
The following windows will show how to use the device.

Fig.4.31 First Interface in Wizard Mode

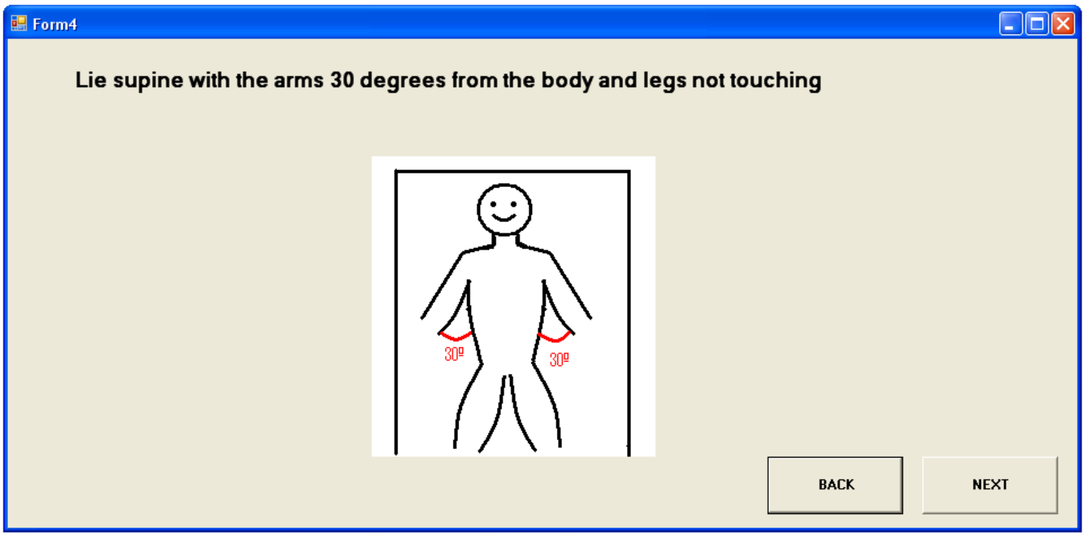
Figure 4.32 shows the next interface, where the patient is requested to connect the evaluation board to the computer.

Conect the device to the computer and press NEXT

Fig.4.32 Interface that requires the user to connect the evaluation board to the computer

When Clicking on next, a message will indicate that the communication between the computer and the AD5933 circuit has been established. The message is the one shown in *Figure 4.16* for Full Control Mode. In case there is any problem and the communication is not possible, the message shown in *Figure 4.17* will warn about this situation.

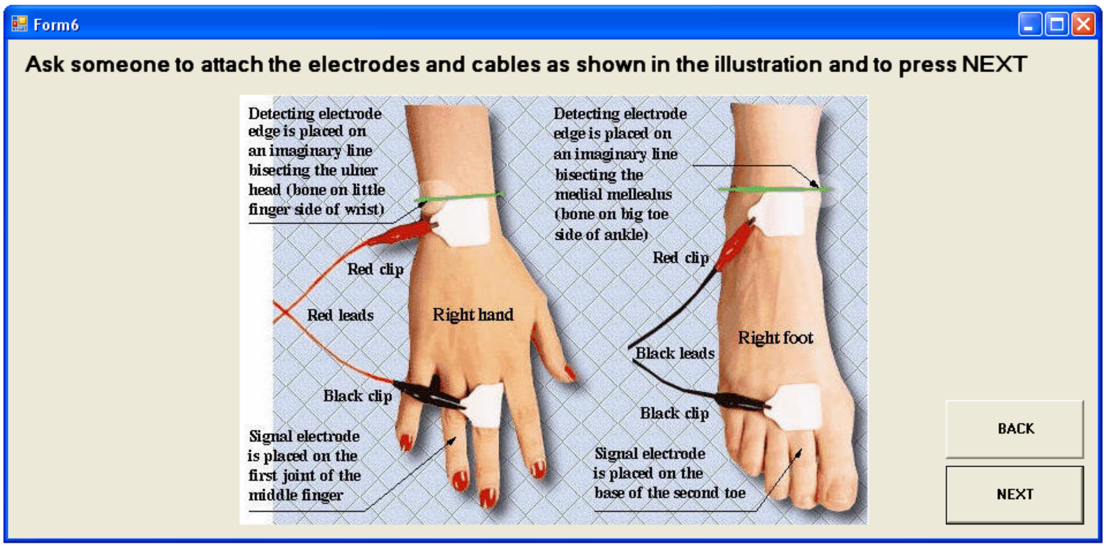
If the communication is possible, the interface shown in *Figure 4.33* will advise the patient to lie head up.



Lie supine with the arms 30 degrees from the body and legs not touching

Fig.4.33 Interface where the user is advised how to remain during the process

Figure 4.34 shows the interface that explains how the electrodes must be attached to the patient.

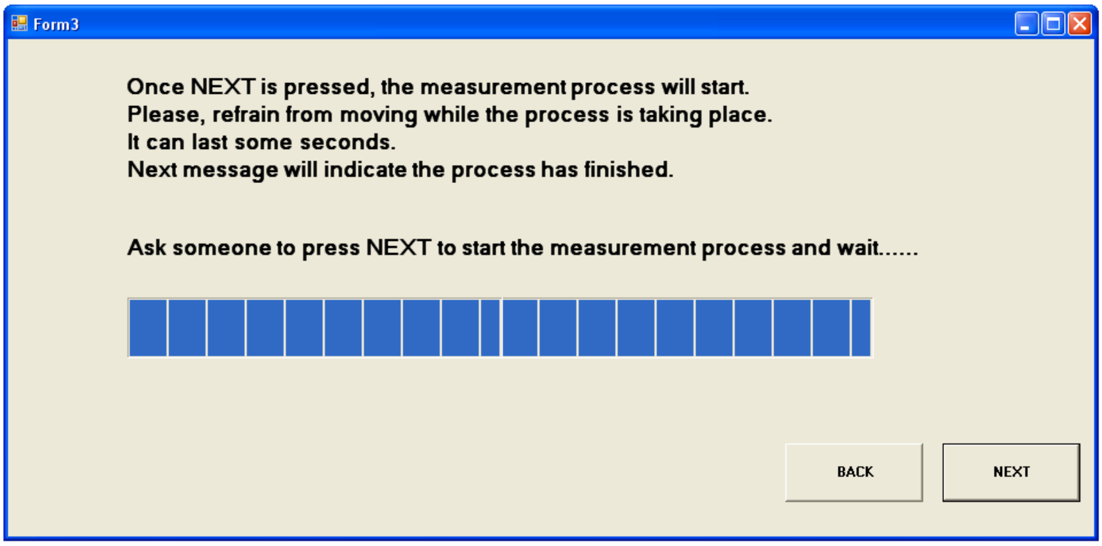


Ask someone to attach the electrodes and cables as shown in the illustration and to press NEXT

Fig.4.34 Interface that explains how to attach the electrodes to the body

Just by Clicking on Next in the interface shown in *Figure 4.35*, the measurement process starts. As it is explained in this interface, the patient should not move until a message indicates the process has finished. That means that someone must help the patient and press the button.

The measurement process consists of the three same steps carried out with the Full Control Mode: Initialize, Calibrate and Measure. The initialization parameters and the calibrating load value are read from a script that was generated with the Full Control Mode. Once the measurement has been taken, a new EDF+ file is created and sent, under the XML format, to the remote server. If there is any problem that impedes the receipt of the file, the message shown in *Figure 4.14* will indicate this. And it will be sent next time a measurement is taken.



Once NEXT is pressed, the measurement process will start.
Please, refrain from moving while the process is taking place.
It can last some seconds.
Next message will indicate the process has finished.

Ask someone to press NEXT to start the measurement process and wait......

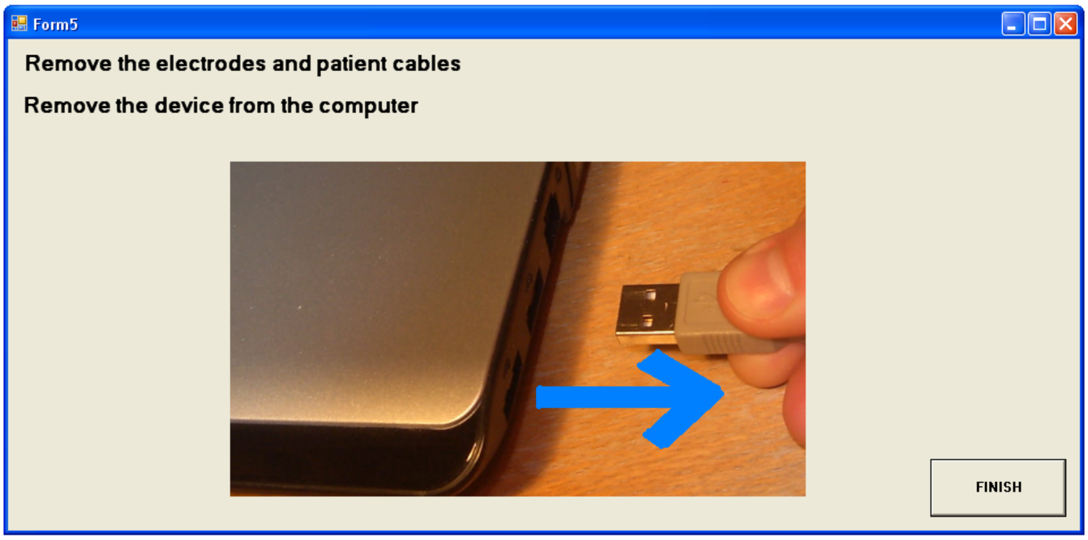
Fig.4.35 Interface where the measurement process can be started

The message shown in *Figure 4.36* indicates that the measurement process has been completed.

The process has been completed successfully

Fig.4.36 Message that indicates the measurement process has finished

Figure 4.37 shows the last interface, which indicates how to finish the application.

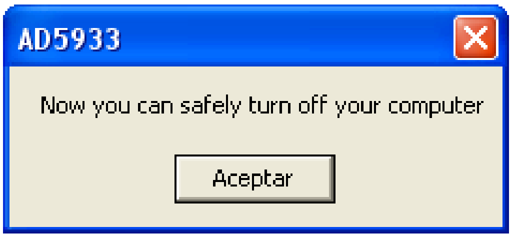


Remove the electrodes and patient cables

Remove the device from the computer

Fig.4.37 Last interface in Wizard Mode

Finally, when the message shown in *Figure 4.38* appears, the user can turn off the computer.



Now you can safely turn off your computer

Fig.4.38 Message that indicates the computer can be turned off

4.3.1.3 Total Architecture

All the code functions that are required to implement both modes, Full Control Mode and Wizard Mode, have been structured in different modules, according to their functionality. *Figure 4.39* shows the whole Home Monitoring Application architecture.

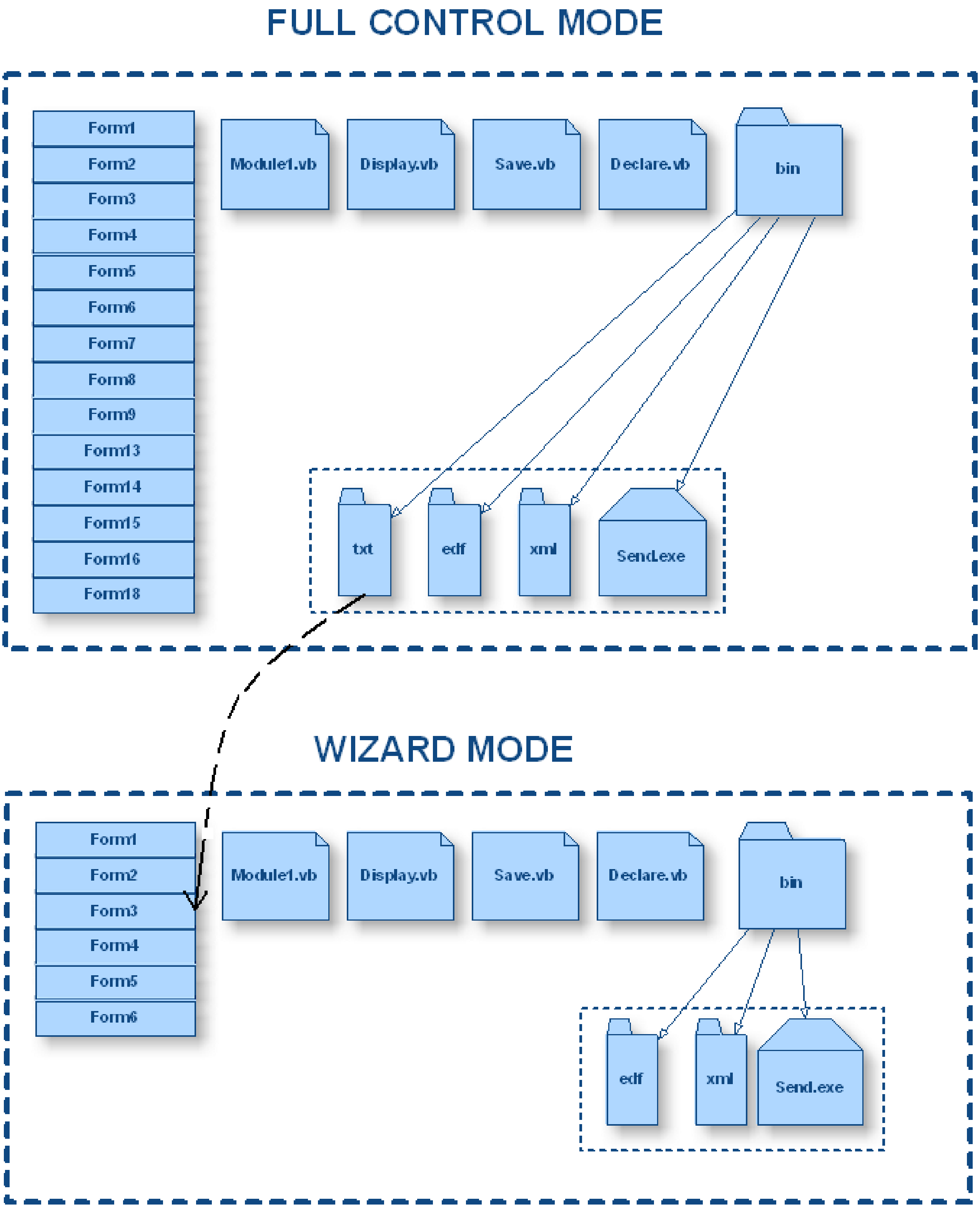


Fig.4.39 Home Monitoring Application Architecture

Every form shown in the picture has its corresponding designer or interface, and contains the necessary instructions to rule the program. The calls to all code functions are written in these forms. Notice that there are more forms in Full Control Mode because it has more functionalities.

Four different modules have been used in order to write all the code functions. These modules are the following ones:

- **Module1**. It contains all the necessary functions to programme the AD5933 registers and to establish the communication between the circuit and the computer. These functions were written in the original software from Analog Devices.
- **Declare**. This module contains the declaration of all global variables. Here it has been added the ones required in the new application.
- **Display.** This module is completely new. All the necessary functions to show the measurements stored in the EDF+ files have been written here. These functions are:
    - CreateGraph
    - CreatGraph2
    - recoverFile
- **Save.** This module is also completely new. All the functions required to create the EDF+ and XML files can be found here. These functions are:
    - CreateEdf
    - Max
    - Min
    - ConvertMonth
    - EncryptFile
    - CreateXML

As it is shown in Figure 4.40, in both modes the folder bin contains:
- A folder called edf, where all the EDF+ files are stored.
-A folder called xml, where all the XML files are stored.
-A file called send. This is an executable file that was generated by an application developed in a previous thesis work **[7]**. This file is used by our new application to send the XML files to the remote server.

In Full Control Mode the folder bin contains one more folder called txt. This folder has a file called Parameters where the Start Frequency, Frequency Increment, Number of Increments and the calibration load value are stored during the Initialization and Calibration processes. As shown in Figure 4.40, form3 in Wizard Mode uses these four parameters to carry out the Bioimpedance measurements.

4.3.2 Web Server Application

The Web Server Application consists of an application that can read the files stored in the remote server. This application is aimed at the medical staff, who could be informed about the progress of the patients. This way the medical supervision would be increased.

The first interface of this application is shown in *Figure 4.40*.

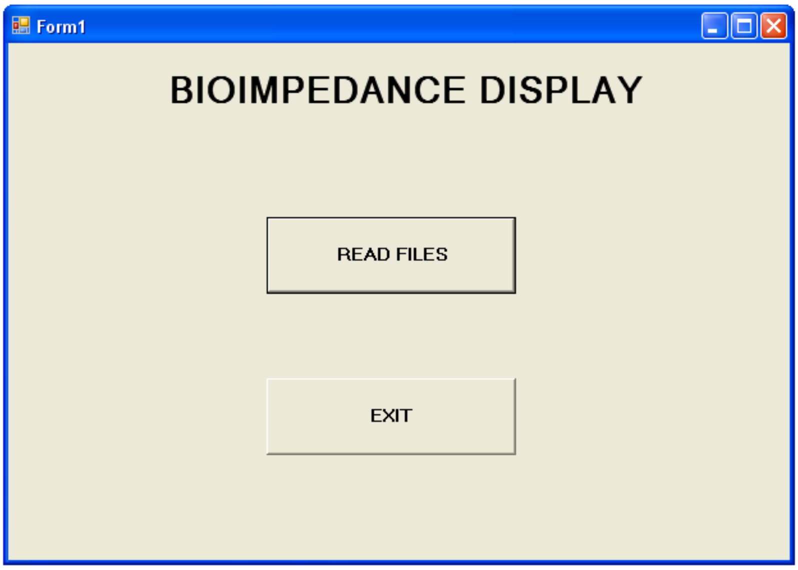


Fig.4.40 First interface in the Web Sever Application

The rest of the interfaces are the same as in Full Control Mode. When Read Files is clicked on, the interface showed in *Figure 4.4* requests the user to choose between displaying only one file or two files. If One File is chosen, the user has to select one file in the dialog box that shows *Figure 4.5*. If Two Files is chosen, this dialog box will appear twice. For a single file, the interface in *Figure 4.6* will request the user to choose the kind of display. Depending on the election, *Figure 4.7, Figure 4.8* or *Figure 4.9* will be shown, with the corresponding display. For two files, *Figure 4.10* will ask the user to choose the kind of display. And depending on the election made, the corresponding display will be shown in *Figure 4.11*, *Figure 4.12* or *Figure 4.13*.

CHAPTER 5

RESULTS & DISCUSSION

5.1 Results & Discussion

The results obtained with the Electrical Bioimpedance Measurement System will be shown and discussed over this section. These results are referred to different functionalities of the system.

5.1.1 Measurement of the Electrical Equivalent Model of tissues

In order to fully test the performance of the measurement system, EBI measurements over tissues should be carried out. Since this system has been done for demonstration purposes only and does not consider the mandatory aspects of Human Factors Engineering and Usability, which are completely out of scope of this project, the electrical equivalent model of tissues will be used instead. This circuit models the electrical behaviour of tissue, and consequently, can be used to check the validity of the measurement system. *Figure 5.1* shows the electrical equivalent circuit used.
And its equivalent impedance value is given by the following expression:

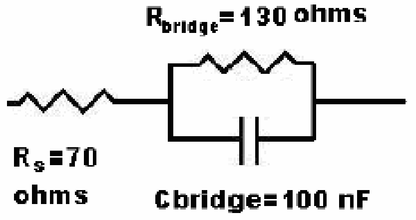


Fig.5.1 Electrical equivalent circuit for human tissue

$$Z_{Skin} = \left(R_S + \frac{R_{bridge}}{1+\left(w \cdot R_{bridge} \cdot C\right)^2} \right) - j\frac{w \cdot R^2{}_{bridge} \cdot C}{1+\left(w \cdot R_{bridge} \cdot C\right)^2} \quad \textbf{(5.1)}$$

Where the real part represents the resistive component of the impedance and the imaginary value represents its reactive component. The frequency dependency of the impedance makes the skin impedance value change along the frequency sweep.

To test the validity of the measurement system, the electrical behaviour of the circuit shown in *Figure 5.1* was simulated with the mathematical program **MATLAB v7.1**. And the same circuit was measured with the measurement system. This way, the results obtained with the different programmes can be compared. *Figure 5.2*, *Figure 5.4* and *Figure 5.6* show the graphics obtained with MATLAB, while *Figure 5.3*, *Figure 5.5* and *Figure 5.7* show the displays obtained with the new system.

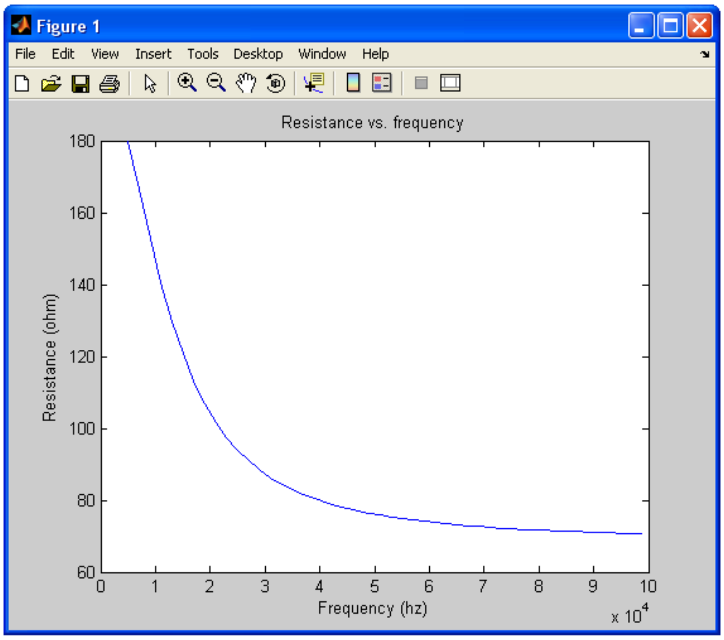


Fig.5.2 Theoretical value of the electrical model used. Resistance vs. frequency

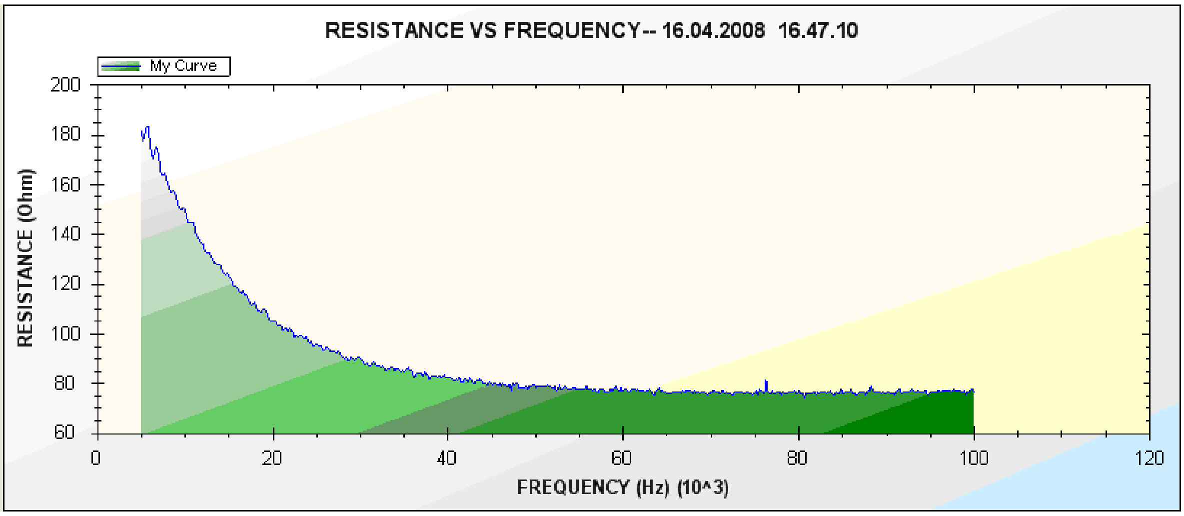


Fig.5.3 Measured value of the electrical model used. Resistance vs. frequency

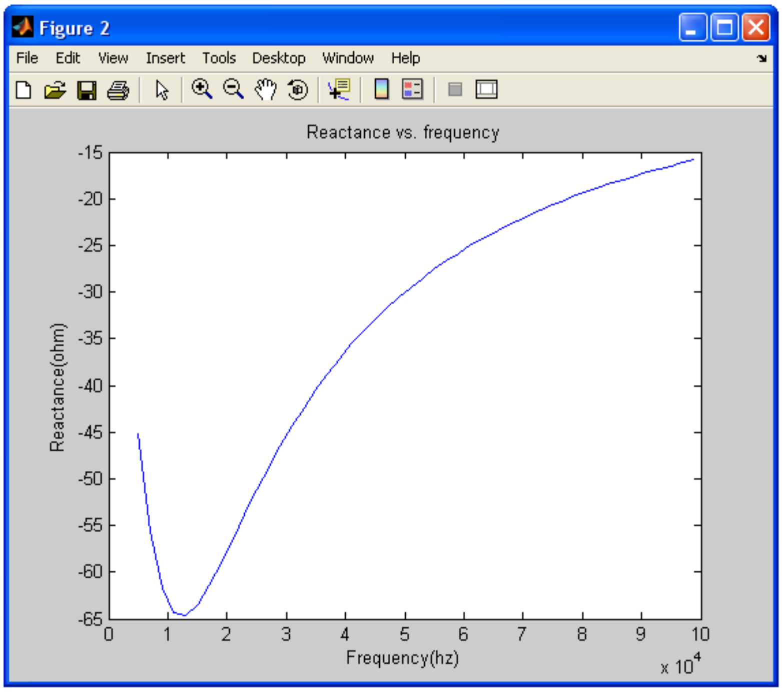


Fig.5.4 Theoretical value of the electrical model. Reactance vs. frequency

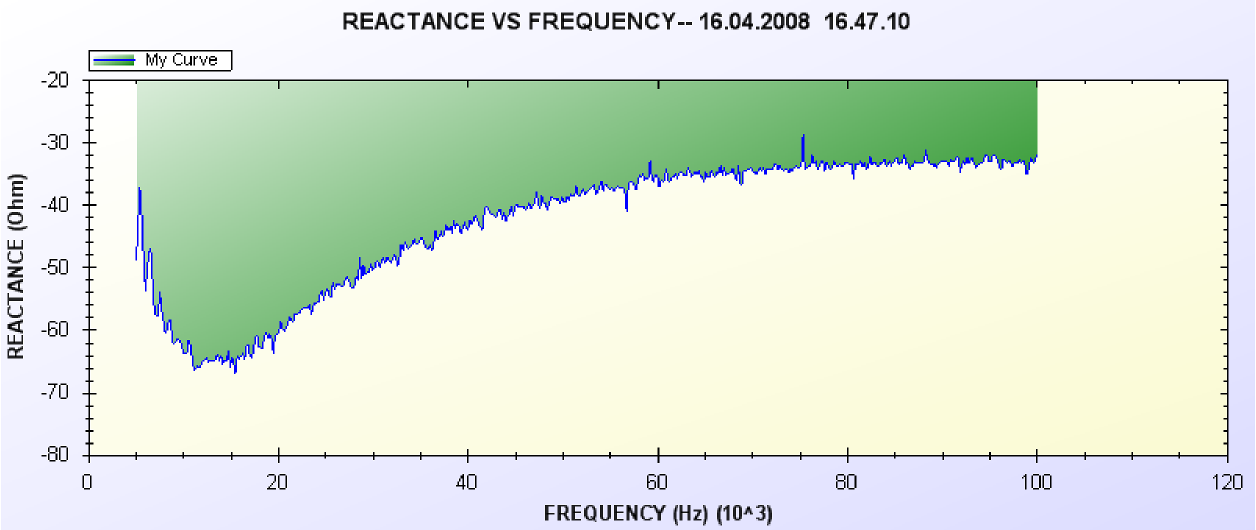


Fig.5.5 Measured value of the electrical model used. Reactance vs. frequency

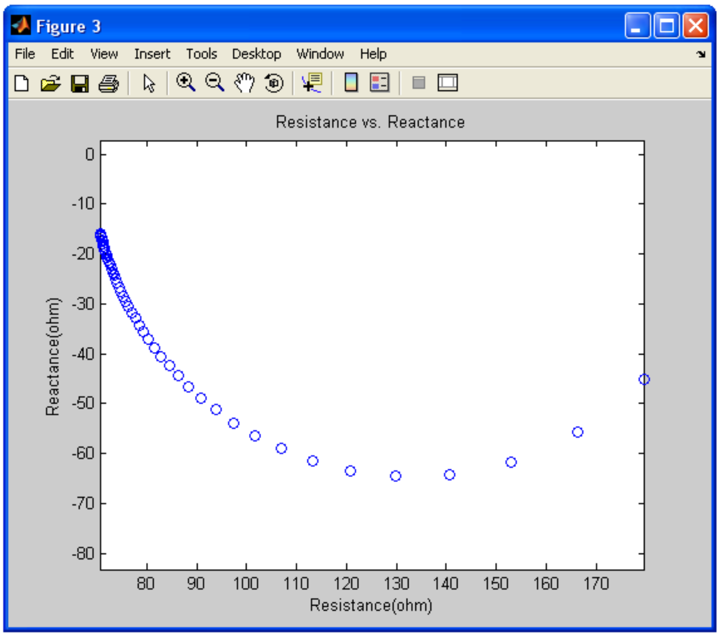


Fig.5.6 Calculated Impedance plot of the electrical model used

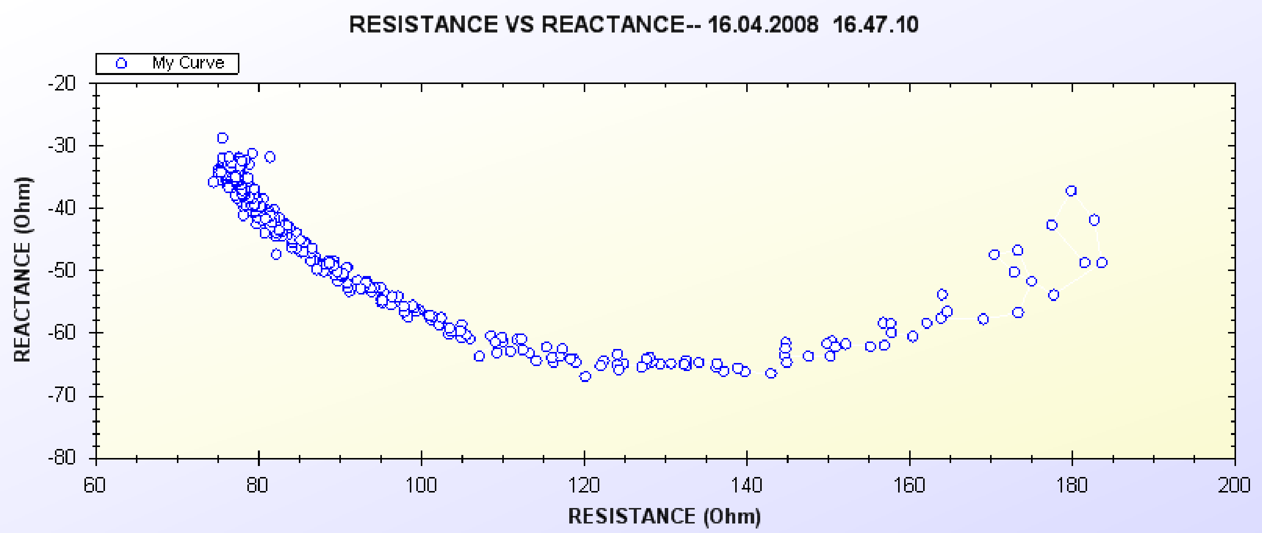


Fig.5.7 Measured value of the electrical equivalent circuit for human tissue. Resistance vs. reactance

As the results show, the measurements are taken correctly by the AD5933 system and they are plotted properly with the new software application.

It is interesting to pay some attention to the impedance plot shown in *Figure 5.7*. In this plot, there are some regions in which the samples taken have a very similar value, what gives rise to a very thick stretch in the plot. For example, when the resistance is between 70 and 110 Ω, there are many redundant points that could be removed without changing the meaning of the graph. In order to design a software application able to distinguish between the transcendental samples and the redundant samples, it would be necessary to study the frequencies in which the values of the impedance plot are practically identical. In these zones of the frequency spectrum, the samples would be taken in a more distant way. But this is a task that is completely out of scope of this Project.

5.1.2 Measurement Storage and Recovery

The Full Control Mode and the Web Server Application can read the measurements stored in EDF+ files. Both applications use exactly the same procedure, so it will be shown only for the Full Control Mode. The way to probe the correct operation of the software is to show, in the same display, the values obtained directly from one measurement and the ones recovered from its EDF+ file. *Figure 5.8*, *Figure 5.9* and *Figure 5.10* show the three different displays that the measurement system can make from an EBI measurement.

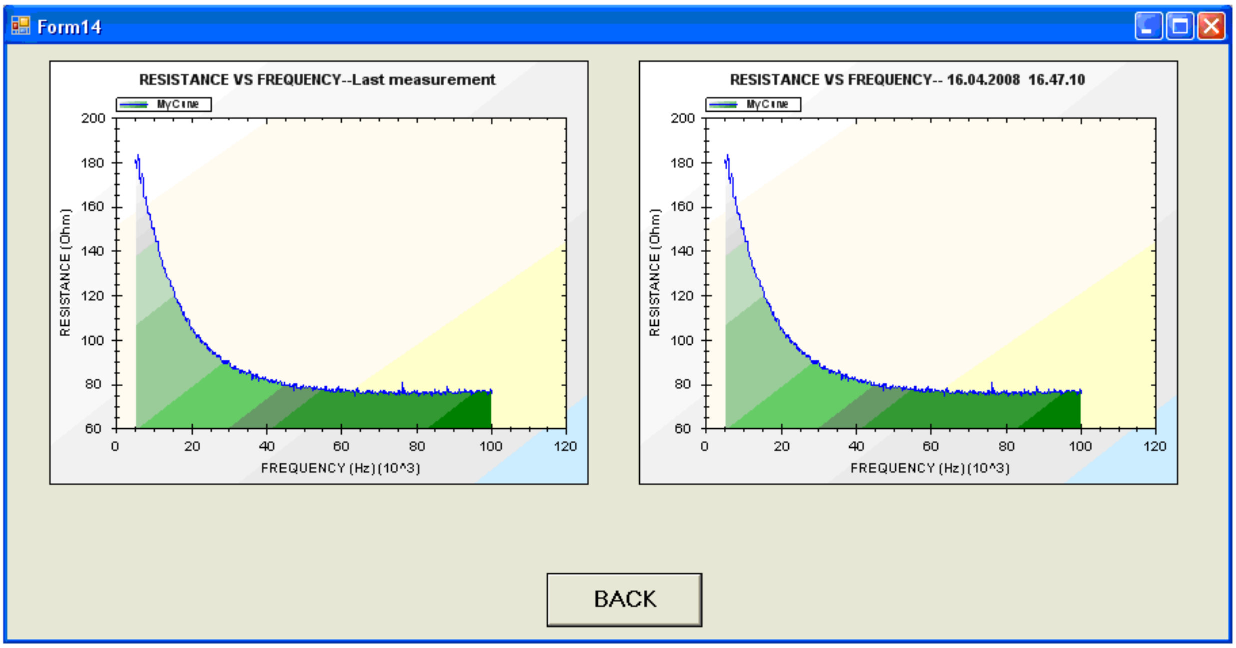


Fig.5.8 Measured value of the electrical model used. Resistance vs. frequency

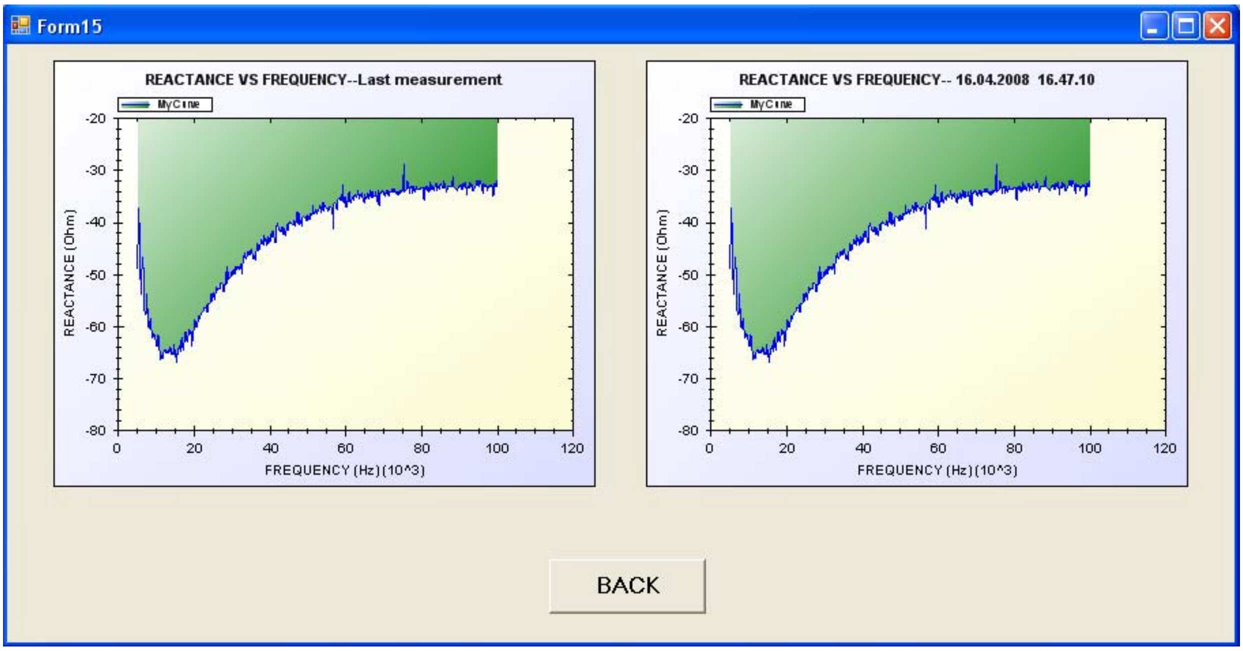


Fig.5.9 Measured value of the electrical model used. Reactance vs. frequency

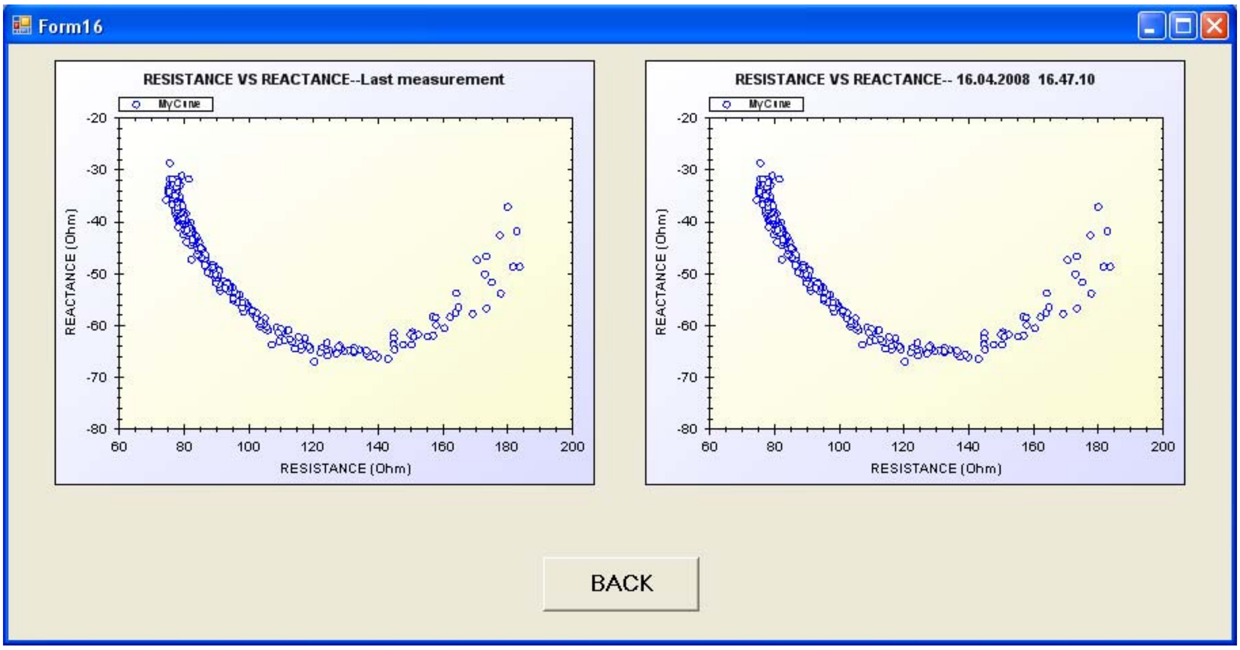


Fig.5.10 Measured value of the electrical model used. Resistance vs. reactance

The plots in the left are taken directly from the measurement, as it can be deduced from their title “Last measurement”; however, the plots in the right show the values recovered from the EDF+ file where the same measurement was stored. And their title is in this case the second part of the file name “16.04.2008 16.47.10”, that is the date and time when the measurement was taken.

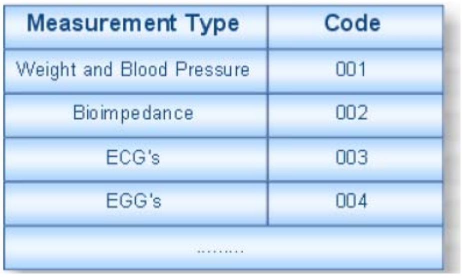
As it can be observed, both plots, the one on the right and the one on the left, for each of the three displays, are exactly the same. That means the system stores and recovers perfectly the measurements.

It is important to consider that EDF+ files contain personal data of the patients, together with the results of their EBI measurements. According to privacy laws about clinical data, confidentiality has to be kept all over the process, what includes the storage of EDF+ in the local machine. In other words, the original files should never be stored. This measurement system encrypts the EDF+ files immediately after creating them, but it also stores the original files in order to recover the measurements whenever it is needed. In order to fully fulfil the privacy laws, it should be studied the way to decrypt the information so that it can be read. But this is something completely out of scope of this Project.

5.1.3 Sending Data to the Remote Server

The Home Monitoring Application can send the XML files to a Remote Server, where the files are stored in a folder called “files”. These XML files have a label called <MeasurementType> which indicates the kind of measurement they contain. Considering that there are other applications sending files to the server, it has been designed a protocol with a different code for each kind of measurement **[7].** This protocol is shown on table 5.1., and allows the different measurements to be processed correctly. As it can be observed, for the case of the Bioimpedance the <MeasurementType> corresponds to 002.

TABLE 5.1: DIFFERENT MEASUREMENT CODES



Measurement Type	Code
Weight and Blood Pressure	001
Bioimpedance	002
ECG's	003
EGG's	004
....	

The Web Server Application has been designed to read the Bioimpedance measurements that arrive to the remote server. And it can read the measurements contained in EDF+ files, but not the information contained in XML files. A new application could study the possibility of processing the XML files that contain Bioimpedance measurements. But once more, this task is out of scope of this project.

CHAPTER 6

CONCLUSIONS & FUTURE WORK

6.1. Conclusions

After all the results shown in the previous chapter, it can be concluded that the Electrical Bioimpedance System fulfils with all the functional specifications that motivated its design. These specifications are:

- Implementation of two different software applications: Home Monitoring Application and Web Server Application.
- Two modes of operation in the Home Monitoring Application: Full Control Mode and Wizard Mode.
- Standardization in data storage through EDF+ format.
- Functionalities of Electrical Bioimpedance measurement and data file management for the Home Monitoring Application. The file management includes creating EDF+ files with the measurements and patient data, encrypting the EDF+ files, encapsulating the EDF+ under XML format and sending the XML files to a remote server.
- Measurement visualization by the Full Control Mode
- Visualization of data recovered from the EDF+ files by the Full Control Mode and the Web Server Application. Comparison of different measurements.
- Secure communication with the remote server.
- An easy way for the patient to carry out the Bioimpedance measurements at home through the Wizard Mode.

It can be added that since this system can operate without the Evaluation Board for certain functionalities, like browsing among measurements, its portability has been increased.

6.2 Future Work

A step further for the system implemented in this thesis work would be providing it with more portability and autonomy, something that could be achieved by means of wireless capabilities. With this goal in mind, the system would require some changes in the hardware, as well as in the software.

Regarding the hardware, the power supply of the system would operate with batteries and the communication port would have to be adapted from a typical USB port to a Bluetooth-based communication port implementing the Serial Port Profile according to the Bluetooth specifications. This way, the system could be controlled from a Bluetooth-enabled computer or handheld device, such as *a* PDA, what would increase the portability and versatility of the system. These two enhancements are being implemented in two other final thesis works.

Since the intended platform to install the software would be a PDA or handheld device, the user interface should be adapted to OS running in the handheld.

Once the system was completed and integrated, it should be possible to perform Electrical Bioimpedance monitoring in patients during normal activity or even at remote locations. This way enabling e-health applications like televisit and telemonitoring.

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SUMARY IN SPANISH

Implementación de un Sistema de Medida de Bioimpedancia Eléctrica para la Monitorización de la Función Renal.

Este Proyecto Fin de Carrera consiste en la implementación de una aplicación software aplicada a un Sistema de Medida de Bioimpedancia Eléctrica para la monitorización de la función renal. Dicho sistema parte de la tarjeta de evaluación de Analog Devices que contiene el Analizador de Redes Conversor de Impedancia AD5933.

El nuevo sistema tiene como objeto proporcionar a los pacientes sometidos a diálisis peritoneal que llevan a cabo el tratamiento en su propio hogar el mismo nivel de atención médica que el obtenido con la hemodiálisis llevada a cabo en los centros médicos.

El principio de monitorización en el que se basa el sistema de medida de Bioimpedancia eléctrica es el siguiente: cuando se produce el fallo renal, la cantidad de fluido intersticial de las extremidades aumenta, dando lugar al edema extracelular. Como consecuencia, se modifican las propiedades eléctricas del tejido, de modo que combinando medidas de Bioimpedancia eléctrica no invasivas con electrodos aplicados sobre la piel y análisis de espectroscopia de la Bioimpedancia eléctrica, dicho edema puede detectarse. Por lo tanto, los cambios que se manifiestan en la Bioimpedancia eléctrica de las extremidades pueden ser utilizados como un indicador eficaz para la detección temprana del fallo renal.

La aplicación software ha sido implementada en Visual Basic.NET y se divide en dos partes: la aplicación instalada en el ordenador del paciente; y la aplicación implementada en un servidor web. La primera de ellas tiene a su vez dos modos de funcionamiento: el modo de control total y el modo wizard.

El modo de control total proporciona las siguientes funcionalidades: medida de Bioimpedancia eléctrica, visualización inmediata de medidas y tratamiento de ficheros de datos. Ésta última incluye: la grabación de las medidas de Bioimpedancia junto con ciertos datos del paciente en ficheros EDF+; la visualización y comparación de las medidas grabadas en dichos ficheros; la encriptación de los ficheros EDF+ para mantener la privacidad del paciente; la creación de ficheros XML a partir de los ficheros EDF+; y el envío al servidor remoto de los ficheros XML. El modo de control total genera un fichero con varios parámetros que definen la medida de Bioimpedancia para que puedan ser utilizados en el modo wizard.

El modo wizard guía al paciente a través de los pasos necesarios para completar las medidas desde su hogar, aunque sólo se ha implementado con propósitos demostrativos, dado que no se han considerado los aspectos obligatorios de Ingeniería de Factores Humanos ni Usabilidad. Éste modo lleva a cabo las funcionalidades de medida de Bioimpedancia, creación de ficheros EDF+, encriptación de los mismos, creación de ficheros XML a partir de los ficheros EDF+ y envío de los ficheros XML al servidor remoto. Las interfaces que muestra este modo contienen, de manera muy gráfica, todas las instrucciones que el paciente ha de seguir para llevar a cabo sus medidas de forma cómoda y fácil desde su propio hogar.

La aplicación implementada en el servidor web permite al personal médico consultar la información enviada al servidor.

Con el funcionamiento de las dos aplicaciones, la instalada en el ordenador del paciente y la instalada en el servidor web, se podría llevar a cabo la teleconsulta.

El sistema utiliza el método de medida de cuatro electrodos, dado que con éste método se elimina la impedancia de polarización que aportan los eléctrodos, y de este modo ésta no contribuye al resultado de la medida.

El formato EDF+ (Formato de Datos Europeo) utilizado para almacenar las medidas es un formato diseñado para grabar cualquier grabación médica, tal como EMG, ECG, o en este caso, medidas de Bioimpedancia Eléctrica. Este fichero se almacena en ASCII y contiene una cabecera, dividida a su vez en dos cabeceras: la cabecera del fichero, que contiene diez campos diferentes con la versión del formato, la identificación del paciente, la identificación de la grabación, el tiempo de inicio de la grabación, el número de bytes de la cabecera, e información sobre las grabaciones de datos. En este caso, sólo hay una grabación de datos; y la cabecera de la señal. Hay una para cada señal contenida en la grabación de datos. También tiene diez campos con información sobre el tipo de transductor utilizado, la dimensión física, los valores máximo y mínimo obtenidos en la medida, el filtro utilizado y el número de muestras en la grabación de datos. Por último, el valor de cada señal obtenida se guarda justo después del último campo de su correspondiente cabecera de señal, en el campo grabación de datos.

Para lograr una comunicación segura durante el envío de datos al servidor remoto, las aplicaciones de cliente y servidor encriptan y des-encriptan respectivamente los datos con una clave común que sólo ellos conocen. El protocolo utilizado para implementar dicha comunicación segura es SSH. Con este protocolo, los ficheros XML se encriptan justo antes de enviarlos al servidor remoto, y se des-encriptan una vez llegan allí.

Dado que el sistema no cumple los principios de Usabilidad e Ingeniería de Factores Humanos, para comprobar su correcto funcionamiento se ha utilizado el circuito eléctrico equivalente del tejido humano. Éste modela el comportamiento eléctrico del tejido. Y los resultados obtenidos con las medidas se han comparado con los valores teóricos obtenidos con el la herramienta matemática MATLAB v7.0. De este modo se ha podido concluir que el sistema mide y muestra correctamente la Bioimpedancia Eléctrica.

Como propuesta de futuro, podría dotarse al sistema con mayor portabilidad y autonomía. Esto podría lograrse a través de una comunicación inalámbrica. De este modo, tendrían que realizarse cambios en el hardware y el software.

En cuanto al hardware, la fuente de alimentación del sistema operaría con baterías, y el puerto de comunicación USB tendría que adaptarse para operar como puerto de comunicación basado en Bluetooth. De esta manera, el sistema podría controlarse desde un ordenador habilitado para Bluetooth o un dispositivo de bolsillo, como una PDA, lo cual incrementaría la portabilidad del sistema**.**

Dado que el software se instalaría en una PDA u otro dispositivo de bolsillo, el interfaz de usuario debería adaptarse al nuevo dispositivo.

Una vez todo el sistema estuviera integrado, sería posible monitorizar la Bioimpedancia Eléctrica de los pacientes durante su actividad normal o incluso en localizaciones remotas. De éste modo se podrían llevar a cabo aplicaciones de e-health como televista y telemonitorización.